

AEDC-TR-00-5



**Radiatively Driven Hypersonic Wind
Tunnel (RDHWT) Program
Magnetohydrodynamic Accelerator Research
Into Advanced Hypersonics (MARIAH II)
Fiscal Year 1998 Annual Report**

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September 2001

Final Report for Period October 1997 through December 1998

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**ARNOLD ENGINEERING DEVELOPMENT CENTER
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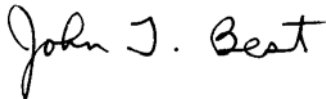
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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) January 8, 2000		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) October 1997 - September 1998	
4. TITLE AND SUBTITLE Radiatively Driven Hypersonic Wind Tunnel (RDHWT) Program Magnetohydrodynamic Accelerator Research Into Advanced Hypersonics (MARIAH II) Fiscal Year 1998 Annual Report				5a. CONTRACT NUMBER DE-AC22-96EW96405	
				5b. GRANT NUMBER 	
				5c. PROGRAM ELEMENT NUMBER 64759F	
				5d. PROJECT NUMBER 	
6. AUTHOR(S) Gloyd A. Simmons et. al.				5e. TASK NUMBER 	
				5f. WORK UNIT NUMBER 	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) MSE Technology Applications, Inc. P. O. Box 4078 Butte, MT 59702				8. PERFORMING ORGANIZATION REPORT NUMBER MSE-34	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Arnold Engineering Development Center/DOT Air Force Materiel Command Arnold AFB, TN 37389-9011				10. SPONSOR/MONITOR'S ACRONYM(S) 	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) AEDC-TR-00-5	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES 					
14. ABSTRACT This report documents the first year's progress on the research for the development of enabling technology for the design of a Mach 8-15 flight duplication wind tunnel. This research program is entitled the Radiantly Driven Hypersonic Wind Tunnel/Magnetohydrodynamics Accelerator Research Into Advanced Hypersonics (RDHWT/MARIAH II) program. Direction of the program is provided by the USAF Arnold Engineering Development Center (AEDC). MSE Technology Applications, Inc. (MSE) is serving as the program prime integrating contractor. Other key team members include the U. S. Department of Energy Federal Energy Technology Center (DOE-FETC), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), and Princeton University.					
15. SUBJECT TERMS test facilities, wind tunnels, hypersonics					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT None	18. NUMBER OF PAGES 338	19a. NAMES OF RESPONSIBLE PERSON Tom Fetterhoff, AEDC/XP
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) (931) 454-5870

ACKNOWLEDGEMENTS

Research documented in this annual report was funded through several U.S. Air Force (USAF) and National Aeronautics and Space Administration (NASA) organizations. Funding for the early research into radiative energy addition to a supersonic flow, conducted in the Radiatively Driven Hypersonic Wind Tunnel Program (RDHWT), was provided by the USAF Arnold Engineering Development Center (AEDC). Laser energy addition testing was conducted at the Air Force Research Laboratory ñ Wright Site (AFRL) with funding provided by AFRL and Princeton University. Funding for the 30-kW electron beam energy addition experiments at Sandia National Laboratories was provided by AFRL with supplemental funding provided by Princeton University. Funding for the NASA MARIAH Project was provided by NASA, and the research was performed under the direction of the NASA Langley Research Center. The USAF MARIAH II Program is funded by the USAF and directed by AEDC. Support is provided to the MARIAH II Program by AFRL through the loan of equipment for experimental research on energy addition to a supersonic flow. The U.S. Department of Energy Federal Energy Technology Center has been a participant in both the NASA MARIAH Project and USAF MARIAH II Program.

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This final report was produced by MSE Technology Applications, Inc., under subcontract with AEDC.

EXECUTIVE SUMMARY

This report documents the first year's progress on the research for the development of enabling technology for the design of a Mach 8-15 flight duplication wind tunnel. This research program is entitled the Radiantly Driven Hypersonic Wind Tunnel/Magnetohydrodynamics Accelerator Research Into Advanced Hypersonics (RDHWT/MARIAH II) program. Direction of the program is provided by the USAF Arnold Engineering Development Center (AEDC). MSE Technology Applications, Inc. (MSE) is serving as the program prime integrating contractor. Other key team members include the U.S. Department of Energy Federal Energy Technology Center (DOE-FETC), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), and Princeton University.

Background

Requirements and Needs – Numerous studies over the past decade or so have revealed a need for the United States (US) to develop military flight vehicles which fly at hypersonic speeds in the atmosphere to serve as transporters for space access; have capabilities of fast response, global reach (strike and reconnaissance); and to provide missile defense. Currently, the development of these various flight vehicles is constrained by the lack of ground-based development test facilities, which are considered necessary to provide affordable development testing (vs. flight testing) and to reduce technical risk to acceptable levels. Studies have revealed that the most pressing need is to develop ground based flight simulation to Mach 15 at flight dynamic pressures up to 2000 lbs/sq ft. This essentially covers flight-in-the-atmosphere test needs for most vehicle development test requirements.

Prior Facility Approaches/Deficiencies - Technologies for duplicating hypersonic flight conditions in ground based test facilities that will provide the required test environments and test time above Mach 7 have not been satisfactorily developed for many important applications. Electric arcs and compression heating have been employed to heat the test gas in a stagnation chamber and expand the test gas through a nozzle throat to the desired velocity. These techniques have proven to provide insufficient run time, unacceptable gas chemistry, and/or unacceptably low gas density in the test gas. Materials capable of withstanding the requirements of high stagnation temperatures and the severe nozzle-throat heat-transfer requirements limit practical run times to a few milliseconds or less at enthalpies required for flight duplication above approximately Mach 10. Consideration has been given to augmenting stagnation energy addition schemes with magnetohydrodynamic (MHD) augmentation. Again research has revealed shortfalls in this approach, mainly an inability to achieve needed flight duplication conditions. Other ideas have surfaced, such as the hypersonic sled track and gun launching, but none have been satisfactorily developed.

Facility Concept – The current facility research is based on the concept of adding energy to the test gas downstream of the nozzle throat thereby reducing the severity of the nozzle throat heat transfer problem and reducing/eliminating gas chemistry problems. The approach used was proposed in 1992 by Professors Richard Miles and Garry Brown, Princeton University whereby thermal energy is added by radiant means to the test gas. Current studies have determined that up to about Mach 12 flight duplication conditions can perhaps be achieved. Higher Mach number duplication is constrained in large part by practical design stagnation pressures and temperatures

of the ultra-high-pressure air supply. Because of this limitation and the need to achieve up to Mach 15 flight simulation, this program also includes research on MHD augmentation of the radiant energy addition process to achieve the Mach 12-15 test conditions.

Program Goals

Overall - The overall goal of this research program is to provide sufficient technology to define the concept design criteria for a medium scale hypersonic wind tunnel (MSHWT) based on future test requirements that are being defined as a part of this study. This means positioning to write design criteria for a MSHWT with all major component technologies demonstrated and exit criteria passed. Depending on funding, the research is expected to take 5-8 years to complete. The final product of this research is the design criteria for the MSHWT. Ultimately, a large scale Test and Evaluation facility may be needed. Thus, this research also keeps this application in mind.

Facility Performance Goals - The MSHWT performance goals are initially set based on requirements for air-breathing propulsion testing from Mach 8-15 and a flight dynamic pressure of 2000 lbs/sq ft. Air breathing propulsion test is considered the most demanding requirement compared to aerodynamic, aero-thermal, and aero-optic forms of testing. The test requirements studies in all these areas, which form a part of this program, will provide detailed facility performance and test criteria. For propulsion testing test time is a major parameter. Test times of several seconds to minutes are required for air breathing propulsion performance, operational, and durability testing.

Major Research Issues – The first year effort has identified major research issues in the areas of test requirements, ultra high pressure air-supply, nozzle survivability and performance, radiant energy addition, MHD augmentation, and test facility systems integration. These research issues are discussed in detail in the body of this report and in the Research Plan in the appendix. The Research Plan is a living guide to the program team for maintaining detailed focus on the research issues, demonstrations required, schedule requirements, and program cost.

Facility Research and Status

Test Requirements Definition - Aero-thermodynamic, aero-optic, jet interaction, propulsion, thermal-structure, and shroud separation tests are the total scope under consideration. However, the initial focus in this requirements study is on air-breathing propulsion testing, which drives the most demanding tests and the overall facility requirements. For airbreathing propulsion testing, studies are in progress to define test needs in terms of flight duplication test conditions including flow quality, facility size, and test times required to perform performance, operability, and durability testing. Results of these studies are expected in FY 00 and will be used to update the definition of the MSHWT. Test requirement studies for aero-thermodynamic and aero-optic tests will follow.

Ultra-High Pressure Air Supply - A dynamic pressure intensifier concept for the UHP air supply for a hypersonic wind tunnel has been selected for development after consideration of other approaches such as air storage systems. This concept meets the primary design requirements of plenum enthalpy in excess of 2,500 kJ/kg, run times of 1,000 sec or more at mass flow rates of pure air of 100 kg/s, and spatial and temporal flow quality. Use of existing engineering

technology and materials for most components provides affordability at moderate risk. The evaluation of several alternative concepts resulted in the selection of a configuration having variably radially supported UHP intensifiers, each with a working volume of approximately 0.03 m^3 arrayed in radial symmetry around an axial manifold. The nominal design point for the plenum is 2,000 MPa at 900 K with an air density of $1,150 \text{ kg/m}^3$ and a specific enthalpy of 2,500 kJ/kg. An array of four intensifiers, each with an internal diameter of 93 mm and a working volume of $3.8(10^{-3}) \text{ m}^3$, provides a run time of approximately 1 s at a mass flow rate of about 10 kg/s through a 3 mm diameter throat. These intensifiers and their radial hydraulic support manifolds are driven by an intermediate pressure system consisting of at least eight intensifiers, which produce a maximum 300 MPa pressure. The energy originally is stored in compressed nitrogen in a large volume ($30\text{--}50 \text{ m}^3$), ASME-approved pressure vessel at a minimum pressure of 35 MPa.

Nozzle - Nozzle survivability, especially for nozzle throats, and nozzle boundary layer properties have been identified as the major issues. Conventional wind tunnel nozzles for hypersonic wind tunnels are exposed to the full stagnation conditions of very high enthalpy and high pressure. The nozzle in this facility concept is exposed to the stagnation conditions mentioned above which represent a much lower enthalpy, but much higher stagnation pressures compared to conventional wind tunnel nozzles for a given flight duplication condition. Experience with nozzle survivability under these different flow conditions currently is non-existent. Thus, experiments have been identified and planned to quantify how serious heat transfer, erosion, and oxygen fugacity threaten nozzle survivability for a variety of nozzle materials. Also, helium film cooling is considered as an alternative if needed. The nozzle flow will be at a Reynolds number of about 10^{10} which is much higher than heretofore experienced anywhere. Experiments are planned to measure boundary layer growth rate and properties for the validation of boundary layer models needed for nozzle design. These experiments are designed, hardware fabricated and installed at Princeton University and will be conducted in FY 99 and 00.

Energy Addition - The heart of the MARIAH II/RDHWT concept lies in the controlled addition of large amounts of energy to a supersonic air flow. In the initial portion of the supersonic flow, thermal energy is added through radiative processes, and followed in the hypersonic region by MHD acceleration to achieve the maximum possible performance. Three approaches to thermal energy addition are being explored: 1) e-beam, 2) lasers, and 3) microwaves. The major challenge in all three cases is to add energy to the supersonic flow with acceptable flow quality for hypersonic testing over long test times. This means that the energy must be added in a uniform, predictable, and stable manner, and the chemical properties of the flow must be maintained as closely as possible to those of atmospheric air, particularly for tests of aeropropulsion systems. The initial approach is to demonstrate controllable energy addition in small-scale, low enthalpy flows, and then move to progressively larger scales. To date, laser experiments at the 10-kilowatt level and e-beam experiments at the 30-kilowatt level have been accomplished and are discussed in this report.

Proof-of-principle laser energy addition experiments at the 10-kW level were conducted in the LHME facility at WPAFB demonstrating controlled, stable laser energy addition to a supersonic flow. These successful experiments were conducted with a 10-kW continuous wave CO_2 laser using a nitrogen flow seeded with trace quantities of SF_6 for absorption of the radiant energy.

Also, stable energy addition by e-beam heating was successfully demonstrated using a 1-MeV e-beam at power levels from 50–100 kW. Changes in Mach number, total enthalpy, and power absorbed were measured on the centerline of the nozzle flow. Absorbed power was measured to be 10 kW for the 50 kW beam power and 40 kW for the 100 kW beam. Time resolved shadowgraph images show a steady transition from the unheated flow to the e-beam heated flow, thereby demonstrating that on the time scale of these experiments, a stable flow with a higher total enthalpy was achieved with heat addition from an e-beam. The experiment demonstrated the successful injection of a high-power relativistic e-beam into an axial magnetic field and subsequent transport of the beam through dense air with focusing as the beam traveled. Subsequent experiments are planned to demonstrate energy addition at enthalpies representative of hypersonic flight and beam power up to 10 MW, assuming intermediate power experiments are successful.

Microwave energy addition to the supersonic airflow has also been considered for application in the MARIAH II/RDHWT facility. Microwave energy addition, although having some merit, appears to be the least promising of the three technologies for this application. Large uncertainties associated with the absence of a compelling energy coupling mechanism by which that energy will be deposited into air, complexities in beam coupling into the flow facility itself, and issues associated with the development of shorter wavelength sources has led to the recommendation that the microwave research be placed on hold at this time. This currently leaves the laser and electron beam as the most probable choices for the thermal energy addition. Current plans are to continue to explore both approaches and select one based on technical viability and capital cost.

MHD Augmentation – MHD augmentation was explored as a means of extending the flight Mach number to Mach 15. The initial modeling study results, which were not optimized, revealed that Mach 14.3 could be obtained. MHD augmentation, for the facility performance goals defined, requires enhancing the electrical conductivity in the flow channel by some exterior means other than by the much explored concept of elemental seeding. The concept of enhancing electrical conductivity in the channel with electron beams was explored and found promising from analytical studies and experiments.

Systems Integration - The systems integration objectives are to ensure that the major components of the MSHWT are compatible with each other in terms of scale, operating regime, interfaces, stability of operation; most importantly, the total MSHWT system must meet its performance, operability, reliability, maintainability, and capital and operations cost requirements. Also, environmentally acceptable and safe operation of the MSHWT through compliance with environmental, safety, and health (ES&H) requirements and safe design and siting practices are required.

Computational models of subsystem components (such as the UHP air supply, nozzle, thermal energy addition, and MHD subsystems) are being used to investigate system performance and subsystem interface issues. Experiments are being designed to evaluate subsystem interface issues while investigating and demonstrating component performance. Integrated system-level cost models are planned to be used to analyze tradeoffs between system cost and performance as well as estimate integrated MSHWT system costs.

A preliminary system performance analysis of a MSHWT has been performed. This indicates that the system goals can possibly be met with e-beam energy addition for the Mach 12 flight conditions and with MHD augmentation for the Mach 15 conditions. With only e-beam heating, the MSHWT is calculated to be capable of test conditions to Mach 12.2 for the 2,000 psf dynamic pressure and Mach 12.7 for a 500 psf dynamic pressure. With MHD augmentation, the analysis indicated Mach numbers up to 14 are perhaps possible. Higher Mach numbers may be possible once the system is optimized.

Concluding Remarks – This first year's work has provided the definition of a needed medium scale hypersonic wind tunnel (MSHWT) with goals of Mach 8-15 flight simulation performance. The exact test time capability and size will be established based on the results of test requirements studies in progress. The major enabling technologies required for the MSHWT have been identified, a research plan and roadmap prepared, and experiments/demonstrations performed in energy addition in supersonic flow via laser and electron beams. The air supply concept has been selected and plans made to demonstrate and validate the approach. Two major culminating demonstration experiments are planned in the program to validate facility system level design, i.e. a full Mach 12 enthalpy 10 MW radiant energy experiment and a MHD augmentation experiment. This program is estimated to take approximately eight years to complete.

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1.0 INTRODUCTION

The U.S. Air Force (USAF) is sponsoring the Magnetohydrodynamics Accelerator Research Into Advanced Hypersonics, Radiatively Driven Hypersonic Wind Tunnel (MARIAH II/RDHWT) Program to develop enabling technologies and conceptual design criteria leading to the design, fabrication, and operation of a Medium-Scale Hypersonic Wind Tunnel (MSHWT) with Mach 8–15 test capabilities. Direction of the program is provided by the USAF Arnold Engineering Development Center (AEDC). This research was initiated in Fiscal Year (FY) 1998 and is based on prior research sponsored by the USAF and National Aeronautics and Space Administration (NASA) on supersonic thermal energy addition (then called radiant heating) and magnetohydrodynamic (MHD) energy addition, respectively. The MARIAH II Program is expected to require approximately 8 years and could lead to the development of a follow-on larger test and evaluation (T&E) facility.

This report addresses the period of performance from October 1997 through June 1999. In addition, closely related and prior research conducted under the sponsorship of other organizations is also reported in this document where appropriate. Prior research includes demonstrations of laser heating of a supersonic air flow by Princeton University conducted at and sponsored by the Air Force Research Laboratory (AFRL), Wright Patterson Air Force Base (WPAFB). Electron beam (e-beam) heating of a supersonic airflow was demonstrated by Princeton University and Sandia National Laboratories (SNL) at the SNL facility in Albuquerque, New Mexico, under the sponsorship of AFRL. These crucial experiments provided an experimental basis for the technologies and concepts to be developed through the MARIAH II/RDHWT Program. Since the results of these experiments are critical to the research in this program and have not been formally documented prior to this report, they have been included herein.

Other prior research documented in this report includes the development of a high pressure, blowdown test facility by Lawrence Livermore National Laboratory (LLNL) using funding provided by AFRL and installation of this facility in the high-pressure laboratory at Princeton University using funding provided by the University. This facility is to be used for conducting high-pressure, high Reynolds number, nozzle boundary layer research for the MARIAH II/RDHWT Program. Development and installation of this facility is documented in this report because of its importance to the research in the MARIAH II/RDHWT Program. Other research included in this annual report was conducted under the sponsorship of the USAF through the MARIAH II/RDHWT Program.

Accomplishments during the first year of the program include both experimental and computational evaluations of key technologies, development of computational models, performance analysis of an MSHWT system concept, ultrahigh-pressure (UHP) air supply concept development, and program planning. Based on UHP trade studies that were performed during this reporting period, a concept was selected, and conceptual and preliminary designs were conducted. Section 5 provides a detailed overview of the various UHP driver concepts considered, the analysis leading to the down selection, and computational results of structural and thermal studies of the selected concept.

Issues related to the primary nozzle leading from the UHP plenum section into the thermal heating section are discussed in Section 6. A nozzle survivability research plan was defined during this program year. Nozzle boundary layer research was initiated with the transfer of a high-pressure blowdown test facility from LLNL to Princeton University. A high-pressure laboratory was prepared at Princeton University to house the blowdown facility. Section 6 also reports on prior high-pressure, high-temperature nozzle materials research that was conducted in a high-pressure facility in Novosibirsk, Russia.

Computational models for evaluating e-beam thermal energy addition to the supersonic nozzle flow were developed and used for evaluating data from the 30- kW (nominal) e-beam experiments and for designing the 100-kW e-beam experiments (see Section 7). Electron beam and MHD performance models were used to evaluate MHD accelerator concepts and flow regimes (see Section 8). An electrical conductivity test cell was used to experimentally determine the electrical conductivity enhancement that results from absorption of e-beam energy in room-temperature air. Electron-beam models were also used to evaluate the test data from this test cell. The experiment and data analysis are discussed in Section 8.

A preliminary system analysis for an MSHWT was initiated to evaluate the performance of the system with thermal energy addition alone (that is, no MHD augmentation) to produce target free-stream test conditions up to Mach 12 with a dynamic pressure of 2,000 psf. Performance of the same system with MHD augmentation was evaluated for simulating target test conditions behind a bow-shock wave at a free-stream Mach number of 15 and the same dynamic pressure. The preliminary MHD analyses were performed for simulation of free-stream rather than post-shock wave conditions. Future analyses will investigate the MHD performance for simulation of post-shock conditions. These analyses are reported in Section 9.

Program planning conducted during the year included the development of a program research plan and preparation of a work breakdown structure (WBS) and a road map (schedule database). In addition, plans for a hypersonic facilities requirements study were developed and initiated. The program planning activities are discussed in Section 4.

2.0 OVERVIEW

2.1 BACKGROUND

A need exists for the United States to develop flight vehicles that fly at hypersonic speeds in the atmosphere, serve as transporters for space access, and have capabilities of fast response, global reach (strike and reconnaissance), and missile defense. Currently, the development of these various flight vehicles is constrained by the lack of ground-based test facilities, which are considered necessary to provide affordable development testing (versus flight testing) and reduce technical risk to acceptable levels. The United States does not have adequate test facilities that can be employed for development and qualification testing of air breathing propulsion flight systems at the necessary flight simulation conditions above Mach 4. Technologies are available for building adequate development and qualification test facilities to Mach 7 but not beyond where some systems would fly (perhaps as high as Mach 20). It is critical that the environment of hypersonic flight be simulated and actually duplicated for most cases in terms of velocity, temperature, pressure, air chemistry, scale, and test time.

To date, technologies for duplicating hypersonic flight conditions in wind tunnels that will provide the required test environments have not been satisfactorily developed. There have been two major technical obstacles to the development of these hypersonic wind tunnels: 1) providing sufficient energy into the air; and 2) the availability of materials that will contain the high temperature, high pressure test gas. Conventional approaches (that is, electric arcs, combustion heating, and compression heating) have been employed to heat the test gas in a stagnation chamber and expand the test gas through a nozzle throat to the desired velocity. These techniques provided insufficient run time, unacceptable gas chemistry, and/or unacceptably low test gas density. Practical run times are limited by materials capable of withstanding the requirements of high stagnation temperature and pressure.

The USAF MARIAH II/RDHWT Program is an outgrowth of previous research studies sponsored by NASA and USAF. Research into the feasibility of using radiant or beamed energy for heating a supersonic flow to produce hypersonic flight test conditions was initiated by USAF as the RDHWT Program in the early 1990s. This program led to proof-of-concept laser heating experiments in 1997 and e-beam heating experiments in 1998. The NASA MARIAH Program was initiated in 1995 to investigate the feasibility of MHD augmentation of hypersonic wind tunnel drivers to produce high Mach number hypersonic flight test conditions. In 1998, the concepts developed under these two programs were merged to form the basis of the MARIAH II concept, and the USAF MARIAH II/RDHWT Program was initiated to perform the necessary R&D to mature this concept. An overview of these prior programs and the MARIAH II/RDHWT Program is presented below.

2.1.1 NASA MARIAH Program, 1995-1997

MSE Technology Applications, Inc. (MSE) initiated the NASA sponsored MARIAH Project in April 1995. The overall objective of the MARIAH Project was to investigate the feasibility of augmenting hypervelocity wind tunnels with MHD technology. The research was performed under the direction of NASA Langley Research Center (NASA-LaRC) (Ref. 1).

The basic requirements of the MARIAH Project were established by conducting a review of the literature of hypersonic ground test facilities, as well as through extensive discussions between MSE, NASA-LaRC, and other members of the hypersonic community. The project's basic requirements were as follows:

- The facility should be a “T&E” facility capable of test durations on the order of tens of seconds to minutes.
- The facility should be capable of testing near full-scale advanced air-breathing engine modules. An 80-ft² test section was selected as the target.
- The facility should be capable of simulating true total enthalpy and thermodynamic conditions implying that post-bowshock Mach numbers, total enthalpies, and entropies must be duplicated. Specifically, the facility must be capable of matching post-bowshock conditions corresponding to a 2,000- lbf/ft² free-stream dynamic pressure with a 5-deg deflection angle shock up to a free-stream Mach number of 16.
- The facility should be capable of providing an airstream chemistry corresponding to the post-bowshock regime of hypervelocity aircraft (that is, minimal dissociation, vibrational nonequilibrium, and contaminants).
- The facility should be a true “T&E” facility implying high testing throughput, high reliability/lifetimes for critical components, and MHD accelerator versatility across a wide range of pressures and Mach numbers.

MSE investigated three separate approaches to satisfying these requirements including 1) classical high temperature, arc heater-driven MHD accelerators utilizing alkali metal seed; 2) unseeded arc heater-driven MHD accelerators with beamed energy addition; and 3) a preliminary investigation into the combined MHD and RDHWT concept now referred to as the MARIAH II/RDHWT concept. Each has the common feature of MHD acceleration of air but differs in the type of upstream driver used, the operational pressure/temperature regime, and the mechanism for the initiation and maintenance of accelerator electrical conductivity.

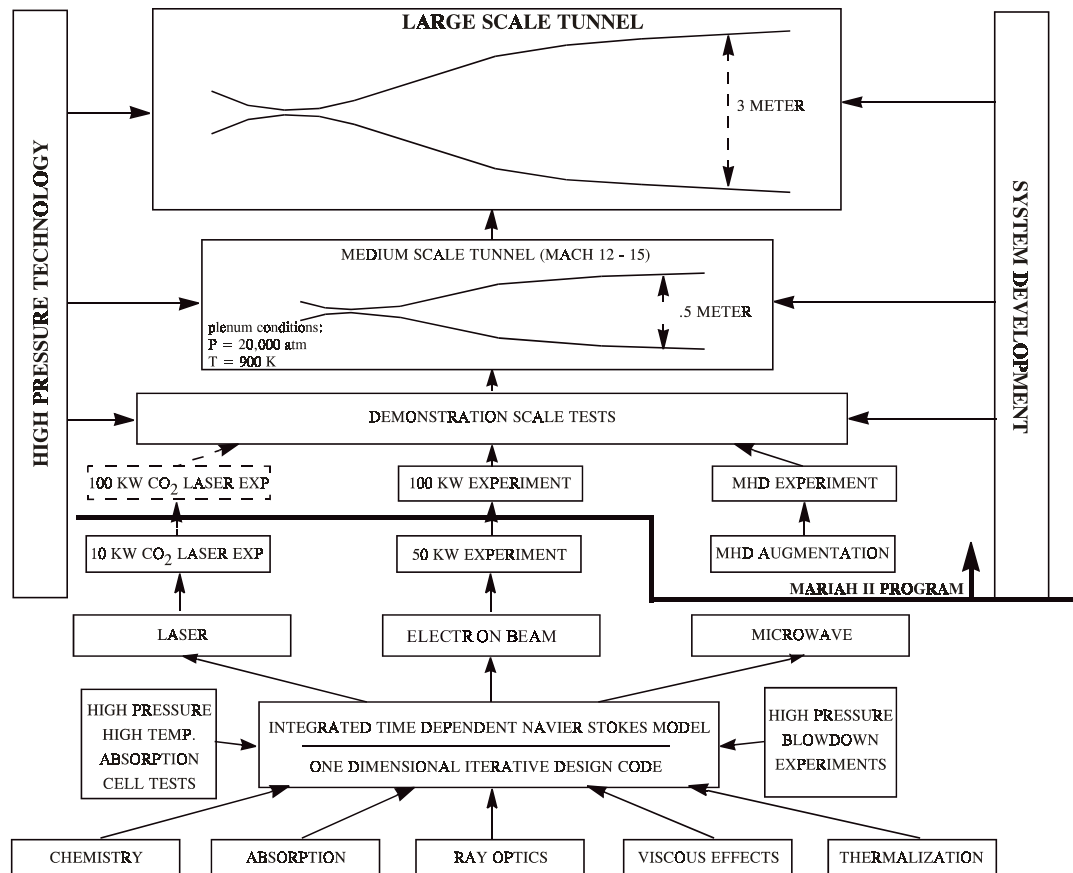
Classical high temperature, arc heater-driven MHD accelerators utilizing alkali metal seed material was the NASA MARIAH Project's most extensively evaluated approach. Several analytical, parametric, and optimization studies of this approach were performed assuming advanced arc heater, high field strength magnet, and relatively conventional, linear, segmented Faraday MHD channel technology. Experiments were also conducted at both the NASA Ames Research Center (NASA-Ames) and the University of Texas at Arlington (UTA). Seeded, arc heater-driven MHD accelerators were found in this study to be incapable of achieving the targeted NASA requirements but were shown to be capable of long-duration testing (on the order of minutes) producing simulated flight conditions currently unattainable with conventional technologies. The high operating pressures required by NASA resulted in significant difficulties for these types of MHD accelerators.

Based on the MARIAH Project's investigation of the three approaches for applying MHD technology for the augmentation of hypervelocity wind tunnels, MSE recommended the MARIAH II/RDHWT concept to be the most promising. MSE's preliminary analysis of this concept indicates it can potentially satisfy all of NASA's target requirements and represents the lowest risk approach to the problem. Therefore, MSE recommended a research and development (R&D) program based on the MARIAH II/RDHWT concept be undertaken to address the technology issues of this promising concept.

2.1.2 U.S. Air Force RDHWT Program, 1992–1998

The RDHWT concept was conceived at Princeton University in the spring of 1992 after it became clear that conventional wind tunnel facilities were inadequate for ground testing requirements above Mach 8 with adequate run time and flow quality for T&E aerothermal, air-breathing propulsion, and aero-optic testing. Early studies of concept definition and feasibility were conducted by two undergraduate students, Jeffrey Guest and Douglas Natelson, who established that such a concept was viable due in large part to the real-gas properties of air. A research program was initiated on August 1, 1992 under support from USAF AEDC. That support continued until November 30, 1996, after which funding continued through AFRL until September 30, 1998. This project was a collaborative effort involving substantive participation from the National Institute for Standards and Technology (NIST), LLNL, SNL, the High Energy Laser System Test Facility at White Sands (HELSTF), General Atomics Corporation, CPI Varian Associates, The Boeing Company, and several groups in Russia including the Institute for Hydrodynamics in Novosibirsk, the Avogadro Center, and the Central Aerohydrodynamics Institute (TsAGI).

Figure 2-1 is a block diagram indicating the various components of the RDHWT program. The funding from AEDC and AFRL supported fundamental research and concept development tasks, which are represented in the lower portion of Fig. 2-1. Early in the project, it became clear that the ultimate performance of the wind tunnel would be limited by the pressure attainable in the plenum section. Modeling of the tunnel performance required that the equation-of-state of air be extended beyond the range where experiments have been made and into the region of UHP on the order of 20,000 atm and beyond. That work was conducted through collaborations with NIST, as well as with groups in Russia. The practical limit of high pressure technology, including the identification of various design concepts for achieving UHP for significantly long (many seconds) run times, led to the participation of the Institute of Hydrodynamics in Russia and LLNL to examine the possibility of using "conventional" hydraulically driven pressure intensifying approaches, as well as and the participation of the Avogadro Center in Russia to explore unconventional approaches including explosively driven concepts. In addition, some work research was undertaken in collaboration with LLNL and the Institute for Hydrodynamics to study the survivability of various nozzle materials.



* Plenum conditions and sizes are approximate

Figure 2-1. Block diagram of the Hypersonic Wind Tunnel Program.

In order for this wind tunnel, the RDHWT concept, to operate successfully, a major fraction of the energy must be coupled into the flow downstream of the throat in the supersonic regime. This coupling must be accomplished in a uniform and stable manner to avoid unacceptable fluctuations of flow properties at the hypersonic test cell location. Since the air is in high-speed motion, the energy can only be added by radiative or particle beam processes. Three such processes were identified and researched in this project. These included lasers, microwaves, and e-beams.

After exploring the projected availability of high power laser systems and various energy coupling mechanisms, it was determined that the most promising laser-based approach was to use the high power hydrogen-fluoride laser, which would deposit its energy into the air through excitation of carbon dioxide molecules. Early work research in the program addressed the spectral overlap of the hydrogen-fluoride laser with the carbon dioxide molecular absorption, particularly at the high temperatures and pressures encountered in the nozzle. This research included a series of experiments conducted at the NIST Laboratory in Gaithersburg with temperatures ranging from room temperature to 1,000 K, and pressures ranging from atmospheric pressure to 1,000

atm. Simultaneously, a new theoretical approach was developed to predict pressure narrowing and other effects that occur under these conditions. Also associated with the laser research was a collaboration with SNL exploring the potential of developing nuclear-pumped lasers that may also be appropriate for this application. In addition, the collaboration with the HELSTF facility at the White Sands Proving Ground was established with the expectation of using their chemical laser systems for laser energy addition tests. The HELSTF laboratory undertook a modification of their 10-kW deuterium-fluoride laser system to convert it to hydrogen fluoride for this application; however, that conversion was not completed during the requisite contract period.

In order to establish the viability of predictably and uniformly adding energy to a high speed flow using a laser system, an experiment was conducted in December 1997 at the AFRL Wright Site using the 10 kW carbon-dioxide laser system at the Laser Hardened Materials Evaluation Laboratory (LHMEL) facility. This radiation is approximately 10.6 microns, rather than the 2.7 microns associated with the hydrogen-fluoride laser, and it is not absorbed by any naturally occurring molecules in air at low temperatures. Therefore, the airflow was seeded with sulfur-hexafluoride to allow energy deposition to occur. The results showed approximately 10 percent change in Mach number, which was temporally and spatially stable (as predicted), and validated the concept of controllable energy addition to supersonic airflows.

Microwave energy addition was explored through collaboration with General Atomics, and CPI Varian Associates, Boeing, and LLNL. Early in this research, the oxygen (O_2) absorption at 60 GHz was identified as a candidate for energy addition. It was clear, however, that this absorption is too weak to allow significant energy deposition into air with reasonable microwave fields. The possibility of increasing the conductivity of air using high energy e-beams was considered, but was temporarily not pursued because of the high e-beam power required and the system complexity. Furthermore, the complexity of coupling the microwave fields into the high pressure airflow was identified to be a major technological challenge. In contrast to lasers, microwaves cannot be brought in from the low pressure test section region since microwave radiation causes breakdown in low pressure air. Various alternate schemes to bringing microwaves in through the walls were proposed and explored in detail by General Atomics. The absence of a promising mechanism for energy deposition and the difficulties of coupling high power microwave radiation into the nozzle led to the decision to set microwave radiation aside (for the time being) as a practical approach for energy addition.

The concept of using e-beams for energy addition was not initially explored in detail since it was feared that the e-beams would cause significant chemistry to occur in the air and lead to a degradation of the flow quality. Given the many advantages of e-beams, including the potential availability of high power e-beam sources, this degradation of the flow quality may be a secondary factor. It is also important to recognize that the e-beam can be steered and focused into the nozzle using magnetic fields, a control factor that is not available in the case of lasers or microwaves. Under AFRL support and in close collaboration with SNL, the possibility of using e-beams for energy addition was explored in depth. This led to a series of experiments that were conducted in the summer of 1998 at SNL demonstrating that e-beams hold excellent promise and could be used as a driver for this wind tunnel concept. However, subsequent experiments and analysis are needed to validate acceptable gas (air) chemistry and flow quality.

2.1.3 MARIAH II/RDHWT Research Program

The 8-year MARIAH II/RDHWT Program is organized into two phases. Phase I is a 5-year program that develops the enabling technology for the air supply system, nozzle system, and thermal energy addition system including experimental demonstrations of these technologies, which are all necessary to achieve Mach 8–12 (or higher) flight simulation. MHD energy augmentation research will also be initiated in Phase I in preparation for MHD energy augmentation demonstration experiments to be conducted in Phase II. The goal of the MHD energy augmentation for the MSHWT is to achieve Mach 15 flight conditions. Phase II is a 3-year research program following Phase I. Phase II research includes preparation of final design criteria for the MSHWT. The program research requirements, experimental demonstrations, exit criteria, and deliverables are defined in the MARIAH II/RDHWT Research Plan (see Appendix A).

Limitations of stagnation heating approaches are potentially circumvented in the MARIAH II/RDHWT concept by adding energy directly to a supersonic flow. A possible scenario is that air from an UHP air supply, operating at 20,000 atm or greater and at relatively low stagnation temperatures (approximately 900 K) is expanded into a supersonic nozzle where energy is added by an e-beam or laser (the two potentially practical methods identified to date). Thermal heating increases the flow enthalpy to that of the desired test condition or MHD entrance condition but unfortunately, also substantially increases the entropy of the flow. An UHP air supply can provide a low entropy plenum condition and potentially allow radiant energy addition to the desired enthalpy without exceeding the entropy of the test condition. However, although a higher operating pressure and temperature than that described above would be desirable, existing materials and UHP technology constrain the air supply to operate below these approximate limits.

As required, the thermally heated flow is then accelerated in a MHD accelerator to achieve the higher flight Mach number, total enthalpy, and entropy conditions of interest. Following thermal and MHD energy addition, the flow is expanded by a nozzle to the required hypersonic velocity (or Mach number) and altitude simulation conditions. It is the intent and goal of this concept to achieve test conditions with good flow quality, little or no dissociated species, and near thermodynamic equilibrium for test periods of one second or greater.

Following prior year studies, initial analytical and experimental investigations of the MARIAH II/RDHWT e-beam energy addition concept were conducted during FY98 under the joint efforts of the MSE, SNL, and Princeton University. Initial one-dimensional (1-D) computer models of MHD and e-beam thermal energy addition processes were developed or improved at MSE and Princeton University and used to simulate the concept. Analyses using these models provided a preliminary assessment of the MARIAH II/RDHWT performance potential. The UHP air supply concepts were developed by LLNL. Initial performance calculations have revealed that the UHP air supply must operate at 20,000 atm or higher and 900 K or higher to achieve Mach 12 flight simulation with supersonic thermal energy addition. In addition, based on the idea of using e-beams to create electrical conductivity in relatively low temperature air, nonflow experiments were undertaken in FY98 to measure the nonequilibrium decay of electrical conductivity. This information is necessary to assess the potential of the MHD augmentation.

2.2 RESEARCH REQUIREMENTS

Research required to demonstrate technologies and establish design criteria for an MSHWT is defined in the MARIAH II/RDHWT Research Plan, Appendix A. The research plan defines analytical and experimental studies to develop and experimentally demonstrate an enabling technology for the design of all major components of the MSHWT system. Major components of this system, which require R&D have been defined as 1) the UHP air supply system, 2) the nozzle system, 3) the thermal energy addition system, and 4) the MHD accelerator. The research plan focuses on providing a hypersonic test capability for flight Mach numbers of 8–15 with dynamic pressure up to 2,000 psf. Good air flow quality (uniform spatial and temporal properties and “clean” air with little or no dissociation) and run time of seconds or greater are required. An MSHWT facility is envisioned to be constructed first and possibly followed later by a large-scale T&E facility. The MSHWT is envisioned to be a medium-scale T&E facility that would provide customer-useful ground-testing capability in addition to providing a demonstration and technical basis for a larger-scale facility.

The research plan provides for development of enabling technologies for the MSHWT in two phases (Phases I and II). Phase I is comprised of a variety of proof-of-principle experiments designed to validate computational fluid dynamics (CFD) performance predictions and demonstrate critical UHP air supply, nozzle survivability, supersonic thermal energy addition technologies, and establish preliminary enabling technologies for MHD energy augmentation. The culminating products of Phase I are 1) experiments that demonstrate thermal energy addition in supersonic flow to near Mach 12 enthalpy and flight altitude (or entropy) at an adequate scale to establish system feasibility; 2) UHP and nozzle system demonstrations at representative MSHWT operating conditions; and 3) performance analyses and design studies for MHD accelerators, which demonstrate the capability of MHD to provide near-Mach 15 test conditions. The UHP air supply system that provides the airflow for the megawatt level experiments is termed the “A-2”. (An ultrahigh-pressure intensifier used for research experiments in Russia was called the “A-1.” The “A-2” will be a second-generation pressure intensifier air supply that incorporates the findings of the Russian experiments.)

The culminating products of Phase II are development and demonstrations of critical MHD technologies and preparation of design criteria for the MSHWT. Goals for the MARIAH II/RDHWT research include the development and demonstration of the required technologies based on the following initial criteria:

- Achieving flight simulation conditions.
 - Free stream Mach 8–12 with 2,000-psf dynamic pressure and supersonic thermal energy addition. Definition of the limits of Mach number >12 simulation at less than 2,000 psf dynamic pressure is also required.
 - Simulation of post-bowshock conditions behind a 5-deg wedge for a free stream Mach 12–15 flight condition with a 2,000-psf flight dynamic pressure. This simulation is expected to require supersonic thermal energy addition with MHD augmentation. Definition of the practical operating envelope for MHD augmented flow is required.

- One second or greater usable test time.
- Near thermodynamic and chemical equilibrium airflow conditions in the test section with near air chemical composition. Spatial and temporal flow quality requirements are likely to be defined by the on-going requirements study.
- A 0.5- to 1.0-meter-scale test section for the MSHWT.

These guidelines result in nominal UHP plenum stagnation conditions of at least 20 kb pressure and 900 K temperature and serve as a guide to the design of the A-2 device. The A-2 device is to be sized based on the size and power requirements of the supersonic thermal energy addition demonstration experiments and the need to demonstrate the technologies at a sufficient scale to obtain design data for the MSHWT air supply. Although this device is not necessarily a model of the MSHWT air supply, it must demonstrate the critical technologies required for the MSHWT and serve as the air supply for the megawatt level energy addition experiments, high Reynolds number nozzle flow development studies, and validate prior nozzle throat survivability studies.

2.3 PROGRAM/TEAM ORGANIZATION

The MARIAH II/RDHWT Program is managed by USAF AEDC. AEDC provides management oversight for all aspects of the program including preparation of the program research plan, preparation of work statements, contracting, direction of work at national laboratories, and directing and conducting the hypersonic facilities requirements study.

MSE is the prime integrating contractor for the USAF MARIAH II/RDHWT Program with responsibilities including program management, system integration, MHD R&D, and preparation of design criteria. Princeton University, as a subcontractor to MSE, is responsible for nozzle system studies, thermal energy addition analytical/experimental studies, and technical guidance relative to the development of the UHP air supply system.

Significant parts of the MARIAH II/RDHWT Program research are being conducted at SNL and LLNL. SNL is designing and performing critical e-beam thermal energy addition demonstration experiments and supports the MHD portion of the program with defined studies and experiments to investigate and demonstrate e-beam enhanced electrical conductivity in air. SNL is also responsible for developing high-power e-beam accelerators for thermal energy addition experiments, preparing design criteria for a MSHWT e-beam accelerator, and designing and fabricating e-beam accelerators for MHD sidewall demonstration experiments. LLNL is responsible for the UHP R&D, design and fabrication of the A-2 UHP air supply (including the plenum and nozzle throat), and design criteria for the MSHWT UHP air supply system. LLNL is also responsible for developing and experimentally demonstrating nozzle throat survivability criteria.

2.4 OVERVIEW OF CONCEPT AND OPTIONS

Technologies for duplicating hypersonic flight conditions in wind tunnels that will provide the required test environments above Mach 7 have not been satisfactorily developed. There have been

three major technical obstacles to the development of these hypersonic wind tunnels: 1) providing sufficient energy into the air; 2) maintaining correct air chemistry; and 3) availability of materials that will contain the high-temperature, high-pressure test gas. Electric arcs and compression heating have been employed to heat the test gas in a stagnation chamber and expand the test gas through a nozzle throat to the desired velocity. These techniques provided insufficient run time, unacceptable gas chemistry, and/or unacceptably low gas density in the test gas. Materials capable of withstanding the requirements of high stagnation temperatures and the severe nozzle-throat heat-transfer requirements limit practical run times to a few milliseconds or less at enthalpies required for flight duplication above approximately Mach 10.

Adding energy to the test gas downstream of the nozzle throat has been considered a possible solution to the nozzle-throat heat-transfer and chemical-dissociation problems. Two ideas have emerged: 1) adding thermal energy to the supersonic test gas by radiant energy means and expanding to the desired velocity, pressure, density, and temperature; and 2) MHD body force acceleration of the test gas followed by an isentropic expansion of into the test section. Both ideas have their respective physical constraints. Radiant heating requires a UHP driver operating to 20,000 atm (near the practical limit of materials) just to achieve Mach 12 simulation at the correct gas entropy. Higher-Mach number duplication would require even higher pressure, which raises additional questions relative to high-pressure generation, containment, and run time.

The MHD approach requires that the test gas be electrically conductive. Seeding the test gas with an alkali metal such as potassium or cesium to achieve the necessary conductivity has been successfully demonstrated at relatively low pressures, provided static temperature is of the order of 2,800 K or greater. However, such high static temperatures have been shown to be impractical for achieving the required flight duplication conditions (Refs. 1, 2). In addition, in the case of engine testing, the alkali metal seed introduces a confounding factor into the test results, inasmuch as it may affect the combustion chemistry and/or ignition times in an unpredictable manner. However, if a means can be found to maintain electrical conductivity at low temperature without undesirable chemistry effects on the test gas, MHD would be attractive. Recently, seeding the gas with an e-beam has been proposed (Refs. 2, 3).

A hybrid concept of coupling supersonic thermal energy addition by radiant means with MHD augmentation may be the optimum approach. This would reduce the pressure requirements on the UHP air supply and also provide a broader range of needed hypersonic test capabilities. Figure 2-2 shows a schematic layout of the MARIAH II/RDHWI concept. In this scheme, supersonic thermal energy is supplied by an e-beam. The thermal energy addition is augmented by an MHD accelerator located downstream of the primary nozzle. For comparison, a conventional wind tunnel concept is also shown. In this case, the thermal energy is supplied ahead of the nozzle at near stagnation conditions by some form of thermal energy addition to the test gas. In Fig. 2-3 the performance of a wind tunnel employing radiant energy addition at supersonic conditions is compared with continuous and blowdown facilities that employ conventional stagnation heating approaches. The latter class of facilities can produce test flows for relatively long test times and therefore is representative of typical hypersonic test and evaluation facilities.

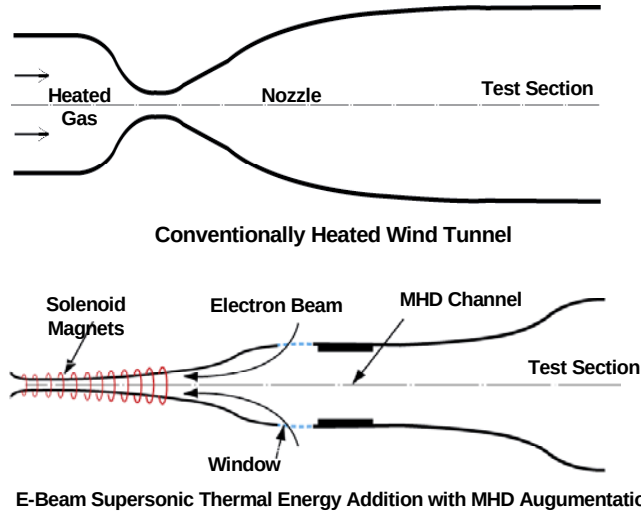


Figure 2-2. Comparison of a conventionally heated wind tunnel with the MARIAH II/RDHWT facility concept.

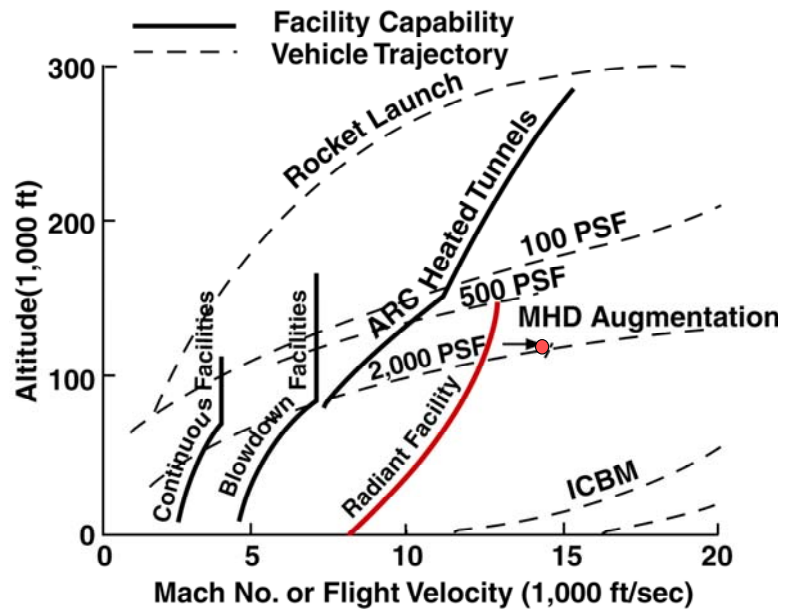


Figure 2-3. Comparison of conventional facilities with a facility utilizing radiant heat addition at supersonic conditions.

With MHD augmentation, some additional test capability appears possible for flight simulation altitudes above approximately 110,000 feet. A maximum Mach number of 14.5 has been calculated by Macheret et al. (Ref. 4) for a flight dynamic pressure of 2,000 psf (considered to be the lower altitude limit of manned air-breathing propulsion applications). At higher altitudes, the MHD augmentation is expected to provide somewhat higher Mach number capability.

The technology overview provided in Section 2.2 is amplified in later sections of this report. Detailed concept drawings of the prototype facility, design issues, performance analysis, and development of detailed analytic models for the energy addition and MHD processes are described in detail in Sections 5 through 8.

2.5 BRIEF OVERVIEW OF TECHNOLOGIES

In this section, the major components of the MARIAH II/RDHWT radiatively heated, MHD augmented hypersonic wind tunnel concept are described. The defined goal of the research program is to develop sufficient technology to prepare design criteria for a MSHWT that will provide true temperature test simulation at flight Mach numbers of 8–15 and a dynamic pressure up to 2,000 psf with adequate flow quality and run time. These conditions will provide a development test capability in the disciplines of air-breathing propulsion as well as aerodynamic, aerothermal, and aero-optical for the development of future hypersonic flight systems.

2.5.1 Ultrahigh-Pressure System*

The UHP system proposed for this application relies on plenum pressures in excess of 1,000 MPa. This system provides the required mass flow of air at a plenum condition having as high an enthalpy as possible. The plenum pressure and temperature operating point is a result of a trade-off between mechanical design, materials properties, energy addition capability, and technical risk. The UHP volume is defined by the plenum condition, run time, and the mass flow rate. Run times vary from a few hundred milliseconds for aerodynamic testing to seconds for propulsion testing to hundreds of seconds for systems testing. Mass flow rates follow from the size of the test section, the dynamic pressure at the test article, and the systems integration between the UHP and energy addition subsystems. In general, the UHP subsystem performance is in the direction of high pressure, high temperature, and large volume.

Large volume ($>1 \text{ cm}^3$) UHP design is a mature field, with materials performance as the primary technical issue. High pressure equipment operating at 1,400 MPa and room temperature is available commercially, and fluid pressures up to approximately 4,000 MPa are achievable in research laboratories. The limiting factor is the strength of the structural materials containing the pressure. Connecting volumes reliably at pressures above 1,400 MPa is difficult; therefore, research in the 2,000–4,000 MPa range has been limited to single manifold systems. Additionally, plenum temperatures above 600 K in a high-pressure gas result in degradation of material strength properties. Chemical reactivity of high-pressure fluid and the high performance alloys

* Portions of this section have appeared in Costantino (1999) [Costantino, Marc, "A Large Volume 2,000 MPa Air Source for the Radiatively Driven Hypersonic Wind Tunnel," International Conference on High Pressure Science and Technology, AIRAPT-17, Honolulu, HI, 25-30 July 1999].

containing it must also be considered. Since it is common for pressure vessels to operate in the plastic range, fatigue life can be a limiting factor for high cycle applications.

The UHP conceptual design must demonstrate the technologies for the operating envelope of the full-scale facility:

- Mach number 8–15;
- Pure air;
- Dynamic pressure: 500–2,000 lbf/ft²;
- Operational time: 1–100 seconds; and
- Air mass flow rate: 1–100 kg/s.

Trade-offs between the UHP and energy addition subsystems result in a nominal plenum operating point of 2,000 MPa and 900 K, with a specific enthalpy of approximately 2,500 kJ/kg (Ref. 5). The density of air at these conditions is approximately 1,150 kg/m³, which can be compared to the density of water at standard temperature and pressure (STP) (1,000 kg/m³) and liquid nitrogen (807 kg/m³). All of these issues are considered in depth in Section 5.

The high pressure, high temperature, large volume, and high O₂ partial pressure requirements for the UHP source results in extraordinary stress management and materials requirements. The primary design challenges for the UHP subsystem of the hypersonic ground testing facility are:

- Connecting UHP volumes;
- Materials strength at $T > 600$ K;
- Reactivity of O₂; and
- Controlling heat transfer from the dense air.

2.5.2 Nozzle System

The portion of the wind tunnel nozzle for a distance of approximately 1 meter downstream of the throat is called the UHP nozzle section. The primary technical challenges for the nozzle are:

- Containing 2,000 MPa air pressure at 900 K static temperature;
- Mechanical strength at high temperatures to carry 2,000 MPa uniaxial stress;
- Chemical reaction with high pressure, high temperature air, particularly at hot spots created by energy flux from the energy addition;
- Mechanical erosion resulting from large shear stresses at the nozzle wall;
- Surface roughness requirements for flows with Rhenium (Re) of approximately 10^{10} ;
- Injection of cooling film gas to manage the thermal load on the nozzle wall;
- Minimizing perturbation of a 7–20 T toroidal magnetic field at the throat (for the e-beam energy addition option);
- Integration with the downstream nozzle section;
- Mechanical erosion/heating resulting from e-beam or laser flux;
- Shape variation resulting from thermal and mechanical stresses;
- Inspection and replacement costs; and
- Damage control upon catastrophic failure.

A detailed discussion of design options and the design requirements for the nozzle is given in Section 6.

2.5.3 Radiant Energy Addition System

In the proposed MSHWT, beamed energy in the form of laser or e-beam radiation will be added downstream of the nozzle throat. Thus, the radiant energy addition section is an integral part of the nozzle. The operating characteristics of a T&E facility are critically dependent on the thermodynamic path followed by the air as it passes through the nozzle. A conventional wind tunnel has only one path, which is an adiabatic constant entropy expansion where the total enthalpy in the plenum is converted to kinetic energy and residual static enthalpy in the test chamber. In the MARIAH II/RDHWT facility, since energy is added downstream of the throat to avoid excessive nozzle throat heat transfer and flow nonequilibrium chemistry effects, there are an infinite number of thermodynamic paths that can be taken before the air arrives in the test section. A major challenge has been to determine which of these thermodynamic paths optimize wind tunnel performance and how closely these paths can be followed given the practical considerations of the nozzle contour, boundary layer growth rates, heat transfer to the walls, and thermal energy addition. Any thermal energy addition process increases the enthalpy, Δh , while simultaneously increasing the entropy, $\Delta s = \Delta h / T$.

The final operating point in the test facility can be represented as a single point on a Mollier diagram. Since the entropy of the flow cannot be reduced (heat cannot be extracted from a hypersonic flow except by radiation), any supersonic energy addition process requires that the initial flow must have entropy lower than the final state. It is this low initial entropy requirement that moves the process as far as possible to the left on the Mollier diagram and necessitates a UHP driver.

Energy addition to the flow by beamed energy is discussed in Section 7. Laser, e-beam, and microwave energy addition were investigated. Section 7 also discusses the down-selection from microwave energy addition. Laser energy addition experiments at the 10-kW level, e-beam experiments at the 30-kW level, and planned e-beam experiments at the 100-kW level are discussed briefly below and in detail in Section 7.

2.5.3.1 Supersonic Thermal Energy Addition

Three approaches have been studied for the addition of thermal energy to the supersonic flow. These include microwaves, lasers, and e-beams. While microwaves may be feasible in the long run, there are several unresolved technical hurdles that have led to deemphasizing the consideration of microwaves in the present study. These include the lack of a satisfactory mechanism for coupling microwave energy into air in a controllable fashion, complexities associated with passing microwave energy into the wind tunnel without initiating breakdown, and questions of wind tunnel scale in relation to the wavelength of currently available high-power microwave sources.

Both energy addition with lasers and e-beams are being pursued. These studies have led to two experiments at the 10-kW level over the past 2 years. Both of these experiments have

demonstrated that thermal energy can be added to supersonic flow in a controllable fashion, leading to a significant increase in total enthalpy and stable flow conditions.

The laser experiment was conducted using a 10-kW CO₂ laser facility at AFRL in Dayton, Ohio. The airflow was seeded with a small amount of sulfur hexafluoride, which is a strong absorber of 10.6-micron CO₂ radiation. Run times typically lasted one second or more, and the data acquired included shadowgraph movies, as well as static pressure measurements along the nozzle, and pitot probe and total temperature measurements at the exit. In this experiment, as with the following one using e-beams, the energy addition led to a predicted reduction in the Mach number since the temperature of the flow increased. The change in Mach angle indicates that Mach number dropped from 4.3 to 3.9. This agrees with predicted results if 8 kW of laser energy is assumed to have been absorbed. Shadowgraph images were taken at video framing rates and showed that the flow stability with energy addition was approximately the same as it was without energy addition (Ref. 6).

Electron beam energy addition experiments were conducted at SNL using their 0.9 MeV HAWK accelerator. In this case, the e-beam was operated with an energy on the order of 30 kW, but only ran for approximately one millisecond. Again, shadowgraph images were used to study shock angle variation and flow stability, but this time, in the 10–100 kHz rate. These images were taken using a new fast-framing CCD camera built by Princeton Scientific Instruments and on-loan from AFRL. A continuous wave argon-fluoride laser provided illumination. Static temperature measurements were made using a new LITA technique that measures the speed-of-sound over an approximately 300 nsec time interval at a point in the flow (Ref. 7). Flow velocity was measured using laser-induced breakdown. More conventional measurement devices intended to measure static pressure along the nozzle, total temperature, and pitot pressure, were less useful since they were subject to large background noise during the e-beam pulse arising from e-beam-generated X-rays.

The observed Mach number changed from Mach 3.9 to 2.7. This change corresponds to an estimated energy deposition into the flow of approximately 10 kW. A direct comparison with the computational model is difficult since much of the e-beam energy was deposited in the wall; therefore, a curve of the e-beam energy deposition profile in the gas could not be established with reasonable accuracy. Nevertheless, shadowgraph images indicated that a stable higher enthalpy flow was generated with e-beam energy addition (Ref. 8).

Both of these initial experiments are far from the regime where a test scale wind tunnel will operate. In order for these energies to produce a significant change in the static enthalpy of the flow, the enthalpy in the plenum was also very low compared to predicted test facility conditions. Pressures were held on the order of 1,200 psi, and the plenum temperature varied between room temperature and 400 K. The major reason for increasing the plenum temperature was to avoid condensation in the unheated flow.

Follow-on e-beam experiments are currently in the planning stages and are anticipated to step to the 100-kW level for the next set of experiments, followed by experiments at the megawatt or multimewatt level. The major objective of the 100-kW experiments is to exercise the technology necessary to focus e-beams into an appropriately scaled nozzle, contour the e-beam so

there is minimal wall heating, demonstrate uniform and stable addition of large amounts of enthalpy into supersonic air, and establish whether adequate flow chemistry is maintained through the energy deposition process. Control of the e-beam profile is expected to allow the energy to be deposited in the core of the airflow while maintaining an annulus of cold air to minimize wall heating problems. The megawatt level experiment is expected to simulate the full specific enthalpy of a medium-scale test facility.

2.5.4 MHD Accelerator System

The MHD energy addition process will be tightly constrained by the required channel inlet and exit conditions. The accelerator inlet conditions cannot be chosen arbitrarily by the MHD channel designer because they are largely dictated by the UHP plenum conditions and the ensuing beamed energy addition. However, system optimization can result in a trade-off between beamed energy addition in the nozzle and in the MHD channel, giving the designer some latitude in the entrance condition to the MHD subsystem. Similarly, the exit total conditions are constrained by the targeted test section conditions although static condition can be varied by selecting the desired exit velocity. The net effect of these constraints is that the allowable entropy increase through the MHD channel is rather tightly constrained, and, in general, must be kept to an absolute minimum. In a broad sense, the purpose of the MHD research is to define the “best” envelope of MHD augmentation through system performance trade studies and perform demonstration experiments to validate the proposed design concepts.

To obtain significant acceleration over a reasonable length, channel designers have historically relied on moderate magnetic fields and high current densities. Most MHD accelerators designed for continuous operation have also relied on the injection of an alkali metal seed to achieve the necessary conductivity levels. To ionize the seed, the gas must be heated to temperatures of 2,800 K or higher, which raises serious materials issues. For example, the MHD accelerators operated at the Central Aerohydrodynamics Institute (TsAGI) in Russia (Ref. 9) were seeded with a eutectic mixture of sodium and potassium and were run at current densities in the range 30–50 A/cm² with magnetic fields of less than 3 Tesla and static temperatures in the MHD channel approaching 4,000 K. The high current densities resulted in large Joule dissipation and relatively low conversion efficiency. While substantial velocity increases were demonstrated, the high Joule dissipation and resulting high exit entropy levels appear to preclude this type of MHD channel from being used to achieve the high total enthalpies and modest entropy levels required for advanced engine testing, although combustor testing may be possible. This point has been discussed in some depth in the literature (Refs. 1, 10, 11).

For this reason, the MARIAH II/RDHWT program has recently focused on an alternate method for sustaining the required conductivity through the MHD accelerator. The method relies on injection of high energy electrons into the air stream. The primary advantage is that this method achieves the required conductivity nonthermally, through the production of secondary electrons created by e-beam injection. This eliminates the requirement for an alkali metal seed, which in turn eliminates the need for high temperatures in the MHD channel.

An experimental effort, described in Ref. 12, has been initiated at SNL for measuring the electrical conductivity induced by e-beams passing through a static test cell filled with air. The

purpose of these experiments is to validate theoretical models of e-beam-induced conductivity, such as those described in Refs. 10 and 13. These experiments, as well as other aspects of the MHD accelerator, are described in detail in Section 8.

2.5.5 Systems Integration

Systems integration includes all of the tasks and activities necessary to ensure that major components of the MSHWT (such as the UHP supply system, the nozzle subsystems, the radiant energy addition subsystem, the MHD subsystem, etc.) are compatible in terms of scale, operating regime, and stability of operation and that the total system meets its performance requirements. The system integration studies span the full 8-year program. The system integration issues are described in detail in Section 9.

2.5.5.1 Key Systems Demonstrations

In general, systems integration issues (like most others) are resolved either through analysis or through experiment. Certain experimental demonstrations at the system level must be performed prior to design of the MSHWT. In general, this testing will be done at a reduced scale and will have the two objectives of establishing the credibility of the analytical simulations and resolving scaling and performance issues. Table 2-1 summarizes both the testing accomplished to date as well as the tests presently planned for the balance of the 8-year program.

Table 2-1. Summary of System Testing for the MARIAH II/RDHWT Program

Test Name	Objectives	Primary Interfaces	Remarks
10 kW Laser Energy Addition Test	Demonstrate laser energy deposition in a supersonic air stream.	Nozzle – laser beam	Completed 12/97
30 kW E-beam Energy Addition Test	Demonstrate e-beam energy addition in a supersonic flow.	Nozzle – E-beam Magnet – Nozzle	Completed 7/98
Static Cell Conductivity Tests	Measure the electrical conductivity induced by an e-beam passing through a static test cell.	E-beam – Window	Phase I completed 7/99 Phase II to commence 1/00
100 kW E-beam Energy Addition Tests	Demonstrate stable energy absorption at high power Demonstrate beam contouring and focusing. Measure chemistry effects.	Nozzle – E-beam Magnet – Nozzle	Testing to commence 11/99
MHD Sidewall Demonstration Experiment	Design and fabricate an MHD sidewall section for e-beam seeding. Demonstrate multiple beam injection and electron beam seeding.	E-beam – Window	Testing to commence mid-2000.
Checkout of the A-2 UHP Facility	Design verification tests	Nozzle – UHP	Early 2002
10 MW E-beam Energy Addition Tests	Demonstrate e-beam energy addition and beam contouring at prototypic conditions	Magnet – Nozzle – E-beam	Late 2002
MHD Accelerator System Demonstration	Demonstrate (in an impulse facility) a subscale MHD accelerator that employs e-beam seeding.	E-beam – Window Nozzle – Accelerator Magnet – Accelerator MHD Power Supply – Accelerator	Testing to commence in 2003. Test planning to commence in 2001.

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3.0 HYPERSONIC FACILITIES REQUIREMENTS STUDY

3.1 BACKGROUND

An effort is currently underway by the AEDC Long Range Planning Office (XP) to define the future test conditions that will define the performance requirements for an aeropropulsion hypersonic test facility. Initial 1-year requirements studies are focused on facility run duration, facility thermodynamic operating conditions (Mach number, pressure, and enthalpy), and facility test section size for performance, durability, and operability testing of a high speed aeropropulsion system. These test requirements are essentially drivers of the facility performance requirements, which in turn will drive many aspects of facility research, development, and design.

The weapon systems to be tested in this facility remain visionary in nature and are not well defined. Classes of systems are identified below to define flight regimes and to size potential scramjet propulsion system concepts as a reference for the analysis tasks defined below.

The types of testing for hypersonic systems include aerodynamic, aerothermal, aero-optics, jet-interaction, impact/lethality, materials/structures, and aeropropulsion. A summary of the existing hypersonic test capabilities is shown in Fig. 3-1. This figure summarizes the capability shortfalls (gaps) that have been identified by comparing the forecasted future test requirements with the existing test capability. Based on the schedules of the forecasted systems/programs and their operating envelopes, some of these shortfalls present critical deficiencies.

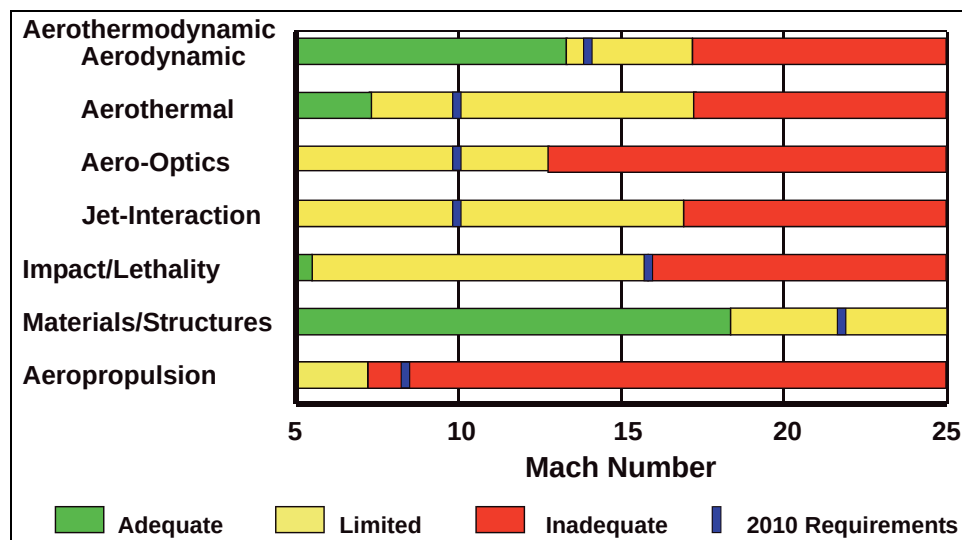


Figure 3-1. Summary of existing hypersonic test capabilities.

For instance, the need to conduct aeropropulsion testing, aero-optics testing and jet interaction testing at Mach numbers less than 8 requires immediate attention. The other shortfalls are noted for higher Mach number test requirements but are not as pressing from a schedule perspective. However, the approach to solving some of these shortfalls may require such large advances in the

state-of-the-art for facility design, construction, and operation that research in the near term is required to be ready to meet the test needs in the far term.

Since the aer propulsion is a compelling shortfall in the near term and over a wide range of Mach numbers above 8, this study will concentrate first on aer propulsion requirements. The other types of testing will also be evaluated with follow-on studies. However, satisfying the aer propulsion test requirements will likely support the other immediate shortfalls, such as aerothermal, aer-optics, and jet-interaction.

3.2 HYPERSONIC TEST REQUIREMENTS

The components of a typical asymmetric hypersonic aer propulsion system are shown in Fig. 3-2. Development of the aer propulsion system is accomplished by testing the individual components, multiple components, and the integrated system. Several different facilities are typically used in the development of these individual components. For example, the inlet may be tested in wind tunnels where true temperature conditions are not provided. However, true temperature conditions will be required for developing the combustor and associated combustion system (for example, fuel injection stages). Aerothermodynamic flight simulation capabilities (that is, encompassing aerodynamics, aer heating, fluid dynamics, and physical processes) (Ref. 1) are essential for development of advanced hypersonic systems. A developmental hypersonic ground test capability must be able to evaluate the integrated aer propulsion system performance, operability, and durability.

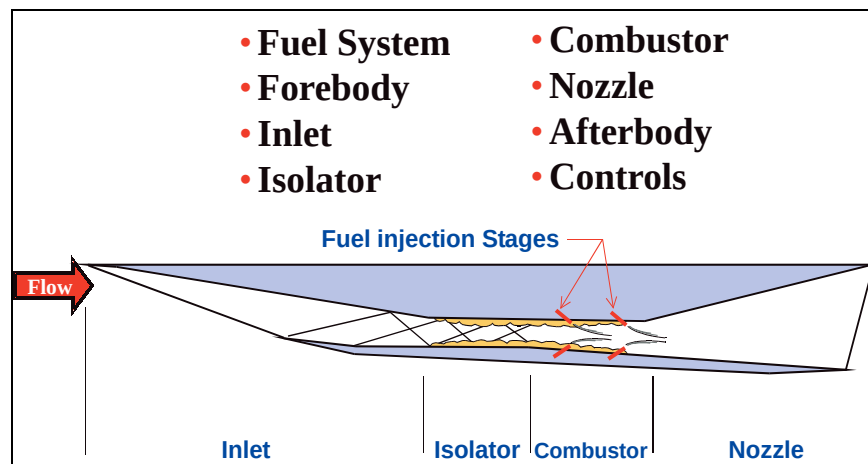


Figure 3-2. Hypersonic aer propulsion system components.

- Aer propulsion system performance entails measuring/assessing:
 - net thrust, specific thrust, and specific impulse;
 - net lift and moments;
 - mass capture; and
 - thermal balance.

- Aeropropulsion system operability entails measuring/assessing:
 - off design operation;
 - inlet starts, unstarts, and instabilities;
 - lightoff and blowout;
 - combustion stability and control;
 - fuel control;
 - inlet distortion (steady state and transient);
 - flight transients (maneuvers/atmospheric);
 - nozzle instabilities; and
 - thermal management.
- Aeropropulsion system durability entails measuring/assessing:
 - temperature limits;
 - thermal stresses and gradients;
 - acoustic loads;
 - mechanical stresses;
 - joints, fittings, and attachments; and
 - laminated material layers.

3.3 HYPERSONIC FACILITIES REQUIREMENTS STUDY

A hypersonic facilities requirements study, as described above, was initiated to define technical criteria for development of a T&E wind tunnel facility capable of testing visionary military systems that are expected to fly in the atmosphere and in the Mach 8 to Mach 15 regime. These technical criteria are needed to establish specific facility performance requirements that must be satisfied in the MARIAH II/RDHWT approach, evaluate other proposed facility concept approaches, and aid in advocacy of new hypersonic facilities.

Aerothermodynamic, aero-optic, jet interaction, propulsion, thermal-structure, and shroud separation tests are the total scope under consideration. However, the initial focus in this requirements study is on air-breathing propulsion testing, which drives the most demanding tests and the overall facility requirements. Facility Mach number, enthalpy, pressure, run time, flow path size, flow quality, test productivity, measurement capabilities, facility capitalization cost, and cost of testing are factors that must be considered in this analysis and study. The salient features and advantages of alternative facility approaches are to be identified and assessed.

An essential element of the project is a trade study of the weapon system development approach to be used by the weapon system Program Manager, depending on test facility capabilities that may become available. For example, could a weapon system Program Manager utilize a short-duration, full-duplication facility to establish air-breathing propulsion systems performance including ignition and start up, and use a longer-duration facility with less than full duplication to establish durability and operability of the same air-breathing propulsion system? Such less-than-full duplication might include chemical nonequilibrium, seed in the flow, and reduced total pressure corresponding to the flow behind one or more oblique shocks.

The requirements study, as envisioned, will accomplish the following:

- Identify potentially real and visionary hypersonic flight systems that will operate above Mach 8.
- Address the performance, operability, and durability test requirements for aerothermodynamic, aero-optic, jet interaction, propulsion, thermal-structure, and shroud separation classes of testing.
- Identify facility run-time, size, thermodynamics, chemical, and flow-quality requirements for testing potentially real and visionary systems.
- Assess the advantages and disadvantages of the various test facility approaches.
- Document the results of the requirements study in a formal written report.

3.4 HYPERSONIC SYSTEM REQUIREMENTS

A number of futuristic systems have been identified in the literature such as the USAF New World Vistas study (Ref. 2). These are manned and unmanned hypersonic vehicles to satisfy a number of missions against various potential threats. A hypersonic air-breathing missile is discussed in the Advisory Group for Aerospace Research and Development (AGARD) report, Aerospace Study 2020 (Ref. 3). A recent National Research Council Report of a Review and Evaluation of the USAF Hypersonic Technology Program infers that USAF would like to have an air-breathing Mach 8 missile by the year 2015 (Ref. 4). This report also envisions a number of other futuristic hypersonic technology applications beyond the Mach 8 missile. Access to space systems still rely solely on rocket propulsion to launch payloads into orbit. Rocket propulsion is currently the only logical means of providing space lift (Ref. 5); however, hypersonic air-breathing propulsion still holds an interest for these systems in the future. These futuristic concepts are still visionary ideas with an emphasis only in demonstrating the technology. None of these concepts are real system development programs with sufficient funding to produce a weapon system. The hypersonic air-breathing propulsion missile is the only potential concept that may evolve into real weapon development program in the near term. However, in planning for a new wind tunnel that takes 10 to 20 years to build, all the potential futures (Ref. 6) must be considered in its development. Figure 3-3 shows that facility acquisition time for major facilities at the AEDC has historically been very long. From this figure, it can be seen that a new conventional test facility has taken an average of 11 years to build. The acquisition of a new test facility should precede a weapon development program by several years prior to Phase 0 for it to be useful to a weapons system development cycle. Hence, the futuristic systems that are only in the minds of the visionaries must also be included in the facility development plan.

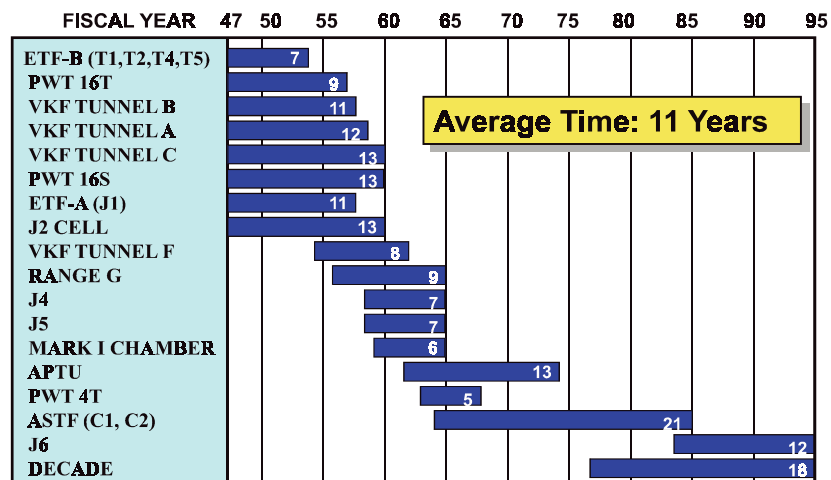


Figure 3-3. Major AEDC Test Facility acquisition time.

The system requirements will be discussed for three classes or types of systems. Once the classes or types of systems are defined, the required T&E capabilities can be defined by performing a gap analysis. The gap analysis in this case is merely a comparison of the existing capabilities with the T&E capabilities required. The process is shown in Fig. 3-4. In this process, the system requirements information is gathered from studies, long-range planning documents, Mission Need Statements (MNS), Mission Area Plans (MAP), and Technical Area Plans (TAP). The system requirements, along with the mission information, will identify the types of testing that will be required. An analysis of the system requirements and the types of testing required to evaluate the system will lead to identification of the test parameters that must be duplicated on the ground. These required test parameters (for example, Mach number, thermodynamics, flow path size, and facility run time) can then be compared to the existing T&E capabilities to identify the gap or shortfall.

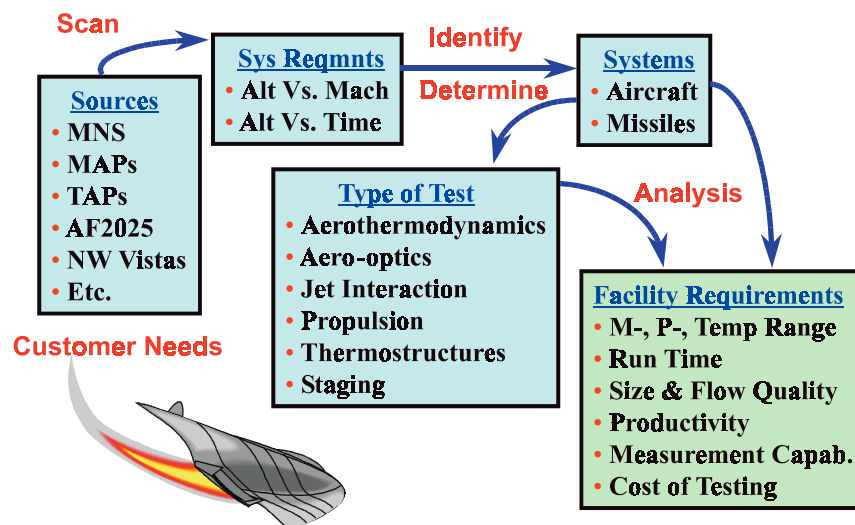


Figure 3-4. Process to determine test facility requirements.

For the initial study on air breathing propulsion test requirements, the systems will be divided into three types or classes of vehicles. They are tactical missiles (Refs. 3, 4), interdiction/reconnaissance vehicles (manned and unmanned), and fully reusable space lift vehicles (also, manned and unmanned) (Ref. 3).

Typical missile concepts are defined in Figure 3-5. These concepts are both launched from an aircraft. The first system is a Mach 6–8 hypersonic cruise missile. The missile weight is approximately 3,500 lb and uses endothermic hydrocarbon fuels and a fixed geometry scramjet propulsion system. The range of this missile is from approximately 800 to 1,200 nautical miles (nm). The second is a Mach 10 air launched guided vehicle weighing approximately 7,000 lb with a range of approximately 200–1,500 nm. A typical mission profile is shown in Fig. 3-6 (Ref. 4). The smaller missile system would be launched from a fighter or bomber in a conventional manner. This missile would likely be used on time critical targets. The larger missile system may have a similar mission profile but for hardened targets.

- **Tactical Missile Concepts - Near Term**
 - **Fast-Reaction, Precision Air Intercept, & Air-to-Surface**
 - **Endothermic Hydrocarbon Fuels**
 - **Air Launched from any Platform - Fighter or Bomber**
 - **Cruise at Mach 6-8 at an Altitude Above 100k ft**
 - **Range of 200-1,500 nautical miles**
- **Tactical Missile Concepts - Long Term**
 - **Weapon for Hard Target Kills**
 - **Launched from Large Aircraft**
 - **Mach 10-12 at an Altitude Above 100k ft**
 - **Range of 1,000+ nautical miles**

Figure 3-5. Tactical missile concepts.

Typical interdiction/reconnaissance vehicles are shown in Fig. 3-7. These are long range Mach 4–10 cruise vehicles that may be either manned or unmanned (Ref. 2). Typically, the lower Mach number systems will be powered by endothermic hydrocarbon fueled air-breathing engines. Liquid-hydrogen fuels will power the Mach 10 or greater systems.

The typical space launch vehicle concepts are shown in Fig. 3-8. These are single-stage-to-orbit (SSTO) or two-stage-to-orbit (TSTO) launch vehicles. Air breathing propulsion systems may power these systems in the future but are currently not sufficiently mature for space launch (Ref. 5). Rocket propulsion systems will continue to be the power of choice for these systems for the next 10–20 years. However, the test facility requirements must include these systems, since facility acquisition time can take up to 20 years (11 years average).

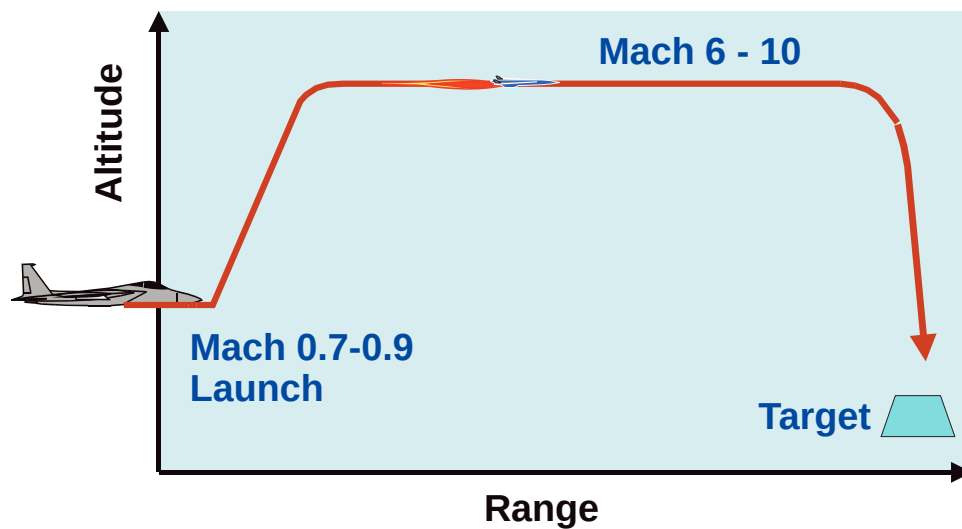


Figure 3- 6. Typical hypersonic missile mission profile.

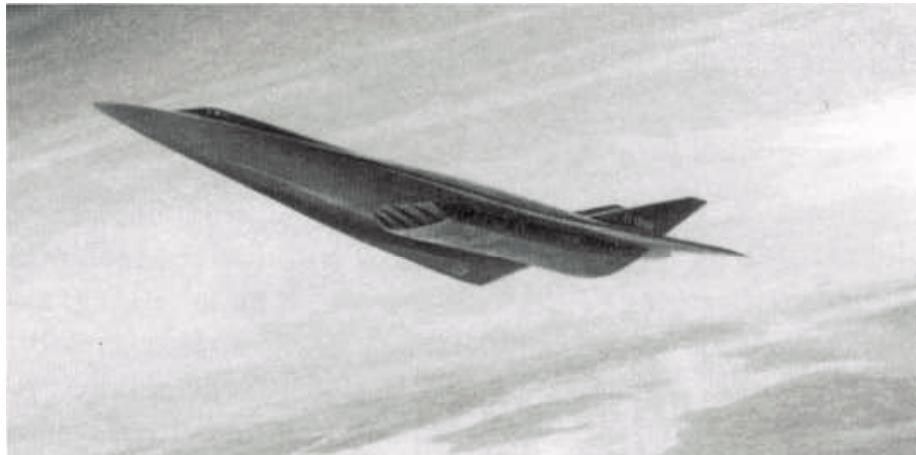


Figure 3-7. Interdiction/reconnaissance vehicle concepts (Ref. 7).

The United States is not the only country interested in developing hypersonic vehicles. Hypersonic system development and research programs are in progress in Japan, France, Germany, United Kingdom, and Russia. Many of these countries are investing in their hypersonic test capabilities to support the programs. Therefore, it is expected that the United States will invest in technology and ground test infrastructure to remain a world leader in hypersonics.

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Figure 3-8. Space launch vehicle concepts.

3.5 RESEARCH REQUIREMENTS

Hypersonic facilities requirements studies were initiated in FY99. These studies first analyze requirements for the test duration, test section size, and thermodynamic test section conditions for the testing of representative hypersonic air breathing propulsion systems in an advanced hypersonic wind tunnel. The second phase of the study will address flow quality. Future studies will include productivity, measurement capability requirements, and cost of testing estimates. In addition, these future studies will also address other types of testing requirements, such as aerodynamics, electro-optics, jet-interaction, impact/lethality, and materials/structures. The types of weapons systems to be considered during these studies will be tactical missiles, interdiction/reconnaissance vehicles, and launch vehicles. It can be assumed that all air breathing propulsion systems will constrain the vehicles to operate at a lower dynamic pressure limit of 500 lbf/ft² and an upper dynamic pressure limit of 2,000 lbf/ft². In addition, the study will be limited to a Mach 8–Mach 15 flight regime.

Critical technical issues that must be considered in the requirements analysis for the development of a pure-air hypersonic wind tunnel operating in the range Mach 8–15 with a dynamic pressure of 500–2,000 psf are:

- **Test duration**—Test time drives any proposed test facility concept and test technique. Test time is critical in establishing facility air storage, energy storage, thermal management, and exhaust management requirements. Air-breathing propulsion testing objectives are usually classified into three categories: 1) performance, 2) operability, and 3) durability testing. Test time requirements must be assessed for all three categories.

- **Test section size**—The size of a T&E test facility is driven by test article size. Therefore, an assessment of the size of potential systems and subsystems that would be tested is required. Size and velocity/altitude simulation requirements determine mass flow requirements. This, along with test time, also drives facility air storage, energy storage, thermal management, and exhaust management requirements. This research plan lead may eventually lead to a large T&E test facility but now is focused primarily on development of design criteria for a smaller MSHWT. It is intended that the MSHWT be sized to accommodate testing of “medium size” air-breathing propulsion systems and possibly subsystems of larger systems.
- **Air chemistry and flow quality**—Air chemistry and flow quality needs for facility testing must be assessed. The allowable tolerances on these factors are important to selecting a facility concept and design of components.

3.6 REFERENCES

1. Miller, C.G., “Aerothermodynamic Flight Simulation Capabilities for Aerospace Vehicles,” AIAA 98-2600, June 98.
2. McCall, G.H. et al., “New World Vistas,” December 1995.
3. Home, N., et al., “Aerospace 2020,” AGARD-AR-360 Vol. I, April 1997.
4. Seebass, A.R., *Review and Evaluation of the Air Force Hypersonic Technology Program*, National Academy Press, Washington, D.C., 1998.
5. Anttonen, J., “U. S. Air Force Space Operations Vehicle,” AIAA 98-1568, April 1998.
6. “Air Force 2025,” Air University Press, Maxwell Air Force Base, Alabama, August 1996.
7. Photo, New World Vistas, A/C and Propulsion Volume.

4.0 PROGRAM PLAN

4.1 OVERVIEW OF RESEARCH PLAN

The MARIAH II/RDHWT Research Plan (Appendix A) was developed to define the detailed research required to establish concept criteria for the MSHWT and to present an estimate of the overall schedule and cost of the research program. The MSHWT system addressed in the research plan is based on thermal energy addition (by e-beam or laser), coupled with MHD accelerator augmentation to achieve the required test conditions. The research plan is a living document to be updated annually to reflect results of the previous year's work and its impact on future research needs.

Version 1 was prepared in November 1998. Subsequently, Version 2 was prepared to reflect the recommendations of the steering committee and to incorporate new knowledge from the research to date.

Eight major research areas for the MARIAH II/RDHWT Program are identified: 1) hypersonic flight systems test requirements, 2) UHP air supply and plenum, 3) nozzle-throat survivability, 4) nozzle boundary layer, 5) nozzle cooling, 6) thermal energy addition, 7) MHD augmentation, and 8) systems integration.

Ultrahigh-pressure gas properties were initially considered as a major research topic, but dismissed since it was believed that sufficient gas thermodynamic property data had already been gathered under the RDHWT program. The current, extrapolated limit of the thermodynamic and transport property equation of state (EOS) for air is 30 kb. If experimental data at pressures above this limit is required, then further research may be required to establish the thermodynamic and transport property data for the UHP gas in this regime. Therefore, gas property research was included as an element of the UHP air supply and plenum research in the research plan

Hypersonic flight system test requirements was later added as a research area within the MARIAH II Program. The research plan was then organized into eight sections addressing each of the research areas described above; the ninth section addressed cost and schedule. Thus, the following is a list of the major sections of the research plan:

- Hypersonic Flight Systems Test Requirements Study
- UHP Air Supply and Plenum
- Nozzle-Throat Survivability
- Nozzle Boundary Layer
- Nozzle Cooling
- Supersonic Thermal Energy Addition
- MHD Energy Augmentation
- Systems Integration
- Costs and Schedule

For the sections other than “Cost and Schedule, the research needs for each area are described in terms of 1) requirements, 2) critical technical issues, 3) alternatives, 4) exit criteria, 5) key demonstrations and experiments, 6) analytical tools, and 7) major deliverables. Estimated cost and schedule for these research areas and the program are addressed in the last section.

The second version of the Research Plan (updated May 17, 1999) is included in this report as Appendix A.

4.2 WORK BREAKDOWN STRUCTURE

To facilitate program management and administration and to comply with USAF standards for acquisition programs, the proposed wind tunnel research was organized using a WBS. The MARIAH II Program WBS was developed to provide a consistent and well-structured framework for documenting and organizing the work leading to the development of the MSHWT, as well as a future full-scale hypersonic T&E facility. The WBS is a primary program management tool for communication, documentation, organization of work, and tracking in the MARIAH II/RDHWT Program. Furthermore, the WBS serves as a basis for the schedule database (the WBS and schedule comprise the road map discussed in the next section), and these provide the basis for the statements of work (SOW) for the program team. The program WBS was developed in accordance with the guidelines of the U.S. Department of Defense (DoD) WBS Handbook (Ref. 1).

The three levels of the WBS that are specifically addressed by the WBS handbook are:

- Level 1 – Entire defense materiel item
Example: Hypersonic Wind Tunnel System (Program)
- Level 2 – Major elements of defense materiel item (prime mission products)
Example: Wind tunnel, support equipment, program management, systems engineering
- Level 3 – Subordinate elements
Example: UHP driver, radiative energy addition system, and MHD

Ten “Common Elements” are defined in the handbook and are intended for use in the program WBS for all defense materiel acquisitions. The common elements listed in the handbook are:

- Integration, assembly, test, and checkout efforts
- Systems engineering and program management
- Training
- Data
- System test and evaluation
- Peculiar support equipment
- Common support equipment
- Operational and site activation

- Industrial facilities
- Initial spares and repair parts

These elements have been included in the MARIAH II/RDHWT Hypersonic Wind Tunnel System WBS, with proper placement, to conform to the guidance of the handbook.

Elements below the third level are specific to the particular defense materiel acquisition (for example, the MARIAH II/RDHWT Hypersonic Wind Tunnel System) and are not addressed by the handbook. Lower level elements in the MARIAH II/RDHWT WBS provide the R&D detail necessary for work scope in each of the research areas.

The first level WBS for developing the MARIAH II/RDHWT Hypersonic Wind Tunnel System is shown in Fig. 4-1. The primary R&D element in the second level WBS is Element 1.0, “Hypersonic Wind Tunnel.” Element 2.0, “System Engineering and Program Management” addresses the program management at the USAF/AEDC level. The third and fourth level elements below the Air Force Systems Engineering and Program Management element (2.0) are shown in Fig. 4-2.

Figure 4-3 expands the WBS to the third level for the wind tunnel system hardware branch. The major elements of the wind tunnel (UHP driver, nozzle, radiant energy addition, and MHD) appear at this level. Element 1.16 “Systems Engineering and Program Management,” provides the management elements at the prime integrating contractor level.

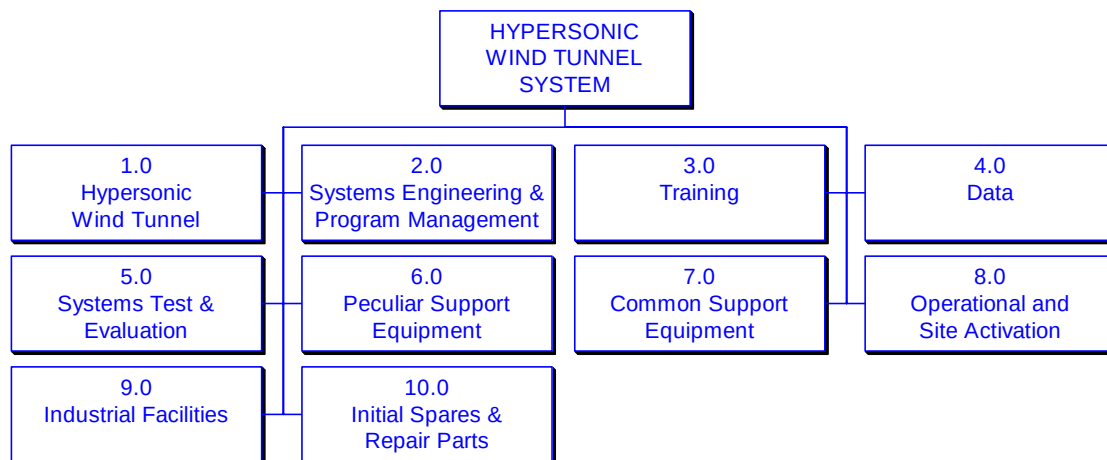


Figure 4-1. Hypersonic Wind Tunnel System top level WBS.

A common structure is incorporated at the fourth level to distinguish between the three major facilities proposed for development under this program (research scale, prototype facility or MSHWT, and the T&E facility). Nine of the ten common elements discussed above and eight elements that are peculiar to this program comprise the common structure at the fifth level (see Fig. 4-4). Detailed structure below the fifth level (not shown) is used for guiding the individual R&D efforts and for preparing the SOW for the subcontractors and national laboratory participants.

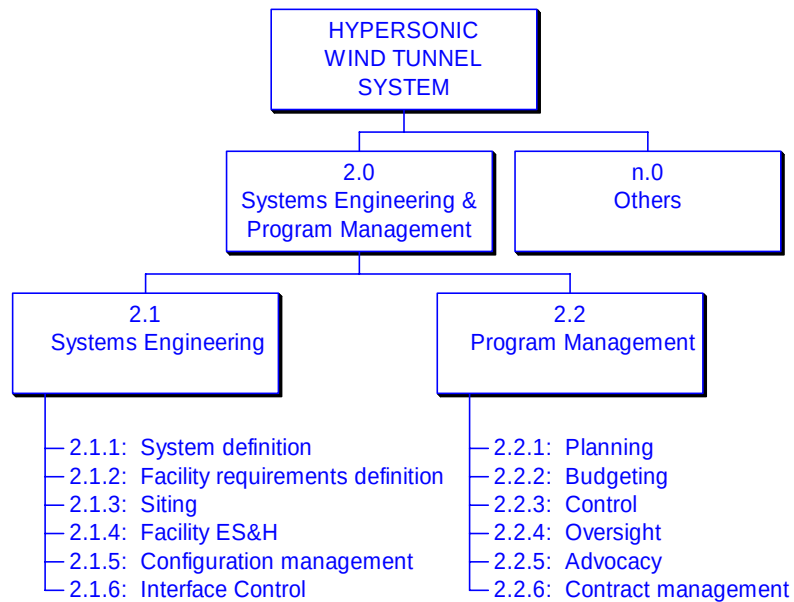


Figure 4-2. USAF Systems Engineering and Program Management WBS.

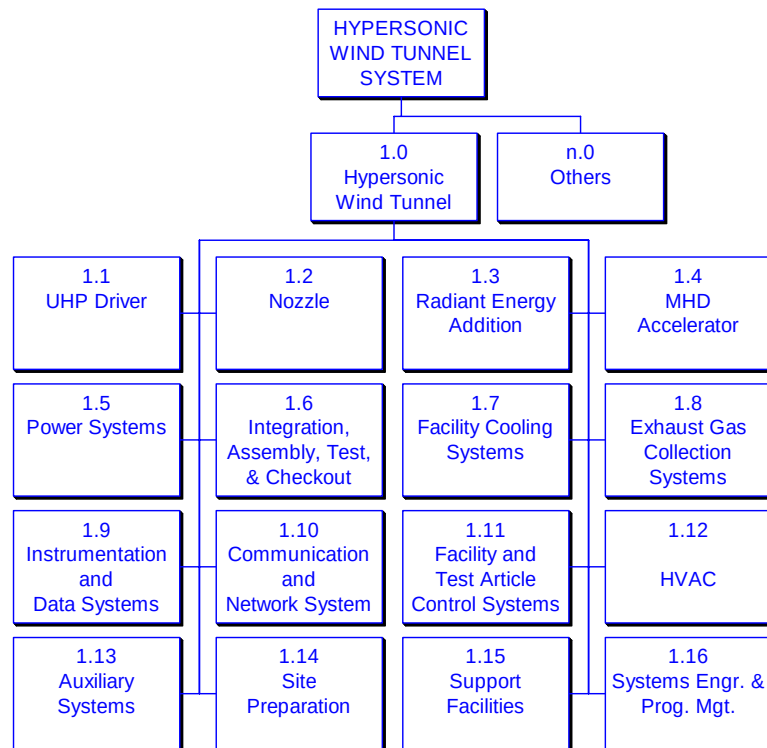


Figure 4-3. Component elements of the Hypersonic Wind Tunnel System WBS.

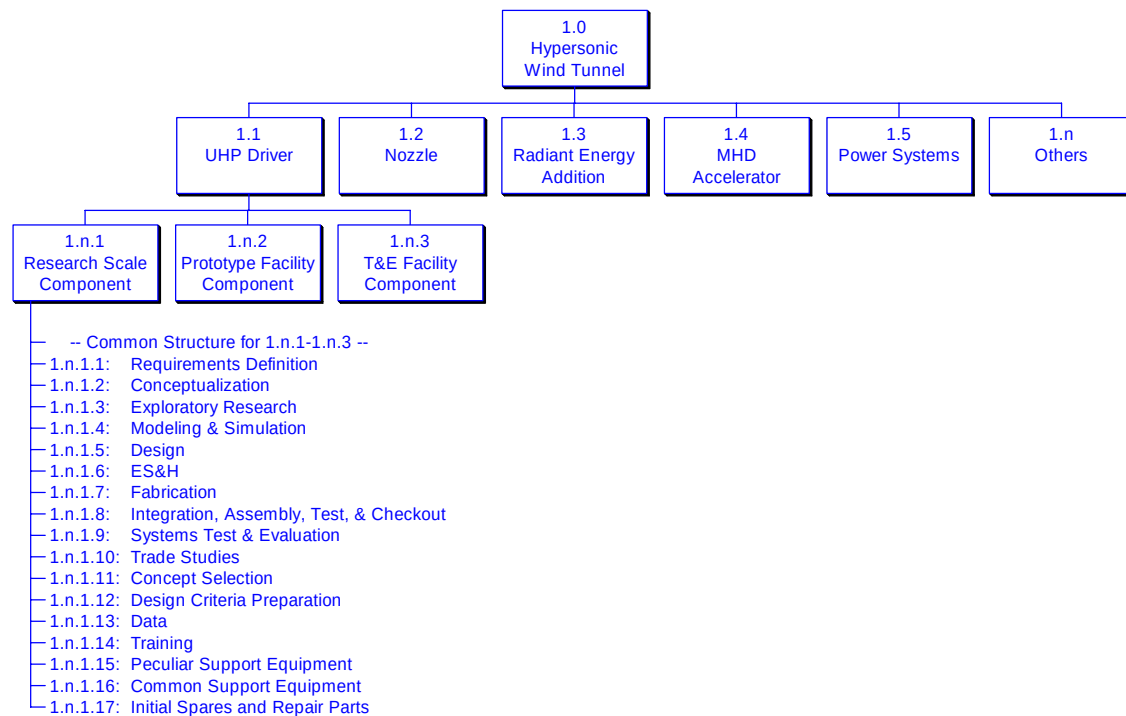


Figure 4-4. Common elements in the hypersonic wind tunnel system WBS.

4.3 ROAD MAP

The MARIAH II/RDHWT Program is anticipated to be an 8-year program culminating in the development of design criteria for an MSHWT. A road map, consisting of the WBS and cost and schedule databases, is utilized for planning, tracking, and documenting the research within this program. The WBS (discussed in the previous section) is the basis for the road map, defining the structure of the program in a product-oriented form. Planning for the development of products for this program, where the products may include analytical and experimental research as well as hardware and software products, leads to the definition of the R&D tasks. These tasks and their interrelationships are defined and tracked using a road map schedule database implemented with Microsoft® Project software. Costs have not yet been implemented in the Microsoft Project database but have been estimated at the third WBS level and are discussed in the MARIAH II/RDHWT Research Plan (see Section 4.1).

Phase I of the MARIAH II/RDHWT Program will be completed in a 5-year period as indicated in the high-level road map overview in Fig. 4-5. During this Concept Selection Phase, UHP, nozzle, thermal heating, and MHD concepts will be defined, evaluated, and demonstrated, and down-selections will be made to the final recommendations for the MSHWT. Concept selection will be based upon T&E requirements and subsystem performance, risk, and cost projections. Phase II, Concept Exploration, is planned as a 3-year period during FY03–05 to investigate the feasibility and performance of an integrated facility system using experimental and computational approaches. A concept definition and design criteria for the MSHWT will be the final products of Phase II.

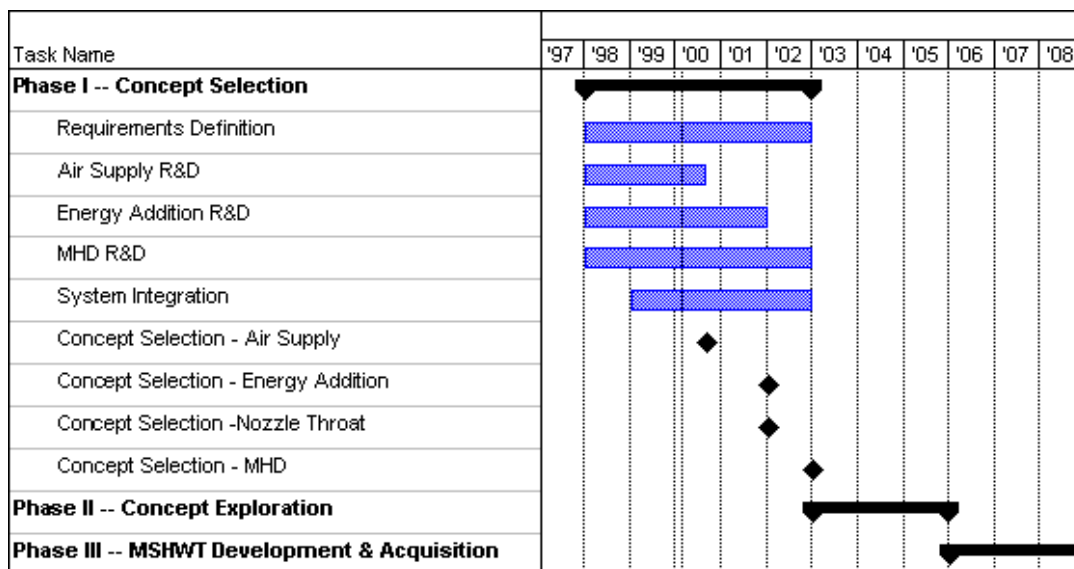


Figure 4-5. High-level road map overview.

A MSHWT will be developed and placed in service during Phase III. Though not shown, a large-scale T&E facility may be designed and constructed during Phase IV. Even Phases II and III will require major DoD acquisitions that are beyond the scope of the present R&D efforts.

An annual update to the roadmap will be performed to incorporate the knowledge gained during the year. This will be prepared in advance of the planning for the following year and will provide the information required for preparation of work plans.

4.4 REFERENCES

1. Department of Defense Handbook – Work Breakdown Structure,” MIL-HDBK-881, 2 January 1998, www.acq.osd.mil/pm/newpolicy/wbs/mil_hdbk_881/mil_hdbk_881.htm.

5.0 ULTRAHIGH-PRESSURE AIR SUPPLY SYSTEM

The MARIAH II/RDHWT concept fundamentally requires an air supply to the nozzle throat at both moderate enthalpy and low entropy, which means UHP and moderate temperature conditions. Various alternative air supply systems have been identified (see Section 5.2). The real gas effects in the EOS of air make a UHP source attractive. The high enthalpy in dense gases decreases the radiative energy that must be added to the supersonic flow, while the low entropy permits an entropy gain during energy addition to the flight condition. However, the technical limitations in generating and containing large volumes of air at high pressures and temperatures place an upper boundary on enthalpy-entropy states accessible at acceptable technical risk.

This chapter describes the progress made toward a conceptual design for an air supply system for medium and large-scale T&E hypersonic wind tunnels. The enabling science and technology for the large-scale facility is developed and demonstrated by fielding an affordable UHP driver for megawatt-scale energy addition experiments. This device, called the “A-2,” also must provide credible design specifications for the air supply for the MSHWT, a user facility that has the operating conditions of the large-scale T&E facility at approximately one-tenth the test section area (see Section 2.2).

System requirements such as test section size, Mach number, dynamic pressure, flow quality (chemical, thermodynamic, and spatial and temporal variations), and run time define the limits of trade-offs between the air supply and energy addition subsystems. In general, the more energy provided by the UHP subsystem, the less required of the energy addition subsystem. In both subsystems, operation at and beyond current industrial limits results in increased risk and cost along steeply increasing curves. The MARIAH II/RDHWT R&D strategy is to accept moderate technical risk in the UHP subsystem. The UHP subsystem concept is constrained by an existing materials and technology envelope that may be somewhat beyond current industrial practices.

Environmental, Safety, and Health (ES&H) must be integrated continuously with the science and technology analysis, engineering design, procurement, fabrication, testing, and operation of the UHP air source. Senior management, who retain the responsibility for ES&H, as well as ES&H staff, who will analyze the ES&H hazards and their mitigation and make recommendations to senior management, must play an active role in the development of the UHP air source design and its deployment. The primary hazards presented by the considerable, approximately 10^8 J, total stored energy in the UHP air source are blast overpressure, static overpressure, shrapnel, noise (both in normal operation and upon catastrophic failure), and asphyxiation. Plans are for the A-2 UHP driver to be designed and built at the LLNL. Siting of the A-2 will depend on a number of factors, not the least of which is the down-selection between the laser and electron-beam energy sources. Any site must meet its ES&H requirements.

5.1 OBJECTIVES

The objective of the UHP portion of the MARIAH II/RDHWT Program is to demonstrate the science and technology of an air source for a large-scale hypersonic ground test facility. This objective is accomplished by 1) developing a UHP air source design concept that can credibly meet the performance requirements for a large-scale facility and 2) operating a device based on this design concept, but sized to match megawatt-scale energy addition experiments.

The nominal performance requirements for the large-scale facility are to simulate hypersonic flight conditions at 100,000 ft altitude (include a test section of approximately 3 m in diameter, Mach 8–15, dynamic pressures from 500–2,000 psf pure air with runs times of the order of 100 seconds). The cost and complexity of the large-scale facility demands a phased R&D program with intermediate objectives. The second intermediate objective, the MSHWT, is a user hypersonic facility with performance similar to the large-scale facility, but with a test section 0.5–1 m across.

The first intermediate objective is the A-2, an R&D device having the following preliminary performance goals:

- Plenum pressure – 2,000 MPa;
- Plenum temperature – 900 K;
- Mass flow rate – 10 kg/s;
- Run time – 1 s;
- Test medium – Pure air; and
- Flow quality – <5 percent variation.

In addition to these performance goals are the following MARIAH II/RDHWT systems goals for the UHP concept:

- Permit only low to moderate UHP subsystem R&D risk to use program resources to address high-risk areas in the energy addition subsystem.
- Design to make time constants (both intra- and intercycle) commensurate between subsystems.
- Design to minimize ES&H risk and cost.

5.2 APPROACH

Several alternative approaches to generating a high Mach number airflow are described below. The selected approach involves use of pure air stored at high pressure and temperature, which is expanded through a supersonic nozzle. The UHP subsystem requirements result in a straightforward down selection to classical, quasi-static, large volume, high-pressure design concepts. The primary limiting factor of these designs for required run time and mass flow rate performance at plenum conditions of 2,000 MPa and 900 K is heat transfer between the air and the UHP pressure component material and the subsequent degradation of material properties. The quasi-static designs also require a converging/diverging nozzle that must couple to a 7 to 10 T magnetic field at the nozzle throat.

In developing a UHP design strategy, the air enthalpy in the plenum can be increased by increasing both the temperature and the pressure. Figure 5-1 shows the relative values of dH/dT and dH/dP at nominal operating conditions. Increasing temperature provides nearly a factor of two greater increase in enthalpy than increasing pressure in the region of interest ($H = 2,000\text{--}3,000$ kJ/kg). However, the derivative of most interest to minimize is “ $dH/d(\text{Technical risk})$ ”; therefore, the products $(dH/dT)(dT/d(\text{Technical risk}))$ and $(dH/dP)(dP/d(\text{Technical risk}))$ should be considered. These qualitative derivatives are quite different in different (P, T) regimes. At pressures below approximately 1,000 MPa, the technical risk of increasing the pressure, $d(\text{Technical risk})/dP$, is relatively low, as is the case for temperatures below approximately 650 K. However, for higher pressures and temperatures, the two derivatives begin to increase rapidly and become comparable. The temperature derivative of technical risk, $d(\text{Technical risk})/dT$, lies in the degradation of material properties and the increase in chemical reactivity of pressure system materials with O_2 . The pressure derivative increases due to the limits of material properties and to design complexity. At the design temperature of 900 K, the temperature derivative $d(\text{Technical risk})/dT$ is the largest; therefore, the strategy is to operate at as high a pressure and low a temperature to provide the required enthalpy. This has the additional advantage of reducing the entropy for a given enthalpy.

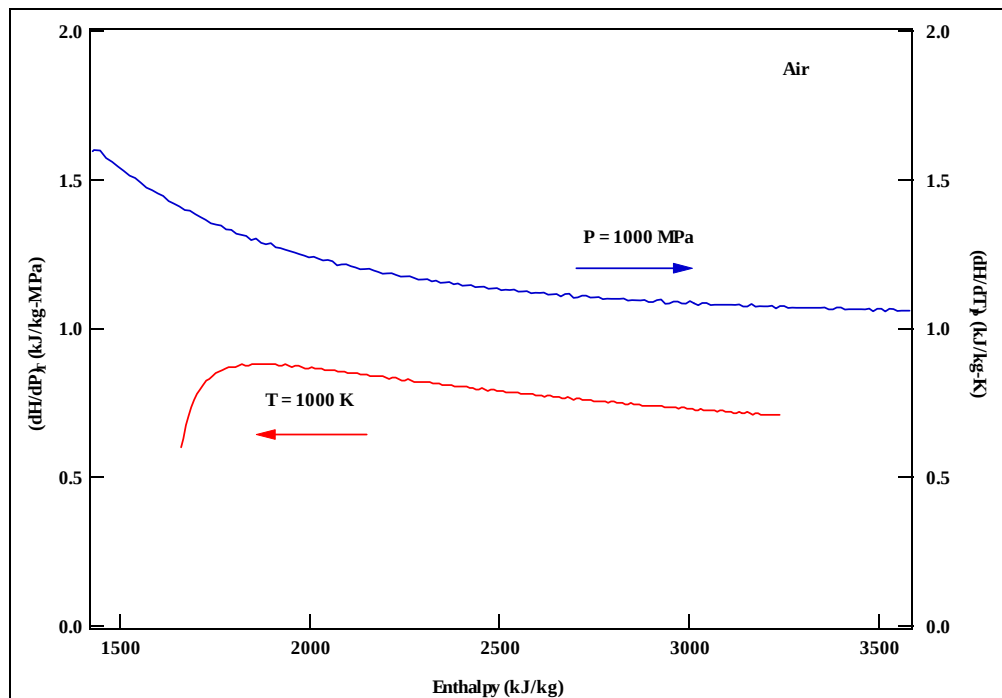


Figure 5-1. Comparison of enthalpy derivatives with respect to temperature and pressure. In the region of interest ($H=2,000\text{--}3,000$ kJ/kg), increasing the temperature provides a larger increase in enthalpy. However, the resulting increase in technical risk is significantly higher than increasing the pressure.

5.2.1 Alternative Approaches

5.2.1.1 Explosively Driven Jets

As explained below, there are no demonstrated technologies employing explosively driven jets that meet the air source requirements for the MARIAH II/RDHWT Program. Explosively driven jets can provide particle velocities of 4,000 m/s. Flow quality, as measured by variations in mass flow rate at the test body, is poor due to jet separation and subsequent atomization. The high jet temperatures behind the shock, as predicted by the Hugoniot relation for air, result in significant creation of nitrogen oxide (NO_x). Run times, as measured by the length of one or more sequentially triggered jets, are limited by the detonation velocity of the explosive and the length of the device. Typical run times are microseconds to milliseconds. Finally, the radial expansion of the dense jet must be managed either by introduction into a duct or along a particular thermodynamic path to obtain the correct entropy at the test article.

Kozorezov (Ref. 1) describes a facility for creating a hypersonic flow by using a jet of liquid air. The method is “suitable to obtain only short term flows.” The scheme is to compress liquid air (10–100 kg) using a hemispherical shaped explosive charge to compress and accelerate it to 4–6 km/s. As the liquid air jet enters the vacuum of the wind tunnel tube, it decompresses, cavitates, and “explodes” into an aerosol and then into gaseous air as it travels down the tunnel. A very fast acting valve at the exit to the explosive chamber closes after the air jet leaves and before the detonation products can leave. No data are presented that describe the dimensions of the liquid jet. The only reference to how the hot, highly compressed liquid jet changes phase to a gas is to a study on low pressure superheated water jets (Ref. 2). In particular, there is no discussion of how the radial momentum, imparted by the relaxation of radial stress in the cylindrical fluid jet as it moves, is trapped. While there may be a lot of experience with shaped-charge jets, those jets are made from liquid metal; therefore, the thermodynamic pressure is low.

There is no compelling conceptual argument that this approach can generate the required Mach number and dynamic pressure at flight conditions for run times of the order of a second. If one assumes a test condition of Mach 12 at a density of $\rho=2.74(10^{-3}) \text{ kg/m}^3$, sound speed $a=285 \text{ m/s}$, and a cross-section diameter of 3 m, the mass required for a flow time t is:

$$m = \rho * M * a * A * t = 66t \text{ kg.} \quad (5-1)$$

If one assumes the axial speed does not change as the jet goes down the tunnel, the diameter of the jet can be calculated if a reasonable assumption is made about its density:

$$D = \sqrt{\left(\frac{4m}{\pi \rho u t} \right)} \quad (5-2)$$

If one assumes density= $1,500 \text{ kg/m}^3$, speed= $5,000 \text{ m/s}$, mass= 66 kg , time= 1 s , then $D=0.003 \text{ m}$. These numbers all appear reasonable. However, the pressure in the liquid jet at $1,500 \text{ kg/m}^3$ is

high; therefore, there is likely a high radial acceleration when the hydrodynamic forces of the shaped charge compression decay. This would tend to blow the jet apart radially (while not changing the downstream momentum).

The essential issue, however, is making a shaped charge jet that lasts for $O(100\text{ s})$. Let $m = \rho u A t$, therefore, for a constant cross section, D , $u \cdot t = \text{length of the jet}$. For $t = 1\text{ s}$:

$$\text{Length} = m / (\rho A) = 66\text{ kg} / [1,500 * (\pi/4) * .003^2] = 6,200\text{ m} \quad (5-3)$$

Extension of this idea to some slower rate of “extrusion” of the liquid jet (for example, a long, cylindrical tube of water collapsed by an external deflagration or magnetic field) is problematic because the water leaving the open end would be pushed out from the collapsing end. This would make the rest of the tube a pressure vessel, thereby requiring a wall strength that would resist the collapsing force.

5.2.1.2 Magnetic/Electric Accelerators

There are no demonstrated technologies employing magnetic or electric accelerators that meet the air source requirements for the MARIAH II/RDHWT Program. Magnetically or electrically driven accelerators can provide particle velocities in the km/s range for subkilogram projectiles. Typical operation occurs through a body force acting on the projectile. For this to work with a neutral fluid, such as liquid air contained in a pipe, the fluid mass is accelerated with a metallic driver. This force results in a pressure in the fluid that must be contained by the pipe wall since it would become a pressure vessel. Subsequent flow along the wall extracts energy from the system, thus decreasing the final enthalpy. Run times are limited by the length of the linear accelerator and are in the range of hundreds of milliseconds for accelerators of the order of kilometers in length. As for the explosively driven jet, realization of the final flow condition requires management of the expansion of the dense fluid after it exits the accelerator.

5.2.1.3 Static Storage System

Certain technologies employ static storage that, with some development, may meet the air source requirements, providing the energy addition subsystem accepts higher risk. In this method (shown schematically in Fig. 5-2), air is stored at some nominal temperature and pressure until shortly before a test and is then released into the plenum-settling chamber through a pressure regulator and heater. The transfer of mass from the storage system results in a rapid decrease in storage system pressure, which is due to the relatively low compressibility of the dense air (at typical conditions of interest, the adiabatic compressibility is approximately $1.2 \times 10^{-4}\text{ MPa}^{-1}$) (Ref. 3). The run time at a constant plenum pressure and temperature then depends on 1) the total volume of the storage system, and 2) the amount of heat that can be transferred to the gas after it leaves the storage system and before it reaches the settling chamber.

The storage pressure and temperature are determined by the secondary creep properties of the pressure system components and by the desire for a pressure system safety factor that permits manned-area operations. Typical storage conditions for 2,000 MPa, 900 K plenum conditions are 800 MPa at 650 K (Ref. 4) assuming an 18 nickel (Ni) maraging steel vessel with a 0.2 percent

offset yield strength of 2,000 MPa at 20°C. The test process first brings the static pressure in the storage system to some pressure above the plenum operating pressure, but below the short time design strength of the pressure vessel. The pressure-regulating device provides a programmed rise in pressure into a heat exchanger that brings the air to the plenum condition. The limiting factors in this approach are managing the heat transfer from the air and the consequent degradation of material properties in the UHP vessels and in the large number of vessels required to maintain flow quality for long run times.

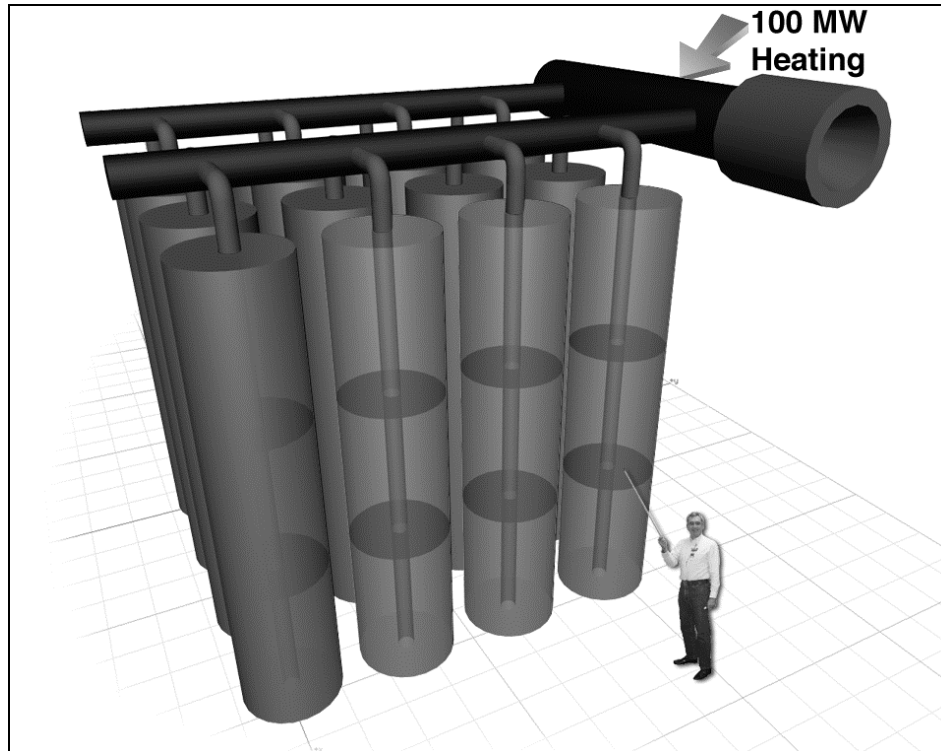


Figure 5-2. Diagram of the “Tank Farm” concept. Air is pumped into and stored in an array of UHP vessels. On operation, the air is heated to reach the desired plenum enthalpy. The primary limitations of this approach are elevated temperature, material properties of the UHP vessels, and addition of approximately 100 MW of heat to the flow.

The three major advantages of this approach are:

- Simplicity – there are few moving parts and high pressure seals (although the UHP vessel design is complex).
- Scalability – adding pressure vessels provides longer run times.
- Cost – fabrication, operation, and maintenance costs are relatively low.

However, the static storage system has the following disadvantages:

- ES&H risk – storage of a large amount of energy approximately 10^7 J in non-American Society of Mechanical Engineers (ASME) approved pressure vessels.
- Heat addition to the air—assuming a (best case) adiabatic compression from (800 MPa, 650 K) to 2,000 MPa, the air temperature at the exit of the storage system is approximately 850 K, thereby requiring the addition of approximately 50 kJ/kg to bring the air to 900 K.
- Development of accessory hardware, such as connections and valves, for 2,000 MPa high temperature service—the present “industrial” limit on accessory hardware is 1,400 MPa at nominal room temperatures (Ref. 5).
- Fabrication, operation, and maintenance of a large number (approximately 100) of pressure vessels.

The static storage system is a viable approach for plenum conditions of the order of 1,400 MPa and 1,000 K, primarily due to its simplicity. In principle, run time and mass flow rate performance requirements are met by adjusting the number and volume of the UHP storage vessels. However, typical initial and final operating parameters for air pressure and temperature indicate a large number (approximately 100) UHP vessels are necessary for a run time of approximately 1 second. This number scales linearly with run time and mass flow rate but can be reduced somewhat if the flow quality performance requirement is relaxed, thereby permitting the plenum conditions to vary smoothly over some range. In this case, a single test run would result in spanning a range of test section Mach number and dynamic pressure conditions. Alternatively, complementary changes in energy deposition by the energy addition subsystem could maintain constant conditions at the test section as the plenum pressure and temperature conditions change. Should the MARIAH II system performance requirements be modified to the neighborhood of 1,400 MPa, 1,000 K, static storage becomes a viable approach.

5.2.1.4 Dynamic Intensifiers

In the dynamic intensifier approach (Fig. 5-3), an array of UHP intensifiers is connected to a manifold that supplies the plenum/settling chamber. The intensifiers (hydraulic devices that convert a low pressure P_l acting on a large area A_l to a high pressure P_h acting on a small area A_h such that $P_h = (A_l/A_h) P_l$) are driven by a low pressure source P_l from an auxiliary hydraulic pressure system. The initial pressure and temperature of the air in the intensifiers are adjusted using an auxiliary air pressure system so that subsequent quasi-adiabatic compression and heat transfer result in the desired plenum condition. Adjusting the number and volume of the intensifiers provides the total air mass required by run time and mass flow rate performance requirements. The limiting factor in this approach is managing the heat transfer from the air and the consequent degradation in material properties of the UHP vessels.

The major advantages of this approach are:

- Scalability – run time and mass flow rate requirements are met by changing the number of intensifiers and the volume of each intensifier.

- Flexibility – continuous Mach number and dynamic pressure test section conditions within the UHP subsystem pressure, temperature, and total mass bounds are accessible.
- Accessory hardware – a feasible solution to multiple volume connectivity at 2,000 MPa exists.
- Safety – the energy required to bring the air to the plenum condition on the order of 20 MJ for a 1 second run time at a mass flow rate of 10 kg/s) can be stored at low pressure (30 MPa) in an ASME-certified pressure vessel.

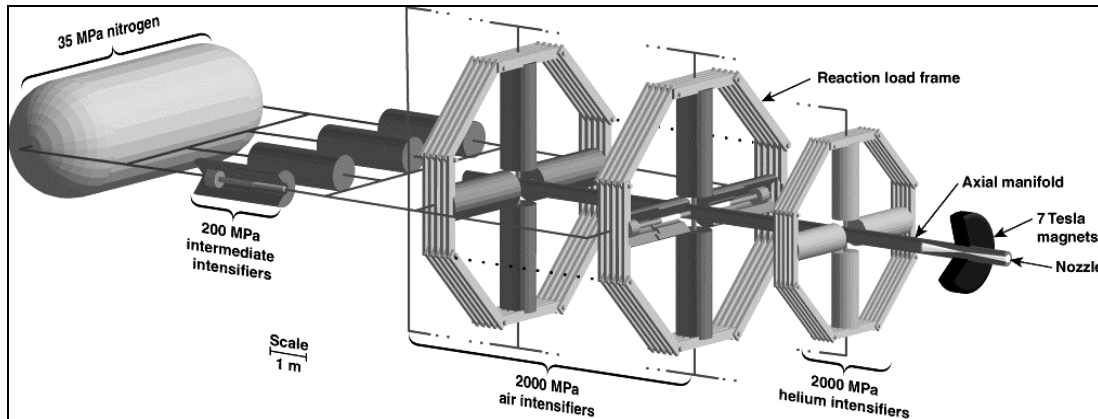


Figure 5-3. Diagram of the dynamic intensifier design concept. A radial array of UHP intensifiers provides air at (P , T) to an axial manifold. The intensifiers are driven by an intermediate set of intensifiers, which are driven by gas stored in an American Society for Testing and Materials (ASTM) pressure vessel. Helium film cooling fluid is added to the flow immediately upstream of the nozzle throat.

The major disadvantages of this approach are:

- Complexity – managing the heat transfer and thermal degradation of UHP vessel materials with temperature requires a complex pressure vessel design plus multiple moving parts and high pressure seals result in increased failure risk.
- Cost – fabrication and maintenance of multiple UHP intensifiers is relatively high.

5.2.2 Approach Selection

The dynamic intensifier approach was selected as having the highest potential for meeting the MSHWT and large-scale facility performance requirements.

Both the explosive and electromagnetic acceleration approaches fail to offer credible design concepts to provide run times in excess of 1 second and to meet air flow quality (in both thermodynamic and chemical properties) requirements. Both have relatively high R&D risk in applying methodologies for subkilogram acceleration of solid projectiles to multikilogram masses of air. Finally, both involve relatively high ES&H overhead costs.

Both of the quasi-static approaches are credible, particularly if the plenum pressure-temperature requirement can be reduced to 1,400 MPa and 1,000 K. Managing the heat transfer between the high-density air and the pressure vessels is the primary design challenge. The T&E-driven performance requirement of 10–100 s test times signifies that a significant fraction of the enthalpy increase of the air due to its dynamic compression is lost (using reasonable estimates of the heat transfer coefficient between the dense air and the confining steel wall). This results in two problems: 1) replacing the lost heat to bring the air to the plenum temperature, and 2) degradation of material properties (Young's modulus and elastic and ultimate strengths) of the pressure vessel material.

Both approaches also require some form of connection between 2,000 MPa volumes. Some of the connections may be along the axial bores of the pressure vessels (as in the static storage approach); however, some require crossbores that generate stress concentration factors of 5–7 times the pressure. While industrial use of crossbores is well demonstrated at pressures up to 1,400 MPa (at room temperature), their use at 2,000 MPa and higher requires a means to reduce the shear stress near the crossbore.

The static storage system was not selected because of the inability to meet airflow quality requirements at the 2,000 MPa, 900 K plenum condition. This criterion requires a storage pressure significantly in excess of 2,000 MPa to provide the air mass to operate at a constant pressure of 2,000 MPa (the pressure-time history is similar to that for an operating pressure of 1,200 MPa, shown in Fig. 5-4). It also requires at least approximately 100 kJ/kg heat input to the flow, under the assumption of an adiabatic compression from the nominal storage conditions of 800 MPa and 650 K. Additionally, expansion of the storage system to meet the 1–100 s run time and 10–40 kg/s mass flow rate requirements results in a storage system having about 1,000–2,000 MPa pressure vessels, each with a volume of approximately 0.03 m³.

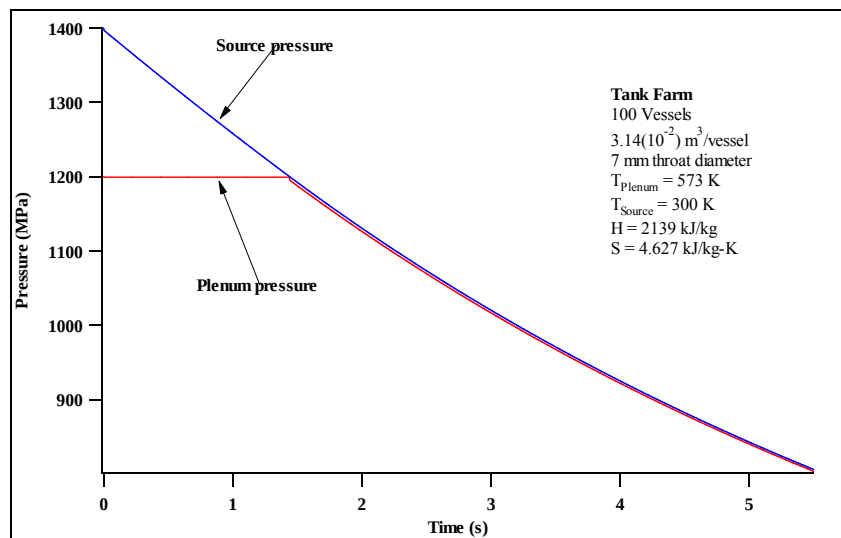


Figure 5-4. Adiabatic blowdown of 3.14 m³ of air. The air is stored at 1,400 MPa, then released to the plenum at a regulated 1,200 MPa, resulting in a constant pressure for approximately 1.5 s.

The dynamic intensifier approach was selected because it has relatively low R&D risk, a credible means to expand the subsystem to large-scale facility run time and mass flow rate requirements, and an acceptable ES&H risk. In addition to the temperature-related issues common to both this approach and the storage system approach, the dynamic intensifier system is relatively complex and expensive. The multiple moving seals, primarily in the high-pressure end of the UHP intensifier, present extraordinarily difficult fabrication and operational maintenance challenges. A detailed description of this design approach follows in subsequent sections.

5.3 DYNAMIC INTENSIFIER: OVERVIEW

5.3.1 General

The MARIAH II/RDHWT energy addition, run time, and mass flow rate requirements imply a large volume at UHP, which in high-pressure technology, are competing design goals. The dynamic intensifier provides solutions to this most serious design challenge for the UHP driver. The primary difficulties for the mechanical design are connecting multiple volumes at pressures greater than 1,400 MPa and fabricating high strength steel sections approximately 1 m in diameter. These difficulties are exacerbated by the change in material properties at high temperatures. While the requirement for a long run time reduces the dynamic synchronization, momentum transfer, and resonant frequency issues present in a device that operates on the millisecond time scale, it creates significant heat transfer problems. At short run times, the air mass–vessel wall system is quasi-adiabatic because there is not enough time for significant heat transfer. However, for run times of 1 second and longer, the heat transfer is adequate to decrease material elasticity and strength properties by almost a factor of two. Fortunately, UHP design principles are well understood and sophisticated, three-dimensional (3-D) finite element analysis (FEA) computer codes are available to model relatively complex geometries.

While laser energy addition remains a viable alternative, energy addition using an e-beam is the baseline design assumption and presents the more demanding design and system integration problem. This energy addition approach requires approximately 10 T axial magnetic fields in the nozzle from the throat to approximately 1 m downstream. The integration of a moderate aperture (approximately 10 cm), high field strength (approximately 10 T) magnet to focus the e-beam at the nominal 3-mm diameter throat is a challenge. Immediately upstream of the throat, the pressure is 2,000 MPa; therefore, the pressure vessel containing the nozzle not only must be small enough to fit into the magnet aperture, it also must be essentially nonmagnetic.

The dynamic intensifier design concept (Fig. 5-3) is comprised of a central, cylindrical manifold (essentially 2,000 MPa pressure tubing) with radial 2,000 MPa intensifiers arrayed in opposing pairs. The total volume of the UHP driver is adjusted by increasing the number (2, 4, 6, or 8) of the intensifiers in each radial plane; adjusting the number of radial planes (in principle, without limit, adding sections of the central manifold); and adjusting the volume of each intensifier. This latter degree of freedom is limited by the fabricability of large, high strength sections. To reduce the financial and safety risk, the upper limit on the volume of each intensifier is approximately $30 \times 10^{-3} \text{ m}^3$ (30 L), which corresponds to a pressure vessel with a 200-mm inner diameter (ID) and a 1,000-mm stroke. This radial array may be operated as a continuous pump by adjusting the number and volumes of the radial arrays so that the cycle time for one stroke of each opposing pair of intensifiers is commensurate with the total number of pairs of intensifiers.

The dynamic intensifier approach makes use of “cascaded” pressure systems. The 2,000 MPa UHP intensifiers are driven by an intermediate pressure system having pressures in the range of 200–300 MPa. This system, in turn, is driven either by compressors or by a large volume (on the order of 10 m^3) of gas at pressures in the range 20–30 MPa. One alternative for the intermediate system is storage of nitrogen in a 250–300 MPa “bottle farm” comprised of 20–100 pressure vessels made from modified U.S. Army M-201 (8 inch) cannon tubes. This storage manifold is maintained at a pressure low enough to provide a safety factor of at least four (permitting manned-area operations for inspection and maintenance), then pumped to operating pressure just before a test. It also has the advantages of relatively low cost and simplicity (no moving parts) and the disadvantage of a requirement for regulating the output pressure to the UHP intensifiers. A second approach to the intermediate pressure system is an array of high pressure (200–300 MPa) intensifiers driven by a low pressure (20–30 MPa) gas that is stored in an ASME-certified pressure vessel. This approach has the advantage of safety and the disadvantages of complexity and cost.

Finally, the dynamic intensifier UHP subsystem is portable. The pressure vessels and load frame are easily separated into components that can be moved with common forklifts and overhead cranes and can be shipped by truck. Installation at a site requires ES&H approval for mitigation of blast, shrapnel, noise, and seismic hazards.

5.3.2 Manifold

The central manifold (roughly 1 cm ID and 20 cm OD) is made of a high strength, oxidation resistant steel (see Table 5-1 for some candidate high performance materials). The ID is defined by requiring the mass flow rate out of the throat and the flow speed of the 2,000 MPa air in the manifold to be low enough not to introduce undesired fluid dynamics effects. Setting this limit as $1/10^{\text{th}}$ the sound speed of air in the manifold, at 2,000 MPa and 900 K, the air density is $1,151 \text{ kg/m}^3$ and the sound speed is 2,660 m/s; therefore, for a mass flow rate of 10 kg/s, the manifold ID is 6.5 mm. The length of this manifold can be increased as required by joining sections as shown in Fig. 5-5. One end of the manifold accommodates the high-pressure feedthroughs required for diagnostics (thermocouples and pressure gauges), prepressurization input, and mechanical motion couplings (as may be required for an internal valve). Figure 5-6 is a sketch of a nominal design for the diagnostics end closure. To provide the area for the various axial penetrations through the end closure, the internal cross sectional area of the section of the manifold at its end must be larger than the 1 cm bore. For fabrication purposes, the nominal 15:1 OD:ID ratio required to hold a 2,000 MPa pressure is provided by an auxiliary pressure vessel that generates an external (inward acting) pressure on the cylindrical manifold. This auxiliary vessel may be of the fixed radial support design (as shown in Fig. 5-7) or of the variable radial support design (shown in Fig. 5-8).

Table 5-1. High Performance Materials

Material	Service T (K)	Property	Room Temperature Value	Service Temperature Value	Percent of RT Values	Ref
Rene 41	900	Ultimate tensile strength	1,430 MPa	1370 MPa	96%	a
Inconel X750	900	Ultimate tensile strength	1,200 MPa	1,050 MPa (at 923 K)	88%	a
Udimet 720	900	Ultimate tensile strength	1,570 MPa	1,455 MPa (at 923 K)	93%	a
Waspaloy	900	Ultimate tensile strength	1,275 MPa	1,170 MPa (at 923 K)	92%	a
Rene 95	900	Ultimate tensile strength	1,620 MPa	1,550 MPa (at 923 K)	96%	b
Udimet 720	900	Yield strength	1,195	1,130 MPa (at 923 K)	95%	b
Rene 95	900	Yield strength	1,310 MPa	1,220 MPa (at 923 K)	93%	b
Inconel X750	900	Yield strength	815 MPa	710 MPa (at 923 K)	87%	b
Waspaloy	900	Yield strength	795 MPa	690 MPa (at 923 K)	87%	b
Udimet 720	900	Dynamic modulus of elasticity	1,195	1,130 MPa (at 923 K)	95%	b
Rene 95	900	Dynamic modulus of elasticity	209 GPa	176 GPa (at 923 K)	84%	b
Inconel X750	900	Dynamic modulus of elasticity	214 GPa	176 GPa (at 923 K)	82%	b
Waspaloy	900	Dynamic modulus of elasticity	213 GPa	177 GPa (at 923 K)	83%	b
Rene 41	900	1,000 hr rupture strength	1,430 MPa	530 MPa (at 973 K)	37% ¹	b
Inconel X750	900	1,000 hr rupture strength	1,200 MPa	320 MPa (at 973 K)	27% ¹	b
18% Ni maraging steel (18Ni2400)	900	Ultimate tensile strength	2,400 MPa	1,830 MPa (at 750 K)	24%	c
18% Ni maraging steel (300)	900	Ultimate tensile strength	2,160 MPa	1,300 MPa (at 810 K)	40%	d
AISI 4340		Ultimate tensile strength	1,380 MPa	550 MPa (at 810 K)	60%	e
AISI 4340		Yield strength	1,380 MPa	415 MPa (at 810 K)	30%	e
ZrO ₂ stabilized		Compressive strength	2,070 MPa			f
Ti-Sn-Al-Mo-Si		Ultimate tensile strength	1,210 MPa	850 MPa (at 773 K)	70%	g
Ti-Sn-Al-Mo-Si		Yield strength	1,030 MPa	622 MPa (at 773 K)	60%	g
¹ Degradation is calculated from (Room Temperature Ultimate Strength – 1000 hr Rupture Strength)/ Room Temperature Ultimate Strength.						
References						
a. "High Temperature, High Strength Nickel Base Alloys," International Nickel Co., New York, 1977; in <i>Heat Resistant Materials</i> , J.R. Davis, Ed., American Society for Materials Fig. 2, p 5.						
b. Sims, C.T., Stoloff, N.S., and Hagel, W.C., Ed., <i>Superalloys II</i> , John Wiley and Sons, 1987; Appendix C, compiled by T.P. Gabb and R.L. Dreshfield, p 575-596; in <i>Heat Resistant Materials</i> , J.R. Davis, Ed., American Society for Materials Table 5, p 232.						
c. INCO Databook, 1976; in <i>Source Book on Maraging Steels</i> , American Society for Metals, 1979, Table 14, p 363						
d. "Aerospace Structural Metals Handbook," revised September 1969, Robert P. Wei, Material Code 1225 (18 Ni Maraging (300))						
e. "Aerospace Structural Metals Handbook," revised December 1982, J.R. Kattus, Material Code 1206 (4340)						
f. <i>Handbook of Astronautical Engineering</i> , Heinz Hermann Koelle, Ed., McGraw-Hill, NY, 1961						
g. Colin J. Smithells, <i>Metals Reference Book</i> , 4 th Ed., Plenum Press, NY, 1967. p 847						

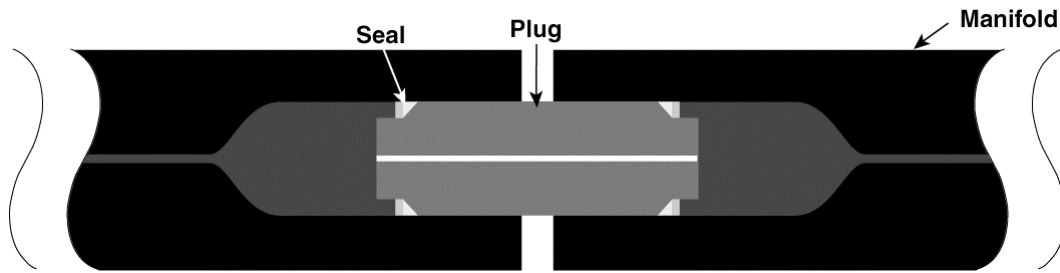


Figure 5-5. Scheme to connect multiple lengths of the axial manifold at 2,000 MPa.

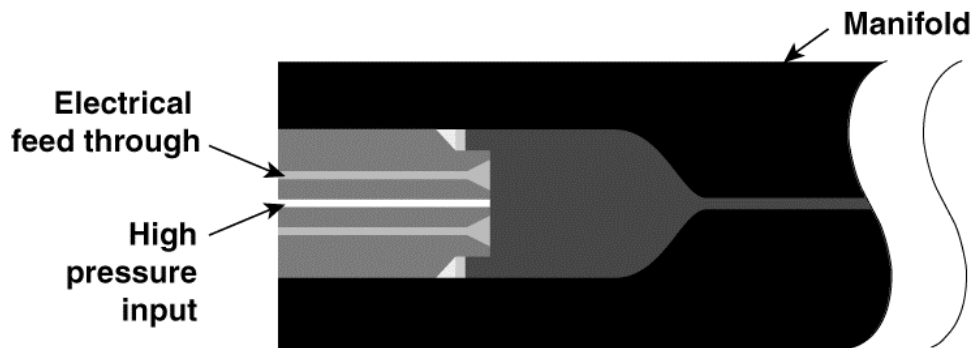


Figure 5-6. Diagnostics end of the axial manifold.

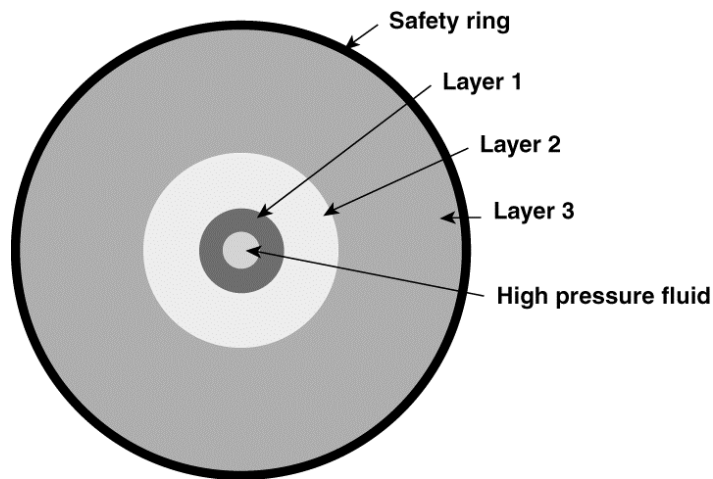


Figure 5-7. Sketch of a multi-component, fixed radial support pressure vessel. Interference fits between the various layers provide a compressive radial stress at the inner bore that may be as high as the compressive strength of the material of the inner cylinder. The materials and dimensions of the various layers are selected to meet stress management and cost requirements.

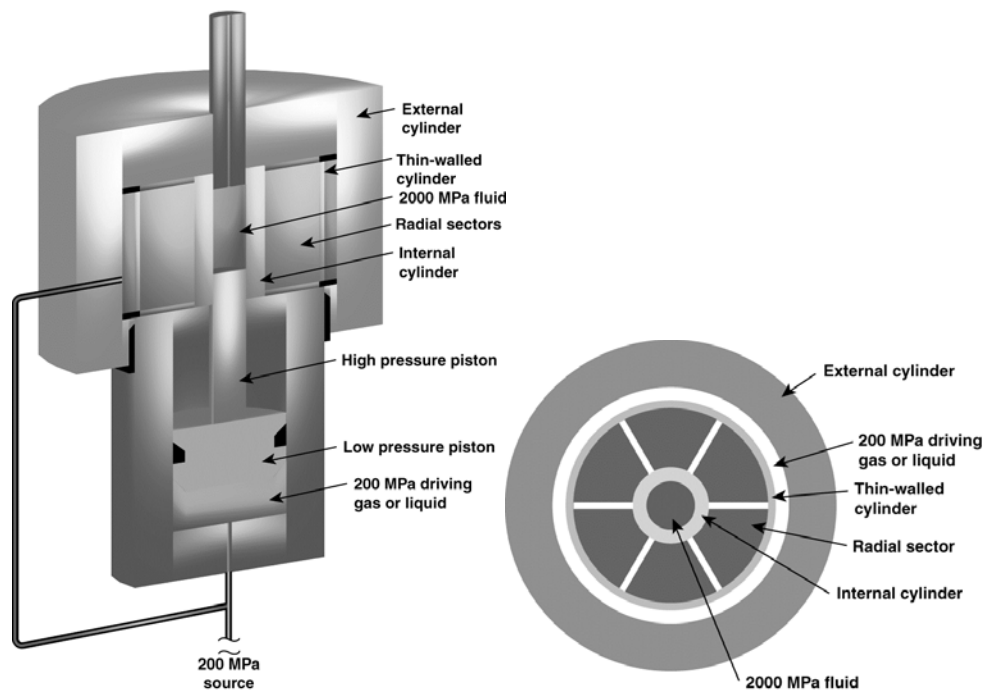


Figure 5-8. Diagram of a UHP intensifier. The force balance on the radial sector provides a variable external radial stress on the external surface of the internal cylinder. The external radial stress is synchronized to the pressure in the internal cylinder, generated by the same 200 MPa source, and intensified by the ratio of the low to the high-pressure piston cross sectional areas.

The other end of the central manifold accommodates the nozzle assembly, a means to introduce a film cooling flow just upstream of the throat, and the coupling to the downstream portions of the wind tunnel (Fig. 5-9). As with the diagnostics end, the ID must be larger than 1 cm to permit a “settling chamber” and a smooth fluid dynamic entrance into the converging nozzle. Using the rule of thumb that the radius of curvature of the entry into a converging nozzle should be 5–10 times the diameter of the nozzle, the ID of the settling chamber is approximately 6 cm for the 3-mm-diameter throat in the 1 s, 10 kg/s baseline design case. A radial array of intensifiers, similar to those providing the UHP air, provides both the variable external radial stress supporting this region and the helium that is injected into the boundary layer to cool the nozzle wall. The proximity of this region to the nozzle throat and the magnet, which in the e-beam energy addition scheme surrounds the nozzle at the throat, creates a significant design challenge.

Immediately upstream of the nozzle throat, the pressure is 2,000 MPa, while immediately downstream (within 10 cm) the pressure drops to the order of a few hundred MPa. The recovery temperature along the nozzle wall is above 900 K, and the gas has an O₂ partial pressure of approximately 400 MPa. Means to introduce a cooling film of helium at the nozzle entrance must be accommodated. The nozzle material in the throat region must permit penetration by a 7–10 T magnetic field that should not be significantly perturbed by nearby dia- or ferromagnetic material,

such as the manifold and its supporting external radial array of intensifiers. This is an extraordinarily difficult problem. A possible approach is to use a high strength, nonmagnetic material, such as a titanium/tin/aluminum/molybdenum/silicon alloy. The yield strength at 900 K is less than a factor of approximately seven of that required to react the 2,000 MPa upstream of the throat, and the OD of the part is constrained to be approximately 10–20 cm by the aperture of the magnet. A wire-wrapped vessel design, with the inner cylinder made of the titanium alloy and the winding from a carbon fiber, is currently the best concept. Using the magnet windings as a structural element in a “wire-wound” pressure vessel design is a possible synergistic solution to the problem.

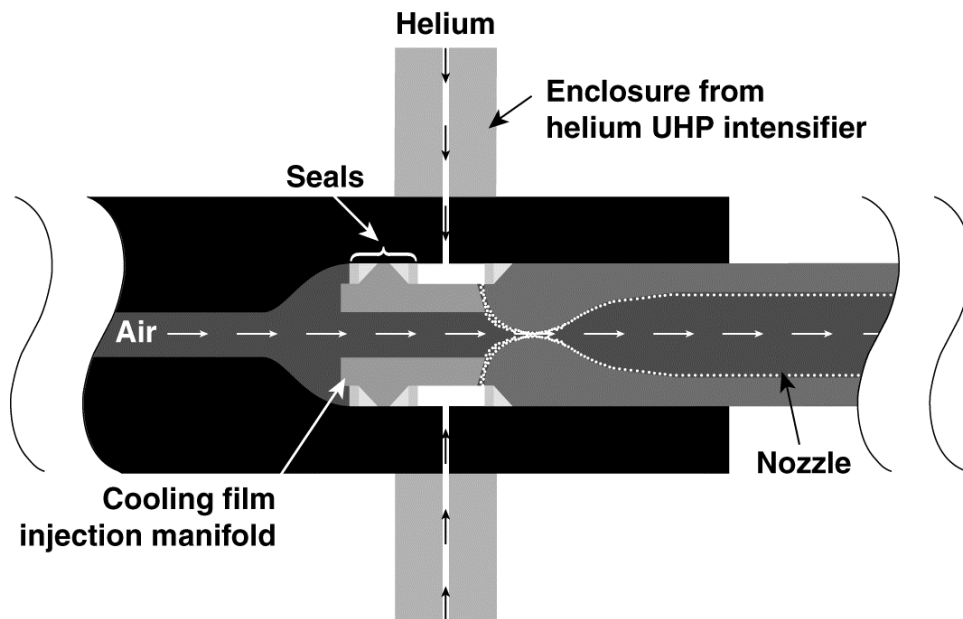


Figure 5-9. Diagram of the nozzle end of the axial manifold. The nozzle/throat is part of the end closure for the manifold. Helium is injected into the boundary layer by means of a radial array of UHP intensifiers, which is similar to the larger intensifiers used for the air supply.

5.3.3 UHP Intensifiers

The radial array of the UHP intensifiers provides an arbitrarily large volume of UHP air. This is achieved by making the intensifiers themselves part of the connectivity scheme to the central manifold. Intensifiers are employed in pairs to react the radial force from the pressure acting on the end closure of the intensifier. The force on this end closure is reacted by the stress at the interface between it and the central manifold. This stress simultaneously provides a high-pressure seal at the interface, which solves the pressure connectivity problem and, at the same time, provides an inward radial stress on the manifold that reduces the stress concentrations owing to the crossbores. The intensifiers themselves are of a classical, variable radial support design. The details of this arrangement follow.

5.3.3.1 Radial Force Balance and Radial Load Frame

In this design, the UHP intensifier is an “open-ended” design. This means the force generated by the pressure acting across the end closure of the vessel is not reacted by a longitudinal stress in the wall of the vessel (as would be the case if the vessel had a closed end or a threaded end closure), but by some external arrangement. This force is considerable [that is, 2,000 MPa acting over an end closure 10 cm in diameter (a nominal design point) results in a 1.6×10^7 N (3.6×10^6 lbf, 1,800 ton) force, less an amount due to friction in the high pressure seal]. Ultimately, the opposing force is reacted by an external load frame.

An imbalance of even a small fraction of this force results in large acceleration of the central manifold. For a nominal 20 cm OD by 3-m long central manifold, a force imbalance of 0.05 percent at the operating point results in a 1 g acceleration. Deviations from symmetry of the two opposed intensifiers cause the force imbalance. These may arise from known differences in cross sectional areas of the end closures, in the friction forces due to the end plug seals, or to the gas pressures in the intensifiers. Differences in pressure may be due to a number of causes. One of the intensifiers may fail either because of a simple pressure leak past a moving seal or because of a catastrophic event. The low pressure (200 MPa) driving the intensifier piston may vary because of asymmetries in pressure drops through tubing, lack of synchronization in upstream pressure regulating systems, or failure of an upstream component. Torques on the manifold, due to the opposing forces not being co-linear, are possible; however, credible moments are small enough that they are balanced by a nonuniform stress at the end closure–manifold interface.

The present design concept addresses the credible risk of a force imbalance due to any of the causes described above by using a cylindrical spacer around the end closure. The spacer is comprised of two halves of a hollow cylinder, separated longitudinally, then fitted around the end closure and between the intensifier body and the manifold. The spacer limits the travel of the manifold by transferring the load on the manifold from the end closure plug to the UHP intensifier body.

The external, radial load frame (Fig. 5-3) reacts the radial force due to the low-pressure (200 MPa) fluid acting on the end closure of the low-pressure end of the intensifier. It also serves as a structural element of the overall UHP subsystem, a barricade for radially directed fragments, and a mounting surface for shielding for axially directed fragments of the intensifier–axial manifold assembly. It is a lattice of rolled steel plate (for example, AISI 1018) with a nominal 10 cm by 20 cm cross section, assembled with shear pins. The components are made of inexpensive stock, are easy to fabricate, and can be handled with common forklifts and overhead cranes. The frame can be assembled either vertically or horizontally. Appropriate seismic stability must be provided for the particular orientation. Final specification of the load frame follows from the dimensions of the intensifier/manifold assembly.

The load frame need not be “stiff,” that is, some deformation under the load is acceptable. Deformation along the radial direction (the direction along the z-axis of the UHP intensifier) due to bending and rotation about the shear pinned corners of the load frame is accommodated by the motion of the end plugs of both the low and the high pressure ends of the intensifier.

5.3.3.2 Axial Force Balance and Axial Load Frame

As for the UHP intensifiers, the pressure in the central manifold is contained by an end closure that is constrained by an external load frame. This external, axial load frame is not shown in Fig. 5-3. Using an internal or external threaded end closure scheme is possible in this design, but has some significant disadvantages. Both internal and external threaded closures result in significant stress concentrations and fabrication and assembly costs. In threaded closures, the axial stress is reacted by a shear stress at the threads, which is brought to design limits by increasing the diameter of the thread. This generally implies an overall cross sectional area larger than the ID of the pressure vessel. For the scale of this device, any increase in the overall OD (resulting from an increased ID) must be avoided.

The axial load frame has four important advantages. First, it provides a simple and fast means to remove the nozzle for inspection or replacement. Nozzle survivability remains a high risk issue, and the costs for servicing it may be a major operational expense. Second, FEA indicates that the external radial stress provided by the floating end closures of the UHP intensifiers create Poisson tensile stresses at the crossbores. (See Appendix B for a summary of the finite element analysis calculations.) This tensile stress is decreased by an external axial compressive stress that is generated by auxiliary hydraulic rams mounted between the axial load frame and the central manifold. Third, the axial load frame provides a convenient reference plane for the remainder of the wind tunnel. While the transient mechanical stresses, deformations, and displacements during the first few tens of milliseconds are not important, the quasi-static axial deformations and displacements due to pressurization and mass flow out the nozzle have an effect on axial alignment. The axial positioning is critical to the integration of the e-beam focusing, which is a function of throat position, magnet position, and e-beam energy distribution 20–100 cm downstream of the throat. Ideally, all the mechanical components (that is, throat, magnets, and downstream nozzle) should have a known and fixed position relative to the e-beam current. Finally, the axial load frame provides significant local blast and shrapnel shielding. A credible failure mode for the central manifold is shear fracture at the end closure. In this event, the likely fragment is the end of the manifold vessel and the end closure with an axial momentum. In a threaded end closure design, protection from this fragment must be provided by a separate barricade. In the floating end closure design with an axial load frame, the load frame itself provides the barricade.

5.3.3.3 UHP Intensifiers

Generating and containing static, ultra-high fluid pressures (for the present discussion, pressures greater than 1,000 MPa; 145,000 psi) is an art that has been developed primarily by Percy Bridgman, who was awarded the Noble Prize in Physics for his research into the behavior of matter at high pressures (Ref. 6). Commercial hardware (for example, pressure vessels, valves, gauges, and connecting tubing) is available for use at pressures up to 1,400 MPa at temperatures near room temperature, but requires considerable experience and care. Pressures above approximately 1,400 MPa fall into the “research” category. The Harwood Engineering Co. produces a 3,000 MPa fluid system with a single UHP volume of approximately 300 cm³. The upper limit for research static fluid pressures (excluding the diamond anvil pressure cell, which has a volume of approximately 10⁻¹³ m³) is approximately 4,000 MPa (Ref. 7). Very little work in large volumes (>10 cm³) is done above approximately 1,000 MPa. Because of the extreme

difficulty in generating and containing these pressures and the serious ES&H issues resulting from the stored energy, the total UHP volume is made as small as possible. In this context, the UHP requirement for the MARIAH II/RDHWT Program for large volumes at 2,000 MPa operated in an industrial mode is a significant challenge.

5.3.3.3.1 UHP Vessel Design: Stress Management

At 2,000 MPa, there are two approaches to managing the hoop stress in a cylindrical pressure vessel: 1) compound cylinders with a fixed external radial stress, and 2) variable external radial stress. Since the UHP vessel is operated with a thermal gradient from the 900 K air at the inner wall to some lower temperature boundary condition at the outer wall, temperature is important both in its effect on material properties and in the thermal stress it generates.

In the compound cylinder scheme, two or more hollow cylinders are assembled concentrically with interference fits at their interfaces. The interferences are optimized (based on material properties) to give a compressive stress at the inner bore just below the compressive yield stress. Subsequent pressurization generates an additive (tensile) hoop stress at the bore, so that the total stress remains elastic. In many cases, the design specifies a maximum pressure that results in a plastic deformation of some fraction of the pressure vessel wall (autofrettage). The advantages of the compound cylinder approach are its simplicity and cost. For the UHP air source, the baseline design using a compound cylinder approach for a high-pressure end of the intensifier is an arrangement of three concentric cylinders with a 10-cm ID and a 100-cm OD.

The limitation of the compound cylinder approach is that the preloaded interference stresses are fixed. At some fluid pressure, the stress (usually at the inner bore) exceeds the elastic limit at the operating temperature, and the vessel deforms plastically. While operation in the plastic regime is normal in the research environment where operational cycles rarely exceed 1,000, fatigue is important in an industrial context where the number of operational cycles is important to the lifetime cost. Additionally, the elastic/plastic boundary is defined by the Young's Modulus, and the subsequent deformation is defined by the work hardening rule for the material. For high temperature, high strength steels, both material properties are strongly temperature sensitive at temperatures above approximately 800 K, decreasing to 50–75 percent of their room temperature values at 900 K. This degradation of material properties results in unacceptable plastic deformation of the inner layer of the compound vessel.

These limitations can be addressed by considering a variable radial support design (Fig. 5-8). In this approach, the hoop stress at the bore of the vessel is the sum of the components due to the internal pressure and the variable external radial stress. This stress may be produced in a number of ways, but typically is generated by applying a radial force to a wedged sector. The advantage of this arrangement is that the inward and outward radial stresses can be managed to operate the various components elastically. The internal pressure is limited in this scheme by the *compressive* strength of the axial end closures and sectors (at room temperature, approximately 2,500 MPa for steels and 4,000 MPa for tungsten carbides) and by the Poisson axial stress in the cylindrical walls.

The baseline design scheme for the variable radial support is a moderately thin (≈ 10 mm) walled inner liner of a high temperature, high strength, oxidation resistant steel (see Table 5-1) supported by an array of eight sectors. The sectors are under a force balance between the outward acting radial stress at the outer boundary of the inner liner acting on the inner boundary of the sector, and the pressure in the fluid chamber acting on the sector outer boundary. At the outer boundary of the sectors is a thin membrane (≈ 5 mm wall thickness) that prevents the fluid pressure from entering the space between the sectors. Since the sectors carry a significant radial stress but only a Poisson hoop stress, they may be made of material that is strong in compression but relatively weak in tension. The fluid pressure loading the outer boundary of the sector is contained by an external pressure vessel. As shown in Appendix B, this fluid pressure is of the order of $1/10^{\text{th}}$ the operating pressure; therefore, for the UHP driver, the external vessel is designed to operate elastically but with a relatively small safety factor of approximately 1.5. Even at this modest safety factor, the OD of the forging for the external vessel is of the order of 1 m for a facility-scale UHP vessel. Results of approximate, scoping calculations for various performance points and UHP intensifier numbers are presented in Appendix B.

In addition to operation in the elastic regime, the variable radial support approach offers the significant advantage of permitting use of a low thermal conductivity ceramic sector to carry the radial stress. Thermal management presents the greatest design challenge for the UHP air pressure source.

5.3.3.3.2 UHP Vessel Design: Thermal Management I—Generating Air Temperature

The UHP operating temperature requirement of 900 K results in two design challenges: 1) generate and maintain 900 K in the air; and 2) manage the effects of the high temperature on the chemical and mechanical material properties.

There are several options in generating the 900 K air temperature. Generally, the more work performed on the air system, the less heat must be added. Thus, adiabatic compression (no heat losses to the outside) from low density to the working density minimizes the addition of heat. However, this approach is limited (using a single compression stroke) by a requirement to keep the length to diameter ratio of the intensifier piston to a reasonable number. In practicality, the starting density is minimized by maximizing the starting temperature and adjusting the starting pressure to give a reasonable compression stroke. The range is relatively broad, but has two “natural” limits on the high side. The service temperatures of organic materials that might be used for pressure seals (that is, O-rings and seal packings) generally are lower than approximately 550 K; and long term material properties (creep strength) become increasingly important at approximately 650 K. As a baseline case, 300 MPa and 518 K are selected and result in an $S = 4.995$ kJ/kg-K isentrope that intersects the working point of 2,000 MPa and 900 K with a density compression ratio of $(1,151 \text{ kg/m}^3 / 716 \text{ kg/m}^3) = 1.61$. The pressure value follows from the general availability of commercial compressors in the 50,000 Psi (350 MPa) range. As the heat transfer from the air to the pressure vessel wall and detailed FEA calculations are made on the intensifier piston is better understood, the density compression may be increased to permit subsequent heat flow from the air to the pressure vessel wall during the stroke and still arrive at the pressure/temperature working point. For example, compressing from 140 MPa and 500 K

using a density compression ratio of 2.2 provides approximately 200 kJ/kg that can be lost to the vessel at a constant pressure of 2,000 MPa.

Compression of Liquid Air

In this approach, the high pressure volume contains liquid air at approximately 0.1 MPa, 79 K and 875 kg/m³ (0.875 gm/cm³). The optimal path (minimum heat added to the system) is to compress at constant entropy to the final density and then to heat at constant density to the final pressure and temperature. Beginning at the air critical point (132.5 K, 3.5 MPa) (this can be done by loading the pressure vessel with boiling air at 0.1 MPa, then applying 3.5 MPa pressure) and then compressing near the critical isentrope ($S \approx 4.4$ kJ/kg-K) to the final density of 1,151 kg/m³, results in $P = 1366$ MPa and $T = 500$ K. Adding approximately 400 kJ/kg at a constant density raises the temperature and pressure to 900 K and 2,000 MPa.

The primary disadvantages of using this method to reach the required plenum conditions are 1) handling liquid air; 2) degradation of material properties (ductility) at low temperatures; 3) adding a large amount (approximately 4 MJ for 10 kg of air) heat externally (by electrical feedthroughs or by conduction through the wall of the pressure vessel) at high pressures; and 4) disadvantageous thermal stress distribution for states in which the internal temperature is lower than external temperature.

External Heating

In this approach, some or all of the total air mass is heated external to the manifold/UHP intensifier array volume and then injected into that volume, thereby generating a starting (P , T) for the subsequent compression stroke. During the early part of the cycle, heat is lost to the steel so that during the constant pressure portion of the cycle, the temperature is relatively stable. Transient heat flow calculations, using directly measured values for the heat transfer coefficient, would provide the ranges for the initial and final temperatures. As an example, 300 MPa compressors would pass room temperature air through a heat exchanger to raise the temperature to some value selected to end up at an initial temperature (for example, 500 K) for the final intensifier compression stroke. This approach has the advantages of 1) the bore of the intensifier does not have to be heated to the initial temperature; 2) using the (free) initial heat of compression to 300 MPa; 3) adding heat external to the intensifier so that the heat can be added resistively using low pressure (300 MPa) electrical feedthroughs or using a packed bed heat exchanger operating at approximately 650 K; and 4) the thermal gradient dT/dr at the intensifier pressure vessel wall provides an inward radial thermal stress that adds to the negative, outward mechanical stress due to the high pressure gas.

For example, an adiabatic compression of air from 40 MPa (6,000 psi, a common industrially supplied gas bottle pressure) at 300 K to 300 MPa results in a gas temperature of approximately 515 K, very close to the baseline temperature for the final intensifier compression stroke. Since heat is lost during the compression (transfer of the gas to the manifold/intensifier array and during residence time in the manifold/intensifier array before the compression stroke), additional heat must be added between the compressor and the manifold/intensifier array. Adequately accurate calculations cannot be made without reliable values for the heat transfer coefficient, which must be measured under similar thermodynamic and geometric conditions (Ref. 8).

Internal Heating

In the internal heating scheme, the manifold/intensifier array is pressurized to some initial (P , T) condition and then heat is supplied to the air either by conduction through the liner or resistive heating in the air itself. Resistive heating using either simple Joule heating of resistors or in arcs requires some means of passing current from room pressure into the UHP volume. This, in practice, is feasible at 2,000 MPa but significantly increases the complexity and risk of the system. Unless the heater inputs were adequately distributed, thermal gradients would require some residence time to decay to a uniform temperature throughout the UHP volume. This is undesirable, since residence time in the UHP volume at high temperature should be minimized to minimize the effect of high temperature on the material properties of the UHP vessel.

An alternative is to heat the inner liner of the intensifier and conduct heat through it into the air. For an air temperature of 518 K prior to the compression stroke, the liner might be heated to 700 K–800 K, or a heat flow balance established between the outer wall of the inner liner and the dense air by a time-dependent heating profile. This would dramatically reduce the heat lost to the liner during the long (approximately 1–100 s) compression stroke. The primary disadvantages are the complexity of heating the inner liner and ensuring that the liner operates at high temperature as well as decreasing its strength to the order of 1,000 MPa. Cartridge, strip, or graphite heaters embedded in the ceramic sector face in contact with the inner liner must be robust enough to support the nearly 2,000 MPa radial stress at the outer diameter of the inner liner. Since, in the variable radial support scheme, the liner is operated at user-determined shear stresses (by adjusting the external radial stress) the loss of strength is not an issue for containment of the hoop stress due to the internal pressure. However, it may be important to maintaining the 2,000 MPa pressure seal provided by the very close tolerances between the piston and the liner.

5.3.3.3.3 UHP Vessel Design: Thermal Management II—Heat Transfer from the Air to the UHP Vessel

Heat transfer from the dense fluid air to the UHP intensifier and the axial manifold is a core problem in the UHP driver design concept. Flow of heat from the fluid causes its temperature to fall below the desired operating point, and flow of heat into the UHP vessel degrades material mechanical properties. The heat transfer coefficient is a critical parameter in thermal management, since it defines the heat transfer between the moving, high-density air and the manifold and intensifier walls. There are no experimental data in this regime. Lemmon et al. (Ref. 9) calculate values for the specific heat at constant pressure, thermal conductivity, and viscosity. For $P = 2,000$ MPa, $T = 900$ K and flow at Mach 0.1 (266 m/s) in a 0.02-m diameter manifold, the heat transfer coefficient h can be estimated using the Dittus-Boelter Equation (Ref. 10) (fully developed turbulent flow with $Re > 2100$ and $Pr > 0.5$):

$$Nu = \frac{hD}{k} = 0.023 Re^{0.8} Pr^{0.4} \quad (5-4)$$

Results are given in Table 5-2. A similar calculation for the intensifier for which a typical fluid speed is 0.3 m/s in a diameter of 0.1 m, yields $h \approx 810$ W/m²-K.

Table 5-2. Estimate Of The Heat Transfer Coefficient Using The Dittus-Boelter Equation For Fully Developed Turbulent Flow With $Re > 2100$ And $Pr > 0.5$; Thermodynamic Data Are From Ref. 9.

P (MPa)	T (K)	C_p (J/kg-K)	Thermal Conductivity (W/m-K)	Viscosity (Pa-s)	Reynolds Number	Prandtl Number	Dittus-Boelter Heat Transfer coefficient, h (W/m ² -K)
2,000	900	1.331(10 ³)	0.339	423(10 ⁻⁶)	1.44(10 ⁷)	1.66	2.54(10 ⁵)

The Dittus-Boelter Equation provides an upper estimate for h . For fully developed laminar flow in a pipe, an experimentally suggested form for the Nusselt Number is (Ref. 11):

$$Nu = 1.86 \left(\frac{\mu}{\mu_w} \right) \left(Re Pr \frac{D}{L} \right)^{1/3} \quad (5-5)$$

where μ_w is the viscosity near the wall of the pipe, μ is the viscosity far from the wall, and L is the distance from the pipe entrance. This form may be more applicable since, at $t = 0$ [immediately at the end of the compression from P_i to P_f (for example, from 300 MPa to 2,000 MPa)], the fluid has a uniform temperature. As the intensifier stroke continues at constant pressure, heat is lost to the wall and generates a thermal gradient towards the core. Taking $\mu_w = \mu$ and $L = 1$ m, the heat transfer coefficient is approximately 1.44(10³) W/m²-K. For transient heat flow in a hollow cylinder, this gives a Biot number that is essentially asymptotic to infinity.

Time-dependent heat transfer between a moving fluid and the wall of a hollow cylinder is parameterized using the Biot number (Ref. 12):

$$Bi = \frac{hD}{2k} \quad (5-6)$$

where h is the heat transfer coefficient, D is the OD of the hollow cylinder, and k is the thermal conductivity of the cylinder material. The Schneider chart for a cylindrical shell with internal radius/external radius $r_i/r_e=0.8$ is shown in Fig. 5-10. The case is for a shell insulated at its external surface $r = r_e$ after a sudden exposure to a uniform temperature convective environment at $r = r_i$. Biot numbers greater than approximately 100 are essentially infinite. For a hollow cylinder, initially at a uniform temperature and subjected to a different bulk fluid temperature at time $t = 0$, the time required for the OD to reach equilibrium with the bulk fluid temperature depends on the Biot number and can be estimated using a Schneider chart (Ref. 12):

$$t = \frac{F_0 r_e^2 \rho c_p}{k} \quad (5-7)$$

where F_0 is the Fourier number, r_e , ρ , c_p , and k , are the external radius, density, specific heat, and thermal conductivity of the of the hollow cylinder, respectively. This is a reasonable

approximation to the case of the UHP intensifier inner liner ($r_i/r_e = 0.05/0.06$) at some initial temperature in contact with air whose temperature has increased suddenly due to an adiabatic compression. For an 18 percent Ni maraging steel inner liner with a 100-mm ID, 120-mm OD, the time required for the OD to reach the temperature of the ID with a Biot number = 100 is approximately 50 seconds. At 1 second (even for Biot numbers greater than 1,000), the external radius increases in temperature only approximately 10 percent of the temperature difference. TOPAZ heat transfer calculations* using various Biot numbers are shown in Figs. 5-11 a-d and indicate similar results. Figure 5-12 shows TOPAZ calculations at $t = 1$ s for various Biot numbers. Assuming an infinite heat transfer coefficient, a substantial fraction of the inner liner is at temperatures greater than 650 K; therefore, the degradation of mechanical properties must be considered.

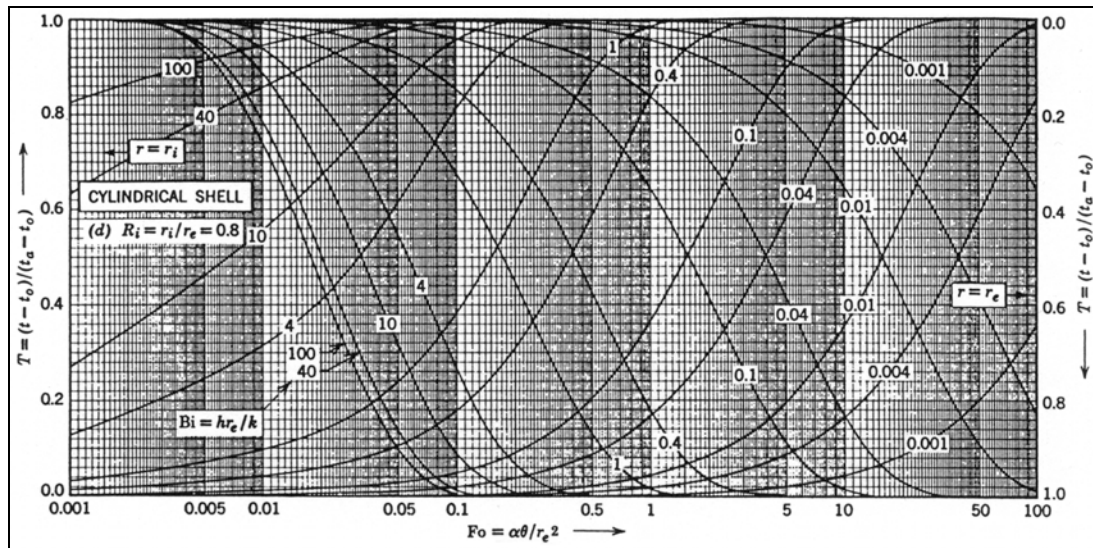


Figure 5-10. Schneider chart for transient heat flow in a hollow cylinder that is insulated on the outside and subject to a step change in fluid temperature on the inside (Ref. 12). F_0 is the Fourier Number, $\alpha = k/\rho c_p$, θ is the time, and r_i and r_e are the internal and external radii of the hollow cylinder. The details of the transient thermal response are important for the large Biot numbers, dimensions, materials, and operational times of the UHP driver.

A large-scale facility with run times on the order of 100 s will require active management of the air temperature. There is a possibility that the A-2 facility with run times on the order of 1 s may avoid this complexity. Experiments to measure the heat flow (Ref. 13) under these conditions are essential to determine whether the complexity and cost of active thermal management is necessary.

* Scott Perfect, Private Communication, 1998.

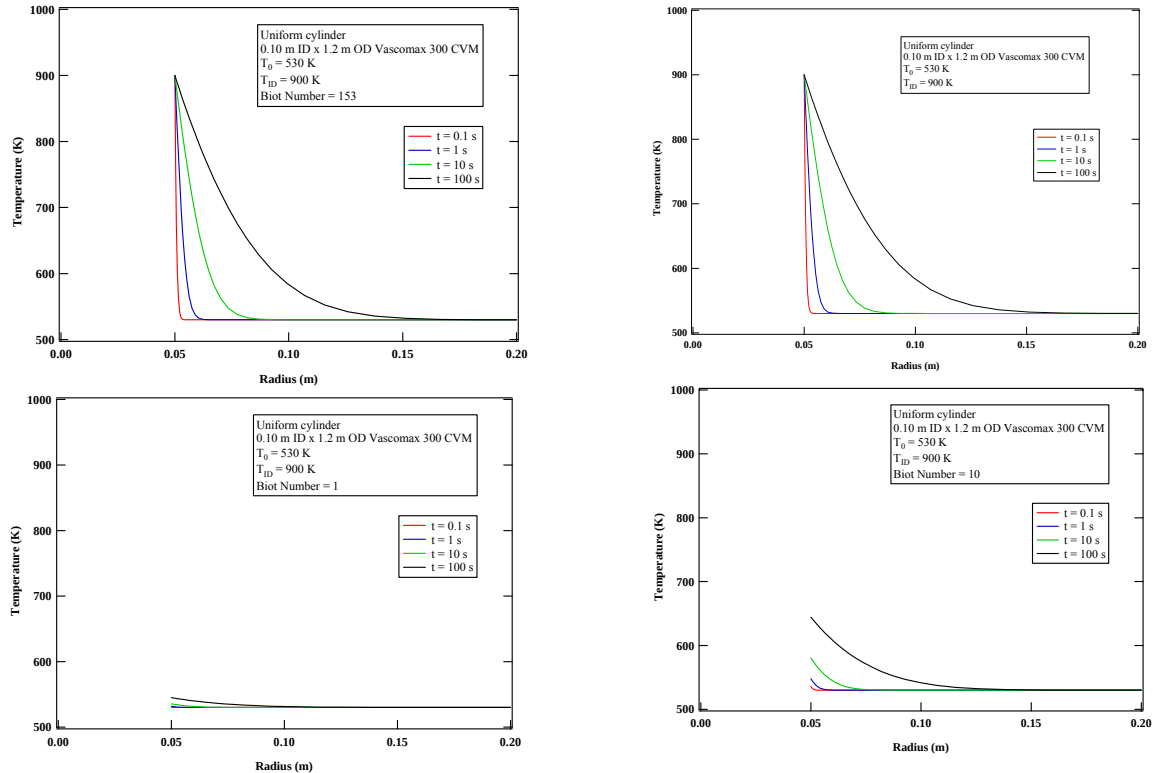


Figure 5-11. Results of TOPAZ transient radial heat flow calculations for a hollow cylinder. The initial temperature is 530 K, with the bulk fluid temperature fixed at 900 K and the outer boundary fixed at 530 K. The material is 18 percent Ni maraging steel, with specific heat=460 J/kg-K, thermal conductivity = 28 W/m-K, and density = 8,000 Mg/m³.*

5.3.3.3.4 UHP Vessel Design: Thermal Management III: Material Properties

Heat transfer from the 900 K bulk temperature in the 2,000 MPa air causes the materials confining the air to heat, which reduces their mechanical properties, increases their reactivity with the O₂ in the air, and generates thermal stresses. As discussed above, reaching the 900 K steady bulk temperature requires heating the air, either through quasi-adiabatic compression or heat exchange, to an intermediate value T_1 most likely in the range 500–600 K at some intermediate pressure, P_1 . The subsequent increase in temperature to a value T_F near its final value (900 K) due to the quasi-adiabatic compression from P_1 to $P_F = 2,000$ MPa occurs over a time of approximately 0.1–1 s. The operational stroke of the intensifier follows in which the entire manifold and the portion of the intensifier bore that contains air is exposed to the flowing, 900 K air. Finally, at the end of the operational stroke, the intensifier piston is retracted, quickly lowering the air pressure and temperature. Thus, there are four regimes: 1) steady state, low temperature (approximately 500–600 K), low pressure (approximately 300 MPa); 2) transient high temperature (500–900 K), high pressure (300–2,000 MPa); 3) steady state high temperature (900 K), high pressure (2,000 MPa), and 4) transient high-to-low pressure (2,000 MPa–0.1 MPa), high-to-low (900 K–300 K) temperature.

* Scott Perfect, Private Communication, 1998.

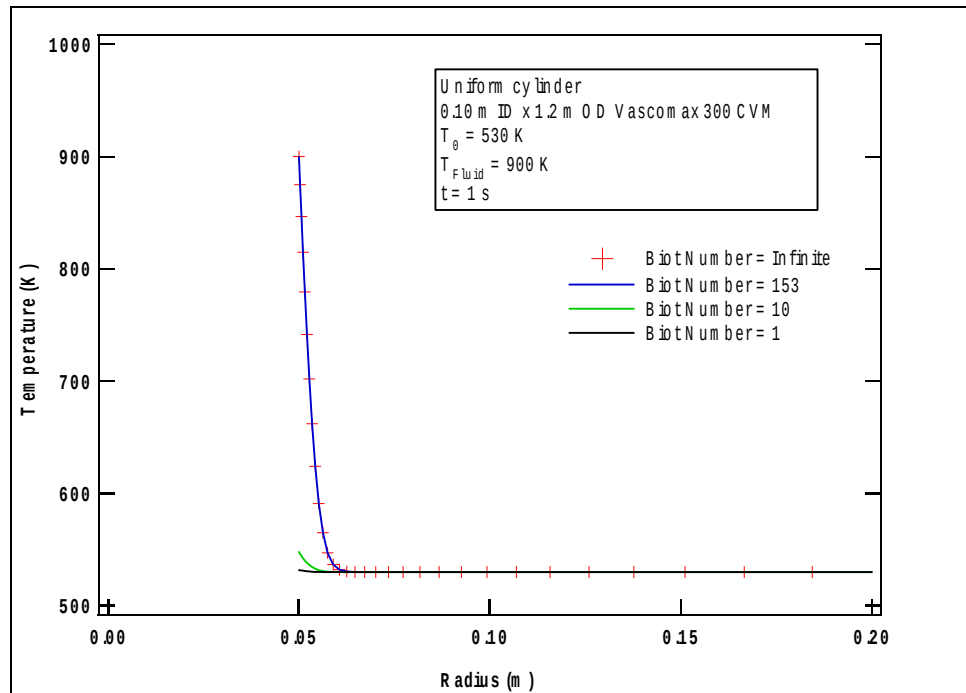


Figure 5-12. TOPAZ calculations for transient radial heat transfer in a hollow cylinder at $t = 1 \text{ s}$. Conditions are the same as for Fig. 5-11. At one second, approximately 50 percent of the inner liner wall thickness is at temperatures high enough ($> 650 \text{ K}$) to compromise its strength.*

In this section, the effects of temperature on material mechanical properties are discussed, chemical reactivity, and the thermally induced stresses.

Effect of Temperature on Material Mechanical Properties

Temperature effects on the mechanical properties of high performance materials generally become important (that is, effects on the order of 10 percent) above approximately 600 K (327°C , 620°F) (Ref. 14). The effects are well-known and with some exceptions, are characterized in readily available reference materials. The temperature effects generally are separated into short and long term. For the purposes of the A-2 design with an operating time of the order of 1 second, short-term material properties are appropriate. However, since the design concept is driven fundamentally by stress management, the long-term properties are appropriate for both the MSHWT and large-scale facility where the operational times are greater than 1 second. For reference, finite difference heat transfer (TOPAZ) calculations indicate the thermal profile in the steel structural elements at 100 seconds is very close to the steady state profile. Therefore, it is assumed that the design must use long term temperature properties. In this context, “long term” refers to thermal equilibrium times, which are important to material properties and thermal stresses. It does not refer to times appropriate to creep, as in a “100 hour rupture strength.” Note

* Scott Perfect, Private Communication, 1998.

where the large-scale facility design specification cannot be met using long-term values, but those for the A-2 can be met with short-term values.

In high-pressure design, the critical stress regions are at areas of stress concentration such as the internal bore, thread roots, and crossbores. The stress concentration for well-designed apparatus (using the internal pressure as the datum) ranges from $(K^2 + 1)/(K^2 - 1)$, where $K = \text{outside diameter/inside diameter}$ for the hoop stress, to over a factor of four times the hoop stress for some crossbore geometries. In UHP research, these concentrations almost always result in plastic deformation and are handled in two ways: 1) accept them and limit the operating pressure to a small (1.2–2) safety factor with respect to the bursting pressure; and 2) design in stress fields that when added to the stress due to the internal pressure result in an acceptable total stress. Operation of UHP vessels in the plastic regime is very common and, in the case of autofrettage, very desirable. For safety purposes, equipment for which the safety factor for bursting is less than approximately three and in which there is a significant ($>10^4$ J) amount of stored energy, is assumed to fail. It is operated remotely (that is, barricaded) to protect personnel and other equipment from collateral damage. Fatigue lifetime is an important issue in such devices as large caliber cannons and chemical and nuclear industry pressure vessels, but not as important in research pressure vessels where the number of operational cycles is low.

The three temperature-dependent mechanical properties that are most important to this problem are elastic modulus, yield strength, and creep. Other properties, such as toughness and ductility, are of concern but are of secondary importance because the operating temperature is high. Figures 5-13 through 5-16 (from Ref. 14) provide a good overview of these high temperature properties for candidate materials. As can be seen, long term values for the elastic modulus decrease by approximately 25–50 percent, for the 0.2 percent offset yield by 25–50 percent, and creep resistance decreases by approximately 50 percent over temperature ranges of less than 100 K.

Table 5-3 is a list of the nominal design service temperatures assumed for various components of the UHP air source. Table 5-1 provides the room temperature and service temperature values for candidate materials. In cases for which data are not available for the service temperature, an appropriate interpolation or extrapolation is used and noted.

There are several immediate conclusions:

- The intensifier inner liner must be supported by an external radial stress, provided by the ceramic sectors.
- The intensifier high-pressure piston and end closures must carry 2,000 MPa uniaxial compressive stress. The shear strength ($\tau = (\sigma_1 - \sigma_3)/2$) at temperature must be at least 1,000 MPa.
- Thermal stresses all work in the right direction (that is, they provide an inward acting radial stress, since $dT/dr < 0$).

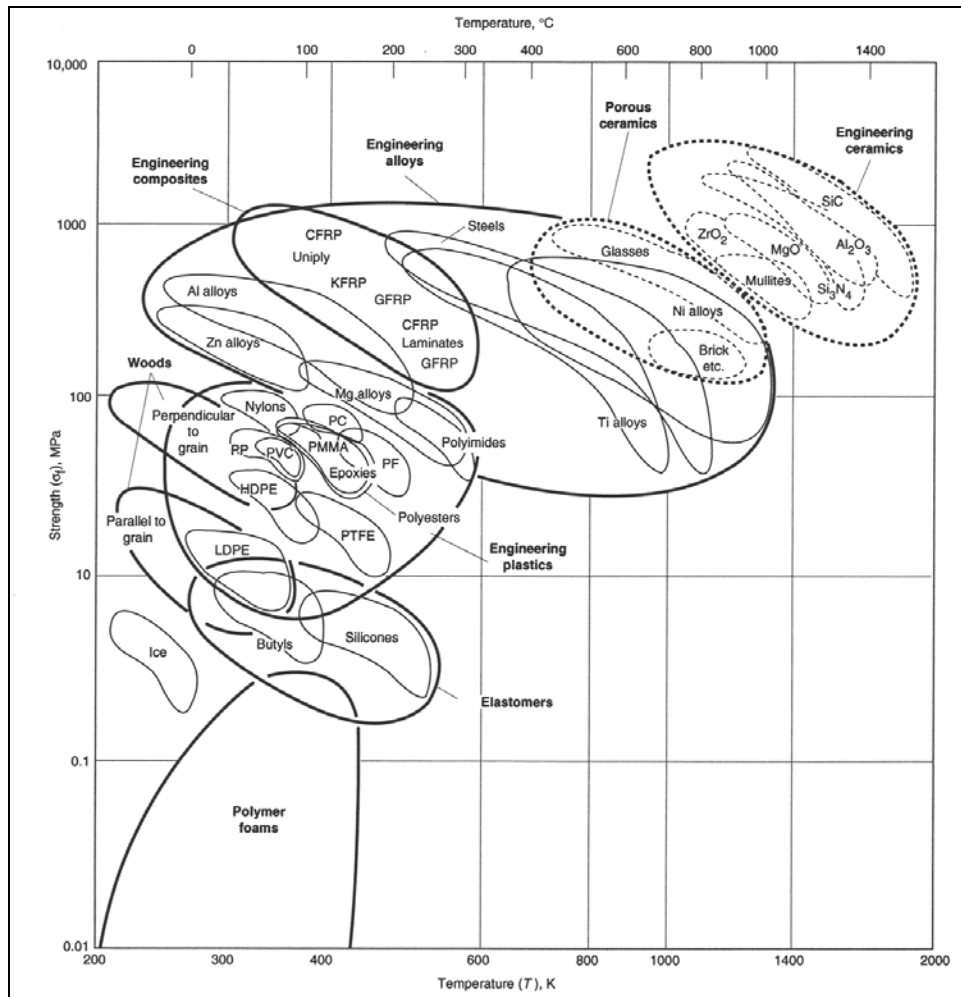


Figure 5-13. Service stress as a function of temperature for various structural materials (Ref. 14).

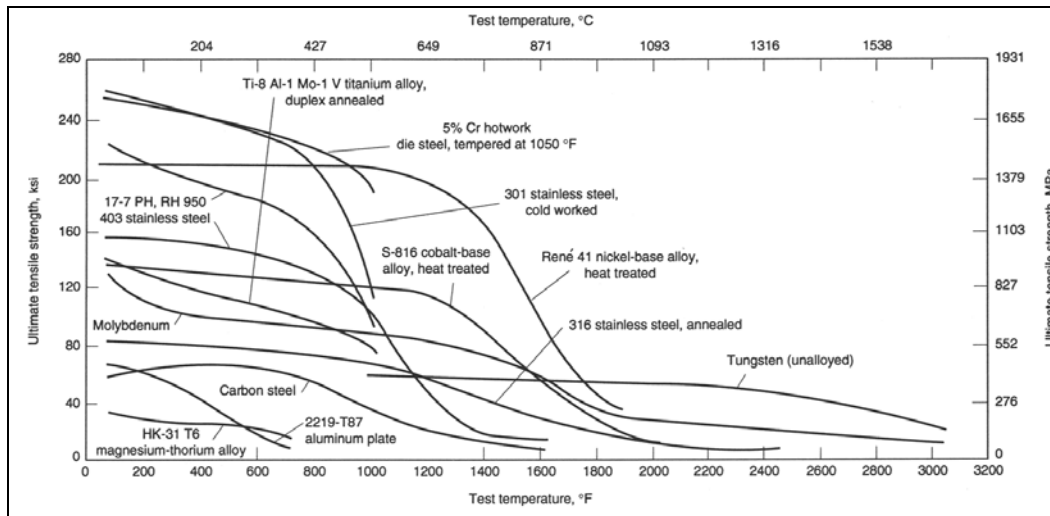


Figure 5-14. Ultimate strength as a function of temperature for various alloys (Ref. 14).

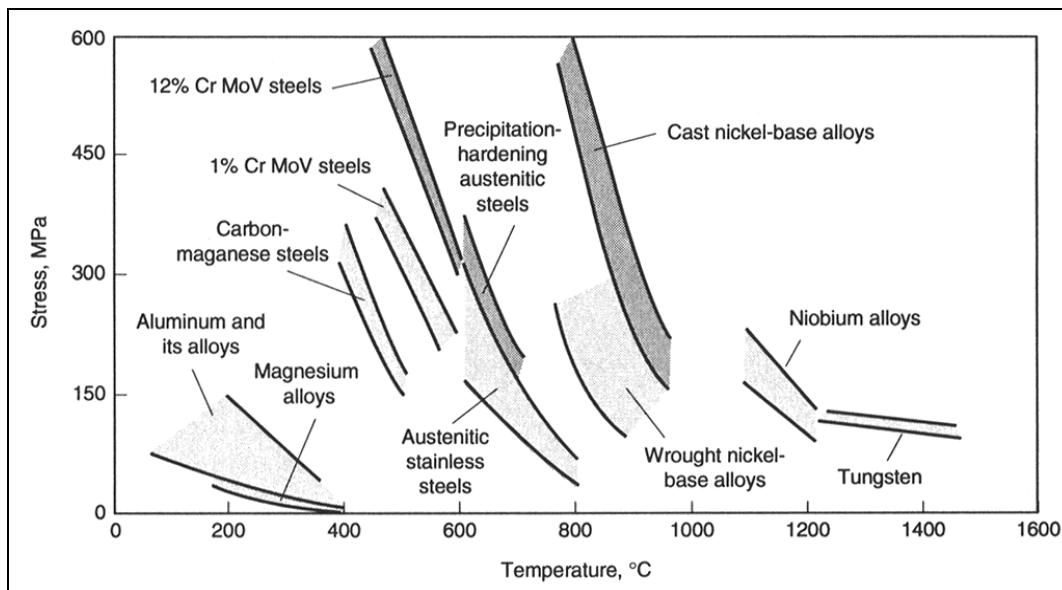


Figure 5-15. Stress to rupture for various alloys (Ref. 14).

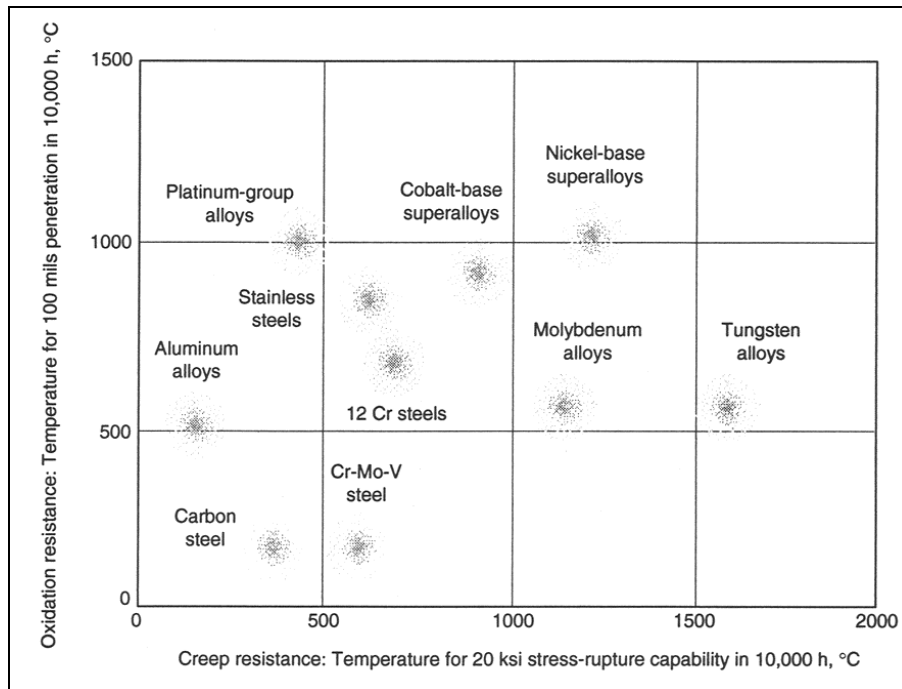


Figure 5-16. Creep resistance for various alloys (Ref. 14).

Table 5-3. Assumed Service Temperatures for UHP Subsystem Components

Component	Service Temperature (K)	Remarks
Manifold end closure (diagnostic end)	600	Maintained at $T < 900$ K by insulating convective flow barriers
Manifold end closure seal (diagnostic end)	600	The seal is at the temperature of the air in contact with the manifold end closure
Manifold end closure (nozzle end)	900	Nominal temperature. The actual surface temperature at the entrance to the nozzle may be higher due to boundary layer effects and to leakage of the energy addition source into the settling chamber.
Manifold end closure seal (nozzle end)	900	The seal is at the temperature of the air in contact with the manifold end closure
Manifold inner cylinder	900	For temperature boundary conditions of 900 K and 300 K at the inner and outer surfaces of the manifold, the steady state temperature distribution is above approximately 600 K for about $\frac{1}{3}$ of the total wall thickness. For a compound cylinder with layers having similar properties, the layer wall ratio is $k = K^{1/3}$, where K is the overall wall ratio. Thus, the inner cylinder is above approximately 600 K and, conservatively, can be assigned a 900 K service temperature. The inner wall temperature may be decreased by using a ceramic tube that closely fits the inner wall to reduce convective transfer.

Table 5-3. Continued

Component	Service Temperature (K)	Remarks
Manifold outer two cylinders	600	The temperature of the outer two layers of a three layer compound cylinder decrease from approximately, 600 K to 300 K at the outer wall. This temperature may be reduced by using a close-fitting ceramic insulator at the inner wall of the manifold.
Manifold safety ring	300	The safety ring is maintained at room temperature.
Intensifier inner liner	900	The inner liner steady state temperature is kept at 900 K to avoid heat loss from the air.
Intensifier sector	900	The inner boundary of the intensifier sector is in thermal equilibrium with the inner liner. For a ceramic sector, the thermal gradient is relatively high for run times of 100 s.
Intensifier sector membrane	300	The membrane is in thermal equilibrium with the intensifier outer pressure vessel, which is maintained at room temperature.
Intensifier sector membrane seal	300	The intensifier membrane seal is at the temperature of the fluid in the intensifier outer vessel.
Intensifier outer vessel	300	The intensifier outer pressure vessel is maintained at room temperature.
Intensifier moving piston (high pressure end)	900	The intensifier piston has a 900 K boundary at the end in contact with the high pressure air and a (nominal) 300 K boundary at the end in contact with the low pressure driver piston. The lateral cylindrical boundary has an intermediate temperature, as it conducts heat from the inner liner.
Intensifier moving piston seal (high pressure end)	900	The seal is at the temperature of the high-pressure air.
Intensifier end closure	900	The intensifier end closure has a 900 K boundary at the end in contact with the high-pressure air and at its internal wall. It has a 600 K boundary at its end in contact with the axial manifold.
Intensifier end closure seal	900	The seal is at the temperature of the high pressure air.
Intensifier end plates	600	The end plates are non-load bearing at their high temperature (900K) region and contain the sector hydraulic fluid at their low temperature (300K) region.
Driver vessel	300	The driver vessel is maintained at room temperature.
Intensifier piston (low pressure end)	300	The intensifier piston is maintained at room temperature.
Intensifier piston seal (low pressure end)	300	The seal is at the temperature of the low-pressure driver fluid.

Fatigue

Fatigue is a serious issue in regions of plastic strain subject to time dependent stress fields. Since an objective of the MARIAH II/RDHWT Program is to demonstrate technologies for a user facility, fatigue lifetime must be considered. As a planning assumption, the operational tempo for the wind tunnel at maximum performance is taken to be one run per day. For each run, the thermal and mechanical stress fields vary over a range of the order of 2,000 MPa or approximately the room temperature yield strength of the materials comprising the UHP driver. For a 200-day working year, 1,000 runs accumulate in 5 years. Assuming 10,000 cycles (usually the lower bound for fatigue analysis) with a safety factor of eight means capital replacement would occur approximately every 5 years. Thus, high fatigue risk components should be designed to permit monitoring and inspection and relatively inexpensive replacement. Components having a high risk for fatigue failure are the manifold, primarily at the crossbore and the transition from the small to large ID at the ends; the high pressure piston; the intensifier and manifold end closures; and the internal bores of all the pressure vessels. Each is addressed briefly in the following discussion.

Manifold—The manifold is a 2,000-MPa pressure vessel having three distinct structural regions (that is, end, crossbore, and body). The end regions (see Fig. 5-6 and 5-9) have an ID of approximately 6–10 cm and house the diagnostics and pressure feedthroughs on one end and the nozzle and cooling fluid injection hardware on the other. Both ends may be provided a radial variable support so that the inner cylinder of the compound vessel manifold operates in an elastic region. However, at the manifold diagnostics end, some provision must be made to prevent the 2,000 MPa air from flowing back into the 300 MPa pre-pressurization system. A good place to install this “check-valve” is downstream from the diagnostics end closure so that it does not carry the 2,000 MPa pressure, thereby removing the requirement for the variable radial external support at the diagnostics end of the manifold. The end closure region at the nozzle end is supported by a radial stress provided by the radially arrayed intensifiers providing the helium cooling gas.

An important feature of the radial UHP intensifier array around an axial manifold design concept is the connectivity between the intensifier and the manifold. This is effected by using the manifold to react the force on the intensifier end closure because of the pressure in the intensifier. The reaction force, which is equal to the product of the intensifier area and the end closure cross section (minus the area of the axial connecting through hole) minus the force owing to the friction between the end closure and the intensifier bore, results in a contact stress (a function of the contact area). The pressure seal between the end closure and the manifold surface is made by adjusting the contact stress to be greater than the pressure. Conveniently, this sealing stress is approximately a constant fraction of the pressure itself, assuming the friction force is relatively small. FEA calculations will provide a guide to the details of the mating surfaces, both for self-alignment and for stress distribution across the interface.

Manifold End Closures—The manifold end closures are cylindrical “plugs” that seal the ends of the pressure vessel. They carry the full 2,000 MPa uniaxial compressive load, if no credit is taken for the radial support offered by the inner cylinder as the end closure expands due to the Poisson radial stress or for inward deformation of the cylinder because of the external radial stress provided by the variable radial support. Fatigue failure of the portion of these cylindrical elements inside the manifold is due primarily to the Poisson contribution of the compressive axial

stresses to other stress fields around feedthroughs or other stress concentrators in the end closure itself.

The diagnostic end closure (Fig. 5-6) has several (6–8) axial holes for a pressure port and thermocouple and pressure gauge electrical feedthroughs. FEA analysis of the stress concentration in this array provides the best configuration for the feedthrough sealing surfaces (conical or spherical) and holes. Commercial apparatus operating in the 2,000–3,000 MPa range (Ref. 5) use classical Bridgman conical feedthroughs with high reliability.

The nozzle end closure contains the inlet to the nozzle, the nozzle throat, and likely extends for several tens of centimeters through the core of the toroidal magnet used to define the e-beam energy addition region. The design of this component is complicated by the requirement that it not significantly perturb the magnetic field. This limits the material selection considerably and results in an extraordinarily difficult design problem, which has yet to be satisfactorily addressed. Managing the deformation of the inner surface (that is, the nozzle inlet, throat, and outlet profile) is critical to understanding the performance of the wind tunnel. At this point, the most likely approach is to use a multicomponent construction with a high-strength titanium alloy as the inner layer and organic fiber wrapping as the outer component. The design of this component will be a major focus of effort during the next program year.

The variable radial support for the nozzle end closure is provided in a way similar to that for the crossbores. At least four intensifiers surrounding the region provide helium gas for film cooling and, simultaneously, a four-fold symmetric radial stress to support the vessel ID. FEA analysis is used to optimize the magnitude and distribution of this stress to control the stress concentration of the crossbore and at the ID of the nozzle end region.

Another region of high shear stress is near the seal between the end closure and cylinder. For the end closure, the seal is an inverted Bridgman unsupported area configuration. On the high pressure gas side of the seal, the radial stress boundary condition is the pressure; at the seal contact, it usually is approximately 1.1–1.5 times the pressure and changes discontinuously to zero on the atmospheric pressure side of the seal. Detailed FEA is required to find the von Mises stresses and associated strains in the region. Nevertheless, 60 years of experience indicates these stresses do not result in failure (even over many pressure cycles) providing there is a “massive area support,” (that is, significant regions of structural material surrounding the region subject to high shear stress). Applied to the sealing region, this normally means the seal is located at least one cylinder diameter deep into the cylinder. Sealing regions closer to the end of the cylinder are subject to shear failure along a (roughly) 45 deg cone intersecting the end face of the cylinder.

Both end closures must be easily accessible for frequent inspection. This accessibility is especially important for the nozzle end closure for which the planning assumption is inspection or replacement after each run. Easily removed axial spacers in the axial load chain provide the axial degree of freedom to withdraw the end closures from the manifold.

Manifold Crossbores—The manifold crossbore region presents an exceptional stress management challenge. Crossbore stress concentrations have been studied thoroughly (Refs. 15–34). Generally, the stress concentration factors (hoop stress with crossbore)/(hoop stress without crossbore) are in the range 2.5–4; therefore, for a thick wall cylinder with $D_o/D_i > 5$ (therefore,

$\sigma_h \approx \sigma_r$), the stress concentration factor can be taken as 3.5. Since the pressure already exceeds the elastic limit, the material near the crossbore is plastic. We manage these stresses primarily by adding an external radial stress using the end closures to the UHP intensifiers (see Appendix D) and an external axial stress using an external load frame. Some decrease in the stress concentration arises through selection of geometry (for example, making the radii of the cross and axial bores the same, adjusting the radius of curvature of the intersection of the cross and axial bore, and offsetting the axis of the crossbore from the axial bore). FEA calculations indicate how to minimize the stress concentration using these geometrical effects. The detailed design calculations are a major effort during the next program year.

Elastic FEA calculations using the application “Mechanica” show the regions of high stress.* The Mechanica calculations show a stress concentration resulting in a von Mises stress of approximately 3.7 times the pressure. Increasing the OD of the manifold by a factor of two (from 200 mm to 400 mm) decreases the stress concentration to approximately 2.5. Not surprisingly, the elastic calculations show that combinations of compressive external stresses on the manifold result in stresses at the crossbore surface that are less than the internal pressure. Varying radial loading boundary conditions on the manifold (that is, by varying the contact area at the UHP intensifier end plug manifold external surface interface) indicates the strain along a portion of the circumference of the crossbore and axial bore holes (generally in a plane normal to the manifold z -axis) can be reduced. At least 4-fold radial symmetry is required, with higher order symmetry providing a uniform external “radial” stress.

Deformation of the crossbore hole in the manifold z -axis direction occurs because the thick-walled manifold cylinder has unconstrained ends. The tensile stress in the manifold z -axis direction causes the circular crossbore hole to become an oval, with major axis along the z -axis. Addition of an external compressive axial stress, by means of an axial load frame already required to react the pressure-induced force on the manifold end plugs, reduces this stress.

Elastic-plastic calculations** using the code “DYNA3D” validate the elastic calculations in terms of the high stress regions. Plastic strains as high as 12 percent (for VascoMax 250 CVM at room temperature with 2,000 MPa internal pressure and a 2,000 MPa external boundary condition on the manifold at the crossbore) occur in the crossbore because of the zero external axial stress.

In summary, the stress concentrations around the crossbores can be reduced to acceptable levels by applying an external variable radial stress (along the crossbore axis) and an external axial stress (normal to the crossbore axis and along the manifold axis). The details of the geometry and magnitude of these externally applied stresses will be developed in fully coupled elastic-plastic-thermal FEA.

Manifold Body—The “body” portion of the manifold is that part of the manifold that is not supported by an external radial stress. As such, it does not benefit from the external variable radial support as in the regions at the ends and the crossbores except near those regions where the radial stress field decays along the longitudinal axis. To take advantage of this effect, the manifold should be as short as possible. The body is a four-layer compound cylinder with a high-

* Marcus Libkind, Private Communication, 1998.

** Scott Perfect, Private Communication, 1998.

strength, high temperature steel (such as VascoMax 350) as the inner liner; a high strength steel (such as VascoMax 350 or AISI 4340) second layer; a high strength steel (such as AISI 4340) third layer; and a mild steel (AISI 1040) safety ring. The interference fits between the layers and can be designed to provide a fixed radial compressive stress (at a constant temperature profile) that can be as large as the yield stress in compression at the manifold bore. The strength of the inner liner at 2,000 MPa and 900 K is only approximately 1,000 MPa. The interference stresses in the compound cylinder design, in addition to the thermal stress, must result in a compressive radial stress near the failure point at the manifold bore at zero internal pressure. Elastic/plastic coupled DYNA-3D/TOPAZ calculations will indicate the extent of the plastic flow due to the reduction of the material properties at high temperature. The layered compound cylinder, together with active external cooling, most likely will adequately prevent propagation of the plastic zone to the external boundary. Use of a ceramic liner to reduce convective heat exchange between the air and the steel wall of the manifold will reduce the temperature of the steel. The loss of dimensional stability at the bore of the manifold is permissible, since there are no components that mate to it. The plastic deformation takes the form of the classic “bulge” of overstressed thick-walled cylinders, which can be monitored externally very easily. Finally, the manifold is designed to be replaced relatively inexpensively.

UHP Intensifier Piston—The UHP intensifier piston carries the 2,000 MPa axial stress due to the high pressure air. It is supported radially in the sealing region at the high-pressure end and may be supported radially along the length of the opposite end that remains outside the UHP intensifier cylinder. Since the remaining portion of the piston must not contact the wall of the UHP intensifier, it is unsupported radially; therefore, the shear stress is about one-half of the pressure. There are schemes in which a supporting fluid pressure around the piston can be provided; however, they have considerable complexity and should be avoided. For operating temperatures below approximately 600 K, high strength steels are adequate to carry the axial load. However, at 900 K, the material properties in the region near the high-pressure seal will be degraded. The extent of this degradation, its effect on the radial deformation of the piston, and the subsequent increase in friction between the piston and the UHP cylinder wall is unknown. Elastic/plastic, fully coupled DYNA3D/TOPAZ calculations will give an indication of the severity of the plastic flow. Use of brittle, high compressive strength materials such as tungsten carbide with a 6 weight percent cobalt may be required.

As for the case of the manifold, the UHP intensifier piston should be relatively easy to access for inspection and replacement. External monitoring is not readily done; therefore, the intensifier assembly should be reasonably easy to remove from the radial reaction frame and the intensifier itself easily disassembled. In industrial operations, intensifiers are cycled out of the UHP driver system for regular maintenance and inspection. Since the intensifier end plug passes through the external two layers of the compound cylinder making the axial manifold, easily removable axial spacers of that length must be installed between the intensifier base and the reaction frame.

UHP Intensifier End Closure—The UHP intensifier end closure connects the UHP intensifier to the axial manifold. Unlike the UHP intensifier piston, the end closure is subject both to an axial compressive load and to an internal radial stress since it has a hole along its centerline. The baseline design for this part is a two- or three-layer compound cylinder. The high-pressure seal at the intensifier end is a classic Bridgman inverted unsupported area seal. In the event the interference fit is inadequate to prevent leakage of the 2,000 MPa gas into the region between the

layers, the end exposed to the gas can be sealed by a layer of plating or some similar method. The end closure cylinder is supported by the UHP intensifier cylinder along its length inside the intensifier (approximately one UHP intensifier ID). The external radial stress provided by the variable radial support vessel on the outside of the UHP intensifier provides this support. The axial frictional force between the end closure and the intensifier bore must be small enough to permit the 2,000 MPa pressure to load the end closure against the axial manifold. While, in principle, the interface stress at the end closure—manifold interface can be adjusted to account for a large friction force acting opposite to the pressure force by specifying the interface area, the friction force should be minimized to permit as large an interface area as possible.

The UHP intensifier end closure passes through the outer layers of the axial manifold and makes up to the outer surface of the innermost layer, with the axial hole in the end closure coaxial to the crossbore hole of the manifold. This is necessary because of the difficulty in sealing the leakage paths offered by the intersection of the crossbore hole with the interference fits between the manifold layers. The end closure region passing through the outer layers of the axial manifold is not supported by a variable radial stress. Unless there is an interference fit in this region, the end closure outer surface is a free boundary, and the end closure must carry not only the radial and hoop stresses due to the internal pressure, but also the axial stress due to the pressure in the intensifier. One approach to providing a variable external radial stress, if required, is to make an interfering conical interface between the end closure and the outermost layers of the axial manifold, while still permitting enough axial movement to allow the end closure to make up to the innermost layer of the manifold. FEA calculations will provide guidance in the design details of this part.

Similar to the axial manifold, the end closure likely will be a three-layer compound cylinder with an OD equal to the ID of the UHP intensifier and a length of about twice the intensifier ID. The ID of the end closure is sized to provide adequate mass flow to the settling chamber and depends (geometrically) on the number of intensifiers in the radial array. The hole nominally is approximately 1 cm in diameter, thus providing an overall OD/ID ratio for the end closure of approximately 10:1. Since the end closure is relatively small, cost is not a significant factor in its design, and all three load-bearing layers likely will be made of a high performance steel such as VascoMax 350. The part can be inspected during the same maintenance cycle as inspection of the UHP intensifier piston. The most serious stress concentration, identified precisely using FEA, likely will be the sum of the hoop stresses at the bore due to the pressure and Poisson stress resulting from the compressive axial stress. As in the case of the manifold, the part is operated plastically with a small safety factor with respect to bursting.

Internal Bores of Pressure Vessels—The maximum shear stress in a cylindrical pressure vessel usually occurs at the boundary of the pressure vessel and the pressure fluid. Shear stress in other regions such as thread roots and blind ends usually can be managed by minimizing the stress concentration factor and increasing the cross-sectional area carrying the load. The shear stress at the bore is managed by adding a compressive radial stress. The usual methods are thermal (by creating a positive temperature gradient dT/dr) through an interference fit between layers of a compound cylinder or through reaction of an external radial force provided mechanically or hydraulically. Substantial literature exists on the fatigue of thick-walled pressure vessels primarily in the chemical engineering, nuclear reactor, and military cannon fields. Fatigue characterization and monitoring is well-developed with the following basic conclusions: 1) a

robust quality assurance program is required to ensure material properties (particularly heat treatment and internal flaw number and size) are within design specification; 2) thick-walled vessels can be operated in the plastic range with small factors of safety on the bursting pressure in an economic and predictable way (indeed, purposeful plastic deformation, termed autofrettage, frequently increases the fatigue lifetime); and 3) fatigue lifetime can be predicted adequately well.

The thick-walled cylindrical sections in this design fall into three groups: 1) sections that must have a high degree of control on the radial deformation at the inner cylinder wall (the UHP intensifier high pressure bore); 2) sections for which a permanent radial deformation at the inner wall is permissible (the axial manifold, away from the end regions); and 3) sections in which the OD/ID ratio is inadequate to use a compound cylinder design (the axial manifold in the end regions). All regions have essentially similar thermal stresses. The requirement for managing the radial deformation at the inner bore results in the use of a variable radial support scheme in which the externally applied radial compressive stress is synchronized with the internal pressure. The sum of these two radial stresses can be adjusted not only to keep the shear stress in the wall of the vessel below the elastic limit so there is no plastic deformation and no serious concern about fatigue lifetime but also to keep the radial deformation of the bore equal to zero. For the last group, either a variable or fixed radial support could be used. In this design, a variable radial support is selected at the nozzle end of the axial manifold in order to provide a means of injecting a cooling gas into the flow upstream of the nozzle. At the diagnostics end of the manifold, either a fixed (compound cylinder) or variable radial support could be used; the former most likely resulting in operation in the plastic regime and the latter in the elastic regime. The second group of sections, the axial manifold away from the end regions and the intersection of the radial UHP intensifier array, most likely will have a compound cylinder design and be operated in the plastic regime with a factor of safety with respect to the bursting pressure. Monitoring the external diameter dimension provides adequate information on the progression of the plastic boundary from inside to outside. Failure occurs upon rupture of the innermost layer.

Effect of temperature on material chemical reactivity

This section addresses the high-pressure/high-temperature reactivity of O_2 with high performance steels only in the most general sense. While oxidation at high temperatures has been addressed by the aerospace community, there is very little experience under the combined action of high O_2 partial pressure and high temperature. Generally, chemical reaction of oxidizing or reducing pressure fluids with pressure vessel steels is avoided by use of an internal vessel containing the reactive fluid and the sample, surrounded by an inert pressure fluid in an external vessel. Karpinski and Kaldis (Ref. 35) describe a device that operates at 250 MPa and 1,700 °C using an internal vessel of Al_2O_3 for O_2 service. The author has performed research at 50 MPa pure O_2 at approximately 1,200 K contained in an Inconel X750 alloy pressure vessel, with no apparent reactivity problems. Topchiyan and coworkers (see Section 6.2) describe catastrophic oxidation of a Vasco SUPREME alloy nozzle in air at a plenum condition of 500 MPa and 1,600 K.

For the purposes of this discussion, air at 2,000 MPa has a partial nitrogen and O_2 pressures of 1,600 MPa and 400 MPa, respectively. The planning assumption, for design purposes, is that trace species and impurities in the air source do not make significant contributions to corrosion. The validity of this assumption, particularly concerning the carburization of the steel due to the CO - CO_2 - O_2 equilibrium and the NO_x concentration, must be established during the next program

year. Nitriding reactions with high performance steels are present, but means for their mitigation lie well within the pressure/temperature/materials envelope of measures required to address the reactivity of O_2 . Because of the dearth of data on the reactivity of materials with high-pressure/high-temperature air, an experimental program to supplement a literature survey may be required.

The threat posed by high-pressure/high-temperature O_2 is well-known (see Ref. 36). The temperature effect arises from the Arrhenius term $e^{-(\Delta H/kT)}$, where the heat of reaction ΔH is large for the elements making up high performance steels: iron (Fe) (Fe_2O_3 : -197 kcal/mol; Fe_3O_4 : -267 kcal/mol); Ni (NiO : -57 kcal/mol); Cr (Cr_2O_3 : -273 kcal/mol); molybdenum (Mo) (MoO_3 : -178 kcal/mol) and cobalt (Co) (CoO : -57 kcal/mol) (Ref. 37). The driving force for oxidation of metals is the change in the Gibbs Free Energy:

$$\Delta G = \Delta G^0 - RT \ln \left[\frac{(a_M)^x (a_{O_2})^{y/2}}{a_{M_xO_y}} \right] \quad (5-8)$$

$$\Delta G^0 = -RT \ln f_{O_2} = -RT \ln(\gamma p)$$

where $xM + (y/2)O_2 = M_xO_y$. The activities, a , of the metal and the oxide are sensibly equal to 1. However, the activity for the nonideal gas, high-pressure O_2 cannot be approximated by its pressure but must be described using the fugacity f . At equilibrium, $\Delta G = 0$ where $\gamma = f/p$ is the fugacity coefficient. Equation of state data for O_2 near 400 MPa and 900 K are not available. However, the similarity of the O_2 and nitrogen EOS permits approximating O_2 properties using the nitrogen EOS. For nitrogen at 400 MPa and 900 K, the fugacity coefficient is 12.85 (Ref. 3). A qualitative picture of this reactivity is shown in Fig. 5-17, where the flammability of carbon steel is given as a function of mole percentage O_2 and total gas pressure. Carbon steel exhibits partial combustion in high-pressure air. The primary mitigation involves eliminating the ignition source energy arising from reaction of O_2 with organics (for example, grease) and from the local heating that occurs when a small, solid impurity in the air flow stream collides with an interior surface.

Information on the kinetics of the oxidation process comes primarily from corrosion studies. All of the three usual rate equations (that is, logarithmic, parabolic, and linear) may apply to the A-2 device. Initial oxidation of the chromium (Cr) in the steel (logarithmic) provides a good protective barrier of Cr_2O_3 that inhibits further oxidation. The long times at high temperatures permit significant diffusion of both O_2 through the protective barrier and metal ions to the surface (parabolic). Finally, formation of stress-induced cracks and erosion of the oxide layer provides fresh surfaces for further oxidation (linear). Many high strength/high temperature alloys have been developed for use in oxidizing atmospheres, primarily for turbine applications (Ref. 38). The extreme environment is handled through a combination of base steel selection, chemical and thermal protective coatings, and backside cooling of the structural member. The use of coatings is an area of active research (Ref. 39).

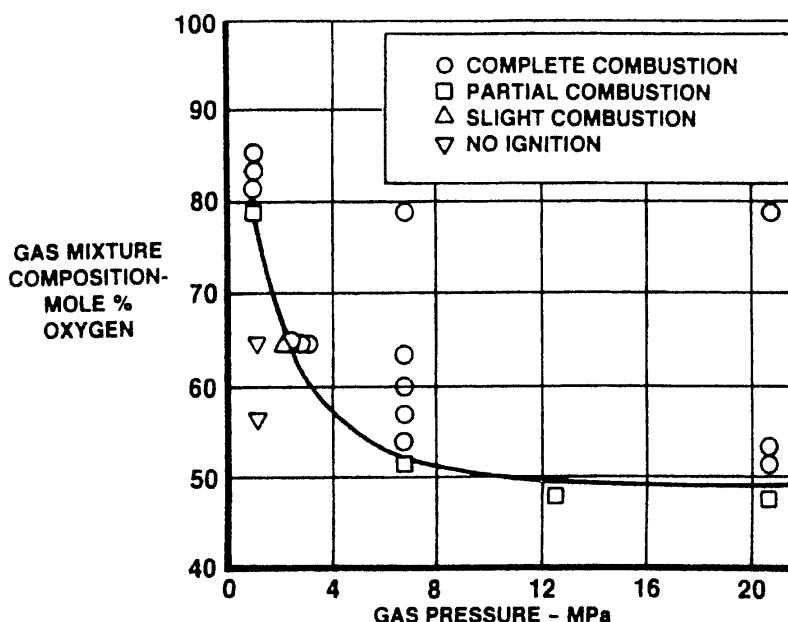


Figure 5-17. Oxygen index of carbon steel as a function of pressure and mole percent of O₂ (Ref. 40).

5.4 SUMMARY

A concept for the UHP air supply for a hypersonic wind tunnel has been developed. This concept meets the primary design requirements of plenum enthalpy in excess of 2,500 kJ/kg, run times of 1,000 s or more at mass flow rates of pure air of 100 kg/s, and spatial and temporal flow quality. Use of existing engineering technology and materials for most components provides affordability at moderate risk. The highest risk components are the throat/nozzle assembly and the crossbore connectors to the UHP intensifiers.

The evaluation of several alternative concepts resulted in the selection of a configuration having variably radially supported UHP intensifiers, each with a working volume of approximately 0.03 m³ arrayed in radial symmetry around an axial manifold. The nominal design point for the plenum is 2,000 MPa at 900 K with an air density of 1,150 kg/m³ and a specific enthalpy of 2,500 kJ/kg. An array of four intensifiers, each with an internal diameter of 93 mm and a working volume of 3.8(10⁻³)m³, provides a run time of approximately 1 s at a mass flow rate of approximately 10 kg/s through a 3 mm diameter throat. These intensifiers and their radial hydraulic support manifolds are driven by an intermediate pressure system consisting of at least eight intensifiers, which produce a maximum 300 MPa pressure. The energy originally is stored in compressed nitrogen in a large volume (30–50 m³), ASME-approved pressure vessel.

The UHP concept has both moderate and high-risk elements. While based on existing engineering practices and materials, it has a volume about a factor of 100 larger than any pressure vessel operated at 2,000 MPa. This introduces a low to moderate risk in material properties of large sections. Operation for times greater than 1 s at 900 K results in significant degradation of room

temperature materials properties. This moderate risk can be reduced by decreasing the operating temperature to approximately 750–800 K and increasing the pressure to approximately 2,300 MPa to maintain the 2,500-kJ/kg enthalpy. The highest risk elements are the nozzle/throat assembly and the crossbore connections between the UHP intensifiers and the axial manifold. The latter can be addressed by design using elastic–plastic, fully thermally coupled FEA that is validated by component testing. The former must be addressed through an R&D program to determine the boundary layer thermal and mass transport properties, followed by component testing for chemical and mechanical survival in high Reynolds number flows as close to the actual conditions as possible.

During the next program year, the UHP design concept will be integrated with the energy addition, fluid dynamics, and test section subsystems. Trade-offs in performance, cost, and risk will result in development of specifications for the UHP air source for the multimegawatt energy addition experiment (the A-2). Environmental, Safety, and Health requirements for the design and operation of the A-2 will be determined and addressed. A quality assurance plan for design, procurement, inspection, assembly, and testing will be developed. Detailed engineering calculations and machine drawings will be executed and cost and delivery estimates will be determined. Procurement of long lead-time components, such as large forgings and ceramic sections, will begin. Component test requirements will be developed and component testing executed within program resources.

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6.0 NOZZLE

6.1 UHP NOZZLE THROAT

6.1.1 Objectives

The objectives of this program element are to provide 1) a UHP nozzle section that meets the A-2 performance requirements for run time and flow quality, and 2) a UHP nozzle design concept that meets the performance requirements for the MSHWT and a large-scale T&E facility. Nozzle survivability is a high risk element in the MARIAH II/RDHWT Program.

6.1.2 Approach

The approach taken to meet this objective is to define the “UHP nozzle section” as the wind tunnel nozzle extending from the UHP manifold to approximately 1 meter downstream of the nozzle throat and integrate the UHP nozzle section mechanical design, the surrounding magnets, and the predicted thermal and chemical conditions at the nozzle surface with the UHP driver design. During this first year, the focus was on developing an integrated, geometrical design concept using the conservative assumptions that the nozzle must contain 2,000 MPa internal pressure at 900 K upstream of the throat, active film and back surface cooling may be required, a uniform axial magnetic field near the throat will be required, and the nozzle assembly must be inspected and possibly replaced after each run. Various schemes are developed to self-consistently meet the sometimes-competing requirements of the UHP driver subsystem, energy addition subsystem, and fluid dynamics subsystem. In the many cases for which specific performance criteria are not established, design assumptions are made to retain as much flexibility as possible. For example, the nozzle wall–fluid heat transfer coefficient is not known; therefore, the transient wall temperature is assumed to be high enough to require active film and back surface cooling. Data for candidate nozzle materials are collected to develop the recommendation for an experimental program for nozzle survivability. An experimental program to validate design concepts such as injection of helium (He) cooling fluid tangential to the nozzle inlet and nozzle materials survivability in the moderately high temperature, high O₂ fugacity, high shear stress environment are described briefly below and in more detail in Section 6-2.

The limitation on overall facility performance by nozzle survivability issues including alternative protection schemes has yet to be established. These issues and alternative nozzle protection schemes must be addressed early in this research program to determine whether or not the stagnation pressure and temperature UHP goals and subsequent energy addition approaches are realistic and fall within possible nozzle survivability limits.

6.1.3 Experimental Apparatus

Experimental apparatus required during FY99 is the 250 MPa high-pressure vessel used at LLNL during 1997 and transferred to Princeton University in April 1999. The apparatus is used to 1) characterize the boundary layer for flows with Reynolds numbers similar to those expected in the A-2 and successor facilities, 2) develop diagnostics for use in subsequent MARIAH II/RDHWT Program research, and 3) validate CFD calculations. During FY98 and FY99, the Princeton

University Team designed and built a high-pressure laboratory and installed/tested the apparatus. The details of that effort are in Section 6.2.

Experimental apparatus likely to be required during 1999 and beyond support efforts at LLNL and Princeton University to validate computer models, make transport property measurements, and test materials and components. A description of the equipment supporting the effort at Princeton University is presented in Section 6.2. Although requirements at LLNL are under development, the following are likely to exist during FY99 and FY00:

1. Static high P_{O_2} , high temperature chemical reactivity materials screening experiments
 - 1.1. High-pressure vessel: 400 MPa, 10-cm ID, 40-cm working length, argon (Ar) working fluid, internal furnace with a 1-cm bore capable of 1,000 °C; with an O_2 compatible inner vessel.
 - 1.2. Associated Ar pressure system and accessories for Item 1.1
 - 1.3. O_2 pressure system and accessories capable of prepressurization to the appropriate isochore to reach 400 MPa at a variety of final temperatures.
2. Dynamic UHP, high temperature blowdown experiments.
 - 2.1. High-pressure vessel: 1,000 MPa, 4-cm ID, 20-cm working length, air/ O_2 working fluid, internal furnace capable to 1,000 °C.
 - 2.2. Associated Ar, air, and O_2 pressure systems and accessories for Item 2.1.

The static high P_{O_2} experiments will supplement literature survey results on the reactivity of air with candidate UHP materials. Based on literature survey results to date, there is no data for oxidation kinetics at elevated O_2 fugacity. The highest fugacity experience appears to be at 400 MPa and 873 K (Ref. 1). Costantino, this author, has performed research at 50 MPa O_2 at 1,200 K in Inconel X750 (unpublished). The dynamic experiments are designed to study directly the effect of high speed fluid flow through candidate nozzle materials at pressure, temperature, and Reynolds number conditions as close as possible to the A-2 conditions without significant investment in experimental apparatus. Plans are for these experiments to be initiated later in CY 2000.

6.1.4 Analytical Methods

Existing elastic (Mechanica), elastic-plastic (DYNA3D), and heat transfer (TOPAZ) codes at LLNL are used extensively to explore design ideas and to provide quantitative results for safety analysis. Many of the elastic and elastic-plastic stress-strain and fatigue problems for the UHP components have reasonably good analytical solutions with which numeric results can be compared. Commercial applications, such as Microsoft® Excel, Synergy Software® KaleidaGraph, Wavemetrics® IGOR, and National Instruments® LabView are used to acquire and analyze data.

The extended NIST EOS for air, O_2 , and nitrogen (N_2) are used to calculate various thermodynamic properties, including thermal conductivity, viscosity, and fugacity coefficients.

The analytical methods used by Princeton University researchers are discussed in the following section.

6.1.5 Princeton Analytical Methods

A suite of numerical models was developed to address most phases of the design work. A diagram of the hierarchy of approximations is shown in Fig. 6-1. The flow approximations range from thermodynamic considerations, through one-dimensional gasdynamics, to axisymmetric gasdynamics in both inviscid and viscous approximations. Adjunct components required for the analysis and design are 1) equations of state at high pressure provided by NIST, 2) models for radiative energy sources in one and two dimensions, 3) a turbulence model, and 4) a model for the boundary layer at high Reynolds numbers.

The thermodynamic approach involves integrating equations of state according to an idealized thermodynamic process already developed and discussed in Ref. 2. This type of analysis provides the relationships between many vital parameters, such as stagnation conditions, throat sizes, radiative power requirements, and achievable Mach numbers, as defined by the idealized thermodynamic operation of the device.

The next level of detail is provided by a one-dimensional gasdynamic model based on the quasi-one-dimensional Euler equations, coupled to one-dimensional models for radiative heat addition. The methodology behind this flow solver is discussed in Ref. 2. This model for one-dimensional analysis is the driver behind an automated design method, which generates nozzle shapes that attempt to duplicate the idealized thermodynamic model within the constraints of the physics of the absorption processes and the fluid dynamics. Preliminary design work is discussed in Ref. 2; however, the method was subsequently improved and now implements a more robust and efficient automatic design algorithm based on a simplex method. A one-dimensional model for e-beam absorption has been developed by Dr. Ron Lipinski of SNL and has been incorporated into the flow code for a fully coupled analytical model. This model is also described in Ref. 2.

Axisymmetric models provide additional analytical detail when conjoined with axisymmetric models for laser and e-beam coupling. The axisymmetric methodology for solution of the unsteady Euler and Navier-Stokes equations is detailed in Refs. 3, 4. The laser model is based on a ray tracing method developed Dr. Richard Moore at LLNL and is detailed in Ref. 2. An e-beam model in axisymmetry is based on a simplified form of this ray tracing procedure. In the model, the rays provide paths along which a one-dimensional assumption is made regarding the absorption physics, in close parallel to the method developed for the one-dimensional flow solver.

The viscous flow solver provides solutions regarding boundary layer growth and interactions with radiative sources. The Reynolds Averaged Navier Stokes equations are closed using the Baldwin Lomax turbulence model. At the Reynolds numbers present in these high-pressure flows, extremely thin boundary layers introduce a numerical difficulty due to the very fine meshes required to resolve the features close to the wall. The boundary layer model can relieve these problems while maintaining the essential physics of the flowfield at the wall. Essentially, a set of boundary conditions is developed for use a slight distance from the wall that is consistent with the fully resolved flowfield in a steady state. The details of this region are expected to be inconsequential in the design process. However, the integral quantities are important, and this method is a way of retaining the correct integral behavior while eliminating the need to resolve the differential features of the flowfield in this problematic region. This method (along with all the methods described herein) will be detailed in Robert Anderson's Princeton University Ph.D. thesis, which is in progress.

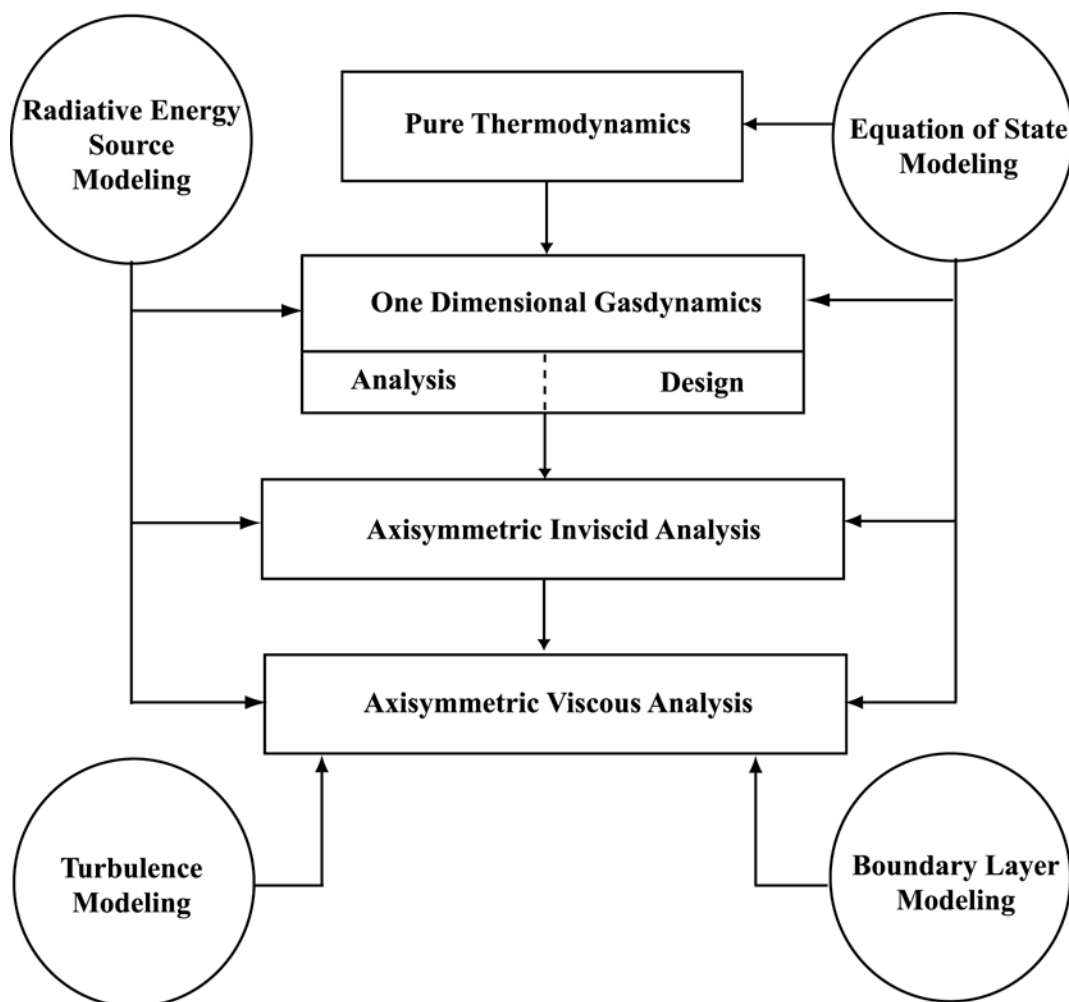


Figure 6-1. Hierarchy of flowfield models for nozzle design and analysis.

6.1.6 Design

Design of the UHP nozzle section to be used with the A-2 in supporting experiments is in its preliminary stage; therefore, the following is a description of the research to date. As additional effort, if changes to design planning assumptions and systems integration occur, the UHP nozzle design very likely will be significantly affected. A planning assumption is that the e-beam energy addition option is selected.

The portion of the wind tunnel nozzle for a distance of approximately 1 meter downstream of the throat is called the UHP nozzle section. The extraordinary difficulty of mechanically integrating the 2,000 MPa pressure vessel that is the settling chamber and nozzle entrance immediately upstream of the nozzle throat with 1) the means to inject a boundary layer cooling film; 2) the 7- to 20-T magnetic field at the throat (for the e-beam energy addition option); 3) the force reaction of the UHP manifold end closures; 4) the diagnostics immediately upstream and downstream of the throat; and 5) the remaining portion of the downstream nozzle make it sensible to define this close-in section of the nozzle as part of the UHP driver subsystem. However, both the fluid dynamics and the e-beam energy addition admit of equally critical technical issues in this region, making it a primary focus for subsystem integration. The “design parameter space” for each of the UHP driver, fluid dynamics performance, and e-beam energy addition subsystems has an optimization that may be inconsistent with another subsystem (for example, a fluid dynamics–energy addition profile that requires a 20-T field axially uniform to within 1 percent may be inconsistent with high strength materials required to contain 2,000 MPa at the throat). Conversely, a fluid dynamics solution that permits a long converging entrance to the throat may permit a 2,000 MPa structural part that will fit into the aperture of a superconducting magnet. Clearly, exceptionally close coordination between the proponents for each of the three subsystems is required from the beginning of the MARIAH II/RDHWT Program design process. The MSE/Princeton University team is responsible for the specific surface profile of the nozzle inlet, throat, and outlet. The LLNL team is responsible for the UHP nozzle section; that is, to include its integration to the settling chamber of the UHP driver, the magnet at the nozzle throat, the load-bearing members of the UHP driver, diagnostics, and the remaining downstream nozzle sections. Further, the UHP nozzle section must permit frequent inspection and replacement at acceptable labor and fabrication costs. The primary technical challenges for the nozzles are:

- Containing 2,000 MPa air pressure at 900 K total temperature;
- Mechanical strength at high temperatures to carry 2,000 MPa uniaxial stress;
- Chemical reaction with high-pressure, high temperature air, particularly at hot spots created by energy flux from the energy addition;
- Mechanical erosion due to large shear stresses at the nozzle wall;
- Surface roughness requirements for flows with $Re = \text{approximately } 10^{10}$;
- Injection of cooling film gas to manage the thermal load on the nozzle wall;
- Minimizing perturbation of a 7- to 20-T toroidal magnetic field at the throat;
- Integration with the downstream nozzle section;
- Mechanical erosion/heating due to e-beam or laser flux;
- Shape variation due to thermal and mechanical stresses;
- Inspection and replacement costs; and
- Damage control upon catastrophic failure.

While many of the UHP nozzle issues have been identified and partially addressed, none have been resolved at this early stage of the design process. The conceptual design for the UHP driver is consistent with solutions to these issues, but significant effort remains to achieve a holistic design.

Figure 5-9 shows the *conceptual* design for the UHP nozzle section in the UHP manifold. Integration with a high field magnet at the throat and with the remaining downstream nozzle section remains to be completed. In this scheme, the nozzle section is a removable end closure to the UHP manifold. It couples to a downstream section (not shown) that can be removed to permit extraction of the nozzle through the bore of the magnet. The placement of this coupling depends at least on the sensitivity of the flow to nonuniformities at the coupling joint, the location and integration with other downstream magnets, and the coupling with the external/axial load frame. This removable section then couples to the remaining downstream nozzle, which is fixed in the laboratory frame of reference.

The settling chamber breakout at the end of the manifold serves three purposes: 1) permit the fluid flowing through the approximately 2-cm-diameter manifold bore at approximately 30 m/s [$u = (dm/dt)/(\rho A) = (10 \text{ kg/s})/[(1,150 \text{ kg/m}^3)(\pi/4)(0.02)^2 \text{ m}^2)] = 27.7 \text{ m/s}$] to settle to mechanical equilibrium at a fluid speed of approximately 1 m/s into the nozzle; 2) provide space and a means to inject cold He into the boundary layer at the entrance to the nozzle; and 3) couple the UHP nozzle to the UHP axial manifold. As discussed in Section 5 and shown in Fig. 5-9, this region of the manifold is supported externally by the radial array of the intensifiers used to inject the He. The internal He shroud serves to isolate the He from the air, both to prevent air from entering the He intensifiers and from He entering the settling chamber, except in an annular region tangent to the nozzle inlet. The shroud is limited in axial position; it follows the nozzle during the initial pressurization transient and during the He flow. During this transient, there is a relative axial displacement between the external load frame and the manifold and between the manifold and the nozzle insert.

The present concept for the UHP nozzle is a compound pressure vessel, approximately 10 cm in OD, having at least three layers. The nozzle must be long enough to be inserted into the UHP axial manifold at least 1 diameter and to permit a magnetic field having the required field strength and uniformity at the throat. In the conceptual design, the magnet has an assumed aperture of at least 10 cm and a depth of 60 cm. If the symmetry plane of the magnet is at the throat, the overall UHP nozzle length is approximately 80–100 cm. All layers of the nozzle must be made of materials that are compatible with the time-dependent magnetic field strength and uniformity required at the throat. The innermost layer is an easily replaceable thin walled liner (approximately 0.5- to 1-cm wall thickness), with a cylindrical external surface and an internal surface having the desired inlet, throat, and outlet nozzle profile. Ideally, the material for this layer can be electroplated onto a mandrel having the desired profile that can serve subsequently as a substrate for protective surface layers applied using chemical, vapor, or physical deposition. These layers are tailored to provide chemical protection, mechanical strength, thermal expansion matching, and epitaxial matching. The boundary of the external surface of this thin-walled liner can carry longitudinal or helical ducts for rear surface cooling. In this scheme, several identical nozzle bodies containing the two outermost layers are available to be fitted with specific internal liners. The OD of the inner, thin-walled liner is a slip fit into the body on initial assembly, which

then is mated to the ID of the body by an auxiliary internal pressurization step. The internal surface profile of the liner is designed to accommodate the radial plastic flow of the liner resulting from this pressurization and to the operating pressure during the flow. Disassembly can be accomplished by pressing out the thin-walled liner, machining it out, or by cooling it with flowing liquid N₂.

The second and third layers of the nozzle are primarily for strength, with the material selected for optimum yield strength with acceptable magnetic properties. This selection promises to be difficult since even the best titanium (Ti)-based alloys [13 vanadium (V), 11 Cr, 3 aluminum (Al), balance Ti] have yield strengths on the order of only 1.4 GPa. Use of an external winding of a nonmagnetic organic such as a carbon filament can provide an external compressive radial stress to compensate for the low metal strength if thermal expansion coefficients can be adequately matched. This external winding also can be accomplished synergistically by using the magnet windings as the external pressure vessel winding. Usual superconducting magnets have the Nb₃Sn superconductor embedded in a copper matrix for thermal inertia and mechanical support. Since the superconducting properties of Nb₃Sn are stress sensitive, NbTi may be required for the superconducting material. Replacing the copper (Cu) with a thermally similar, but stronger, material may permit winding the magnet directly onto the UHP nozzle body. A thermal gradient $dT/dr < 0$ provides an additive, compressive stress to the nozzle.

The conceptual design for the He (or Ar or cold N₂) cooling film injection addresses several issues: 1) generating He at a pressure at or above the air pressure in the settling chamber and synchronized with the air pressure; 2) providing a total volume of cooling gas [currently assumed to be of the order of 10 percent of the air flow volume] that is commensurate to the total air volume; 3) providing a variable radial support to the UHP manifold end closure region that is synchronized with the pressure in the settling chamber; and 4) providing a means of injecting the He in a continuous annular ring just upstream of and tangent to the nozzle inlet. Design issues remaining to be resolved are: 1) prepressurizing the He into the high-pressure end of the intensifier, 2) minimizing the He heating during the operational cycle, and 3) starting and stopping the He flow.

Nozzle survivability continues to present the highest technical risk for the UHP driver. The chemical reactivity depends on the reactants, their activities, and the temperature. None of these quantities is known adequately for the boundary layer condition. The design planning assumption is that the inner nozzle wall will have a thermal and diffusion barrier layer, either through its natural composition and initial oxidation (as in formation of Cr₂O₃, BeO, Al₂O₃, etc.) or a barrier laid down using a chemical, vapor, or physical deposition process. Research in this area has only just begun, with a focus on reviewing turbine engine and water-jet technology. There is a requirement for limited experiments to gain some notion about the kinetics of the oxidation process. These experiments will involve a dual-pressure manifold apparatus consisting of an alumina inner manifold and a standard steel pressure vessel outer manifold containing a furnace that heats the alumina manifold. Candidate nozzle materials are contained in the alumina manifold, which is connected to a room temperature O₂ pressure system. Argon pressure in the outer manifold balances the O₂ pressure in the alumina manifold and protects the furnace windings. Standard Arrhenius reaction rate experiments will be made for a test matrix of temperature and O₂ pressures.

Other important technical questions involve the mass diffusion rate of O_2 across the boundary layer and how this rate depends on the various boundary layer conditions during the entire operational cycle including the transient conditions at the beginning and the end of the steady flow, as well as the effect of the He injection and surface roughness. A low diffusion rate may mean that O_2 in the boundary layer can be depleted using a “getter” upstream of the nozzle throat. This results in an O_2 poor boundary layer, thereby reducing the O_2 fugacity and the subsequent reaction rate with the nozzle wall.

Similar results for the heat transfer coefficients across the nozzle wall/boundary layer interface are required to define the heat load on the nozzle wall. The wall temperature is a critical number that has a significant effect on materials selection for strength and chemical reactivity as well as on the requirements for front and back surface cooling. Data from existing supersonic and hypersonic wind tunnels may be useful if they can be extrapolated to the longer run times for the A-2 and the MSHWT. During the next program year, the Princeton University team will conduct 275 MPa blowdown experiments at Reynolds numbers similar to those expected in the hypersonic facility in an attempt to characterize the boundary layer and the heat transfer coefficient at the air–wall interface.

6.1.7 Results

A preliminary geometry design concept for the UHP nozzle appears to be consistent with the technical issues of coupling the UHP nozzle to the UHP manifold, injecting a cooling fluid if needed, integrating the nozzle with a high field magnet, and coupling the UHP nozzle to the remaining downstream nozzle section. The conceptual scheme also supports back surface cooling and frequent inspection and replacement of the portion of the nozzle in contact with the flow. The primary technical issues involve material properties, mass transport of O_2 across the boundary layer, and heat transport across the fluid–wall interface. Most critical of the material properties are chemical reactivity with high temperature air at high O_2 fugacity and high temperature strength of nonmagnetic materials.

6.1.8 Conclusions

The UHP nozzle section is the highest technical risk component in the UHP driver subsystem. A preliminary geometrical design concept appears to be consistent with UHP, energy addition, and fluid dynamics subsystem integration. The design concept also appears to support acceptable operational costs. Significant effort is required in literature survey of high strength nonmagnetic materials, chemical reactivity at high temperature and O_2 fugacity, and thin film thermal and chemical barrier layers. Research is required in mass diffusion rates of O_2 across the boundary layer, heat transport across the fluid–wall interface, chemical reactivity at high temperature and O_2 fugacity, and mechanical surface erosion in hot/high Reynolds number flows.

6.1.9 Recommendations for Future Research

The UHP nozzle section effort must focus on:

- Integration of the UHP nozzle with the UHP driver, energy addition, and fluid dynamics subsystems.

- Literature survey to determine mechanical and chemical reactivity properties of candidate UHP nozzle materials.
- Experimental and theoretical effort to determine O_2 transport across the boundary layer.
- Experimental effort to determine the UHP nozzle wall temperature and heat transport coefficient across the fluid-wall interface.
- Experimental effort to measure chemical reactivity of air with candidate UHP nozzle materials.
- Experimental effort to measure chemical and mechanical erosion of candidate UHP nozzle materials under high O_2 fugacity, high temperature, and high Reynolds number flows.
- Experimental effort, as required, to measure mechanical erosion of candidate UHP nozzle materials with film cooling gases.

Items 1 and 2 are fully funded for FY99. Items 3 and 4 are being undertaken by the Princeton University team. Items 5, 6, and 7 should soon be undertaken.

6.2 NOZZLE SURVIVABILITY RESEARCH

6.2.1 Objectives

The objective of this program element is to reduce the technical risk of the MARIAH II/RDHWT system nozzle. Activities to accomplish this provide 1) computational capability to predict conditions at the air-nozzle interface, 2) basic thermal and mass transport data for the pressure/temperature/composition conditions in the boundary layer, 3) data on thermal gradients in the nozzle wall, 4) data on reactivity of candidate nozzle materials at the A-2 operating conditions, and 5) tests of various nozzle threat mitigation strategies, such as film cooling.

6.2.2 Approach

Nozzle survivability is a high- technical risk element of the MARIAH II/RDHWT Program. The planning assumption is that systems integration will reduce this risk (and other, high-risk elements) as much as possible, but that the nozzle will remain a high risk. The present assumption is that the nozzle surface is exposed to a flow of pure air from a plenum condition of 2,000 MPa and 900 K. It is likely that other material design limitations will cause these conditions to move up in pressure and down in temperature. It is unlikely that the plenum temperature condition will increase. Section 6.1 contains an overview of the UHP nozzle section and its integration with the UHP, energy addition, and fluid dynamics subsystems. This section is a description of the issues relevant to the boundary layer-nozzle surface interface.

The approach to the nozzle survivability research consists of several elements. The first is to use CFD calculations and room temperature experiments at high Reynolds numbers to characterize the boundary layer to include measurements of boundary layer growth, wall recovery

temperature, O_2 transport across the boundary layer, and heat transport across the fluid-nozzle wall interface. Second, literature survey and laboratory experiments provide information on high temperature mechanical strength (in shear), thermal transport, and chemical reactivity of candidate materials. Finally, component testing provides confidence that nozzle wall cooling methods such as injection of an He film or back wall cooling are effective.

6.2.3 Experimental Apparatus

6.2.3.1 High-Pressure/High Temperature Experiments Using the Institute of Hydrodynamics A-1 Apparatus

Beginning in the late 1960s, workers at the Russian Academy of Sciences Lavrentyev Institute of Hydrodynamics and the Design-Technology Institute of High Rate Hydrodynamics in Novosibirsk, Russia, developed an apparatus to generate hypersonic flows of air. Professor Marlen Topchiyan of the Institute of Hydrodynamics and Dr. Valerii Pinakov, Senior Researcher at the Institute of High Rate Hydrodynamics have led this research. Their laboratory-scale apparatus, termed “A-1”, is designed for flows having plenum pressures in the range of 2,500 MPa at temperatures in excess of 1,500 K. To date, flows in N_2 at 1,000 MPa and 2,000 K and in air at 600 MPa and 1,700 K for times of approximately 100 ms have been achieved. The primary limitation on the operating condition is the failure of the nozzle resulting from the high temperatures resulting from the compression of the gas. In the case of N_2 , the limitation appears to owe to erosion of the nozzle. The Russian group has undertaken some development of nozzle materials that can sustain these temperatures, with a focus on Al-Cu alloys. These nozzles appear to sustain the high fugacity O_2 environment but failed due to material “creep.”

As part of a previous contract with the USAF (Ref. 5) through Princeton University, use of the A-1 to perform screening tests on a variety of candidate nozzle materials provided by LLNL was planned. After refurbishing the A-1 device, the first of these tests was performed using a Vasco Supreme alloy nozzle made at Novosibirsk. The composition of the Vasco Supreme is 1.5 percent–1.6 percent carbon (C), 0.15 percent–0.3 percent silicon (Si), 0.15 percent–0.3 percent manganese (Mn), 12 percent–13 percent tungsten (W), 4.5 percent–5 percent Cr, 4.75 percent–5.25 percent Co, balance Fe. The nozzle profile is shown in Fig. 6-2.

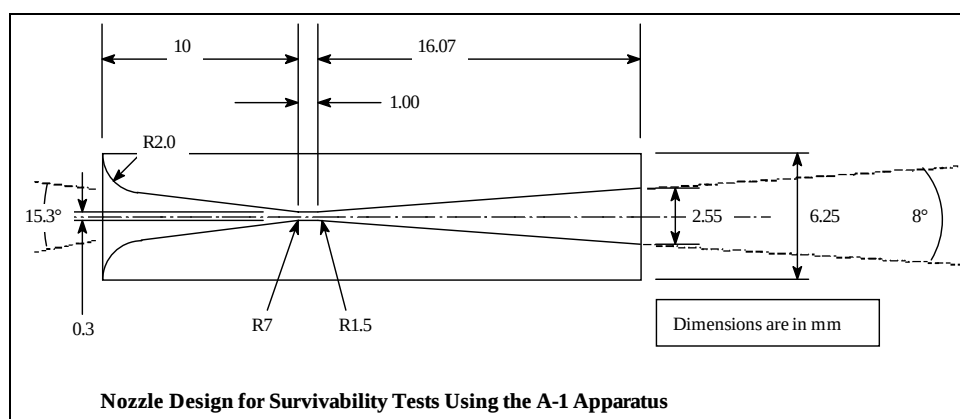


Figure 6-2. Schematic of the nozzle used in nozzle material screening tests at the Institute of Hydrodynamics, Novosibirsk, Russia.

As-built dimensions and surface conditions were not reported. This test was to be followed by tests using nozzles provided by LLNL. Eleven nozzles were fabricated from the materials listed in Table 6-1 for testing in the A-1 facility. The intent of these tests was to determine whether high strength, high temperature, oxidation-resistant materials commonly available in the United States would be suitable for the nozzle. Rhenium, known to have poor oxidation resistance, was included because of its very high melting temperature and strength. Even though the operating temperature in the A-1 is somewhat higher than the plenum temperature in the A-2 and the MSHWT, the recovery temperature at the nozzle wall in those apparatus is likely to be near the A-1 operating temperature.

**Table 6-1. Candidate Nozzle
Material Delivered to
the Institute of
Hydrodynamics**

Material	Quantity
Tantalum (Ta)	1
Cr	2
Re	2
Rene 41	2
VascoMax 350	2
Inconel X750	2

6.2.3.2 High Reynolds Number Experiments Using a 275 MPa, Room Temperature Blowdown Apparatus

The nozzle boundary layer experiments will be conducted at Princeton University in the 275 MPa blowdown facility. This facility has recently been built in the basement of the Princeton Engineering Quadrangle and includes a 12-foot by 15-foot by 8-foot explosion isolation room that is located in a pit below the laboratory floor. This pit runs the length of the laboratory and contains the explosion room, which is surrounded by wood-lined steel walls. Also located in the pit, but outside of the explosion wall, is an optics table that supports an argon-fluoride (ArF) excimer laser and optical beam-steering elements. The laser beam is directed into the explosion room through a window in the wall. Inside the explosion room is the high-pressure plenum, which has a maximum allowable working pressure (MAWP) of 300 MPa (43,500 psi), maximum operating pressure (MOP) of 275 MPa (40,000 psi), and volume of 2.97 liters. The control panels and data acquisition stations are located above the pit in the main laboratory. An elevation view is shown in Fig. 6-3, and a floor-plan view is shown in Fig. 6-4.

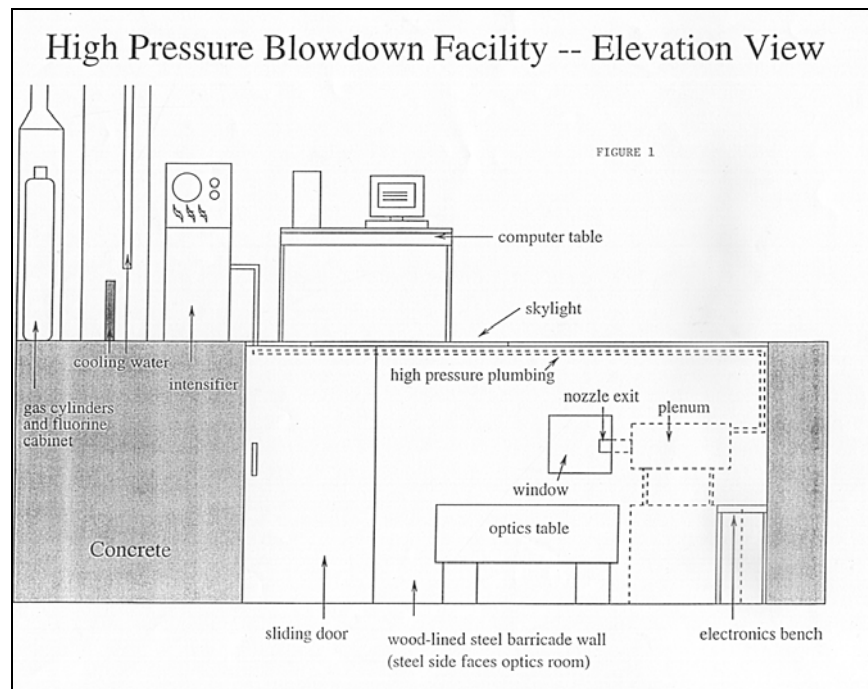


Figure 6-3. Elevation view of the Princeton University high-pressure/high Reynolds number experimental facility.

Facilities located in the pit are shown with dotted lines in Fig. 6-4. The blowdown chamber assembly was built and initially tested at LLNL. The nozzle itself has been fabricated at LLNL using a precision-machined aluminum mandrel, which was Ni-plated and subsequently etched out to form an extremely smooth and accurate nozzle contour (see Section 6.1). The facility will generate flows with Reynolds numbers on the order of $10^9/m$. This Reynolds number is unprecedented in ground test facilities and approaches the Reynolds number of the full MARIAH II/RDHW device. Note that although the large-scale facility is expected to run at 2,000 MPa and 900 K compared to 300 MPa and 300 K for this facility, the Reynolds numbers are similar because the incompressibility of air at these pressures means that the density only differs by approximately 30 percent. That difference is further mitigated by the temperature dependence of viscosity. The blowdown test facility is brought up to full pressure by placing a plug in the nozzle exit, which is held in-place with a solenoid-operated latch mechanism. Flow is initiated by activating the solenoid, thereby releasing the plug. At full volume, test times on the order of 10 to 100 msec are expected.

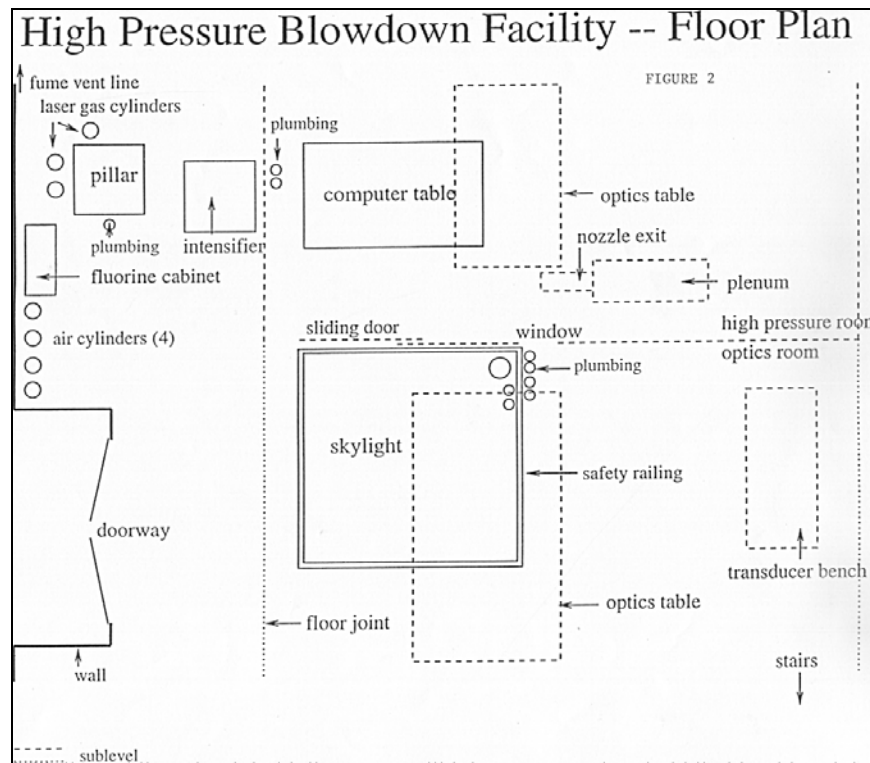


Figure 6-4. Plan view of the Princeton University high-pressure high Reynolds number experimental facility.

The main objectives of this facility are the following:

- Verify high-pressure gas EOS through measurements of total enthalpy.
- Establish boundary layer growth rate under real gas high Reynolds number conditions, including the effects of roughness.
- Determine real gas wall recovery temperature.
- Measure heat transfer rates at the wall.
- Explore wall cooling strategies.
- Establish baseline data for the validation and development of theoretical and numerical models which, in turn, will be used to design the MSHWT and the large-scale facility.

The primary objectives during CY 1999 and 2000 will be the measurement of total enthalpy and variation of total enthalpy with time to establish the range of operating conditions, as well as the study of the boundary layer growth rate and its variation with Reynolds number. During the approximately 100-msec run time, the Reynolds number varies over a wide range, so many different points of operation can be explored.

Preliminary tests on system safety, pressurization, run time, and data acquisition will be conducted using a dummy nozzle so that the expensive contoured nozzle does not sustain damage. These tests will also be performed using a reduced volume to minimize hazards. Subsequent tests will be conducted first at full volume and then with the contoured nozzle. Completed program elements are described in Section 6.2.6. The remaining experimental plan follows:

Task Estimated Completion Dates

- Reinforce barricade. (16 July 1999)
Replace the ¼-inch-thick cleats with ½-inch-thick cleats on the plate directly above the vessel if the MARIAH II/RDHWI Program chooses to run at near the maximum working pressure of the vessel (300 MPa). The initial series of experiments will be at pressures less than 170 MPa (25,000 psi).
- Measure dimensions and surface roughness of dummy and primary nozzles. (30 July 1999)
To assess the extent to which the flow erodes the nozzle throat, initial measurements of the dummy nozzle constriction and the primary nozzle throat will be made using precision bore gauges. The measurements will be repeated periodically as the nozzles are run to assess the throat erosion. We anticipate that the primary source of erosion will be particles in the flow, perhaps from the wearing of a seal. An approximate measure of the surface roughness of the primary nozzle is necessary to determine if the wall is acting as a smooth or rough wall as well as future studies where the effects of roughness on the boundary layer growth may be investigated. An optical method directly for determining the approximate surface roughness is being investigated.
- Primary nozzle (Nozzle #2) assembly and instrumentation. (27 August 1999)
The primary nozzle needs to be installed and configured for an actual experiment. A high-speed transducer that can monitor both stagnation pressure and temperature has been ordered. The data acquisition software is operational. The pressure transducers must be installed in the primary nozzle, and the nozzle must itself be mounted in the pressure vessel. The exit latch assembly must be manufactured and mounted at the primary nozzle exit. Additionally, the whole system must be leak-tested.
- Data runs with the primary nozzle. (1 September 1999 through 15 October 1999)
Pressure measurements along the nozzle contour will give confirmation of supersonic exit flow as well as insight into the nozzle boundary layer growth. Experiments will be performed at several stagnation pressures ranging from 35 to 170 MPa. Higher pressures may be investigated after this initial series. A Rayleigh scattering system using an ArF laser and high-speed camera will be set up and calibrated during these experiments.
- Exit flow diagnostics I. (15 October 1999 through 1 December 1999)
The experiment will be run at several stagnation pressures, and Rayleigh scattering images of the exit will be obtained. These images will provide a direct measurement of the boundary layer thickness as well as giving a visualization of the highly under-expanded exit flow. The pressure measurements will be continued, and the inferred boundary layer thickness at the exit will be compared with the direct optical measurements.

- Exit flow diagnostics II. (1 December 1999 through 20 December 1999)
An Ar-ion laser and high-speed camera will be used to obtain a Schlieren movie of the exit flow. Visualization of the startup process associated with the highly under-expanded flow is of particular interest.
- Exit flow diagnostics III. (15 January 2000 through 15 March 2000)
The goal of this task is obtain an optical measurement of the exit Mach number of the flow. Spark velocimetry will be used to infer the centerline flow velocity. Laser-induced thermal anemometry (LITA) will be used to obtain a direct measurement of the sound speed in the exit flow. Implementing the LITA technique in this flow will be quite challenging due to the extremely large index of refraction gradients.
- Wall temperature and heat transfer studies. (beginning 15 March 2000)
From measurements of the wall temperature versus time and knowledge of the stagnation temperature versus time, it is possible to infer the wall recovery temperature. The merits of various measurement techniques such as thin-film gauges and high-speed thermocouples are being investigated, but until the pressure measurements and flow diagnostics are completed, these heat transfer studies will not become a focus of the efforts.

6.2.3.3 High Oxygen Fugacity–High Temperature Experiments at LLNL

Experiments to measure effects of temperature and O_2 fugacity on candidate nozzle materials are described in Section 6.1. The first major objective is to screen candidate materials in static O_2 pressures of 400 MPa (roughly the partial pressure of O_2 at a total air pressure of 2,000 MPa) and at temperatures as far above 1,000 K as possible. This region is completely unexplored and has a relatively high technical risk. The intent of the experiment is to determine whether currently available elemental metals and alloys can survive the nozzle conditions of the A-2 device before embarking on more expensive risk reduction experiments involving surface layers and materials development. The second objective is to expose selected nozzle materials and surface profiles to air flows that replicate as close as possible the expected conditions for the A-2 apparatus, with a focus on the effects of mechanical erosion.

6.2.3.4 Component Tests and Experiments at LLNL/Princeton

The conceptual designs for many of the components of the A-2 apparatus must be tested to reduce the technical risk. Among the most important of these are the survivability of organic and low melting point metal seals, the effect of heat transfer to the structural elements (pressure vessel walls, end closures, and pistons) during the operational cycle, the force balance for the radial array of UHP intensifiers, and the scheme to inject He into the boundary layer upstream of the nozzle throat. The current MARIAH II/RDHWT Program funding profile will result in not performing some of these tests and accepting the higher technical risk of using only model calculations with conservative assumptions. Since the design planning assumption is that material properties alone will not ensure nozzle survivability, the priority effort in component testing will be injection of a cooling film and its thermal and mass transport effects in the boundary layer. If funded, these experiments will likely be carried out at Princeton University using the 275 MPa blowdown apparatus and the flow baseline data obtained in the experiments described in the High

Reynolds Number Section 6.2.3. Mass injection into the flow and its segregation in the boundary layer, O_2 transport across the He-rich boundary layer, and heat transport across both the boundary layer and fluid/nozzle wall interface all are of interest.

6.2.4 Results

6.2.4.1 High-Pressure/High Temperature Experiments Using the Institute of Hydrodynamics A-1 Apparatus

The Novosibirsk group made two nozzles (Fig. 6-4) from the Vasco Supreme alloy, with throat diameters of 0.3 and 0.57 mm, respectively. The 0.57-mm nozzle was run in an N_2 flow at 300 MPa and 1,450 K for 204 msec with no apparent damage. It was then exposed to an airflow at 500 MPa and 1,600 K. The nozzle ignited at the exit of the throat region and burned as shown in Fig. 6-5.

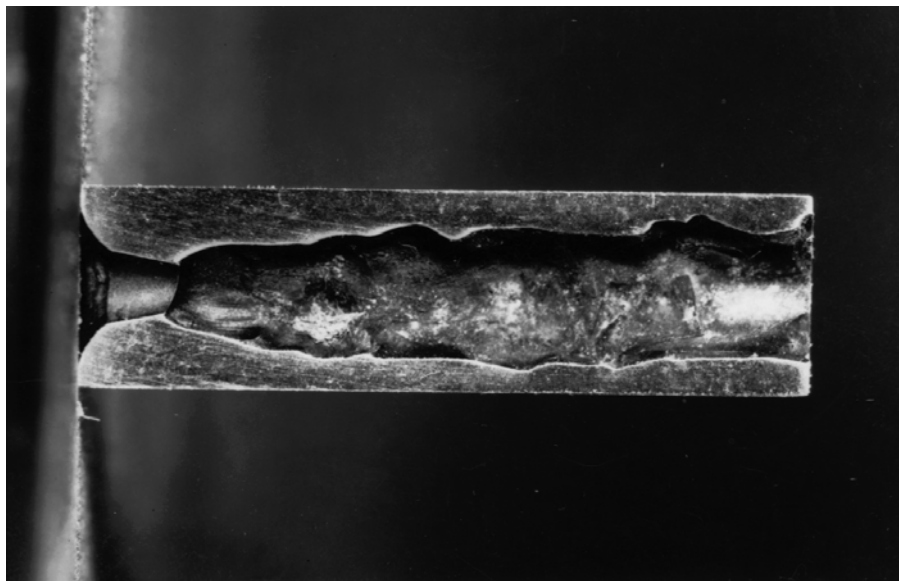


Figure 6-5. Results of air flow at 500 MPa and 1,650 K for about 290 msec through a nozzle made of Vasco Supreme alloy. A schematic of the nozzle is in Fig. 6-4. The nozzle throat diameter originally was 0.57 mm.

There appears to be no plastic deformation of the nozzle. The boundary between the burned and unburned parts appears to be at the end of the linear section of the nozzle throat where there is a rapid change in the surface profile as the nozzle opens from a 0° to 8° half angle. Initial erosion and subsequent ignition may have occurred here due to separation of the boundary layer. The 0.3-mm-throat-diameter nozzle was tested using only N_2 . No erosion or chemical reaction was observed below plenum pressures of 300 MPa; however, at 500 MPa, marked surface roughness was observed downstream of the throat. Based on these results, further testing was halted, and none of the 11 nozzles supplied by LLNL were tested.

The 500 MPa, 1,600 K point was selected for the air experiment because that appears to be the highest value obtainable using the Cu-metal oxide composite developed by the Novosibirsk group. In this approach to managing both the oxidation and high shear stress environment in the nozzle, Cu is “alloyed” with Al, beryllium (Be), or similar metals having highly stable oxides. The alloy is then ground to provide particles with a large surface-to-volume ratio and small diffusion distances and is sintered in O₂. For example, the O₂ oxidizes the Al to create a dispersed second phase of Al₂O₃. The assembly is then extruded to provide billets from which a nozzle can be made. This approach results in a composite with the thermal properties of Cu but with the better mechanical properties of a dispersion-hardened metal matrix composite. However, the high temperature mechanical properties are limited by the low melting temperature of Cu. As the surface heats to approximately 0.8T_m, the shear strength decreases, and the surface deforms under the drag force of the boundary layer. Nevertheless, the Cu-metal oxide appears to survive the oxidizing atmosphere of about 100 MPa pure O₂ at 1,600 K.

Use of metal oxides as materials is generally limited by their low tensile strengths. This limitation can be overcome in principle by mechanical design that holds the nozzle in a net compressive load. Sapphire (Al₂O₃) is a well-known, very stable oxide that even has been used as a large volume pressure vessel material. Beryllium oxide is extremely stable but reacts with water vapor (Ref. 6).

6.2.4.2 High Reynolds Number Experiments Using a 275 MPa, Room Temperature Blowdown Apparatus

The construction of a high-pressure laboratory, located in the basement of the Engineering Quadrangle at Princeton University, is complete (see Figs. 6-2 and 6-3). The 275 MPa apparatus, with pressure generating system, pressure transducers, and a computer data acquisition system (DAS) was loaned to Princeton University by LLNL. It has since been installed and pressure tested to 240 MPa (35,000 psi) using a dummy nozzle. Nozzle #2 (see Section 6.1), which is to be used in the first boundary layer experiments has been received. A fixture to test the fast pressure transducers was made using a steel block with a hole having a high-pressure connection on one end and threads for the pressure transducer mounting on the other end. The transducers have been tested by pressurizing and rapidly discharging the small test volume. Although this flow is too slow to provide a rigorous calibration, all six transducers give similar readings.

The surface condition of the nozzle is critical to interpretation of the boundary layer growth measurements and the validation of the CFD models. An optical method to indicate degradation of the nozzle surface is under development. This will provide a very useful, qualitative measure of the degradation from the known initial surface smoothness. A 5-μm particle filter has been ordered and will be installed near the entrance of the pressure vessel to reduce erosion from entrained particulates.

The dummy nozzle has been run at 240 MPa with filler blocks inside the pressure vessel to reduce the volume to 10 percent of the maximum volume. An approximate run time of 0.3 seconds was achieved; and although sound pressure levels of the flow exiting the nozzle were not measured, the noise at the operator station was found to be tolerable when suitable ear protection was used.

6.2.5 Conclusions

Nozzle survivability is recognized as a primary MARIAH II/RDHWT Program high-risk element. Commitment of significant resources to R&D of new nozzle materials and surface coatings for nozzle survivability should be deferred until the proposed operating conditions are defined by subsystem integration. However, experiments to study the erosion due to high Reynolds numbers, to study injection of a cooling gas into the boundary layer, and to study mass and heat transport in the boundary layer should be undertaken in parallel with the A-2 design effort. Effort to date has included limited laboratory testing, construction of a high Reynolds number research facility, and a literature survey of candidate nozzle materials. The single laboratory test of a high temperature, high strength, oxidation-resistant material (Vasco Supreme) resulted in ignition and catastrophic burning of the nozzle. Further nozzle testing using other candidate alloys and elemental metals was suspended because of the high risk of damage to the apparatus and because the plenum conditions did not match sufficiently well those for the A-2. A high-pressure research laboratory was constructed at Princeton University and the LLNL 275 MPa pressure system was installed. The literature survey indicates essentially no data for the chemical reactivity of materials at high O_2 fugacity and temperature. Nozzle survivability risk must be managed by using a combination of systems integration tradeoffs, i.e., nozzle material R&D must be limited to functionally graded surface layers, and mitigation approaches such as injection, a gas upstream of the throat, and utilizing a systems design that permits economical inspection and replacement.

6.2.6 Recommendations for Future Research

The nozzle survivability technical risk can be reduced by pursuing the following activities during years 1999 and 2000:

- Establish the O_2 fugacity temperature environment along the nozzle profile to provide specifications for chemical kinetics experiments on candidate nozzle materials. This includes measuring the heat and mass transport across the boundary layer. The heat transport measurements will define the nozzle surface temperature for Arrhenius reaction kinetics and the nozzle thermal profiles for diffusion of alloy species from the inside of the nozzle to the oxide layer. Mass transport measurements across the boundary layer will determine the usefulness of “getter” surfaces that strip the boundary layer of O_2 upstream of the nozzle throat and of the need for injection of an inert gas to displace the air in the boundary layer.
- Perform chemical kinetics experiments on candidate nozzle materials under static conditions. The O_2 pressure should range to 20 percent of the plenum pressure and the temperature to the upper bounding value of the recovery temperature at the nozzle wall. These experiments should include an ignition source to simulate local hot spots in the nozzle surface that result in combustion. This research will provide a down selection for nozzle materials and will serve as a baseline to distinguish chemical static effects from the dynamic effects present in the flow.
- Perform dynamic erosion experiments at conditions as close to the A-2 operating condition as possible for air, He, and N_2 . These experiments, using the baseline static experiments to separate the purely chemical reactivity effects, will provide bounds for material strength and surface roughness for the nozzle wall.

- Perform testing of cooling fluid injection schemes to develop techniques to mitigate the adverse effects of high temperature and O_2 in the boundary layer. These experiments are also necessary to measure the mass transfer across the boundary layer.

The present research plan does not provide adequate funding to reduce the nozzle survivability technical risk to an acceptable level. A major contributing factor to this cost is the requirement to make conservative assumptions about the various threats (recovery temperature, effect of surface roughness, thermal profile, chemical reactivity, shear strength) the nozzle must survive. Therefore, a reasonable strategy is to make a steady effort to understand the physics and chemistry of the boundary layer nozzle wall, followed by a focused program to mitigate the known threats using materials R&D and fluid injection schemes. The FY98 accomplishments and FY99 plan are consistent with this approach.

6.3 275 MPA BLOWDOWN EXPERIMENTS

This section is a description of the LLNL contribution to the 275 MPa blowdown experimental program. The objective of the program is to make nozzle boundary layer performance measurements at Reynolds numbers [$O(10^9)$] very near to those of the large-scale MARIAH II/RDHWT facility. The experimental data provides information about thermal and mass transport across the boundary layer, recovery temperature at the nozzle wall, and boundary layer growth. Additionally, the data is used to validate CFD codes that form the fundamental basis for design and performance calculations for the MARIAH II/RDHWT Program. Finally, the experiment provides a laboratory platform for the development of supporting technologies, such as nozzle fabrication and nozzle wall cooling strategies. The initial series of these experiments was conducted at LLNL from June 1995 to March 1997, in collaboration with members of the Princeton University team. The apparatus was shipped to Princeton University in April 1999. Since the results have not been described elsewhere, other than in monthly reports to sponsors and reports at Steering Group/Integrated Project Team meetings, this section is a summary of the program at LLNL. It also includes a description of the fabrication of the second nozzle for the experiment (Nozzle #2) to be used for the planned experiments at Princeton University.

6.3.1 LLNL 275 MPa Blowdown Experiments

During the period June 1995 to March 1997, existing high-pressure apparatus at LLNL was modified and proof-of-principle (POP) experiments were conducted to characterize supersonic flows at high Reynolds numbers. The objectives of the LLNL series of experiments were to 1) assemble the high-pressure apparatus and DAS, 2) learn how to build the high-pressure nozzles, and 3) develop an experimental protocol to measure high Reynolds number flows. Senior technicians and graduate students assisted in the experiment and learned how to work safely with high pressure. As previously described, the apparatus was moved to Princeton University in April 1999 to continue the research.

The experiments consisted of a 100 msec adiabatic expansion from a maximum $2.97(10^{-3})m^3$ volume at a maximum of 300 MPa pressure at room temperature N_2 (density = $811 kg/m^3$) through a 400-mm-long supersonic nozzle. Adequate run times were achieved with approximately $5.55(10^{-4}) m^3$ gas volume. The pressure vessel has a MAWP of 300 MPa and an

MOP of 275 MPa. Operation at up to 300 °C gas temperature is possible, with an appropriate decrease in MAWP. Diagnostics included initial plenum pressure and temperature and dynamic pressure at six locations along the nozzle. The experiment, with a stored energy of $1.95(10^5)$ J, was located in Room 1406, Building 292 at LLNL. The minimum 4-foot-thick, reinforced concrete walls provided blast, shrapnel, and noise protection. The apparatus and experiment are discussed in the LLNL Engineering Safety Note ENN 96-905 and Operational Safety Procedure 292.15. The original nozzle profile (Nozzle #1), given in Table 6-1, was provided by the Princeton University team, with a design objective of providing a measurable boundary layer growth without choking the flow. A schematic of the first nozzle is presented in Fig. 6-6 and its assembly into the Harwood Engineering pressure vessel in Fig. 6-7. LLNL machine drawing numbers for the Nozzle #1 are AAA95-104651-00 (3 sheets). The nozzle was made of AISI E4340 heat treated to R_C54. This nozzle presented a significant fabrication challenge, with the problem to produce an essentially arbitrary cylindrical profile at the bottom of a 3-mm-diameter, 400-mm-deep hole with a surface smoothness of approximately 0.2- μ m average surface deviation. Preliminary surveys of commercial vendors indicated costs approximately \$25,000 to produce one part, with no commitment to meet surface profile and smoothness specifications. To establish the level of effort, fabrication using precision reaming was selected, since the tooling and LLNL machining costs were of the order of \$10,000. Tungsten carbide reamers having the desired surface profile were used to make the finish cut in a prebored 3-mm hole. As shown in Fig. 6-8, this process resulted in a surface profile similar to the desired profile but suffered from displacement along the z-direction and in unacceptable surface roughness. Both the profile and the smoothness can be improved through the use of a lapping operation but at a significant cost. A further disadvantage of this approach is that the nozzle is monolithic, and changes to the surface profile require a completely new part. Further, state-of-the-art measurement tools are not adequate to characterize the surface profile and smoothness. The other design requirements for the nozzle (i.e., sealing to the pressure vessel end closure, sustaining 300 MPa pressure, mounting for the six PCB Piezotronics Mdl 119M27 fast pressure transducers, and triggering the flow) were met satisfactorily.

Signals from each of the six transducers were amplified using calibration-matched PCB Mdl 402M65 amplifiers, followed by PCB Mdl 482A17 signal conditioners. The transducers have a rise time of 2 μ sec and a natural frequency of 500 kHz. The signals were passed through a National Instruments (NI) NB-DMA2800 direct memory access board into a 12-bit, 1 megasample/second NI NB-A2000 D/A board in a Macintosh Quadra 950 desktop computer. NI LabView Version 4.0 software was used to acquire and manipulate the data. Data rates were up to 40 μ sec/point, where each point is a data collection cycle across the six transducers. Static pressure was measured using a calibrated Teledyne-Taber Mdl 2107 (0–50,000 psig) pressure transducer. Static temperature was not measured and was assumed to be ambient (22 ± 3 °C).

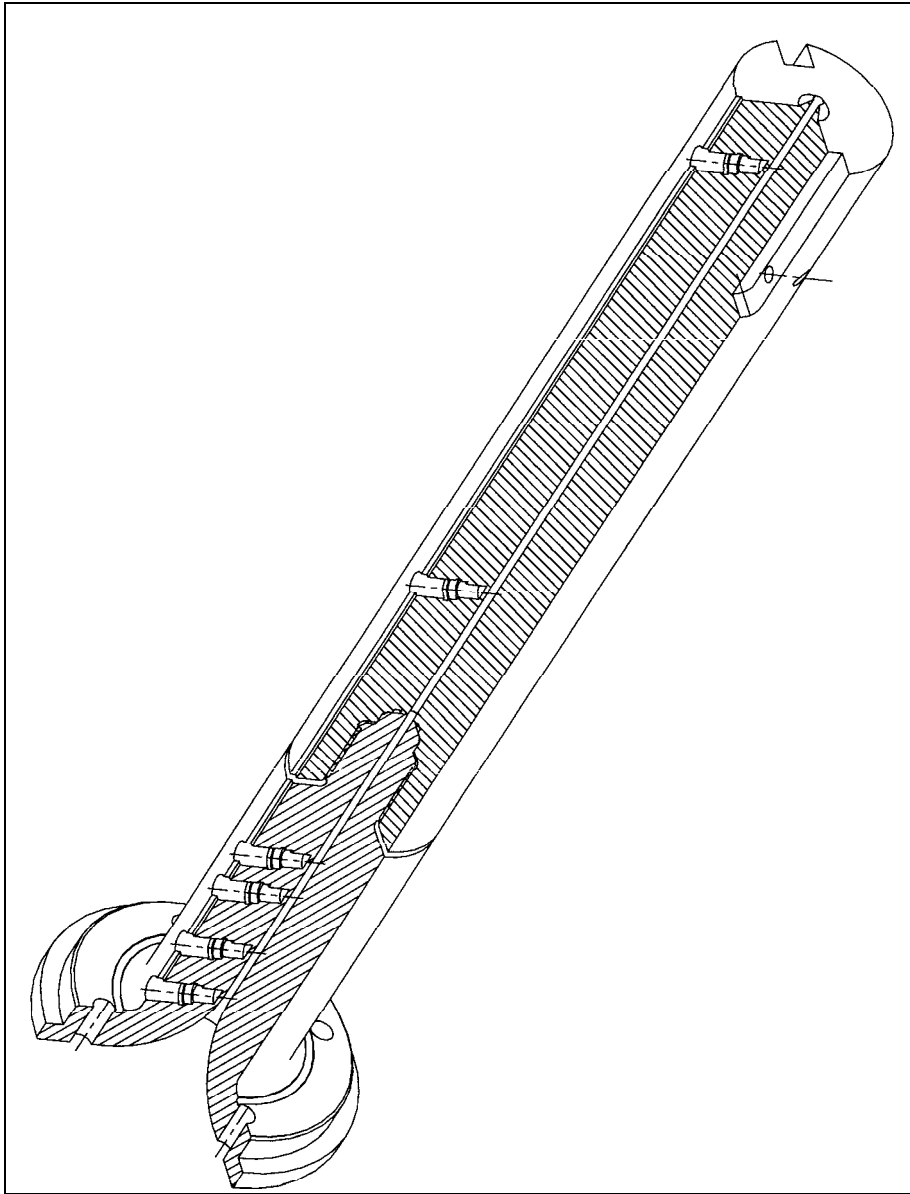


Figure 6-6. 275 MPa blowdown Nozzle #1. The 400-mm nozzle is made of two sections, threaded together at 49 mm downstream of the 3-mm-diameter throat.

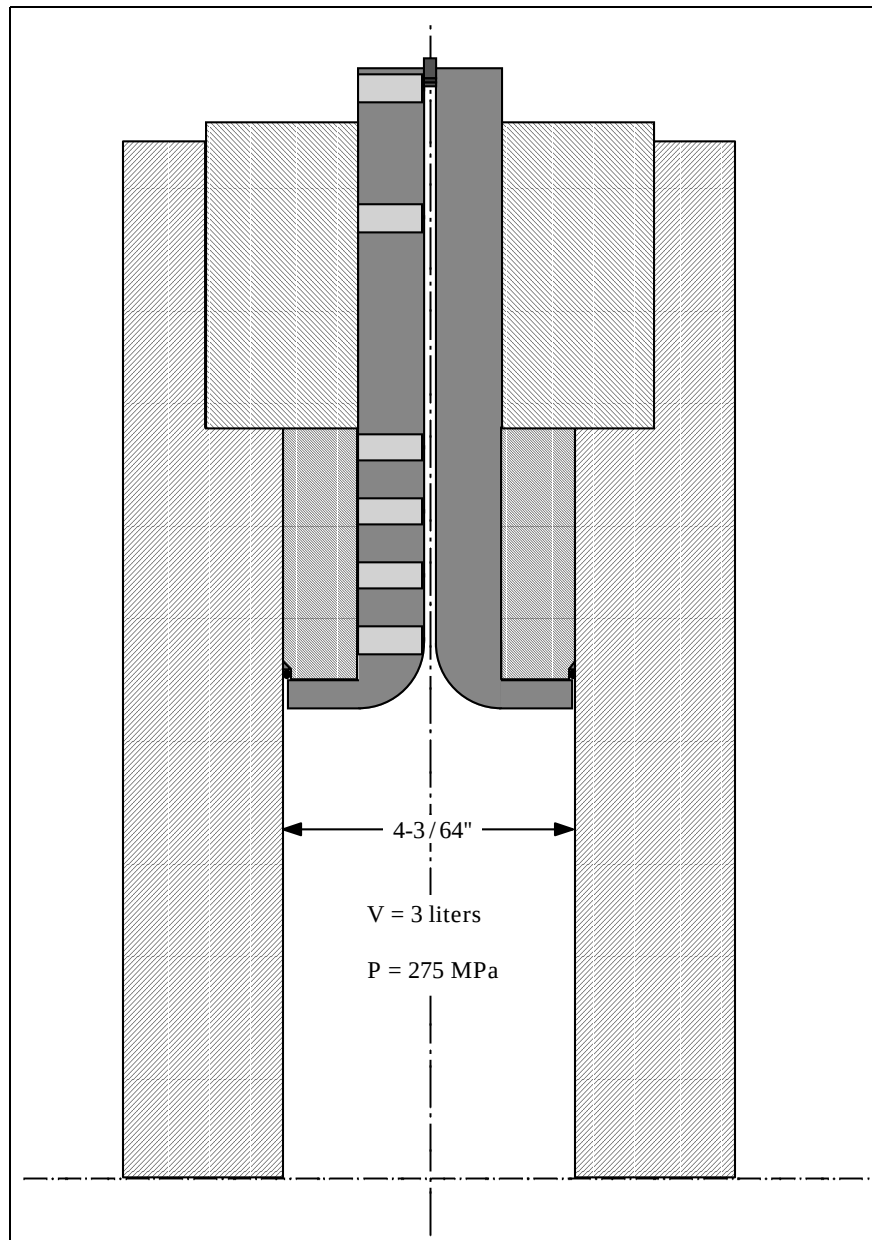


Figure 6-7. Schematic of the assembly of the nozzle into the high-pressure vessel.

Peak sound levels were measured by LLNL Hazards Control personnel during an N_2 blowdown from 225 MPa. At a 1-meter unobstructed distance from the nozzle exit, the peak impulse was measured to be 153.6 dB. At a distance of 2.4 m on the operator side of the 1.2-m-thick concrete door to the experimental area, the peak impulse was 123 dB. The door to the area was slightly ajar to permit passage of pressure tubing and diagnostics cabling, thus resulting in a sound transmitting area around its perimeter of approximately 0.1 m^2 .

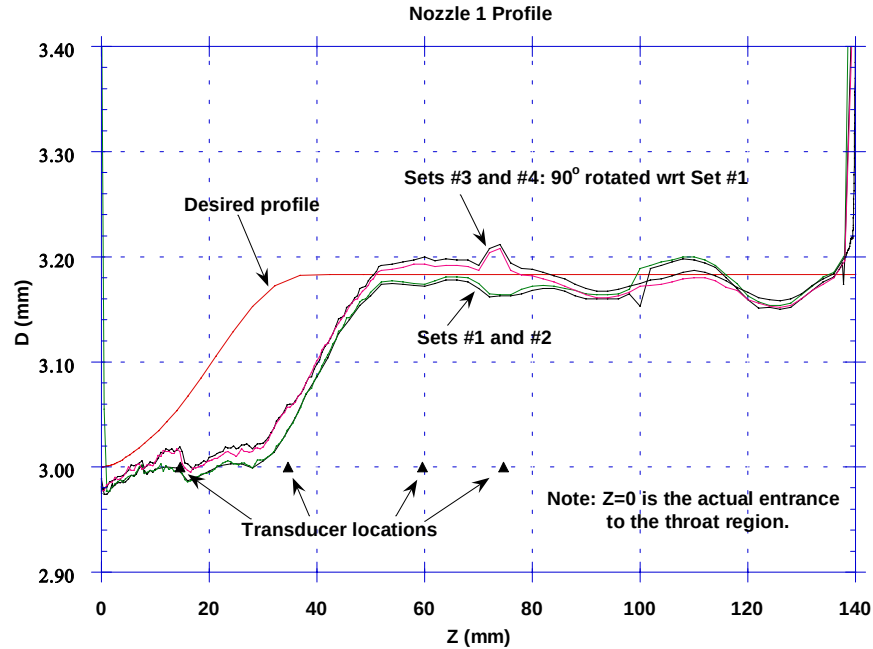


Figure 6-8. Nozzle #1 profile. D is the diameter and Z the distance downstream from the throat. Measurements were made using a Dyer Co. (Lancaster, Pennsylvania) bore gauge with a sensitivity of 0.001 mm.

A total of 28 shakedown and data acquisition runs were made using N_2 and He. Each run consisted of establishing a static pressure and temperature in the vessel and nozzle and then venting the system by releasing a sealing plug at the exit end of the nozzle. By Run #18 it was evident that the flow was choking at the exit of the 400-mm nozzle; consequently, the extension portion of the nozzle was removed, and the remaining runs were made with a nozzle length of approximately 49.6 mm. Transducer locations relative to the nozzle throat are presented in Table 6.2.

Table 6-2. Transducer Locations Along the Flow Axis for Nozzle #1. (Origin is at nozzle throat.)

Transducer	Location (mm)
1	0
2	20.0
3	45.0
4	60.0
5	180.0
6	370.0

Figure 6-9 shows typical raw data from shot 702902, with $P_0 = 40,000$ psi (276 MPa) N_2 .

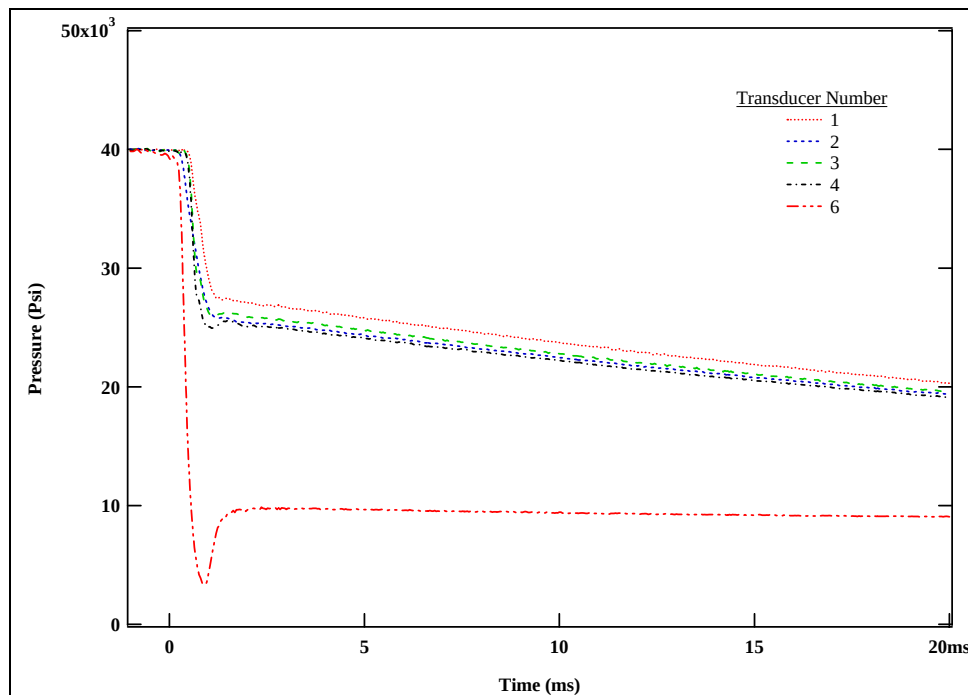


Figure 6-9. Typical raw data. Shot 702902. $P_0 = 40,000$ psi N_2 . The transducers were mounted consecutively along the nozzle, with Transducer 1 at the throat.

The LLNL experiment series results are summarized:

- An apparatus to study high Reynolds number, supersonic flows at plenum conditions ($V = 3(10^{-3}) \text{ m}^3$, $P \leq 300 \text{ MPa}$, room temperature) was developed. Pressure fluids were air, N_2 , and inert gases. A fast DAS was developed to measure pressure along the nozzle with a pressure resolution of approximately 0.05 MPa and a time resolution of 1 μsec /data channel.
- Fabrication technology using precision tungsten carbide reamers is not adequate to make arbitrary monotonic increasing cylindrical nozzle profiles having better than 0.1 percent error on the profile diameter and a surface smoothness of better than 0.1 μm average peak to valley deviation.
- During this early research phase, nozzle surfaces and shapes were likely to be nonideal, so profiles should be designed with adequate area expansion to ensure supersonic flow.

6.3.2 275 MPa Blowdown Experiments: Development of Nozzle #2

The precision reaming technology used in the fabrication of the first nozzle for the 275 MPa blowdown experiments was inadequate to provide an accurate nozzle profile and surface smoothness. The nominal specifications for the profile shape are of an accuracy of approximately 0.1 percent on the monotonic increasing cylindrical diameter and a surface smoothness of

approximately $0.1\text{ }\mu\text{m}$ average peak to valley deviation. The electroplating technology used to fabricate Nozzle #2 appears to have potential to meet these requirements. This section is a description of the fabrication steps for Nozzle #2.

A schematic of Nozzle #2 is shown in Fig. 6-10. The LLNL machine drawing numbers are AAA98-110677-00, AAA98-110678-00, AAA98-110679-00, and AAA98-110680-00. The approach is to make a nozzle insert fitted to an AISI E4340 steel nozzle body. The nozzle body is made from the original, monolithic Nozzle #1 by boring an axial hole to receive the nozzle insert and by relocating the six pressure transducer mounting points.

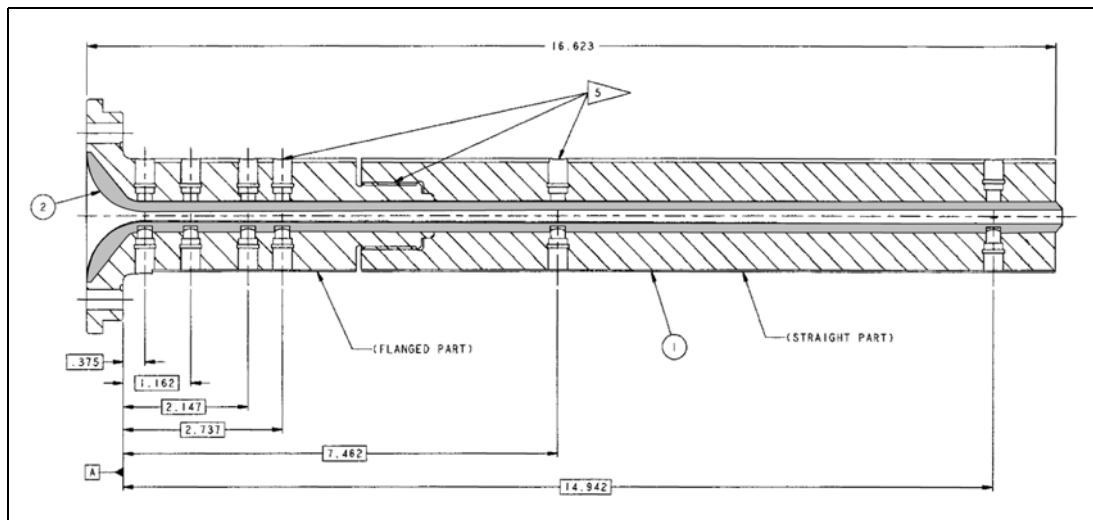


Figure 6-10. Schematic of the 275 MPa blowdown experiment Nozzle #2. The AISI E4340 steel nozzle body, originally the monolithic Nozzle #1, was modified to accept the nozzle liner, shown as the shaded section. The nozzle liner was fabricated by electroplating nickel onto an aluminum mandrel, machining the external surface, then leaching out the aluminum. The upper set of pressure transducer ports were part of the Nozzle #1 experiment and were sealed for the Nozzle #2 experiment. Dimensions are in inches.

The nozzle insert is made by electroplating an approximately 1-cm-thick layer of Ni on an Al T6061 mandrel having the desired nozzle shape and surface finish (Fig. 6-10). The rough external Ni surface is then machined to a push fit to the nozzle body, pressure tap holes are drilled through the Ni into the Al (to avoid burrs on the internal nozzle surface), and the Al mandrel is leached out. The nozzle insert is then inserted into the steel body with a viscous fluid, such as vacuum grease, between the body and the insert to isolate the pressure taps. The Nozzle #2 prototype total cost was approximately 300 hours, including drafting, machining, plating, leaching, inspection, and supervision. The estimated cost for “production” nozzle liner replacements, each of which may have a different profile and surface finish, is approximately 40–80 hours, which primarily is for the precision machining of the mandrel and inspection.

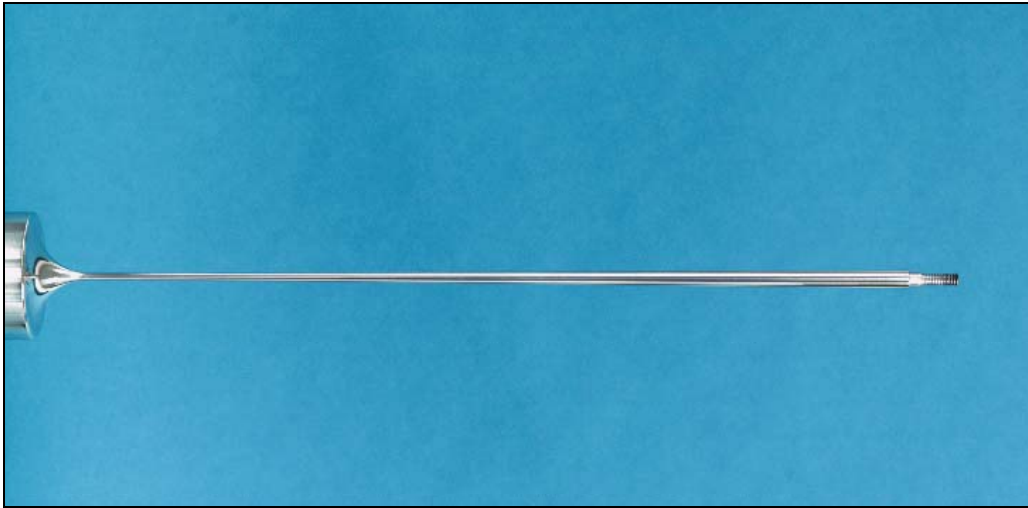


Figure 6-11. T6061 Al mandrel onto which the Nozzle #2 Ni liner was electroplated. The nozzle is approximately 400-mm long, with a throat diameter of 4.0 mm opening to an exit diameter of 8.89 mm. The inner surface of the Ni liner is an atom plane replica of the outer surface of the mandrel, which can be economically precision machined and inspected.

The profile inspection of Nozzle #2 is shown in Fig. 6-11.

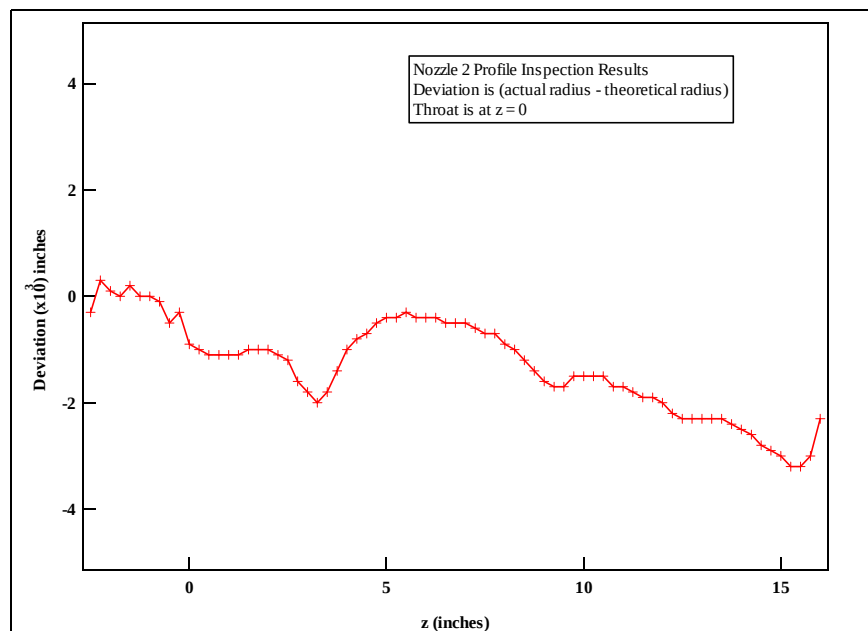


Figure 6-12. Inspection results for the T6061 Al mandrel for Nozzle #2. The ordinate is the deviation from the theoretical profile, and the abscissa is the length along the nozzle, with the throat a $z = 0$.

The theoretical profile is:

$$d(mm) = 4.000 + 6.980(10^{-5})z^2 \quad (6-1)$$

This approach has several advantages. The electroplated internal nozzle surface is an atom plane replica of the external surface of the mandrel. This means the profile-machining step is on an external, cylindrical surface, which permits a variety of precision machining and polishing technologies. In the case of Nozzle #2, the external surface of the T6061 Al was rough machined, and the final profile was made using a numerically controlled EDM wire-cutting technology. Final polishing was done by hand with crocus cloth. The second major advantage is that the profile and surface finish can be measured directly by inspecting the external surface of the mandrel. This avoids the requirement to measure the shape and surface finish smoothness of a few millimeter diameter profiles at the bottom of a 400-mm hole. A third advantage is that the inner surface of the nozzle can be built up of several layers, each (in principle) applied using a different technology (e.g., thermal and chemical barriers could be applied to the mandrel surface using various coating technologies). Intermediate layers to match thermal expansions and to reduce epitaxial mismatches can be applied, followed by the final plating of the nozzle liner. A fourth major advantage is that the nozzle liner is replaced easily, simply by pressing it out of the nozzle body. Nozzle liners having different profiles can be used with the same nozzle body. Rapid turnaround of the nozzle assembly is possible if two or more nozzle bodies are available.

In conclusion, a promising approach to fabricating nozzles for the MARIAH II/RDHWT Program has been developed. The approach appears to meet the several requirements for research on high Reynolds number supersonic flows near room temperature, viz., precise control of the nozzle cross-sectional area, surface smoothness of the order of hundreds of nanometers, and economical fabrication. The flexibility to lay down “designer” layers on the internal surface of the nozzle to serve as thermal, chemical, and diffusion barriers; to control surface erosion; and to match thermal expansion coefficients in likelihood will be important to the high O₂ fugacity, high temperature, high shear stress environment in the A-2 and successor devices.

Table 6-3. Nozzle #1 Profile

Axial distance from the throat (cm)	Diameter (cm)	Axial distance from the throat (cm)	Diameter (cm)	Axial distance from the throat (cm)	Diameter (cm)
0.0000	0.30000	1.5300	0.30622	3.0600	0.31662
0.0450	0.30002	1.5750	0.30652	3.1050	0.31682
0.0900	0.30006	1.6200	0.30682	3.1500	0.31700
0.1350	0.30010	1.6650	0.30714	3.1950	0.31716
0.1800	0.30018	1.7100	0.30746	3.2400	0.31732
0.2275	0.30028	1.7550	0.30776	3.2850	0.31748
0.2700	0.30038	1.8000	0.30810	3.3300	0.31760
0.3150	0.30050	1.8450	0.30842	3.3750	0.31772
0.3600	0.30062	1.8900	0.30876	3.4200	0.31784
0.4050	0.30076	1.9350	0.30908	3.4650	0.31794
0.4500	0.30090	1.9800	0.30942	3.5100	0.31802
0.4950	0.30106	2.0275	0.30976	3.5550	0.31810
0.5400	0.30122	2.0700	0.31010	3.6000	0.31816
0.5850	0.30138	2.1150	0.31044	3.6450	0.31822
0.6300	0.30156	2.1600	0.31078	3.6900	0.31826
0.6750	0.30174	2.2050	0.31112	3.7350	0.31828
0.7200	0.30192	2.2750	0.31146	3.7800	0.31832
0.7650	0.30210	2.2950	0.31180	3.8275	0.31834
0.8100	0.30230	2.3400	0.31214	3.8700	0.31834
0.8550	0.30275	2.3850	0.31246	3.9150	0.31834
0.9000	0.30270	2.4300	0.31280	3.9600	0.31834
0.9450	0.30292	2.4750	0.31312	4.0050	0.31834
0.9900	0.30314	2.5200	0.31344	4.0500	0.31834
1.0350	0.30336	2.5650	0.31376	4.0950	0.31832
1.0800	0.30358	2.6100	0.31406	4.1400	0.31832
1.1275	0.30382	2.6550	0.31436	4.1850	0.31830
1.1700	0.30406	2.7000	0.31464	4.2300	0.31830
1.2150	0.30432	2.7450	0.31492	4.2750	0.31828
1.2600	0.30456	2.7900	0.31520	4.3200	0.31828
1.3050	0.30482	2.8350	0.31546	4.3650	0.31828
1.3500	0.30510	2.8800	0.31572	4.4100	0.31830
1.3950	0.30536	2.9275	0.31596	4.4550	0.31832
1.4400	0.30564	2.9700	0.31618	4.5000	0.31834
1.4850	0.30594	3.0150	0.31640	15.2400	0.31834

6.4 REFERENCES

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7.0 THERMAL ENERGY ADDITION IN SUPERSONIC FLOW RESEARCH AND DEVELOPMENT

7.1 OVERVIEW

The heart of the MARIAH II/RDHWT concept lies in the controlled addition of large amounts of energy to a supersonic airflow. In the initial portion of the supersonic flow, thermal energy is added through radiative processes and followed in the hypersonic region by MHD acceleration to achieve the maximum possible performance. Three approaches to thermal energy addition are being explored: 1) e-beam, 2) lasers, and 3) microwaves. The major challenge in all three cases is to add energy to the supersonic flow so that the flow quality remains acceptable for hypersonic testing over long test times. This means that the energy must be added in a predictable manner, leading to a uniform, stable flow whose chemical properties are maintained as closely as possible to those of atmospheric air.

Throughout this discussion, the term, "thermal energy addition," is used to describe the deposition of energy into the supersonic flow regime. The mechanisms involved in this energy deposition process differ depending on whether the energy is carried into the flow by laser beams, e-beams, or microwaves. Only radiant sources such as these are viable, since the flow cannot be brought to stagnation. In all cases, the objective is to add to the thermal energy of the flow. That thermal energy is converted into kinetic energy by controlled expansion.

The initial approach is to demonstrate controllable energy addition in small-scale, low enthalpy flows and then move to progressively larger scales. To date, laser experiments at the 10-kW level and e-beam experiments at the 30-kW level have been accomplished and are discussed in this report. Experiments using microwaves for thermal energy addition have not been conducted and are not projected in the near future due to both technical concerns regarding the viability of microwave energy addition in a full-scale facility and funding limitations. A discussion of these technical concerns follows this overview.

This systematic approach has been motivated by the need to reduce risk and establish the practicality of scaling up to medium- and full-scale facilities. The modeling effort has moved in concert with the experimental program, acting as a primary design tool for the experimental configurations and giving performance predictions against which experimental results are compared. The experimental results, in turn, have been used to validate those aspects of the model that are appropriate to the scale of the experiment. This iterative process is continuing to the next step with the projected 100-kW e-beam energy addition experiment that is being planned for late fall 1999 at SNL.

7.2 OBJECTIVES OF THE RADIANT HEATING RESEARCH AND DEVELOPMENT

The objectives of the radiant heating R&D are to determine the feasibility of achieving flow enthalpies for long run times to support T&E testing at Mach numbers above 8, or as high as practical. Specific objectives are:

- Experimentally show that radiant heating of a supersonic flow at successively higher heating rates can lead to a high quality supersonic flow of higher total enthalpy.
- Demonstrate that the fully coupled fluid mechanical/radiant energy properties and absorption models can predict the experimental results at increasing power levels.
- Use simple models of the MARIAH II/RDHWT wind tunnel concept to explore the technical limits and performance envelope of such a system and to undertake preliminary system tradeoff studies particularly between various forms of radiant energy addition.
- Develop a detailed and coupled radiant energy and fluid mechanical model for both laser and e-beam energy addition that includes the real EOS for air at very high pressures and the unsteady 2-D axisymmetric Navier-Stokes solver with a Baldwin-Lomax turbulent boundary layer model.

7.3 DOWN SELECTION FROM MICROWAVE ENERGY ADDITION

The initial RDHWT Program identified three approaches for the addition of energy to the supersonic airflow (i.e., lasers, e-beams, and microwaves). All three of these technologies have been demonstrated at the megawatt scale and have the potential for additional scaling to the 10- to 500-MW level that is expected to be required for an operational hypersonic wind tunnel facility considering the limits of scale and test conditions addressed in the MARIAH II/RDHWT Research Plan. While both e-beams and lasers continue to be considered viable technologies for energy addition, various technical issues suggest that controllable energy addition by microwave may not be feasible (at least with today's technology). The recommendation to proceed with e-beam and laser technologies and to de-emphasize microwave technology was reached following a variety of studies conducted at Princeton and through collaborations with CPI Corporation, the Boeing Company, LLNL and General Atomics Corporation. The major technical concerns with microwaves are (Ref. 1):

- very low microwave absorption into air;
- microwave beam coupling into the wind tunnel; and
- tunnel cross section dimension compared to microwave wavelength.

A considerable amount of effort went into the study of various mechanisms for coupling microwaves into air. The first suggestion was to use the O₂ microwave absorption line, which occurs at approximately 60 GHz. This is attractive since 60-GHz, high-power microwave sources have been developed by the DOE in association with the Plasma Fusion Program. For the MARIAH II/RDHWT wind tunnel concept, the energy must be deposited into air at pressures in excess of 100 atm and at temperatures up to a few thousand K. While there have been no measurements of O₂ microwave absorption under these conditions, there have been measurements up to 50 atm, which indicate an absorption length of approximately 20 m. The peak of the absorption at high pressure is shifted to significantly lower frequencies and does not increase very rapidly with density. In the wind tunnel, the energy must be deposited over a length scale approximately 1 m and at a low supersonic Mach number to meet the test condition goals. Use of the O₂ absorption would require that the tunnel be configured as a high Q microwave resonator in

order to deposit a reasonable amount of energy over a 1-m distance. This means that field intensities on the order of gigawatts (GW)/cm² or more will be required. As the O₂ density drops, higher power levels may be necessary to continue the energy deposition. These power levels are close to, and in some cases, exceed the electrical breakdown threshold of high-pressure air.

Other absorption mechanisms were examined including pressure-induced transitions in N₂ and transitions in seed molecules such as carbonyl sulfide (COS). In the case of pressure-induced transitions, the fact that energy can only be deposited in the ultrahigh (>10³ atm) pressure section of the wind tunnel severely limits its performance. In particular, in virtually all cases of interest, the maximum rate of energy addition is at constant Mach number. This requirement avoids choking but leads to a significant reduction in density near the exit end of the energy addition section. Mechanisms that require high density cannot continue to deposit energy in this regime.

Operating the microwave energy addition process at powers above the breakdown threshold for air is a possibility that has not been considered in detail. At the required air densities, this microwave-induced breakdown is expected to be highly unstable; however, the instabilities may be random enough to cause some averaging over the flow. A more serious issue may be the reflection of the microwave that occurs once breakdown has been initiated. In essence, the regions of high conductivity shield other regions in the flow; however, this may be mitigated by strong magnetic fields. Due to funding constraints, further exploration of this area has not been undertaken.

The second technical concern relates to the coupling of the microwave field into the wind tunnel. It is well known that microwaves cause electrical breakdown to occur in low-density air much more easily than in high-density air. This is because the breakdown process is driven by the acceleration of an electron to a high enough energy, thereby creating ionization. This acceleration is slowed by collisions, and therefore breakdown is achieved more easily at lower densities where fewer collisions occur. This is not the case for lasers where the oscillation frequency of the electromagnetic field is much higher than the collision frequency. For microwaves, this breakdown at low density severely complicates strategies for coupling energy into the energy addition section of the wind tunnel. Bringing the microwaves in from downstream, as is proposed for both e-beams and lasers, will not work since breakdown will occur well before the microwaves reach the desired energy addition region. Bringing microwaves in through the throat may be a possibility but raises serious engineering issues due to the UHP driver system through which microwaves must pass. Introducing microwaves through the walls exposes the walls to unacceptably high field intensities, thereby leading to wall heating and potentially to breakdown. The very small diameter of the energy addition section (approximately 1 cm) indicates that even high transparency windows will not be able to accommodate the required energy flux levels. Consequently, aerodynamic windows have been suggested, and the preliminary design of such windows was undertaken by General Atomics Corporation. General Atomics Corporation proposed a phased array, aerodynamic window concept that may be used to pass MW-level microwave beams. It remains unclear, however, whether sufficiently high field strength microwave beams can be passed through the high temperature, low density boundary layer without inducing breakdown. Due to the varying density in the energy addition section of the flow, several stages of aerodynamic windows and microwave power levels must be incorporated.

The third technical concern relates to the microwave wavelength in relation to the scale of the tunnel cross section. Studies of the propagation of microwaves into a converging wind tunnel section have been made by CPI Corporation in cooperation with the Boeing Company. For tunnel diameters less than approximately 1.6 cm, the TE_{141} circularly polarized cylindrical mode resonance at 55.92 GHz is reflected back out of the energy deposition region. In principle, lower order modes will penetrate to lower diameters, but these modes are difficult to launch given the requirement that the microwaves must pass through the walls into the tunnel. Higher frequency microwave sources are under development, and an extrapolation to the range of 130 GHz to 250 GHz MW-scale sources was conducted by LLNL in conjunction with the FOM Institute in the Netherlands and the Soliton-NTT Research Center in Moscow. Their conclusion was that such a source could be extended to 5 MW and made tunable in this regime by using technology under development in the Netherlands.

These reports leave the possibility of microwave energy addition as a method for energy deposition into the MARIAH II/RDHWT wind tunnel. However, large uncertainties associated with the absence of a compelling energy coupling mechanism by which that energy will be deposited into air, complexities in beam coupling into the flow facility itself, and issues associated with the development of shorter wavelength sources has led to the recommendation that the microwave research be placed on hold at this time.

7.4 MAJOR EQUIPMENT AND SYSTEMS TO SUPPORT THE EXPERIMENTAL RESEARCH

Major equipment and systems that have been acquired or built for the radiatively driven wind tunnel experiments include:

- Small-scale blowdown wind tunnel facility that consists of the following components:
 - three interchangeable supersonic nozzles;
 - a gas manifold system for supply of tunnel gases; and
 - an electrical heating system to heat plenum gases.
- Ultrahigh pressure blowdown facility consisting of the following major components:
 - two nozzles;
 - high-pressure intensifier;
 - gas manifold systems to supply gases to and from the intensifier to the nozzle; and
 - blast-proof room for safe enclosure of the experiment.
- Flow diagnostic equipment includes:
 - piezoelectric and strain gauge pressure transducers, thermocouples, and signal conditioners with amplifiers;
 - ArF excimer laser, dual-pulsed PIV Nd:YAG laser and computer-controlled intensified charged-couple device (CCD) camera; and
 - two computer-controlled digital acquisition systems.

- Modification of the HAWK Electron Beam Facility includes:
 - reconfiguration of the HAWK electron accelerator at SNL to produce several milliseconds of 1-MeV electrons at up to 500 kW;
 - construction of 0.1- to 3.2-T steering and transport solenoids with a 5-cm bore to guide the e-beam into a wind tunnel nozzle during blowdown; and
 - development of beam diagnostic equipment for solenoidal beam transport.

7.5 ANALYTICAL EXPERIMENTAL METHODS

7.5.1 Gasdynamic Energy Addition Code Development at Princeton University

The primary objective of this task is to develop a detailed and coupled fluid mechanical and radiant energy addition model for both laser and e-beam energy addition to the supersonic flow downstream of the throat. In both cases, the underlying fluid mechanical model is an unsteady 2-D, axisymmetric Navier-Stokes solver with a Baldwin-Lomax turbulent boundary layer model. The model uses a tabulated EOS for air as a subroutine (provided by NIST) (Ref. 2). For laser energy addition, the energy coupling is provided through a ray tracing code where the energy integrated over a sub-area of the source is allocated to each ray and is then absorbed according to an exponential law along each ray. The energy addition is fully coupled in the sense that the path of each ray is updated after each time step due to the change in the refractive index field. For the e-beam energy addition case, a separate Monte-Carlo code is used, which calculates the trajectories of a large number of electrons and finds the mean energy deposition rate at each location for a given density field. With this energy deposition law, the fluid mechanical model is updated, and the two codes are iterated to a steady-state solution. These codes assume thermodynamic equilibrium. Further development is to include the molecular dynamics of the laser energy addition process in the laser case and the concentrations of ions and chemical species in the e-beam energy addition process. This development is under way

In addition to these detailed, unsteady 2-D viscous codes, simpler 1-D and 2-D inviscid codes for both laser and e-beam energy addition are being developed for initial system and performance envelope studies.

The 1-D inviscid code is used exclusively for system and performance envelope studies. In particular, the code has been used to study the “inverse problem” in which an ideal thermodynamic path for the heat addition is first found theoretically, and the code then finds an area distribution such that the best approximation to the ideal case is achieved. Consequently, a much deeper understanding of the performance envelope of MARIAH II/RDHWT concept has been gained, particularly for the e-beam case.

A detailed 2-D, axisymmetric unsteady code for an inviscid flow with laser heating has been completed, and a similar code for e-beam heating is nearing completion. In the laser case, predictions of laser absorption, including wall reflections, were made and compared with the 10-kW CO₂ laser experiment (see Section 7.6). At much higher power and correspondingly higher flow density, important effects associated with ray refraction are predicted to randomize the energy addition and steer the laser beams away from the walls.

The viscous version of this code has been developed and used to examine boundary layer displacement and other viscous effects. Unfortunately, at the extremely high Reynolds number of the MARIAH II/RDHWT wind tunnel flow, the calculation takes far too long for it to be used in an unsteady energy addition calculation. A wall function version of the code is presently being developed to overcome this limitation.

7.5.2 Electron Beam Energy Deposition

Energy deposition by an e-beam into flowing air in a wind tunnel nozzle requires transport of that beam from the downstream side of the nozzle, through a small hole in the nozzle wall, around a slight bend, and upstream toward the throat while simultaneously reducing its radius to follow the contour of the nozzle walls. This is achieved by injecting a relativistic e-beam onto a strong axial magnetic field that guides it along its path. The field converges as it approaches the throat and therefore tightens the beam as it nears the throat in spite of scattering in the air. The magnetic field suppresses the usual instabilities that plague unguided e-beam transport through free air.

Although the development of the process is extremely challenging, the major elements of this approach have been demonstrated experimentally (as described in Section 7.8). Modeling of the process is similarly challenging; however the MARIAH II/RDHWT Program team is fortunate to have available a detailed Monte Carlo e-beam simulation code that was developed during the Cold War to simulate radiation effects from detonating nuclear weapons.

This code, the Integrated Tiger Series (ITS), models the trajectories of electrons one at a time as they scatter off atoms in matter they penetrate. It also models and tracks the production of secondary electrons produced by the process. The axisymmetric version (CYLTRAN) includes the option for axial magnetic fields that can guide the electron trajectories. The code has been benchmarked by numerous experiments over the past decade and a half and is very well suited for this application (Ref. 3).

In a fully detailed calculation, the energy deposition rate from the e-beam would be determined by the ITS code and used by the Princeton University gas dynamic code in an iterative process; however, this is a somewhat cumbersome process. Therefore, an attempt is being made to derive an empirical algebraic relation that closely modeled the results of the more detailed ITS code, which could be easily incorporated into the gas dynamics code.

The ITS code was used to calculate the energy deposited in uniform air by a uniform e-beam confined by a strong axial magnetic field. The beam was large enough in diameter so that radial expansion was negligible, and this was verified by looking at several radial zones. Four initial beam voltages were considered (that is, 1, 2, 5, and 10 MV). A set of power deposition curves was made from the results of these runs.

Figure 7-1 shows the power deposition rate as a function of integrated aerial density from the start of the beam (solid curves). The deposition rate, q , is given in terms of MW/cm^3 for a beam with an initial uniform current density $j = 1 \text{ A}/\text{cm}^2$ going through air with a density of $\rho = 1 \text{ g}/\text{cm}^3$.

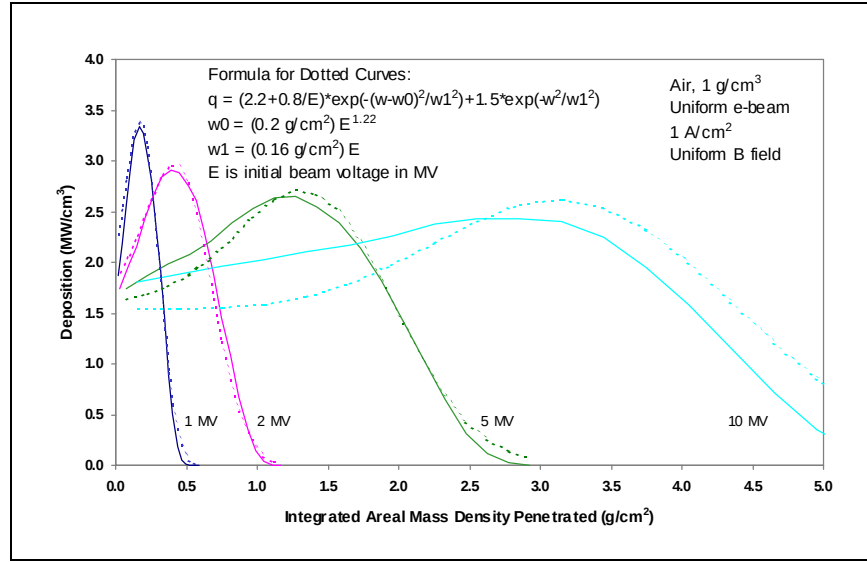


Figure 7-1. Energy deposition by uniform e-beam on strong axial magnetic fields.

This rate (q) should scale linearly with initial current and air densities. The solid curves in the figure are from the code runs. The dotted curves are based on the following empirically fit formula:

$$q = (1 \text{ MW/cm}^3) \left(\frac{j}{1 \text{ A/cm}^3} \right) \left(\frac{\rho}{1 \text{ g/cm}^3} \right) \left(\left(2.2 + \frac{0.8 \text{ MV}}{E_0} \right) \exp \left(-\frac{(w - w_0)^2}{w_1^2} \right) + 1.5 \exp \left(-\frac{w^2}{w_1^2} \right) \right) \quad (7-1)$$

where:

$$w = \int \rho \, dx$$

$$w_0 = (0.2 \text{ g/cm}^2) \left(\frac{E_0}{1 \text{ MV}} \right)^{1.22}$$

$$w_1 = (0.16 \text{ g/cm}^2) \left(\frac{E_0}{1 \text{ MV}} \right)$$

and where E_0 is the initial electron voltage (in MV), and w , w_0 and w_1 are in units of g/cm^2 . There is no obvious physical basis for the formula (except possibly the Gaussian form); however, it fits the calculated curves with convenient functions. The formula works reasonably well for 1 MV to 5 MV, but starts to degrade at 10 MV.

This then allows a simple way to determine the local power deposition of the beam. One keeps track of the total accumulated number of g/cm^2 of air that the beam has passed through (i.e., w) and uses this in the above formulae along with knowledge of the local current and air densities.

This power can be distributed across the local nozzle diameter with the appropriate radial profile if a 2-D energy deposition estimate is required.

Note that since the power absorbed scales with the integrated areal density (w) traversed, the beam will be able to penetrate better into the denser and hotter air near the throat if the nozzle diverges strongly rather than weakly.

7.5.3 Optical Diagnostic Techniques

Due to the importance of the flow field properties and the difficulty obtaining data in the presence of high flux radiative beams and parasitic x-rays, much of the data was taken using optical techniques.

7.5.3.1 Temperature

A variant of the LITA technique was developed to measure the speed of sound and static temperature at the center of the flow. Static temperature measurements using this technique were performed during the e-beam energy addition period, and a 5 percent uncertainty was obtained from static measurements in the unheated flow. In this technique, the sound speed at a point in the flow is measured over approximately 300 ns. This accuracy of this technique has been verified by experiment at the low temperatures (90 K) in a cold static cell (Refs. 4, 5).

7.5.3.2 Velocity

To measure flow velocity, a simple flow tagging technique was developed during the tests and used in the e-beam heating experiments. In this technique, a small (approximately 2-mm-wide) laser induced plasma is created by focusing the second harmonic output of the Nd:YAG laser at the nozzle exit. The flow velocity is determined by measuring the displacement of the plasma along the flow axis over time. The initial plasma creation and the location of its displaced center of mass are recorded on a single image with a single laser pulse by a double exposure of the CCD camera used to record the image (Ref. 6). One exposure is taken when the plasma is created and the other at a time delay large enough to image and measure a displacement with good accuracy. The velocity measurements during the e-beam experiment had an uncertainty of 2 percent or approximately 15 msec^{-1} for most runs.

7.5.3.3 Density

Rayleigh scattering of an ArF laser beam was used to measure flow density across the nozzle exit plane. Rayleigh scattered light is directly proportional to gas density and laser intensity. Since laser intensity varies from shot to shot, calibration of signal intensity to density for each shot is required. Rayleigh scattering images are calibrated to absolute density by simultaneously imaging the ambient air in the same frame. Ambient air density was calculated from temperature and pressure measurements during the tunnel run.

7.5.3.4 Shadowgraph

Thirty-two consecutive shadowgraph images of the flow were used for time resolved measurements of flow stability and Mach number over the energy addition period. The framing rate of these images varied from a few hertz for the laser energy addition experiments, up to 100 kHz for the short pulsed e-beam experiments. The Mach lines produced by a small cone placed in the flow were used for these measurements. Figure 7-2 is a shadowgraph image of the unheated flow illustrating the position of the Mach lines used to determine the Mach number. The horizontal white lines in the image are damaged pixels in the CCD chip.

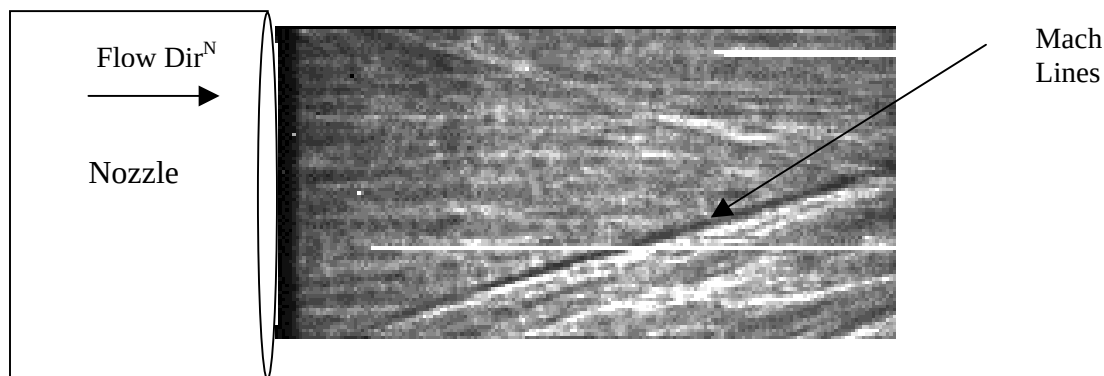


Figure 7-2. Shadowgraph of unheated flow.

7.5.3.5 Electron Beam Characteristics

The primary characteristics of the e-beam, which are needed for understanding of the experiment, are initial voltage (electron energy), current, diameter, axisymmetric symmetry, and centroid displacement off centerline. The initial voltage is obtained from the accelerator voltage monitor. Some beam energy is lost as it travels through the beamline exit foil and the air outside the nozzle exit; however, this amount is small and can be estimated from either the ITS code or known tabular data for electron energy loss in foils and air.

The beam current is determined for each shot from a Pearson current monitor just before the beam exit foil. (A Pearson is a coil wound around a toroidal ferrite core that the beam passes through; it automatically integrates the dB/dt of the beam as its current rises). The current is determined near the entrance to the beam nozzle with another Pearson but not during actual data acquisition shots since the monitor interferes with the flow diagnostics. The beam output is reproducible; therefore, this solution is acceptable. A flat plate current collection device ("Reed" probe) is another method for measuring beam current at various axial locations when the air is not flowing.

The beam location and shape is determined by having it hit a thin Mylar™ foil to produce light and photographing the results. This can be done successively at various locations in the beam path, but not when the air is flowing. Extrapolation of the beam size and shape from 1 atm stagnant air conditions to multi-atm flowing air must be accomplished with the ITS code. The Mylar™ foil also gives some information on total beam current via its brightness.

7.6 PRINCETON UNIVERSITY/AIR FORCE RESEARCH LABORATORY LASER ENERGY ADDITION EXPERIMENTS

7.6.1 Objectives

The purpose of the laser energy addition experiment test was two-fold:

- To provide a proof of concept of the laser energy addition to a supersonic flow using a 10-kW continuous wave CO₂ laser. The radiant energy of the laser was absorbed by the SF₆ molecules seeded into the N₂ flow and was rapidly thermalized from SF₆ modes.
- To validate numerical models that predict the energy deposition, flow quality, and dynamics of the e-beam/flow field interaction.

7.6.2 Hardware Overview/Experimental Configuration

A diagram of the energy addition experiment is shown in Fig. 7-3. It consists of a high-pressure front end, copper or aluminum nozzle, exhaust chamber, and a beam delivery tube (Ref. 7).

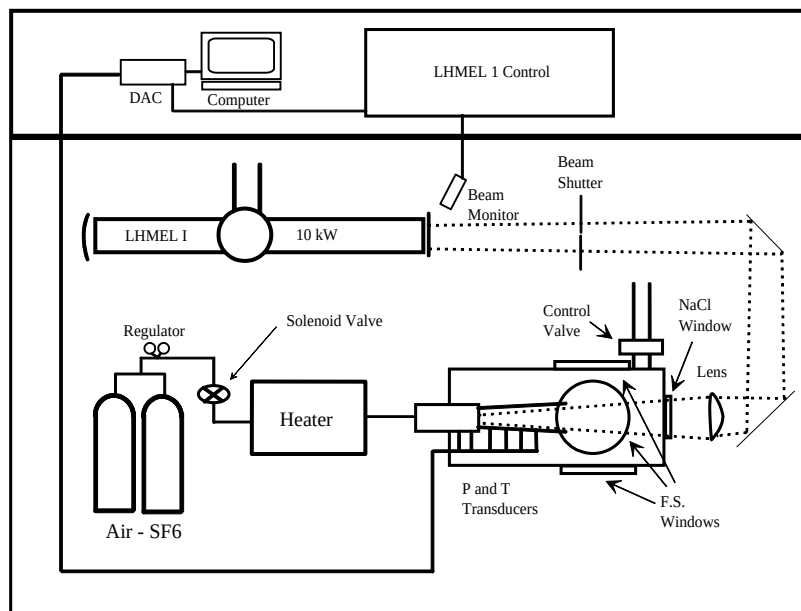


Figure 7-3. Diagram of the 10-kW CO₂ laser heated wind tunnel.

The Laser Hardened Materials Evaluation Laboratory 10-kW laser (LHMEI I) at Wright Patterson Air Force Base (WPAFB) was used as a source of stable, continuous energy for durations of 0.1 to 5 seconds. The laser beam was focused into the nozzle flow with a 1.5-m focal length zinc selenide (ZnSe) lens. To reduce absorption of the beam by the gas in the exhaust chamber, a beam delivery tube was used to bring the unattenuated beam as close as possible (3 inches) to the exit of the nozzle. A ZnSe window was placed at the end of this tube to transmit the laser radiation into the nozzle. The exhaust chamber was maintained at approximately the same

pressure as the exit pressure of the nozzle (~ 1.4 psia). Two 0.5-m-long (throat to exit) nozzles were constructed. The first was made of aluminum to verify the numerical machining code and handling procedure, and the second was made of copper for high thermal conductivity and high reflectivity of the laser radiation. The copper nozzle had a throat diameter of 6 mm and exit diameter of 34 mm. A plenum pressure of approximately 325 psia and temperature of 15 °C was used for most of the experiments. The aluminum nozzle, which has lower reflectivity than the copper nozzle, was used prior to the copper nozzle to determine the worst case effect of full laser power absorption in the nozzle walls. Gas for all runs was supplied to the nozzle by four 304 SCF gas cylinders of N_2 with 250 ppm of SF_6 .

Pressure and temperature were measured in the plenum, and each nozzle was instrumented in the supersonic region with five static pressure transducers. A pitot probe and total temperature probe were placed at the exit of the nozzle, thereby blocking a small part of the incoming laser beam. Shadowgraphy was employed to image shock structure at the exit of the nozzle, and the presence of condensation was monitored by Rayleigh/Mie scattering from a Nd:YAG laser. A measurement of integrated energy addition laser intensity was made for all test runs.

7.6.3 Summary of Experiments

Laser energy addition experiments were conducted for times ranging from 0.1 to 5 seconds; and for all exposure times, a steady flow field was observed. A rapid transition from the steady flow field in the absence of energy addition to a steady flow field with energy addition was also observed. Changes in Mach number and pitot pressure at the nozzle exit were recorded and observed to follow energy addition predictions. Static pressure increases along the nozzle also confirm that controlled energy addition was achieved.

7.6.4 Experimental Results

Shadowgraphs of the flow around the probe used for pitot pressure and total temperature measurements are shown in Fig. 7-4 for the copper nozzle flow. A shadowgraph without energy addition, recorded before the laser was activated, is shown in Fig. 7-4a. Bow shocks created by the pitot and total temperature probes are seen, and an approximate Mach number of 4.2 was calculated from the Mach angle. In this image, an oblique shock created by the overexpanded flow is also evident, and static pressure measurements made 1 inch inside the nozzle and in the exhaust chamber provide a Mach number of 4.3 (pitot measurements also give an exit Mach number of 4.3). Figure 7-4b is a shadowgraph image taken with energy addition just following laser activation. A Mach number decrease is evident from the increase in Mach angle of the bow shock around the probe, and a Mach number of 3.91 was calculated. Figures 7-4a and 7-4b are single frames taken from a 5-second video tape record of the flow prior to, during, and after energy addition. The shock angle and flow properties were constant for all times that the laser was activated.



Figure 7-4a. Shadowgraph of flow around pitot pressure and total temperature probe at the nozzle exit with *no energy addition*. Flow is from right to left.



Figure 7-4b. Shadowgraph of flow around pitot pressure and total temperature probe at the nozzle exit with *energy addition*. Flow is again from right to left. A comparison between the Mach angle of Figs. 7.4a and 7.4b shows a decrease in Mach number from 4.2 to 3.9.

Measurements of heat addition in the Al nozzle also follow the predicted changes in pressure along the nozzle. Current predictions match static pressure measurements along the nozzle if 8 kW of power were absorbed within the (Al) nozzle. This implies that 2 kW were absorbed by the gas in the exhaust chamber (before the laser entered the nozzle and by the nozzle wall). These predictions are approximate since accurate absorption coefficients are not available. Pitot measurements provide a Mach number decrease from 3.26 to 2.37 for the Al nozzle. This drop in Mach number is verified by shadowgraph images. Note the lip shock disappears, indicating pressure increase to match the cell pressure with energy addition.

7.6.5 Conclusions

Controlled, stable laser energy addition to a supersonic flow was demonstrated. Energy addition via absorption of laser energy by trace quantities of SF_6 has proven to be an effective way to demonstrate and study the laser energy addition process at the 10-kW level.

This proof-of-principle experiment has been a fundamentally important step toward the development of the MARIAH II/RDHWT concept. Further modification of the energy addition model to include more accurate absorption coefficients will enable better comparisons between experimental data and the Princeton University model.

In the 1-MW flow facilities, gas densities will be approximately 100 times higher than those encountered in the 10-kW experiment; propagation of incident laser light will be significantly deviated by density gradients in the flow, particularly by the boundary layer along the wall of the nozzle. These higher laser power densities will require the development of new techniques to couple the beam into the flow since few optical materials exist that will survive the high power density of the laser and the high temperature and pressure of the gases exhausted from the nozzle. An intermediate step toward the MW-scale experiments could use the 100-kW LHME II laser. At this scale, many of the existing components and experience from this test series could be used. Such results from an intermediate experiment would provide important insight into higher pressure, higher power tests.

7.7 ELECTRON BEAM SYSTEMS DESIGN AND MODELING

7.7.1 System Configuration For Electron Beam Energy Addition

E-beam technology may be used for two aspects of the MARIAH-II Concept. E-beams can be used to add energy to the flowing air just downstream of the nozzle throat as well as to create conductivity in the cold gas well downstream of the throat to facilitate MHD acceleration in that region. Figure 7-5 shows a possible configuration for e-beam energy addition. Two 50-MW electron accelerators inject tight e-beams obliquely through the wall of the wind tunnel nozzle downstream of the throat but upstream of the MHD section. The beams are captured on the converging field lines of a strong solenoidal magnet that surrounds the nozzle near the throat. As the electrons propagate toward the throat, they follow the field lines as they converge. This creates a focusing force, which helps overcome the scattering in the air within the nozzle. The beam electrons collide with the air molecules, thus heating the flowing air. A strong magnetic field can keep the beam centered and away from the nozzle wall, which avoids excess heating of the nozzle wall. Figure 7-6 shows electron trajectories for such a configuration as simulated by the ITS electron-photon trajectory code.

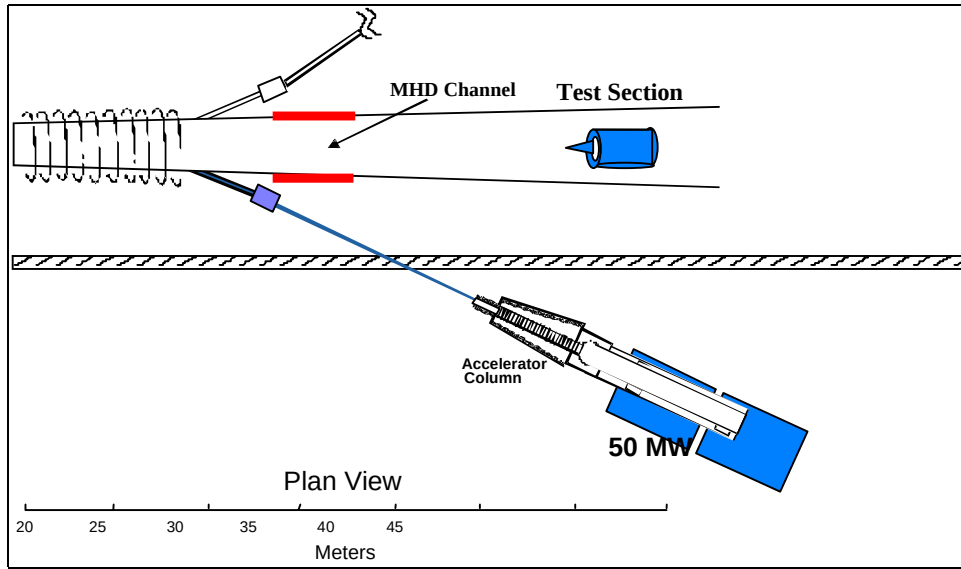


Figure 7-5. Possible configuration of e-beam heating in a MARIAH II/RDHWT Hypersonic Wind Tunnel Concept.

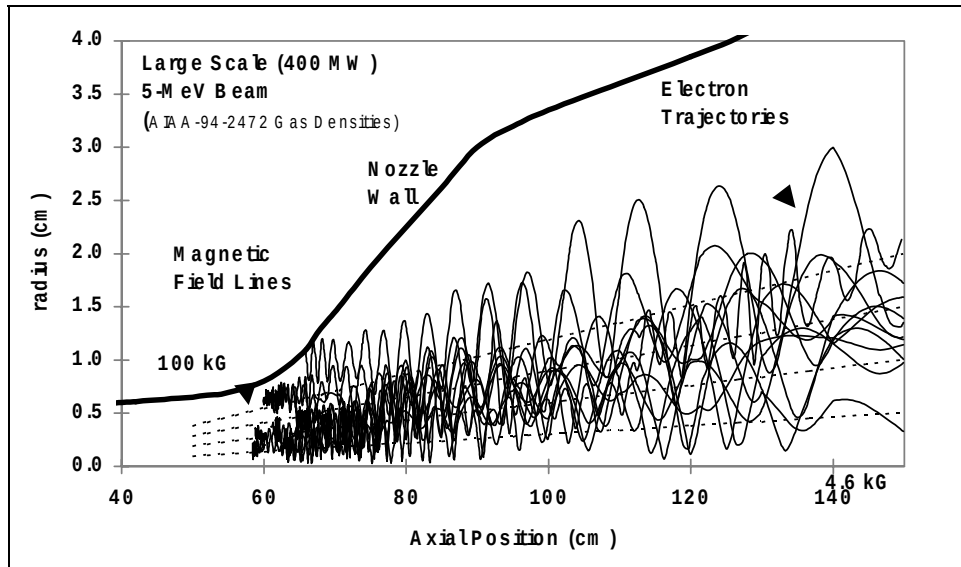


Figure 7-6. Electron trajectories following converging magnetic field lines through dense air.

7.7.2 Electron Beam Profile Contouring for Suppression of Wall Heating

The transverse power deposition profile in the first e-beam energy-addition experiment was approximately of a Gaussian shape. In that case, a significant fraction of the e-beam energy was deposited in the wall. To suppress wall heating, it is desirable to have more of a top hat shape detector beam in which there is a large central core with uniform power distribution and a

surrounding halo with no power deposition. A strong magnetic field and an e-beam that is initially either uniform or annular are required to achieve this goal. An annular beam would reduce the requirements on the magnetic field.

To investigate the specifics of wall heating, several simulations were run. The first set of simulations was evaluated using the geometry of the 30-kW class experiment, with the same nozzle and blowdown air densities, but assuming stronger magnetic fields and different beam injection shapes. The first simulation was run with 10 magnets at full power (0.5 to 3.0 T from the foil to the throat). The beam is assumed to be uniform with a diameter of 0.50 cm at the exit foil (which is placed at 84 cm from the nozzle throat and just inside the first magnet). To reduce confusion, all intervening apertures were removed for this run. Figure 7-7 shows the radial volumetric power distribution normalized by the local centerline power level as a function of the local nozzle radius for this first simulation. Each curve represents the beam profile from the centerline to the wall at various distances ranging from 22.5 to 47.5 cm downstream of the throat. The beam is essentially a Gaussian distribution with no central flat region.

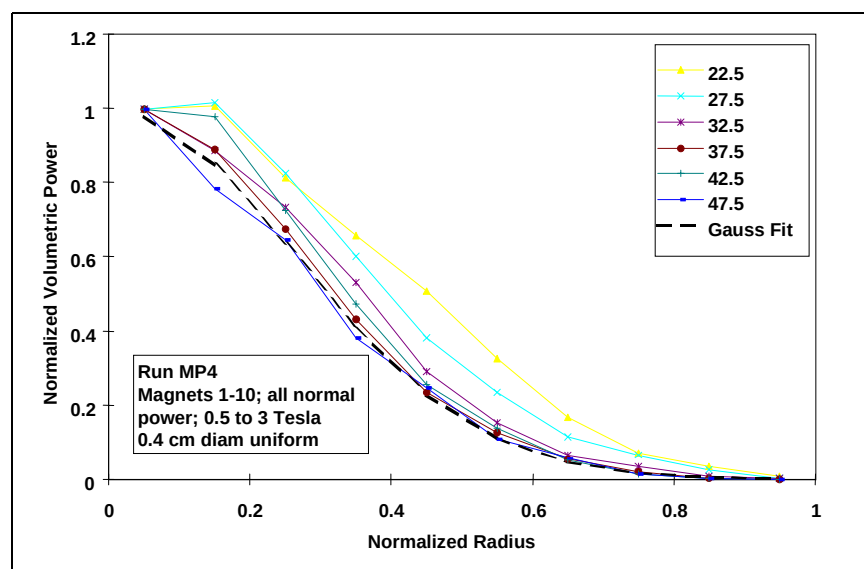


Figure 7-7. Radial power for 0.5- to 3-T and a 0.5-cm-diameter uniform beam. (Curves for various distances downstream of throat, cm).

An annular beam with a 1.0-cm ID and 1.5-cm OD was used for the second simulation. Placing a 1-mm-thick, 1-cm-diameter steel or copper disk on the centerline of the Be foil could make such an annular beam. Figure 7-8 shows the results. The annulus is filled in by beam collisions producing a relatively flat central region that extends out to a normalized radius of approximately 0.4. Note also that the power takes another 0.6 of radial extent to decay. Figure 7-9 shows the same beam with twice the magnetic field strength. In this case, the higher magnetic field causes the hole in the annulus to be preserved, but the decay to near zero at the wall occurs over a normalized radial extent of only 0.4, significantly less than the laser heated case.

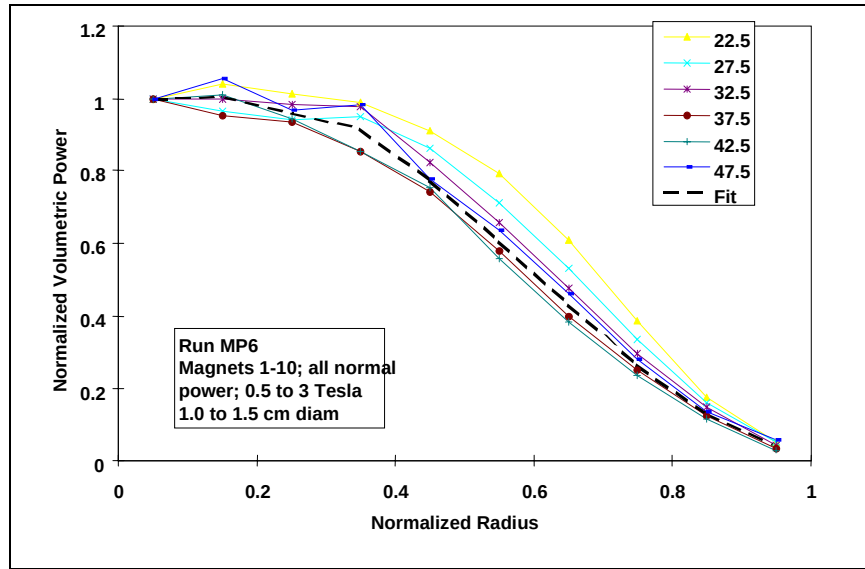


Figure 7-8. Radial power for 0.5- to 3-T and a 1.0- to 1.5-cm-diameter annular beam. (Curves for various distances downstream of throat, cm.)

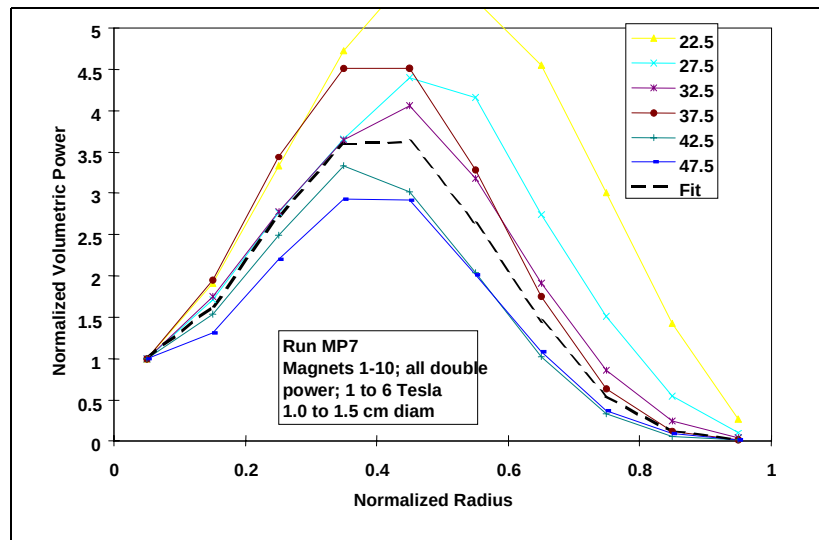


Figure 7-9. Radial power for 1- to 6-T and a 1.0- to 1.5-cm-diameter annular beam. (Curves for various distances downstream of throat, cm.)

Figure 7-10 shows the case for an annular beam with a 0.2- to 1.8-cm diameter and a magnetic field strength double that of the first simulation (1 to 6 T). There is a very pronounced flat top, and the edge is again approximately 0.4 in radial extent. Figure 7-11 shows the result for a quadrupled field (2 to 12 T) with a uniform beam 2.0 cm in diameter. For this case, the edge is approximately 0.2 in radial extent.

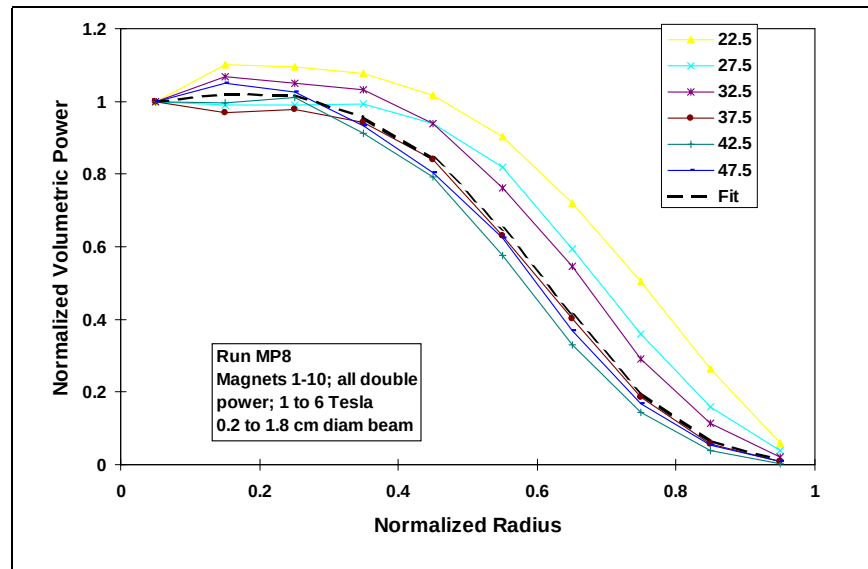


Figure 7-10. Radial power distribution for 1- to 6-T and a 0.2- to 1.8-cm-diameter annular beam. (Curves for various distances downstream of throat, cm.)

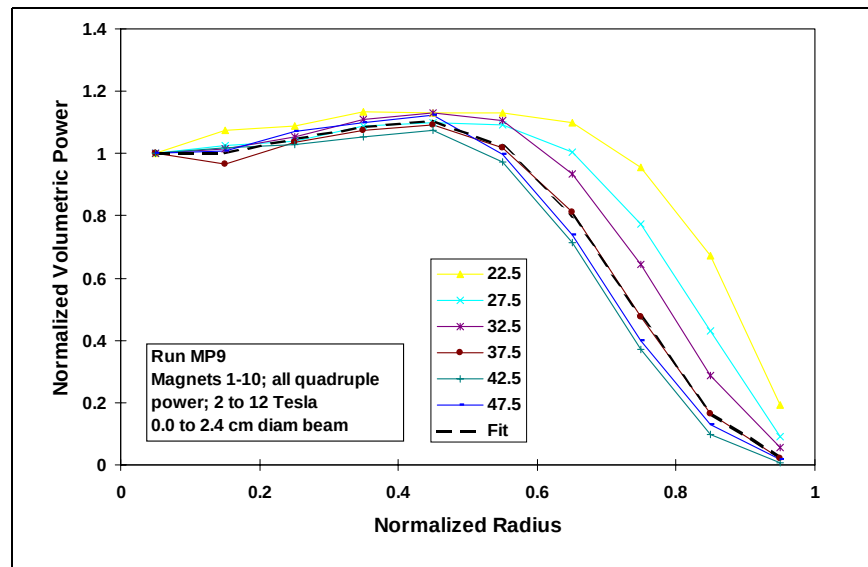


Figure 7-11. Radial power distribution for 2- to 12-T and a 2.8-cm-diameter uniform beam. (Curves for various distances downstream of throat, cm.)

These are only a few samples, but they show that the shape of the deposition and the amount of wall heating can be controlled by shaping the e-beam at the entrance and by using a sufficiently strong magnetic field.

The next set of conditions considered were those expected for the MSHWT using the nozzle shape and gas densities that were used by Princeton University for their recent analysis of the “Mach 12” design (Ref. 8). The plenum pressure for this case was 20,000 psi. However, because an annulus of cold gas flowing around the heated core (to permit nozzle survival) is required, the nozzle diameter was enlarged by 50 percent (from 4.5-mm diameter to 6.75 mm) and the total mass flow rate was increased correspondingly. Figure 7-12 shows the assumed magnetic field strength for this case, Fig. 7-13 shows the energy deposition, and Fig. 7-14 shows the radial energy deposition profile.

With the exception of locations near the throat, the energy deposition in the wall is negligible. This suggests that a slightly stronger field is required near the throat or perhaps a slightly larger throat to reduce the higher energy deposition in this region. The radial profile appears flat in this simulation from the centerline to approximately 40 percent of the enlarged nozzle diameter. Again, this suggests that either a stronger field and a slightly larger initial beam or a larger nozzle diameter is required. However, the results suggest that a uniformly heated core with acceptably low nozzle wall heating by the beam is achievable for a MSHWT if a magnetic field of approximately 20 T to 30 T is obtained. Such magnets have been produced for steady operation (many minutes) with bores in excess of 10 cm.

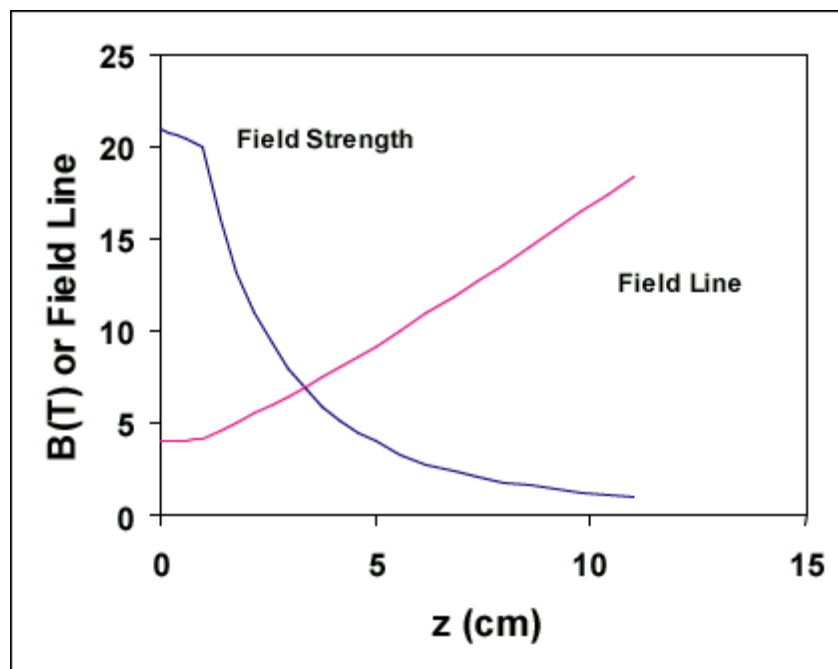


Figure 7-12. Assumed magnetic field strength for a preliminary analysis of the MSHWT.

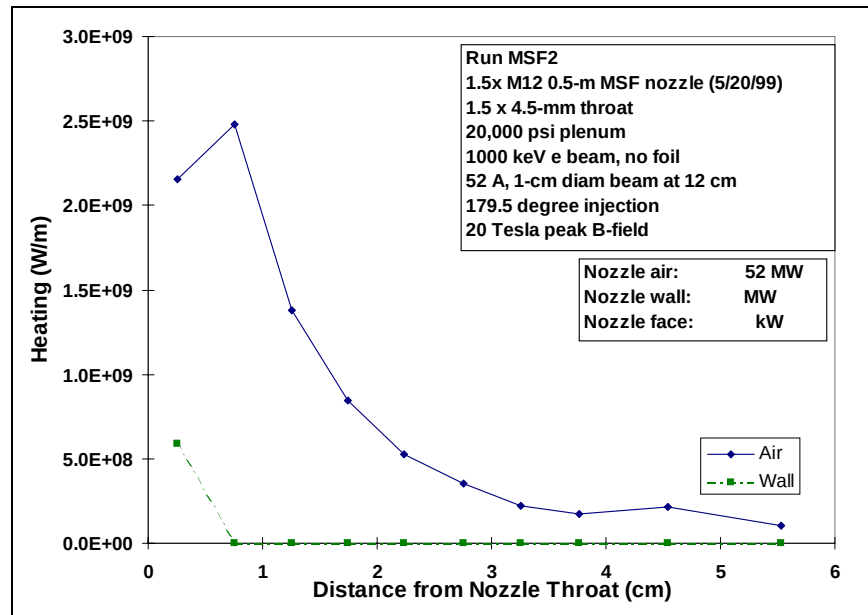


Figure 7-13. Energy deposition along the nozzle for a preliminary analysis of the MSHWT.

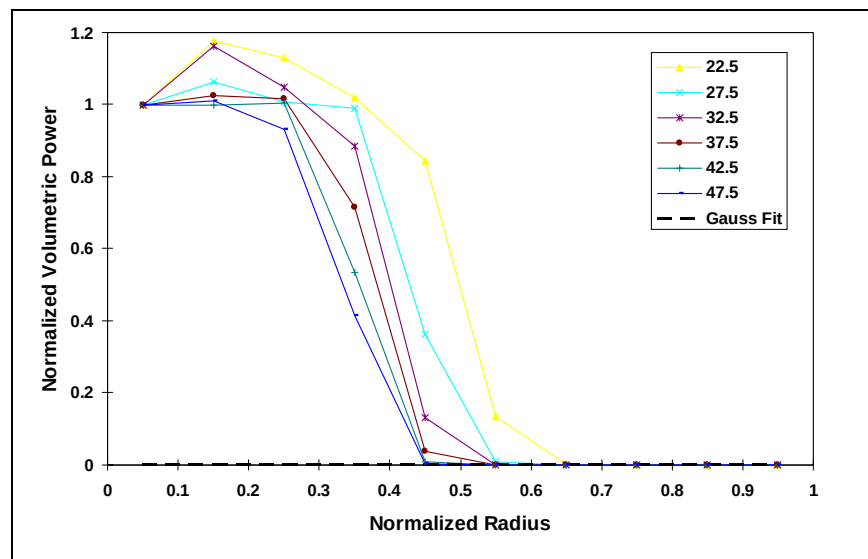


Figure 7-14. Radial energy deposition for a preliminary analysis of the MSHWT. (Curves for various distances downstream of throat, cm.)

7.8 30-KW ELECTRON BEAM EXPERIMENTS AT SANDIA NATIONAL LABORATORIES

7.8.1 Objectives

The goals of the 30-kW e-beam energy addition experiment were to:

- Demonstrate controlled energy addition with an e-beam to supersonic flow for the first time.
- Extend the demonstrated envelope for radiant energy addition from 10 kW (LHMEL) to 30 kW.
- To validate numerical models that predict the energy deposition, flow quality, and dynamics of the e-beam/flow field interaction.

The experiment was performed by a team composed of Princeton University and SNL personnel with financial support and some diagnostic equipment (the fast framing-rate camera) provided by AFRL at WPAFB. Princeton University headed the team and provided the nozzle, blowdown system, flow diagnostics, and flow modeling. SNL provided the e-beam, guiding magnets, beam diagnostics, and experimental facility.

7.8.2 Hardware Overview/Experimental Configuration

Figures 7-15 through 7-17 show the configuration of the experimental setup. Figure 7-15 shows the blowdown nozzle, beam transport magnets, and accelerator exit (with Be foil). The gas flows from left to right, and the e-beam flows from right to left. There are four “nozzle magnets” surrounding the nozzle (numbered 1 through 4). These magnets increase in strength from 4 to 1 so that the beam will be focused to a tighter size as it propagates from right to left in the figure. Figure 7-16 shows an overview of the setup with gas bottles, blowdown nozzle, magnets, accelerator, and laser diagnostics in the foreground as well as the Hawk accelerator in the background. Figure 7-17 shows a closer view of the magnets and shutter. The shutter is used to protect the Be foil when the air is flowing and opens only when the accelerator fires.

A diagram of the Mach 3.9, blowdown wind tunnel used for the energy addition experiments is shown in Fig. 7-18.

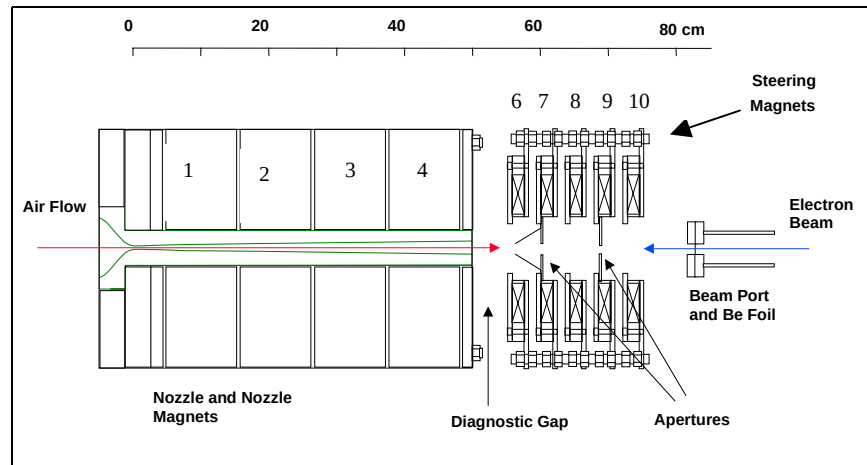


Figure 7-15. Schematic of the final configuration of the experiment.

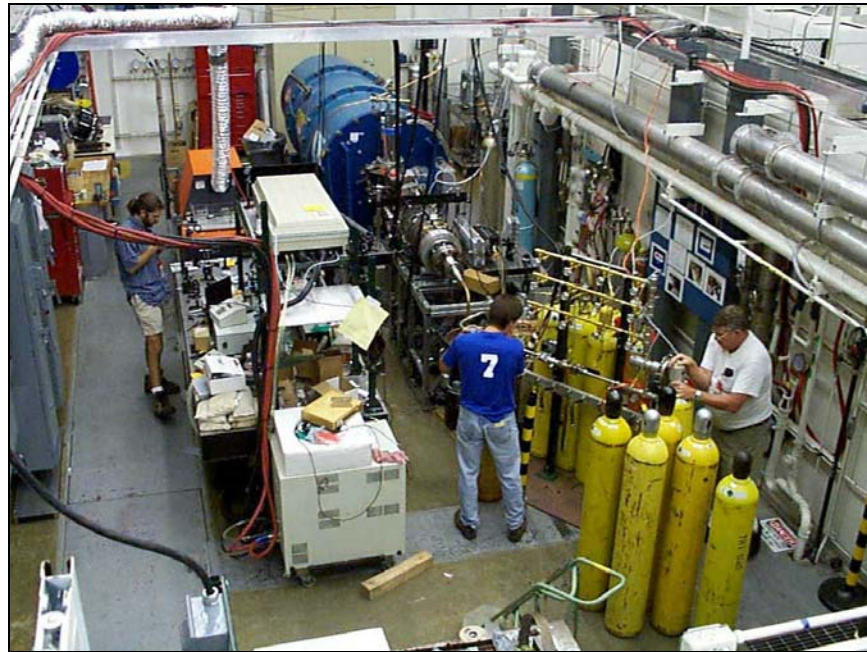


Figure 7-16. Overview of the experiment.

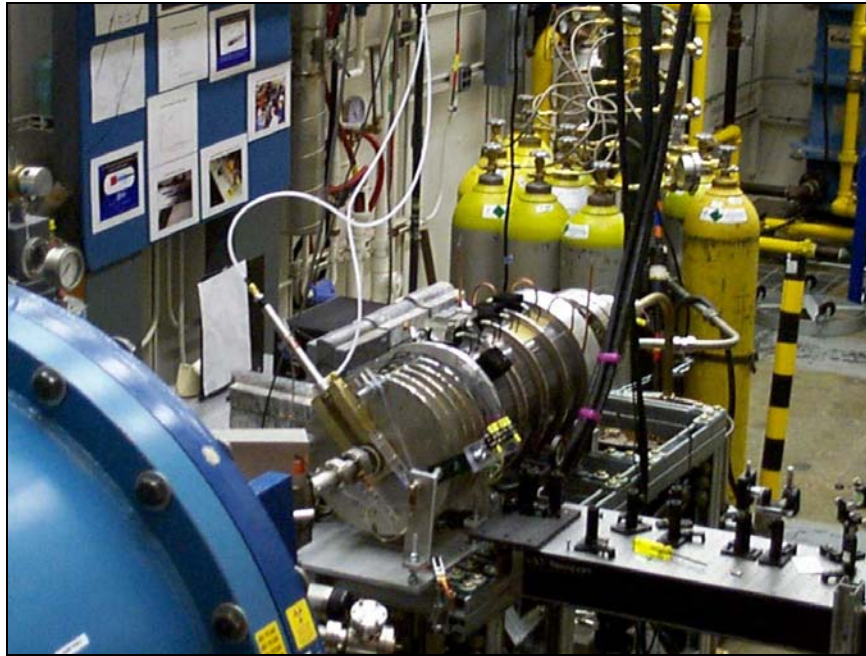


Figure 7-17. Accelerator, beam port, shutter, steering magnets, and nozzle magnets.

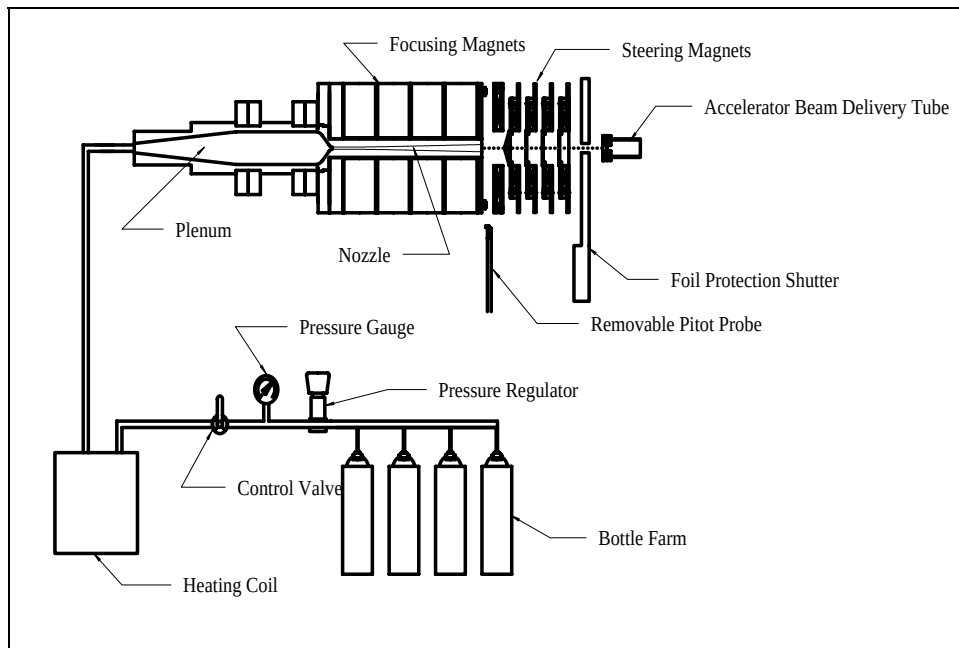


Figure 7-18. Diagram of the 10- to 50-kW e-beam heated wind tunnel.

Gas for the tunnel was supplied by twelve 2,400-psi cylinders of breathing air connected to a manifold system that provided a flow rate of 0.5 kg/sec and nominal plenum pressure of 1,250 psi (85 atms). The nozzle flow was heated by passing it through a 17-foot-long electrically heated stainless steel pipe placed between the gas manifold and the plenum. A nominal plenum temperature of 400 K was maintained for the e-beam experiment. The plenum conditions were maintained as close as possible to the above values for all tunnel runs so that results from different diagnostics could be compared. The nozzle was constructed of Al with a throat diameter of 6 mm and an exit diameter of 20 mm. The nozzle flow was exhausted into the ambient laboratory air at local atmospheric pressure (12.4 psi). The e-beam was introduced into the nozzle through the exit of the nozzle via a series of beam steering magnets. A cone and apertures were placed at a distance of approximately 4 cm from the nozzle exit to stagnate the flow, thereby decreasing the pressure on the 5-mil Be foil used to couple the e-beam out of the accelerator. To reduce gas density in the path of the e-beam, gaps in the steering magnets allowed a radial outflow of gas ahead of the foil. Magnets were placed along the length of the nozzle to focus the e-beam within the nozzle.

A 900-keV e-beam is created in the HAWK accelerator with a variable current and duration (nominally 50 to 500 mA and 50 to 2,000 μ sec). Electron beams normally scatter severely in air (with typically a 45-degree cone half-angle at this voltage). Therefore, to transport the beam roughly one-half meter into the nozzle, the beam was captured onto a strong axial magnetic field. The beam also had to be guided from the vacuum region of the accelerator into the room air by passing the beam through a 5-mil (0.0127-cm) Be foil window. The beam was easily injected onto the magnetic field lines. However, on several occasions, the magnetic field focused the beam onto the foil, causing the beam to burn a hole through the foil. A fast closing valve protected the Hawk hot cathode from the incoming rush of air.

A beam-diagnostics system was developed that allowed photos of the beam cross-section to be taken at various axial locations without having to shut down the accelerator to enter the HAWK cell. It consists of a 10-mil Mylar™ disk attached to a moveable tube in the nozzle magnets and a digital camera remotely controlled by a computer. A string and an RS-232 cable over the laboratory barrier wall allowed manual remote control. This greatly increased the rate at which data could be acquired.

The magnetic field strength versus position was measured with a low, steady current, and scaled up to the baseline current. (Measurements at 1 to 3 T during the 1-second pulse for normal operation are difficult.) The field agreed well with the design calculations.

Beam propagation experiments and nozzle magnet alignment were initially performed without the nozzle present inside the magnets to allow better beam diagnostics.

Initially there was some difficulty propagating the beam into the nozzle magnets, but after carefully adjusting the alignment, a 47-kW, 3-msec, 900-kV e-beam was propagated to the beam-entrance of the nozzle magnets (that is, 50 cm from where the throat of the nozzle would be located). The Gaussian beam diameter between e^{-1} points was 1.6 cm at that location, and no beam instabilities or diameter increases were observed as the duration was increased from 0.1 msec to 3 msec. The beam then propagated easily through the 5-cm-diameter aperture of the nozzle magnets. The beam diameter at 28 cm from the throat location was 1.4 cm.

Figure 7-19 shows the strength of the magnetic field for the nominal conditions for this transport. The total field with all magnets powered is indicated as well as the contribution due to each individual magnet. The magnets used in this configuration were the nozzle magnets (magnets 1 through 4) and steering magnets 6 through 9 (see Fig. 7-15). Magnets 3 and 4 were wired in series to reduce their strength because they had a deflecting effect on the beam when run at full power. The “steering magnets” were no longer bent into an arc but were still referred to as steering magnets. The surface of the last nozzle magnet is at 50 cm from the throat, the last steering magnet is at 69 cm, and the foil is at 68.5 cm.

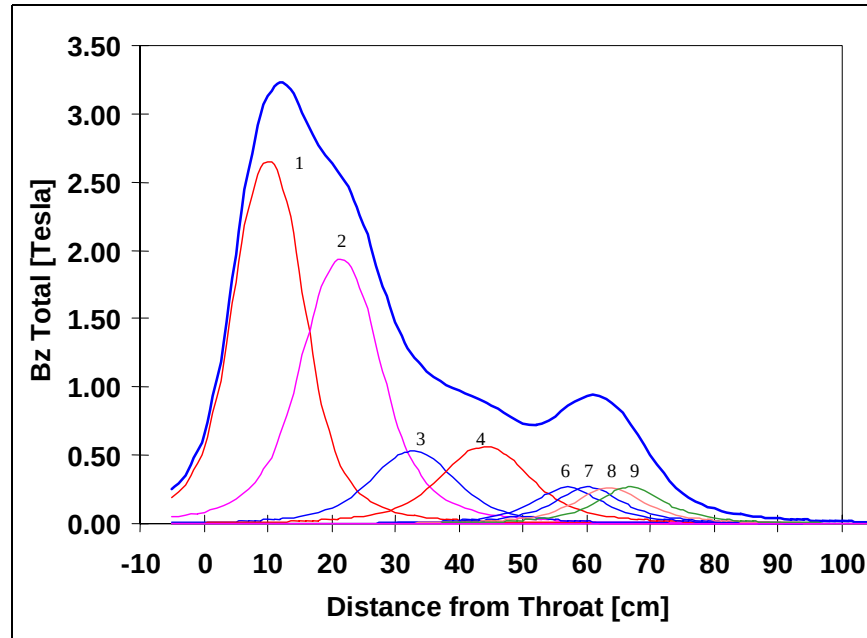


Figure 7-19. Magnetic field configuration for beam transport studies.

The beam was predicted to grow after passing through the 5-mil Be foil and then to be focused by the increasing magnetic field. Figure 7-20 shows the beam profile at 0, 20, and 50 cm from the foil for some shorter-duration shots (0.1 msec). These images were taken with a digital camera (Kodak™ DC-120) as the beam hit a scintillator (10-mil Mylar™). As predicted, the beam expanded after passing through the foil and then contracted as it followed the converging field lines.

The last photo is deep inside the nozzle magnets and corresponds to 12 cm from the nozzle throat. However, the nozzle was not inserted for this test series so that the scintillator images could be obtained. Additionally, there were no apertures between the nozzle exit and the foil. This data shows the ability of a strong converging axial magnetic field to confine and focus the beam and overcome the scattering as the beam travels through air.

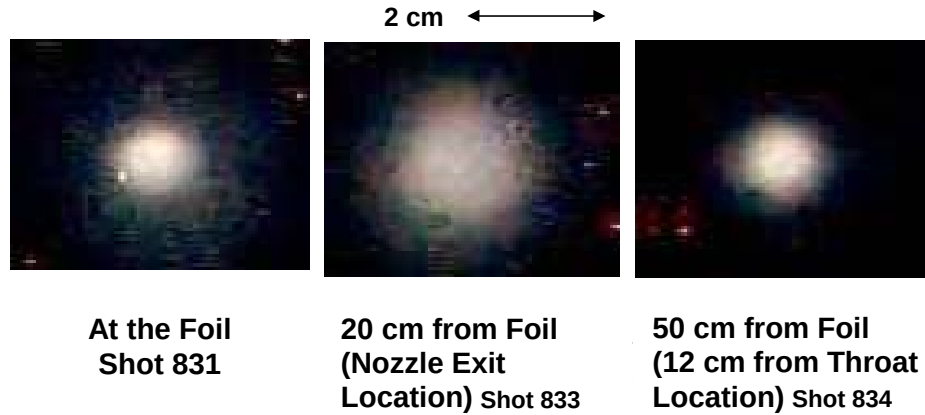


Figure 7-20. Beam profiles at three locations with all magnets activated (not final configuration).

A deflection cone and an aperture were inserted into the steering magnet array to deflect some of the air flow from the nozzle. This was necessary to protect the 5-mil foil from overpressure and breakage. Figure 7-21 shows the final configuration of the magnets, cone, aperture, and Be foil. The magnetic field strength for Data Sets 1 and 2 of the experiment is also shown. Magnets 1 and 2 were not used for many of the experiments because they deflected the beam away from the Be foil aperture. This limitation was not overcome until the last day of the experiment (as will be discussed later). Without the added strength of magnets 1 and 2, the beam was not as well focused as in the previously described studies. However, it was sufficiently focused to obtain data on beam-flow interactions, so the experiment was performed.

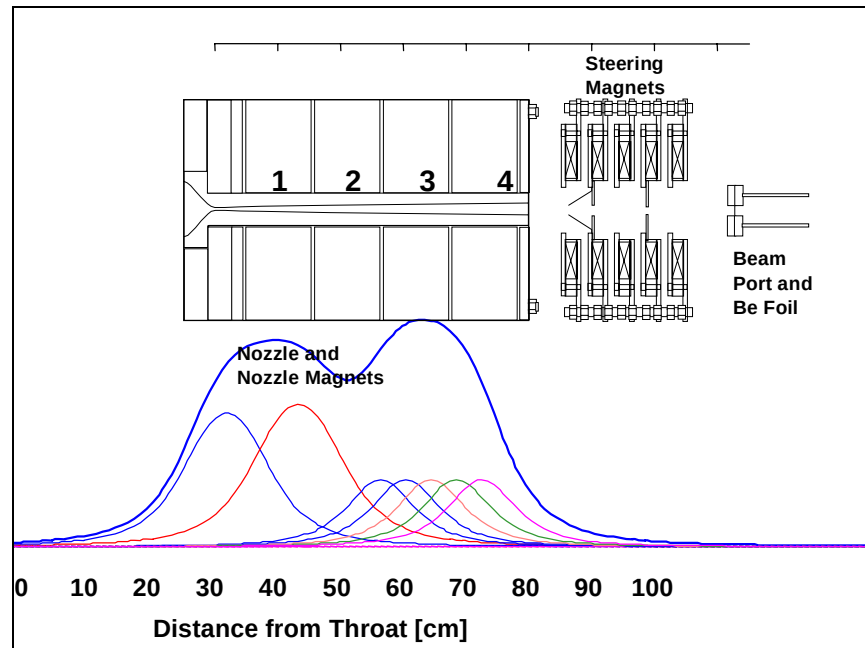


Figure 7-21. Configuration and magnet field strength for Data Sets 1 and 2.

The small pressure transducers and the thermocouples embedded in the nozzle suffered from excessive noise from Bremsstrahlung x-rays generated by the e-beam, so optical diagnostics were used for essentially all of the experiment. Figure 7-22 shows the diagnostics in operation. The green is scattered laser light from the diagnostic beams. The blue entering the magnets is the e-beam. The e-beam was activated for 2 msec in this photo. Figure 7-23 shows a closeup of the e-beam alone as it is focused by the converging magnetic field.

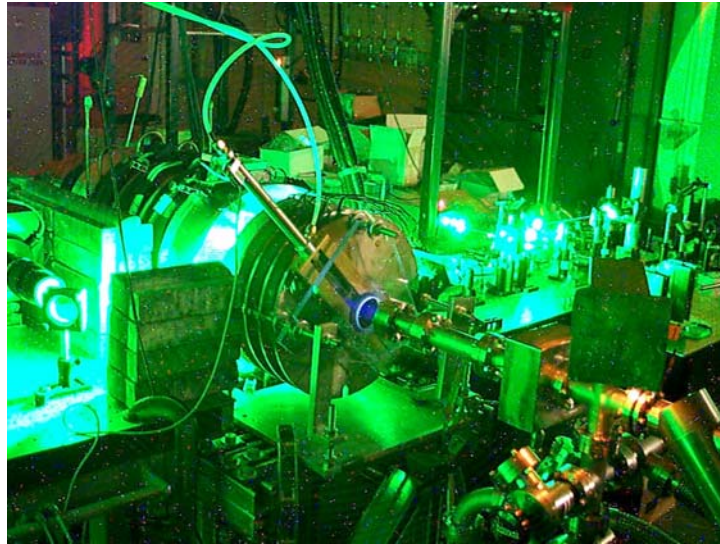


Figure 7-22. Laser diagnostics.

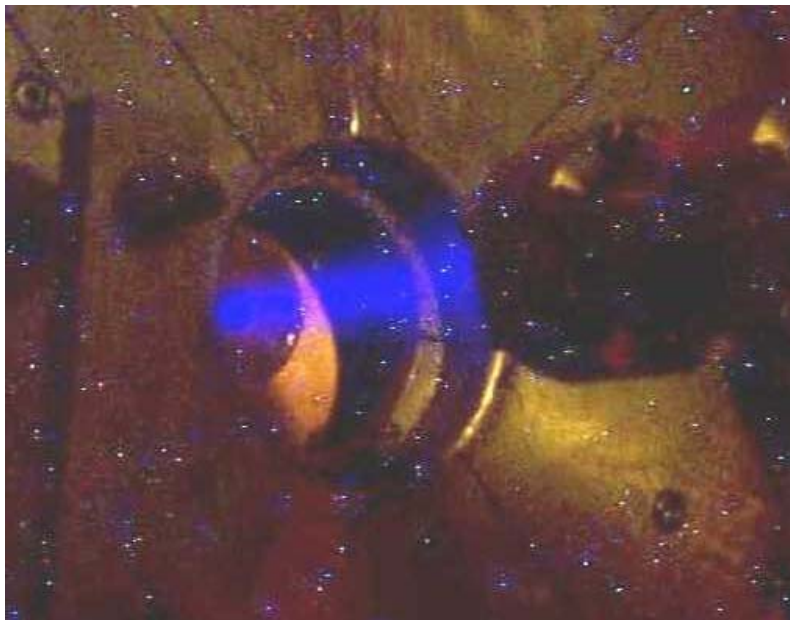


Figure 7-23. E-beam being focused by the converging magnetic field.

7.8.3 Results

7.8.3.1 Experimental Data Summary

Approximately 59 successful data tests were obtained with simultaneous air flow through the nozzle, e-beam energy addition, and data collection from diagnostics. A summary of the data obtained is shown in Table 7-1. The column labeled as “Nzl Pwr” lists the calculated power going into the 2-cm aperture of the nozzle exit; it is based on the measured beam current in that diameter with nonflowing air. Data Set 1 represents the bulk of the data collected. Data Set 2 was taken with Rayleigh scattering as a diagnostic to examine exit flow density. The results from Data Set 2 were not analyzed in detail but are noted here for future reference.

The last three tests (Data Set 3) were made with a better-aligned system, a smaller diameter beam, and at some additional risk to the foil. Mu metal was wrapped around the nozzle exit to exclude magnetic fields from the beam line power to its exit from the HAWK accelerator. This reduced the amount of beam offset induced when the additional nozzle magnets were activated which in turn, resulted in a tighter beam. The total e-beam power at the nozzle exit (beam entrance, air exit) within a 2-cm diameter was 92 kW, and it is estimated that a larger fraction of this power was deposited into the air than in Data Sets 1 and 2 because of the smaller beam.

7.8.3.2 Experimental Results

Flow diagnostics were performed with e-beam power values ranging from 23 to 110 kW into the nozzle. These values are approximate at the nozzle exit because the power could not be measured during a test. Most of the flow measurements were performed at a nozzle exit e-beam power of approximately 50 kW. Because the e-beam was not tightly focused; much of this energy was deposited into the nozzle wall, and only a fraction was deposited into the nozzle air as will be discussed shortly. Eight runs with this focusing were performed at the 100-kW power level as part of Data Set 2. A final set of three measurements were performed with the e-beam focused more tightly into the nozzle than in previous tests (Data Set 3). Significantly more power was absorbed into the flow for these tests, which was evidenced by a large change in Mach number from 3.9 to approximately 2.3.

Thirty-two temporally resolved shadowgraph measurements of Mach number for the heated flow were made with the fast framing camera. Single test shot measurements of velocity and static temperature at the nozzle exit were also used to determine Mach number for different times during the e-beam duration. These measurements were made at the center of the nozzle at a distance of approximately 3 mm from the nozzle exit plane. Figure 7-24 is a plot of Mach number with time for both the shadowgraph and velocity temperature measurements for a typical Data Set 1 run of approximately 800 μ sec.

The Mach number decreases from Mach 3.9 to 3.2, and a steady state appears to have been reached within 400 to 500 μ sec. This also indicates that at least part of the e-beam energy is absorbed and collisionally relaxed on a timescale at least as fast as the transit time of the flow in the nozzle.

Table 7-1. Energy-Addition Tests With Blowdown and Data Acquisition. (Only Data Sets 1 and 3 have been analyzed in detail.)

Shot	Date	t (ms)	Diagnostics	Nzl Pwr (kW)		Shot	Date	t (ms)	Diagnostics	Nzl Pwr (kW)
Data Set 1						Data Set 1 (Cont.)				
1070	8/11	2.5	Shadowgraph	23		1168	8/26	0.5	LITA & Spark	49
1071	8/11	1.0	Shadowgraph	52		1169	8/26	0.5	LITA & Spark	46
1073	8/11	1.0	Shadowgraph	51		1170	8/26	0.5	LITA & Spark	51
1076	8/12	1.0	Shadowgraph	53		1171	8/26	0.5	LITA & Spark	47
1081	8/13	0.5	Shadowgraph	53		1172	8/26	0.5	LITA & Spark	49
1082	8/13	0.5	Shadowgraph	53		1173	8/26	0.5	LITA & Spark	47
1083	8/13	0.5	Shadowgraph	47		1174	8/26	0.5	LITA & Spark	48
1084	8/13	0.5	Shadowgraph	49		1175	8/26	0.5	LITA & Spark	47
1089	8/13	0.5	Shadowgraph	51		1176	8/26	0.5	LITA & Spark	51
1090	8/13	0.8	Shadowgraph	48		1177	8/26	0.5	LITA & Spark	47
1091	8/13	0.8	Shadowgraph	48		1178	8/26	0.5	LITA & Spark	46
1146	8/25	0.5	LITA	49		1179	8/26	0.5	LITA & Spark	48
1147	8/25	0.5	LITA	47						
1149	8/25	0.5	LITA	46		Data Set 2				
1150	8/25	0.5	LITA	49		1181	8/27	0.5	LITA & Rayleigh	49
1151	8/25	0.5	LITA	48		1182	8/27	0.5	LITA & Rayleigh	49
1152	8/25	0.5	LITA	45		1183	8/27	0.5	LITA & Rayleigh	50
1153	8/25	0.5	LITA	47		1184	8/27	0.5	LITA & Rayleigh	49
1154	8/25	0.5	LITA	47		1185	8/27	0.5	LITA & Rayleigh	45
1155	8/25	0.5	LITA	48		1188	8/27	0.2	LITA & Rayleigh	117
1156	8/25	0.5	LITA & Spark	51		1189	8/27	0.2	LITA & Rayleigh	110
1158	8/25	0.5	LITA & Spark	47		1190	8/27	0.2	LITA & Rayleigh	113
1159	8/25	0.5	LITA & Spark	45		1191	8/27	0.2	LITA & Rayleigh	117
1160	8/25	0.5	LITA & Spark	45		1192	8/27	0.4	LITA & Rayleigh	123
1161	8/25	0.5	LITA & Spark	46		1193	8/27	0.4	LITA & Rayleigh	107
1162	8/25	0.5	LITA & Spark	49		1194	8/27	0.4	LITA & Rayleigh	120
1163	8/25	0.5	LITA & Spark	45		1195	8/27	0.4	LITA & Rayleigh	110
1164	8/25	0.5	LITA & Spark	48						
1165	8/26	0.5	LITA & Spark	45		Data Set 3				
1166	8/26	0.5	LITA & Spark	45		1237	8/28	0.5	Shadowgraph	92
1167	8/26	0.5	LITA & Spark	52		1238	8/28	0.5	Shadowgraph	92
1168	8/26	0.5	LITA & Spark	49		1239	8/28	0.8	Shadowgraph	90

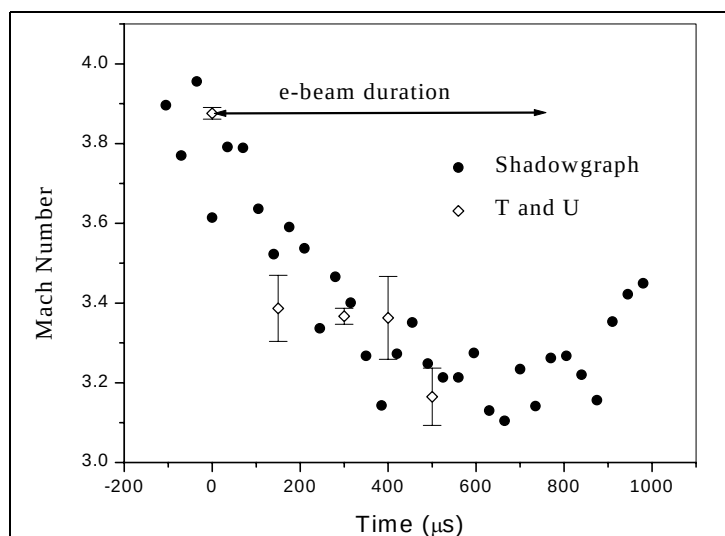


Figure 7-24. Comparison of Mach number calculated from Mach angle and average values calculated from velocity and temperature measured at nozzle exit.

Figure 7-25 shows Mach number plot calculated from each of the 32 shadowgraph images for run 1239 of Data Set 3. For this power level of 90 kW into the nozzle, the Mach number drops from 3.9 to an approximate minimum of 2.3, indicating significantly more energy coupling into the flow than in Data Set 1.

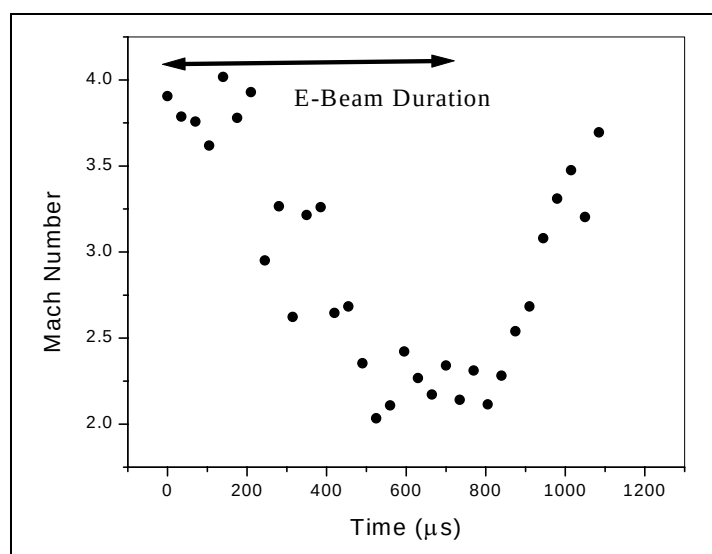


Figure 7-25. Change in Mach number calculated from 32 shadowgraph images for 90-kW e-beam into the air and nozzle wall.

The total enthalpy of the unheated flow was calculated from measurements of plenum temperature. The total enthalpy at the nozzle exit during heating was calculated from static temperature and velocity measured at a single point at the nozzle exit. An average change in total enthalpy of 7 percent was calculated from measurements made during the 50-kW experiments (Data Set 1). This corresponds to an average change in total enthalpy of 20 kJ/kg, or 10 kW of absorbed power measured on the centerline of the flow for a flow rate of 0.5 kg/sec. Figure 7-26 is a plot of power absorbed at different delays during the energy addition process. Each data point represents a single set of measurements for a separate run of the wind tunnel and e-beam facility. The large uncertainties for each run are primarily due to uncertainties in the optical measurements of temperature (5 percent) and velocity (2 percent). The nonuniform radical distribution of the e-beam causes more energy to be deposited along the centerline than at the edges of the flow. This contour leads to further uncertainty in the interpretation of the data.

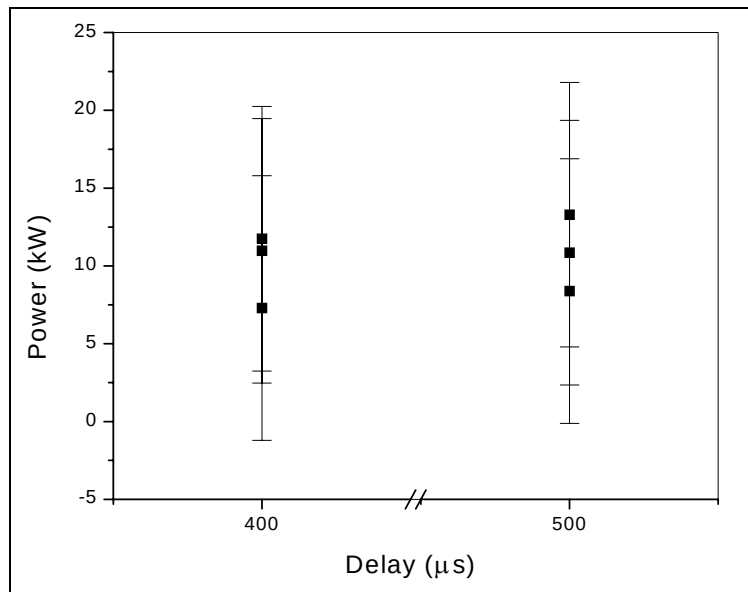


Figure 7-26. Power absorbed for different delays after the e-beam is fired into nozzle flow. Power is calculated from the total enthalpy change determined from the velocity and temperature measurements and the mass flux for each run.

An upper limit estimate of the change in total enthalpy and power absorbed can be determined from the Mach number measurements under the assumption that the velocity does not change significantly during energy addition. For the final test, a minimum Mach number of 2.3 was measured, which corresponds to an estimated temperature of 262 K for a velocity of 750 m/sec (note: only Schlieren measurements were made during this run). This corresponds to a change in total enthalpy of approximately 150 kJ/kg and 40 kW of absorbed power. The power is calculated by noting on the shadowgraphs that e-beam power was localized in the center of the flow and was

heating only approximately half the flow. Due to the uncertainty in the heating profile a 30 percent error is ascribed to this measurement.

7.8.4 Electron Beam Energy Addition Modeling and Comparison to Experiments

The conditions for the three data sets of the energy addition experiments were analyzed to better estimate the amount of power being deposited into the flowing air. It was not possible to monitor the energy deposition amount and radial profile directly while blowdown was occurring. However, the total current in the beam port just before the beam passes through the Be foil was monitored and recorded for each test, thereby giving a single scaling parameter for each test. The current reproducibility was typically approximately ± 5 percent. In addition, the current was measured in stagnant air within a 2-cm diameter at the nozzle exit. This measurement was compared with code predictions. From this comparison, the code was used to extrapolate to blowdown conditions (for which the air was denser). Figure 7-21 shows the magnetic field used in Data Set 1 (and 2).

Figure 7-27 shows the predicted electron trajectories (moving from right to left in the figure) for Data Sets 1 and 2 as determined by the CYLTRAN module of the ITS code. Note that the beam starts to converge as it enters the solenoidal field. It is important to position the Be exit foil so that the beam is still large enough when it passes through the foil that it does not heat too much. When the beam passes through the foil, it scatters considerably as seen by the large angle of divergence shortly thereafter. This divergence quickly maps into a helical path due to the axial magnetic field. This path appears as an oscillation in the r-z plot.

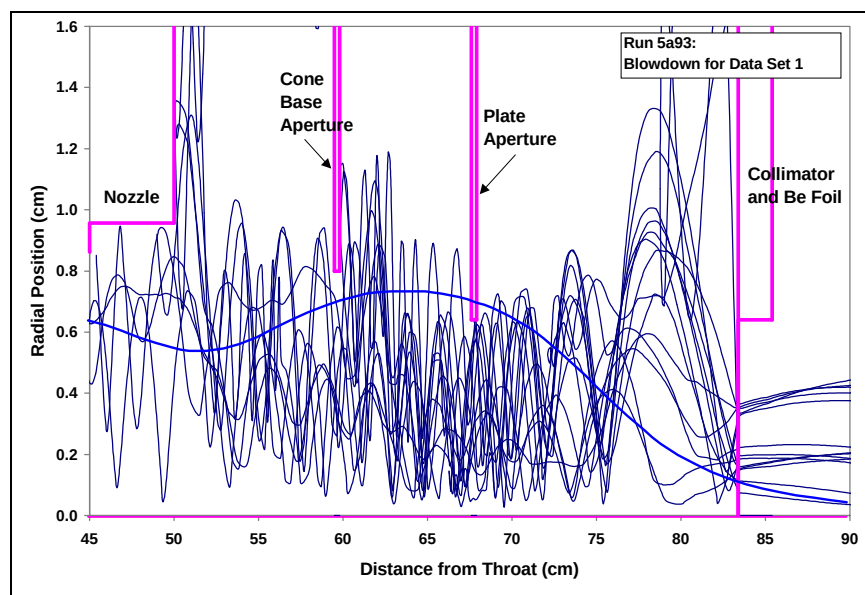


Figure 7-27. Calculated electron trajectories for Data Set 1; thick curve is B-field strength.

The amplitude of the radial oscillations reduces quickly because the magnetic field increases as the beam approaches the nozzle. This focusing is sufficient to allow the beam to pass through the apertures placed between the nozzle and the foil to protect the foil from the nozzle exhaust. (Only two apertures are modeled since the aperture at the top of the cone is the same size as the one at the base of the cone and is very near to it.) Unfortunately, after passing through the cone aperture, the beam begins to diverge because of accumulated scattering events and diverging magnetic field lines. Nonetheless, by the time the beam gets to the nozzle exit, most of it is still smaller than the 2-cm opening of the nozzle exit. The magnetic field lines then converge again, and the beam refocuses a bit.

Calculations were made using many thousands of trajectories, and the energy deposited in the air and hardware was summed. Figure 7-28 shows the calculated energy deposition. The beam current entering the aperture surrounding the Be foil was set to the measured amount (140 mA). The gas density in the nozzle was modeled based on inputs from Princeton University's wind tunnel code. However, there was some uncertainty concerning the gas density downstream from the nozzle in the e-beam path between the foil and the nozzle exit. The air exits the tunnel pressure matched but at a density close to three times that of the atmosphere due to the low temperature. That air is quickly heated by the e-beam as it mixes with room air and passes through the orifices. Therefore, as an estimate, the gas density in this region was set at 0.001 g/cm^3 , close to the density of the atmospheric air in Albuquerque, New Mexico.

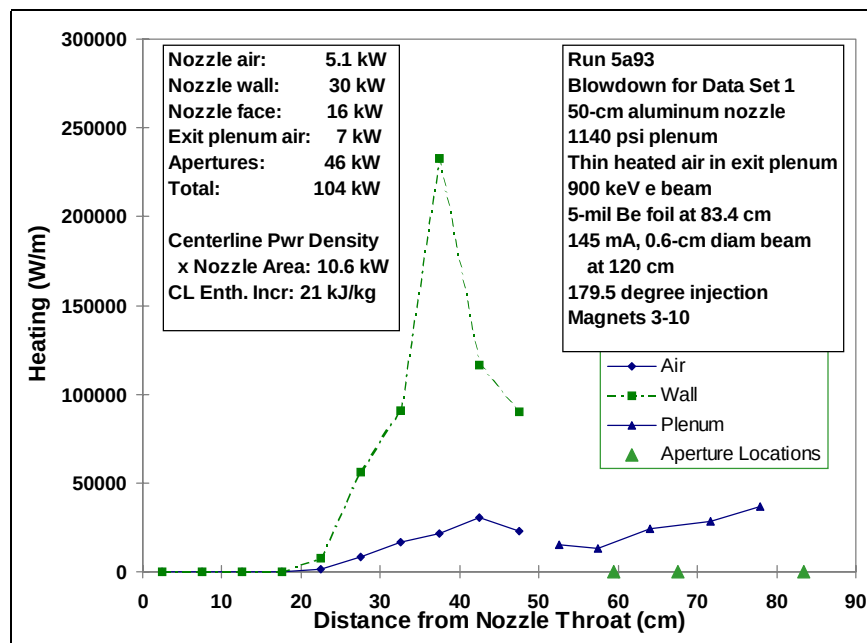


Figure 7-28. Code predictions of power distribution for flowing air for Data Set 1.

The amount of power deposited in various locations was then summed and is listed in the figure. With these conditions, the amount of power calculated to be deposited in the gas within the nozzle is 5 kW. In addition, the radial deposition profile is predicted to be approximately

Gaussian with a Gaussian radius to the e^{-1} point equal to 0.68 times the local radius of the nozzle wall. Figure 7-29 shows this distribution normalized to the local centerline power density and local nozzle radius. Integrating under this curve, the peak to average power for the nozzle at any axial location was found to be approximately 2:1. Therefore, if the enthalpy increase in the nozzle flow is measured on the centerline and this enthalpy increase is multiplied by the total mass flow of the nozzle, the resulting number is predicted to be 10 kW, although the actual total energy deposited in the gas is 5 kW. That is, the centerline enthalpy increase is predicted to be 20 kJ/kg, although the total average enthalpy increase across the flow is predicted to be 10 kJ/kg. The predicted centerline enthalpy increase agrees well with the values measured in Data Set 1.

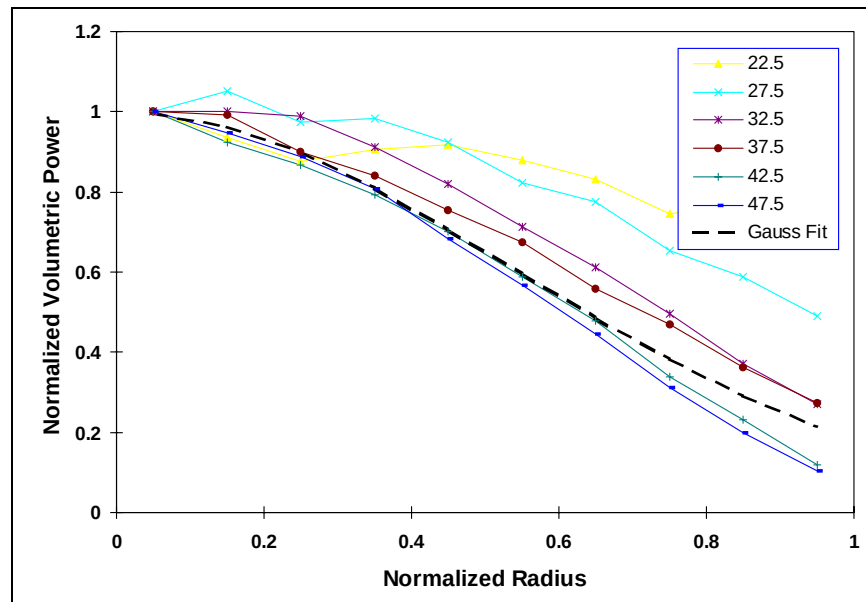


Figure 7-29. Radial power deposition profiles for the Data Set 1 calculations, normalized to the local centerline power and nozzle radius. (Curves for various distances downstream of throat, cm.)

A similar set of analyses was performed for Data Set 3. (Data Set 2 was identical in setup to Data Set 1, except for a higher power level, which scales linearly, however, Mach number measurements were not made since Rayleigh imaging required the use of the same laser source.) Figure 7-30 shows the much-improved magnetic field, and Figure 7-31 shows results of the blowdown calculations. The code predicts that 115 kW would be absorbed in the nozzle gas and wall, and the measurement of beam current at the nozzle exit shows 120 kW. The code then predicts that 57 kW is absorbed in the blowdown air. Again, there is a radial distribution, which is near Gaussian, and in this case, the Gaussian radius to the e^{-1} point is approximately 0.38 times the local nozzle radius (as shown in Figure 7-32).

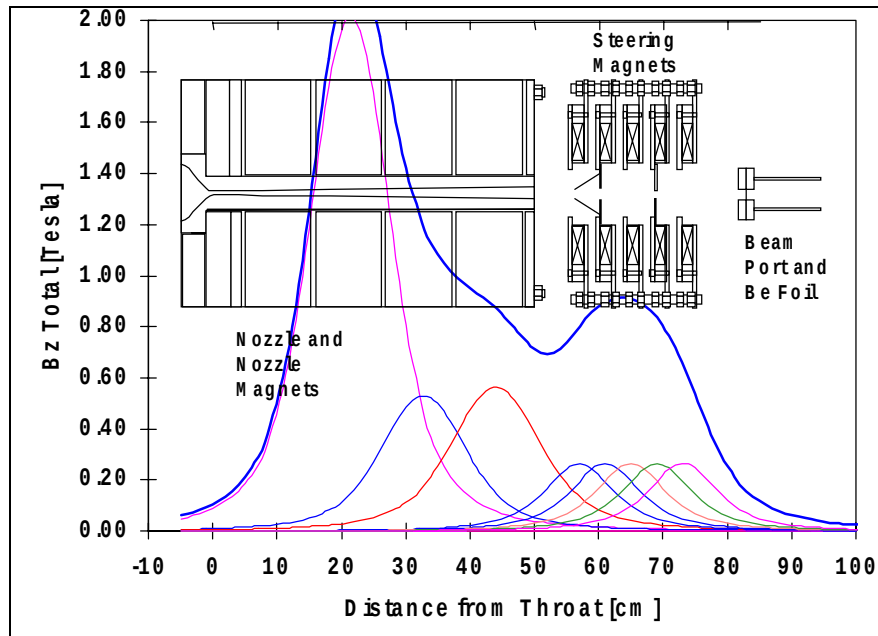


Figure 7-30. Magnetic field strength for Data Set 3.

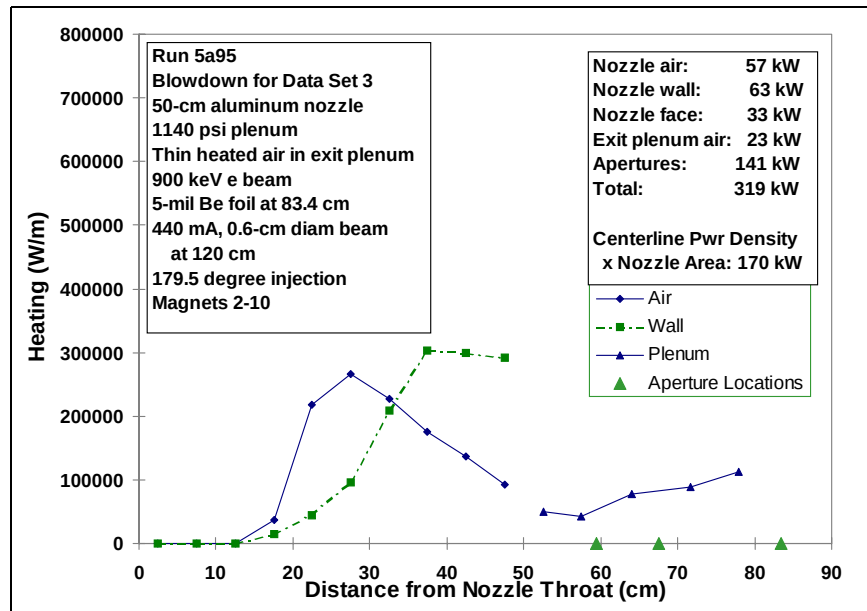


Figure 7-31. Code predictions of power distribution for flowing air for Data Set 3.

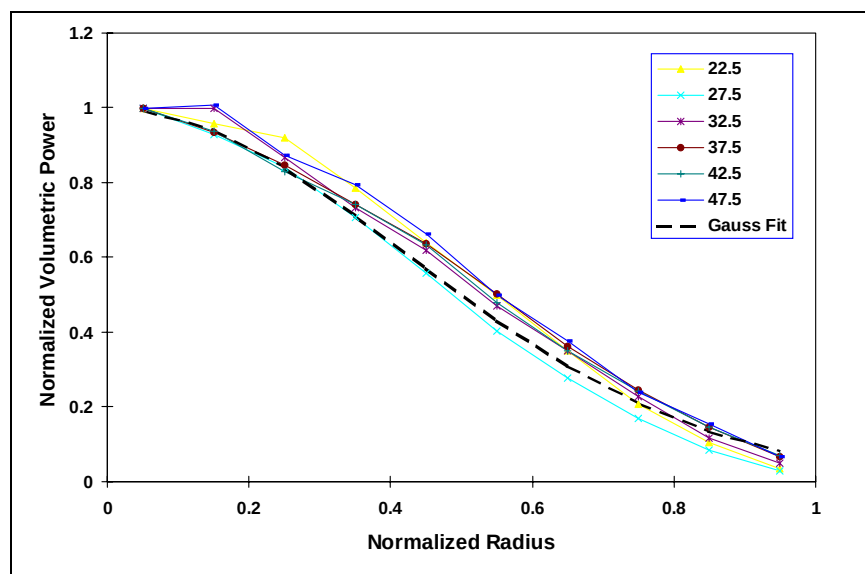


Figure 7-32. Radial power deposition profiles for the Data Set 3 calculations, normalized to the local centerline power and nozzle radius. (Curves for various distances downstream of throat, cm.)

7.8.5 Conclusions

Energy addition by e-beam heating has been successfully demonstrated using a 1-MeV e-beam; the changes in Mach number (0.7), total enthalpy (20 kJ/kg) and power (10 kW) absorbed were measured on the center line of the nozzle flow for 50 kW of e-beam power entering the air and nozzle wall combined. For the final test runs, an increased e-beam power (100 kW) and tighter focusing produced a change in Mach number from 3.9 to a minimum of 2.3. From this Mach number change, an estimated power of 40 kW was absorbed in a localized region of the flow. Time-resolved shadowgraph images show a steady transition from the unheated flow to the e-beam heated flow, thereby demonstrating that on the time scale of these experiments, a stable flow with a higher total enthalpy was achieved with heat addition from an e-beam.

The power absorbed by the flow was modeled for the 50-kW tests. However, the change in total enthalpy was small compared to total enthalpy of the unheated flow, and a large uncertainty exists in both the total enthalpy and power absorbed in the flow. The amount of power deposited into the walls of the nozzle could not be measured in this experiment, and thus a total power/energy partition within the experimental system could not be determined. If all the energy can be coupled into the nozzle air flow by strong focusing, the optical measurements of absorbed power used in this experiment could, in principle, be used to determine the degree to which thermalization has occurred.

The optical measurements were primarily successful in measuring flow properties because they could be carried out remotely from the e-beam and could thus be shielded effectively against the x-rays. In the future, experiments that address flow quality, thermalization, and long term flow stability will give a more complete picture of e-beam heating of a supersonic flow.

The experiment demonstrated the successful injection of a high-power relativistic e-beam into an axial magnetic field and subsequent transport of the beam through dense air with focusing as the beam traveled. No apparent instabilities were observed; however, some residual difficulties in initial beam injection and centering were encountered. It is planned that these will be corrected in future experiments.

The conclusions from the modeling are:

- The ITS code models the beam behavior and energy deposition well, based on the calibration tests and beam size photos; and
- The power deposited in the flowing air in the nozzle was approximately 20 percent of the beam for Data Sets 1 and 2, and approximately 45 percent of the beam for Data Set 3, where better beam focusing was achieved.
- The centerline power deposition was greater than the radial average power deposition by a factor of 2, 2, and 3 for Data Sets 1, 2, and 3, respectively. Because of this radial dependence, care must be taken in interpreting the experimental results.

7.9 PLANNING FOR 100-KW ELECTRON BEAM ENERGY ADDITION EXPERIMENTS

The 30-kW e-beam energy addition experiment demonstrated deposition of significant e-beam energy into a supersonic gas for the first time. The 100-kW deposition experiment is a follow-on experiment. Because of the short timeline available for the 100-kW experiment once FY99 funding was received, some preparatory work was performed under the e-beam model development task.

The primary objectives of the 100-kW experiment are:

- Demonstrate deposition at a higher power level and enthalpy increase than accomplished previously.
- Demonstrate strong deposition in a central core of flowing air, much lower deposition in the surrounding annulus of flowing air, and negligible deposition in the nozzle wall.
- Demonstrate deposition for at least three heating rise times to determine whether the flow is stable.
- Measure the gas chemistry changes caused by e-beam deposition in the flowing air.
- Validate e-beam energy addition and flow response models.
- Obtain the experience base needed for higher power experiments and to determine the feasibility and cost of a medium-scale hypersonic wind tunnel facility.

The upcoming 100-kW energy addition experiment was modeled with the expected magnetic fields and beam and using the same nozzle as used in the 30-kW experiments. The gas density was the same as the 30-kW experiment in these preliminary assessments. To increase the total amount of power and beam duration that could pass through the foil, the foil was increased from a 1.3-cm diameter to 2.54-cm diameter, and the thickness was increased from 0.0127 cm (5 mils) to 0.0254 cm (10 mils). The beam was increased proportionately to spread its energy over a wider area. This also results in a more uniform energy deposition radially inside the blowdown nozzle. The effect of the Mu-metal around the Hawk beam port was modeled explicitly; seemingly allowing easier injection of the beam into the magnetic field. The plenum apertures also were increased slightly in diameter, and the magnets between the nozzle and the beam port were stretched out slightly to provide a higher field at the accelerator exit foil.

Figure 7-33 shows the resulting energy deposition as calculated by the ITS beam deposition code. For a nominal 107-kW beam deposited in the blowdown air within the nozzle, only approximately 12 kW is deposited in the nozzle wall. This should be low enough to determine the energy partition from the beam into the translational state of the gas. Looking at the energy deposition rate in the foil determined by the code, the beam duration was estimated to be up to 2 to 3 msec. With approximately 770 m/sec in a 0.5-m-long nozzle, steady state is expected to be reached in approximately 0.65 msec. Therefore, this duration should be sufficient to achieve three rise times of the flow response to the beam. If not, the power can be slightly reduced to study stability for longer durations.

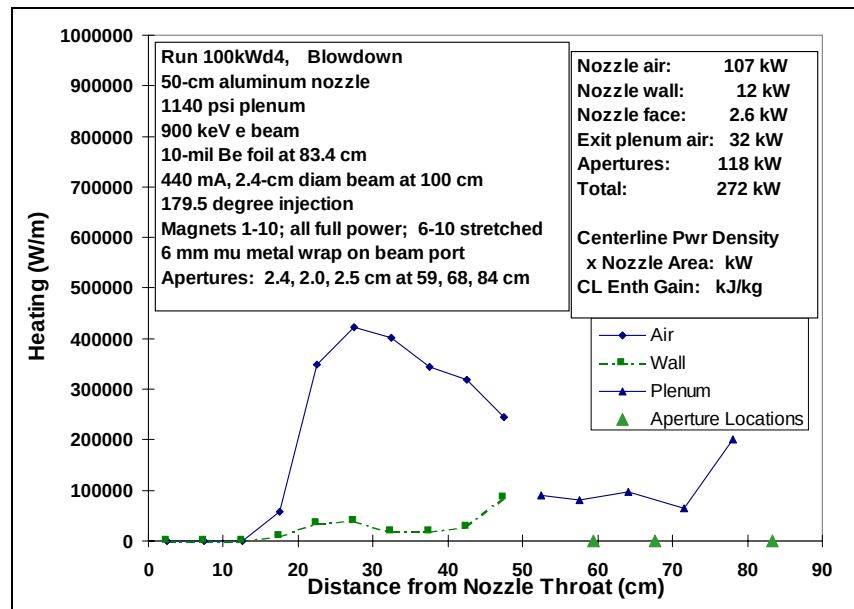


Figure 7-33. Predicted power deposition for 100-kW experiment with larger exit foil.

Figure 7-34 shows the predicted normalized radial power deposition in the nozzle at various axial locations (indicated in the legend as centimeters from the throat).

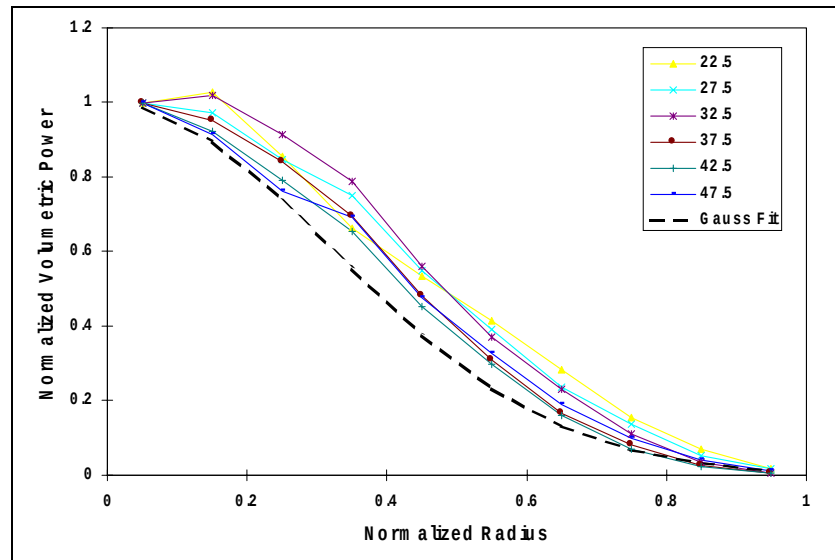


Figure 7-34. Predicted normalized power radial distribution at various axial locations in the nozzle. (Curves for various distances downstream of throat, cm.)

Much of the existing experimental equipment used for the first e-beam experiment will be also used for the 100-kW experiment. The gas manifold system is being upgraded to supply a higher mass flow rate to the nozzle, and the beam steering and focusing magnet configuration is being changed to shape and center the e-beam so that only a small amount of the input power is lost to the nozzle walls.

7.10 CONCLUSIONS

Work conducted over this past year on e-beam energy addition, combined with prior work performed on laser energy addition, indicates that thermal energy can be directly added to the supersonic region of an expanding air flow in a controllable and predictable manner. The major steps that have been made with regard to each of the energy addition processes are summarized here.

7.10.1 Down Selection from Microwave

Preliminary studies conducted both at Princeton and elsewhere indicate that energy addition by microwave must overcome at least three major technological hurdles in order to be viable. These include 1) the absence of a compelling energy coupling mechanism by which microwave energy can be deposited into air, 2) complexities associated with coupling the microwave through either low pressure air or walls and boundary layers into the high pressure flow, and 3) issues associated with the development of shorter wavelength sources that can penetrate into the small diameter, high-pressure region where the energy must be deposited. These technological concerns, coupled with funding limitations, has led to the recommendation that microwave research not be pursued at this time.

7.10.2 Laser Energy Addition

The 10-kW CO₂ laser energy addition test that was conducted at the LHMEF Facility was the first demonstration of controlled laser energy addition to a supersonic flow. The data taken during this test clearly indicates that laser energy addition is a viable method to increase the enthalpy in a stable, repeatable, and predictable manner. Tests were run with two nozzle configurations over time intervals as long as 5 seconds. Shadowgraph movies taken both with and without energy addition show stable flow structure and clear changes in shock angle, corresponding to the absorption of approximately 80 percent of the laser power into the flow. These experiments were conducted using a CO₂ laser operating at 10.6 μm , and the energy was coupled into the air through absorption into trace quantities (250 ppm) of SF₆ that was seeded into N₂.

7.10.3 Electron Beam Energy Addition

Experiments conducted this year for the first time show that e-beams can be used for controllable energy addition into supersonic air. This was demonstrated using a 0.9-MeV e-beam at power levels ranging from 23 to 123 kW. Changes in Mach number, total enthalpy, and power absorbed were measured on the centerline of the nozzle flow. Absorbed power was measured to be 10 kW for a 50-kW e-beam in the initial experiments and 40 kW for a 90-kW e-beam in the final experiments where magnetic focusing was improved. Time-resolved shadowgraph images show a steady transition from the unheated flow to the e-beam heated flow, thereby demonstrating that, on the time scale of these experiments, no instabilities were observed and a significant increase in total flow enthalpy was achieved. Some difficulties were encountered in the magnetic focusing of the e-beam deep into the nozzle. Those difficulties led to an uncertainty in the amount of power deposited into the walls of the nozzle, and, therefore, uncertainty in the total power/energy partition between power deposited into the flow and power deposited into the wall. In the initial two data sets, the total enthalpy change was small (7 percent) compared to the total enthalpy of the unheated flow, due in part to the low power (50 kW) and in part to the poor focusing. For the last several runs, a shield was erected to protect the accelerator from magnetic field effects, and better focusing was accomplished. Those few runs were not well instrumented, but Schlieren images indicate a much greater Mach number change, leading to an estimate of four times as much power deposited into the flow.

Attempts to measure flow properties using classical pressure and temperature probes failed due to the background noise associated with x-rays generated by the e-beam. All the measurements therefore relied on the optical measurements, which were primarily successful in measuring flow properties because they could be carried out remotely from the e-beam and could thus be shielded effectively against the x-rays. This suggests that, in the future, more reliance on optical probes will be required to address such issues as flow quality, thermalization, and long-term flow stability. This includes optical-based pressure sensors, which are currently being tested.

The experiments also demonstrated a capability of controlling the profile of the e-beam in order to keep the primary energy addition region centered along the centerline of the flow and avoiding both direct energy deposition at the walls by electrons and significant energy deposition into the flow near the wall. These results suggest that wall heating problems normally associated with hot boundary layers in hypersonic flows could be significantly reduced through careful control of e-

beam contours. Models show that these contours can be made essentially flat topped if high magnetic field strengths are used.

The e-beam experiment demonstrated the successful injection of a high power, relativistic e-beam into an axial magnetic field and subsequent transport of the beam through the dense air with focusing as the beam traveled. No apparent instabilities were observed; however, some residual difficulties in initial beam injection and centering were encountered. A follow-on experiment at the 100- to 150-kW level is planned in which better beam focusing and centering are expected.

7.11 RECOMMENDATIONS FOR FUTURE RESEARCH

The experimental and analytical results achieved to-date suggest there are no technological show-stoppers associated with e-beam or laser energy addition. Major issues remaining are primarily associated with scaling to higher pressures, higher powers, and longer run times. In the experiments conducted to-date, the flow densities have been relatively low compared to the densities required for a full-scale wind tunnel facility. At the higher densities there will be a stronger interaction between the flow and the laser or e-beam. This coupling mechanism must be studied in order to ensure that stable energy addition can be achieved in the regimes necessary for wind tunnel operation. Flow coupling will also have an important impact on wall heating. In the case of lasers, the density gradient across the boundary layer is expected to steer the beam away from the wall. For e-beams, a density gradient arising from the contoured energy deposition may also cause a small amount of beam steering. Other aspects that must be examined include flow quality, and, particularly, in the case of e-beams, the chemical composition. The initial follow-on set of experiments that are to be conducted involve well-controlled e-beam energy addition at the 100- to 150-kW level with diagnostics for the study of beam profile effects, e-beam-induced flow chemistry, and flow field predictability. These experiments will use an expanded optical diagnostics suite including optically based embedded pressure sensors in the nozzle. These measurements are expected to give a much more complete picture of the uniformity and predictability of e-beam heating. A continuation of these experiments and follow-on experiments at the 1-MW level and subsequently 10-to 50-MW levels are recommended.

7.12 REFERENCES

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8.0 MHD RESEARCH AND DEVELOPMENT

8.1 MHD ACCELERATOR CONCEPT DEVELOPMENT

An MHD accelerator is a device for accelerating a gas by applying a Lorentz body force ($\mathbf{J} \times \mathbf{B}$ force) to the flow. The device therefore requires both a static magnetic field applied transverse to the flow direction and a current flow imposed across the duct, normal to the magnetic field. The body force per unit mass (that is, acceleration) is proportional to the product of the current that is applied across the duct and the magnetic field. The primary advantage of MHD compared to other energy addition methods is that it is capable of adding some fraction of the input electrical power directly as push work. This part of the input energy does not increase the entropy, a decisive advantage for this application, whereas the portion added as Joule dissipation does increase entropy. At the same time, MHD performance is constrained by the requirement that the entropy of the gas as it exits the MHD duct be equal to the specified test section entropy. Since entropy increases through the mechanism of Joule dissipation, the latter requirement imposes limits on how much Joule dissipation can be tolerated through the MHD system while still achieving the targeted test section conditions. In the following sections, these and other issues are discussed, and progress towards resolving key technical issues is reported.

It is noted that most of the research results reported below are of an exploratory nature. While the high level MHD requirements are discussed in Section 8.1.1, no specific, quantitative performance goals for the MHD accelerator have been defined to date. An objective of the modeling work reported in Section 8.2 is to develop computational tools to assess the range of performance attainable from MHD accelerator systems. To adequately define the MHD performance objectives, it will be necessary to define the envelope of possible conditions at the inlet of the MHD accelerator. This depends greatly on the design and operation of the upstream energy addition and air supply systems. As is discussed in Section 7, much progress has been made in the past reporting period toward defining this upstream performance envelope. These results will provide guidance towards defining credible MHD performance objectives during the coming year.

8.1.1 Requirements

The flight Mach number, dynamic pressure, and altitude define the total enthalpy and entropy goals to be achieved in the test section of the MSHWT. The MHD augmentation will be constrained by the channel inlet flow enthalpy and entropy, gas conductivity, wall heat transfer limitations, boundary layer growth rates, and the thermodynamic energy addition process used. The inlet enthalpy and entropy conditions are defined by the thermal energy addition processes upstream of the MHD channel. Broadly speaking, the purpose of the MHD research is to define the “best” envelope of MHD augmentation within these constraints and to perform demonstration experiments to validate the proposed design concepts.

To clarify these statements, consider a flow in an MHD channel with velocity $\mathbf{U}$ in the x (streamwise) direction with an imposed magnetic field $\mathbf{B}$ in the z (transverse) direction. We consider a Faraday configuration, for which the streamwise current flow is (ideally) zero. Then the electrical power input per unit volume is $\langle \mathbf{J} \cdot \mathbf{E} \rangle = \langle J_y E_y \rangle$, where the brackets denote a

cross-sectional average. Note that J_y is the current density (amp/cm²), and E_y (V/m) is the electric field in the y direction. The push work is the work done on the gas and is equal to $\langle J_y UB \rangle$. The conversion efficiency η is defined as the ratio of the push work to the total electric power input:

$$\eta = \frac{\langle J_y UB \rangle}{\langle J_y UB + J_y^2 / \sigma \rangle} \quad (8-1)$$

Note that the second term in the denominator is the Joule dissipation. Devices such as arc heaters add energy exclusively by means of Joule dissipation. Such devices cannot supply push work and thus have a conversion efficiency of zero. For MHD to be useful, it will be necessary that the system have a reasonably high conversion efficiency; otherwise the device offers no essential advantage over an arc heater. As discussed by Macheret et al. (Ref. 1), the conversion efficiency is related to the load factor $K = E_y / UB$ by the simple relationship $K = 1/\eta$. In the absence of heat transfer and viscous dissipation, the rate of entropy increase and Joule dissipation are related by the expression:

$$\dot{m} T \frac{dS}{dx} = A(x) J_y^2 / \sigma \quad (8-2)$$

In the last expression, $A(x)$ is the cross-sectional area of the channel at station x . It is also to be noted that the net acceleration, a , is given by:

$$a = \frac{J_y B}{\rho} - \frac{1}{\rho} \frac{dP}{dx} \quad (8-3)$$

The above relationships essentially determine the requirements for the MHD accelerator. To summarize these requirements:

1. Because the entropy in the test section is fixed and because the rate of entropy rise through the MHD channel is proportional to the Joule dissipation, it will be necessary to limit Joule dissipation through the MHD channel. The entropy rate equation above suggests there are two strategies for minimizing this entropy increase: operate either at low transverse current densities or high conductivities. In practice, both strategies must be pursued to achieve the necessary matching of the exit entropy to the test section entropy.
2. Minimization of Joule dissipation implies that the accelerator must work at high conversion efficiencies, η . Since η is the inverse of the load factor, high conversion efficiencies imply that the load factor, $K = E_y / (UB)$, must be close to 1 throughout the MHD channel.
3. The expression for acceleration shows that to achieve high acceleration, it will be desirable to operate at low mass densities. For systems that rely on sustaining nonequilibrium conductivity (such as e-beam-seeded systems), this requirement is essential. A low mass density (substantially below 1 kg/m³ through the MHD accelerator) greatly reduces the recombination and attachment rates, thus enabling some residual level of conductivity to be sustained.

4. For reasons of material integrity and air chemistry, it will be very desirable to maintain low static temperatures through the MHD channel. Previous experimental MHD channels have mostly relied on alkali metal seed to achieve the requisite electrical conductivity. The ionization was accomplished thermally by raising the gas temperature to 2,500 K or higher. This high working temperature has contributed to severe erosion of insulator, electrode, and sidewall materials, thus seriously limiting channel lifetimes. Consequently, the MARIAH II/RDHWT Program team has embarked on a study to evaluate the feasibility of operating the MHD channel at low to moderate temperatures. Since thermal ionization of an alkali metal seed is not feasible in this regime, alternative methods for enhancing the conductivity of the air stream are sought. The most promising method, which is currently being pursued, is seeding by e-beams.

Active cooling in the walls and/or injection of a buffer gas into the boundary layer are options for thermal management of the boundary layer and wall temperatures. Note that operation of the MHD channel at moderate core temperatures does not alone ensure low to moderate wall temperatures. At high Mach numbers, the wall recovery temperatures may be quite high irrespective of core conditions unless active cooling is employed. This is recognized as a potentially serious problem that must be resolved as part of the MARIAH II/RDHWT research effort.

5. Additionally, the MHD accelerator must provide an air stream that has minimal and known levels of dissociated species and contaminants. It must also provide reasonable flow uniformity in the test section.

Historically, requirement (1) has been difficult to achieve. To obtain significant acceleration over a reasonable length, channel designers have relied on moderate B fields and high current densities. Most MHD accelerators designed for continuous operation have also relied on the injection of an alkali metal seed to achieve the necessary conductivity levels. To ionize the seed, the gas must be heated to temperatures of 2,800 K or higher, which raises serious materials issues. The MHD accelerators operated at the Central Aerohydrodynamics Institute (TsAGI) in Russia, for example, were seeded with NaK, a eutectic mixture of sodium and potassium, and were run at current densities in the range 30 to 50 amp/cm², magnetic fields of less than 3 T, and static temperatures approaching 4,000 K. The high current densities resulted in large Joule dissipation, a relatively low conversion efficiency, and very short electrode lifetimes. While substantial velocity increases were demonstrated, the high Joule dissipation and resulting high exit entropy levels appear to preclude this type of MHD channel from being used to achieve the high total enthalpies and modest entropy levels required for advanced engine testing. This point has been discussed in some depth in the literature (see for example, Baughman et al. Ref. 2 and Simmons and Nelson, Ref. 3). For this reason, the MARIAH II Program has recently focused on an alternate method for sustaining the required conductivity through the MHD accelerator. The method relies on injection of high energy electrons into the air stream. The primary advantage is that this method achieves the required conductivity nonthermally through the production of secondary electrons, which eliminates the requirement for an alkali metal seed. This in turn eliminates the need for high temperatures in the MHD channel. A further discussion of the MHD performance requirements is given in Ref. 4.

8.1.2 Research Objectives

Based on the requirements discussed above, a program of R&D has been defined to reduce the technical risks associated with designing and building a novel MHD accelerator of the kind described above. The objectives of the MHD R&D Program can be summarized as follows.

- Formulate analytical models that describe the kinetics of e-beam ionization and recombination. Progress in this technical area is described in Section 8.2.
- Develop computational models capable of simulating MHD accelerators that employ e-beam seeding in air. Such models, when coupled with a fluid dynamics model (either 1-D or 2-D) must be capable of estimating electrical conductivities and MHD body forces, pressure, temperature, total enthalpy, and entropy as a function of distance along the MHD accelerator duct. The 2-D model also must be capable of evaluating the effects of the nonuniform core-heated flow coming into the inlet of the channel. This work is summarized in Section 8.2.
- Conduct experiments to measure the electrical conductivity of air as a function of beam parameters (i.e., beam energy and beam current density) and mass density. These experiments will provide validation of the computational models described in the previous paragraph, especially with respect to the e-beam kinetics and charge exchange mechanisms. Preliminary conductivity measurements were made in a static cell at SNL during the summer of 1999. The results of these experiments are addressed in Section 8.3.
- Develop a credible design concept for an MHD sidewall section that will support e-beam injection. This implies that a scheme must be found for integrating the e-beam injection into the sidewall design. Since it is clear that many separate e-beams will be necessary, the window and beam accelerator designs must be compatible with this requirement. Two alternative schemes are currently under consideration, as discussed in Section 8.4. An experimental demonstration of the sidewall section in a high-speed flow environment is also planned.

Sections 8.2 through 8.4 document the research accomplished during the current reporting period in support of these four major objectives.

8.1.3 Technical Approach

Recent analyses (Refs. 1, 5) have shown that to obtain the best performance of the MARIAH II/RDHWT hypersonic wind tunnel, the MHD accelerator must operate at low temperatures (200–1,500 K) and pressures (approximately 0.1 atm). The low temperature precludes the use of the traditional method of conductivity generation by seeding the hot air with alkali metals. Therefore, cold hypersonic MHD channels must rely on a nonthermal ionization mechanism. Of course, ionization is nonequilibrium in all glow discharges. In this case, electrons receive energy from an electric field, and high electron temperature can be sustained because of the slow electron-molecule energy exchange resulting from large mass difference. With mean electron energy of at least a few electron volts, there is a substantial fraction of high-energy electrons capable of ionizing molecules in collisions. However, there are major obstacles to using this ionization

mechanism in MHD channels. First, to minimize Joule heating and entropy increase in the channel, an effective electric field must be very low (Refs. 1, 5), resulting in electron temperatures below 1 eV. Such electric fields and electron temperatures would not be adequate for the needed ionization of air. Introducing a seed with low ionization energy, and thus combining seeding with nonequilibrium ionization, may seem attractive. However, this approach is very problematic because of the mixing problem and short-circuiting through the boundary layer.

Another problem associated with nonequilibrium ionization is an instability that tends to break an initially uniform cold diffuse plasma into narrow hot arcs. Indeed, if a fluctuation locally increases temperature and reduces density, an increased electron mean free path would allow electrons to gain more energy from the electric field, resulting in higher local electron temperature. This would locally enhance ionization and Joule heating, which would increase temperature even further. Both high gas density and strong magnetic fields tend to restrict electron mobility and heat conduction, thereby preventing local fluctuations of temperature and electron density from dissipating rapidly and thus lowering the instability threshold.

Devising an effective and stable method of generating an adequate nonthermal ionization is the first-order problem in developing hypersonic MHD devices. The approach currently being recommended is to inject high-energy e-beams into the channel along magnetic field lines.

High-energy e-beams are the most efficient ionization sources. For the most efficient transfer of the required ionization energy to an outer-shell electron, the mass of the incident particle should be equal to the electron mass. Therefore, photons and heavy particles (atoms, ions) are much less efficient. Additionally, in a plasma such as that in glow discharges where mean electron energy is a few eV, only a small fraction of the electrons (the high-energy “tail”) would actually do the ionization while most of the energy received from the electric field is spent on excitation of molecular and atomic states as well as heating. In contrast, high-energy beam electrons would collisionally ionize atoms and molecules with very high probability, and secondary electrons would cause additional ionization. Therefore, a cascade of electrons is generated as the beam slows. The net effect is approximately one ionized molecule or atom for every 35 eV lost by the beam. This ionization cost is only 2 to 3 times greater than the ionization energy of air molecules. Thus, devising an effective and stable method of generating an adequate nonthermal ionization is the first-order task.

The basic configuration of a Faraday MHD channel with e-beam ionization is shown in Figs. 8-1 and 8-2.

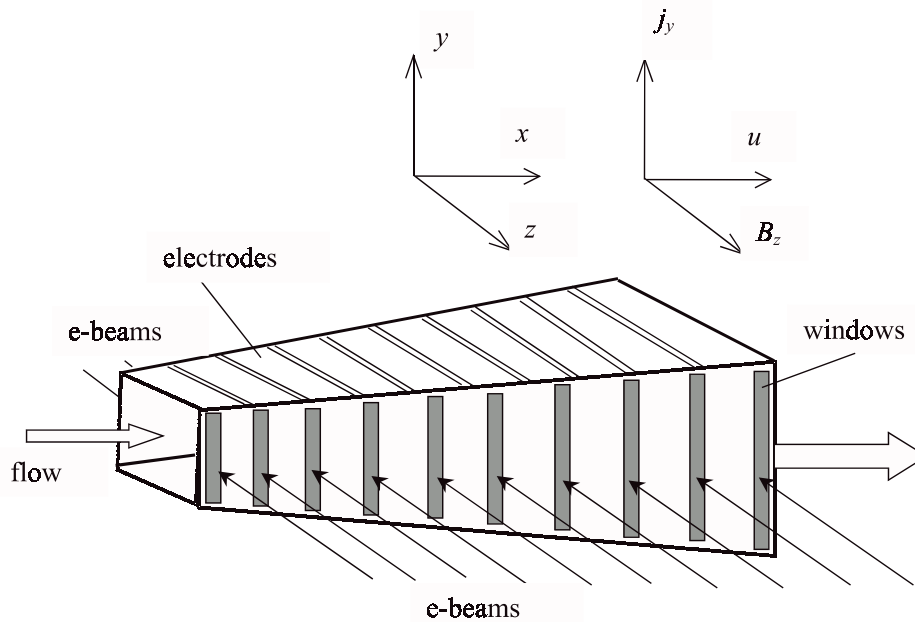


Figure 8-1. Schematic of an MHD channel with e-beam ionization.

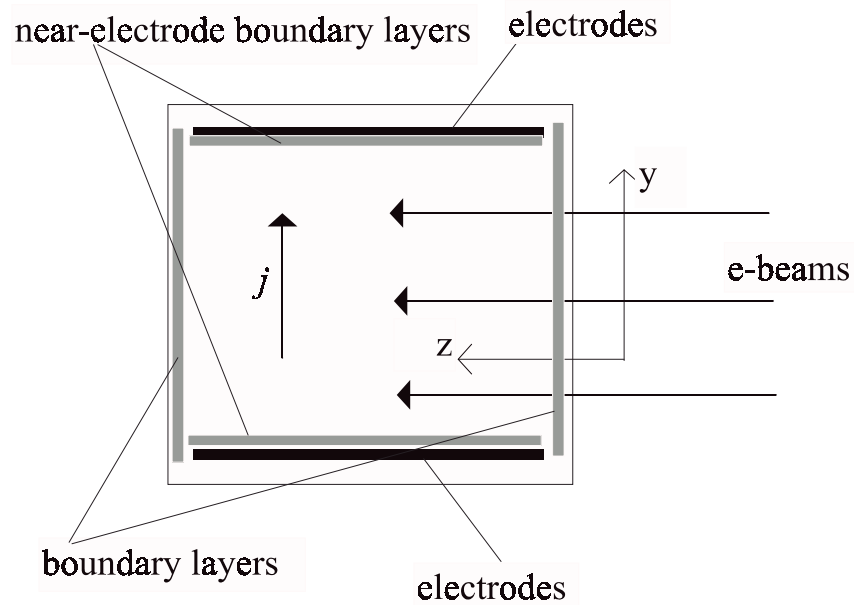


Figure 8-2. Schematic of MHD channel with e-beam ionization: cross-sectional view.

An array of individually ballasted, segmented electrodes creates a transverse electric field and generates an electric current. The magnetic field, orthogonal to both the electric field and the flow

direction, produces the accelerating $j \times B$ force. Total flow enthalpy is affected not only by the $j \times B$ force but also by the inevitable Joule heating and the energy input from the ionizing beams. The beams, as shown in Figs. 8-1 and 8-2, must be injected along magnetic field lines since the electrons tend to spiral around the field lines. Calculations show that the Larmor radius is less than a millimeter under expected operating conditions of MARIAH II/RDHWT MHD channels.

To add an enthalpy of a few MJ/kg to an air stream at densities on the order of 0.1 atmospheric density over a reasonable length (for example, 1 to 4 m), an electron number density of at least 10^{12} – 10^{13} cm⁻³ is required (Refs. 1, 5). Estimates performed in Refs. 1 and 5 indicate that this electron number density could be sustained by an array of e-beams with energy of 10 to 50 keV and beam current density of between 1 and 100 mA/cm².

As a practical matter, it would be very difficult (if not impossible) to have e-beams fill the entire sidewall of the channel more or less uniformly. Indeed, the beams must be generated in a vacuum and injected into the channel through some type of foils or windows. The windows or foils would be heated by the beams passing through and must also be of sufficient mechanical strength. If the beam current density is approximately 1 mA/cm² or less, thin metallic foils with passive cooling should suffice (Ref. 6). For higher beam current densities, either active cooling or the new technology of so-called plasma windows or ports (Refs. 7, 8) must be utilized. In any case, e-beams will be passed through only a part of the sidewall, and Fig. 8-1 shows the pass-through foils or windows as a periodic array of strips.

The energy loss rate of beam electrons is nearly independent of energy if the electron energy is greater than a few hundred keV (Refs. 6, 9). However, in the 30-keV range, the energy loss per unit length traversed increases strongly as the electron energy decreases. Thus, the energy deposition per unit length by the beam is not uniform across the MHD channel. In addition, the electrons tend to follow the magnetic field across the channel since any attempt to travel perpendicular to the field lines results in a helical path due to the Lorentz force.

Modeling of the e-beam generated ionization profile across the channel will be addressed in the next section. To conclude this section, several advantages of the ionization by e-beams are listed:

- E-beams represent the most efficient way of ionizing cold gases. Even at low temperatures and electric fields, an adequate electrical conductivity for MHD operation can be created with reasonable beam energy and current.
- Since at high electron energies ionization cross sections increase when the incident electron energy decreases, beams injected from the sidewall would generate higher ionization inside the channel than near the wall. Thus, the problem of short-circuiting through the hot, highly conductive, boundary layer and severely limiting performance of conventional MHD devices can be minimized in devices with e-beam ionization.
- Plasmas with externally sustained ionization are inherently much more stable than those of self-sustained nonequilibrium discharges. Indeed, ionization generated by e-beams is essentially decoupled from both temperature and electric field. A local positive fluctuation in temperature that would have led to arcing instability in self-sustained discharges would result

in reduced ionization by e-beams and reduced local heating, thereby stabilizing the plasma. Moreover, although strong magnetic fields would be beneficial for MHD operation, conventional MHD devices cannot operate at high values of Hall parameter. (The Hall parameter is the ratio of the electron cyclotron frequency to the electron-heavy particle collision frequency.) At high Hall parameters, electron mobility across a magnetic field is sharply reduced. This prevents electron density fluctuations from rapidly dissipating, thereby leading to an instability similar to the ionization-thermal instability at high pressures. Although, stability of MHD plasmas with external ionization has not been previously studied, it is reasonable to expect that use of an ionization source independent of temperature and local electron density can break the instability loop, thus allowing stable operation at higher Hall parameters.

8.2 PROGRESS IN THE MODELING OF MHD ACCELERATORS

The MHD modeling effort is currently focused on analyzing the physics of cold hypersonic MHD accelerators with e-beam-induced ionization, using both quasi-1-D and multi-dimensional computer codes. Based on the operating requirements and the analysis conducted to date, e-beams appear to be the best means of sustaining conductivity in the MHD channel.

Significant progress toward the mathematical modeling of the MHD accelerator has been made during the reporting period. To understand the modeling results discussed below, it is useful to subdivide the governing physics into three categories: 1) the gasdynamic model; 2) the beam propagation model; and 3) the charge exchange and kinetics models. With respect to this classification, the research accomplished thus far can be summarized as follows: 1) 1-D and 2-D models for the gas dynamics have been employed; 2) the beam propagation models are 1-D in the Z coordinate, and 3) the charge exchange models developed to date are 1-D in either Y or Z, or they are algebraic.

Computational codes have been developed to implement these models, and preliminary computations using these codes have been performed. Four different simulation models are presented below. These differ primarily in the degree of coupling between the gas dynamics and beam propagation and also with respect to the type of gas dynamic (1-D or 2-D) model that was employed.

The model described in Section 8.2.1 can be described as a 1-D gas dynamic model coupled to a 1-D model for the three particle species (electrons, ions, and neutrals). The spatial variable for both gas dynamics and charge exchange kinetics is X. In this case the beam propagation is not explicitly modeled, the implicit assumption being that the particle fluxes are uniform in the Y and Z directions. A unique feature of this model is that it includes equations for vibrational energy exchange.

Section 8.2.2 describes a model in which a 2-D gas dynamics model in X and Y is coupled to a 1-D beam propagation model in the Z variable. The charge exchange reactions are modeled as source terms in the particle flux balance equations for each of the species. To simplify the gas dynamic computation, it was assumed that pressure was constant throughout the computational domain.

Electrode sheaths are the subject of Section 8.2.3. This is the only one of the four models that is capable of simulating the cathode and anode fall regions. The beam propagation is modeled through a set of 2-D species flux conservation in the coordinates X and Y . Charge exchange kinetics is modeled as in Section 8.2.2 through the use of source terms. This model can be implemented (in a computational sense) to simulate either the (X, Z) directions (neglecting $\partial/\partial Y$ terms), in which case it becomes a model for the sidewall sheaths; or in the (X, Y) directions (neglecting $\partial/\partial Z$ terms), in which case it becomes a model for the electrode sheaths. The latter case is the one for which detailed computations are presented.

In Section 8.2.4, a model based on Monte Carlo methods is described. The driving idea in this approach is to compute individual electron trajectories of a few electrons by employing the equations of classical dynamics. A random collisional forcing function is superimposed on the governing dynamical equations to provide an approximate picture of the electron distribution in coordinate space. These codes, called the Integrated Tiger Series Codes (ITS) (Ref. 10), were initially developed at SNL for the purpose of studying the interaction of e-beams with a background gas or solid material. An attractive feature of these codes is that they are capable of computing the energy deposition into the gas as a function of beam coordinate. Another attractive feature is that they can accurately simulate the effects of an applied magnetic field.

Detailed descriptions of each of these models are given in Sections 8.2.1 through 8.2.4.

8.2.1 Quasi-One-Dimensional Accelerator Model

To evaluate performance limits of the MHD accelerator with ionization by e-beams and of the overall MARIAH II/RDHWT hypersonic wind tunnel, 1-D calculations can be very useful. When a specific regime is found promising from the 1-D analysis, further 2-D and 3-D computations can be performed to investigate flow structure (i.e., ionization profile, velocity and temperature field, and boundary layers). Of course, the 1-D code should include a reasonably simple but essentially correct model of ionization kinetics and molecular vibrational relaxation.

The latter can certainly be important. Indeed, a substantial portion of the energy that plasma electrons receive from the transverse electric field can be channeled into vibrational excitation of air molecules (primarily N_2). Since the static pressure and temperature in the channels are expected to be low and the gas residence time inside the channel quite short, most of the energy of vibrational excitation could be simply convected out with the flow without relaxation. This would affect both gas dynamics inside the channel and the exit flow quality.

To develop the 1-D model, equations describing the charged particle kinetics and vibrational relaxation were coupled with a quasi-1-D flow code, resulting in an efficient tool for analyzing and optimizing system performance. The quasi-1-D computations agree well with the more sophisticated 2-D modeling. This model has been used to identify the optimal range of e-beam parameters and to suggest injection of the beams through foil-covered slots spaced periodically along the channel. The working assumptions of the modeling effort were:

- (a) A 20,000 atm plenum pressure;
- (b) energy addition to high density supersonic flow by relativistic e-beams;

- (c) subsequent acceleration in a low temperature MHD channel which uses 10 - 30 keV e-beams for ionization.

The computational results discussed in Section 8.2.2 indicate it would be possible to achieve Mach 14.3 flow with a dynamic pressure of 2,000 psf.

8.2.1.1 Vibrational Energy Processes

Assuming most of the vibrational energy is stored in N_2 and that N_2 relaxes in collision with O_2 molecules and atoms, the vibration-translation relaxation time can be written as (Ref. 11):

$$\tau_{VT}^{-1} = N \left[7 \cdot 10^{-10} \exp(-141T^{-1/3}) + \alpha \cdot 5 \cdot 10^{-12} \exp(-128T^{-1/2}) \right], \text{ sec}^{-1} \quad (8-4)$$

where N is the total number density of the gas, T is the static temperature in Kelvins, and α is the mole fraction of atomic O_2 . The vibrational energy equation then can be written as:

$$\frac{d(N\varepsilon_v)}{dt} + N\varepsilon_v \nabla \vec{u} = -\nabla \vec{q}_v + Q_v - \frac{N[\varepsilon_v - \varepsilon_v^0(T)]}{\tau_{VT}(T)} \quad (8-5)$$

where q_v is the vibrational energy flux due to molecular diffusion. In hypersonic flow, at moderate or high densities, the q_v term is always negligible compared with the convective term. The term Q_v in Eq. (8-13) is the rate of vibrational excitation per unit volume; ε_v and $\varepsilon_v^0(T)$ are the nonequilibrium and thermally-equilibrium values of vibrational energy per molecule.

For 1-D steady flow, the vibrational energy equation can be rewritten as:

$$\frac{dE_v}{dx} = \left[Q_v - \frac{E_v - E_v^0(T)}{\tau_{VT}(T)} \right] / u + \frac{E_v}{\rho} \frac{d\rho}{dx} \quad (8-6)$$

When the deviation from equilibrium is not very large, nonequilibrium and equilibrium vibrational energy can be expressed through the respective temperatures (T_v is the vibrational temperature) by the Planck formula:

$$E_v = N\varepsilon_v = N \frac{\hbar\omega_0}{\exp(\hbar\omega_0/T_v) - 1}; \quad E_v^0 = N\varepsilon_v^0 = N \frac{\hbar\omega_0}{\exp(\hbar\omega_0/T) - 1} \quad (8-7)$$

where $\hbar\omega_0$ is the lowest vibrational quantum of N_2 molecules. Vibrational free energy and entropy per molecule can be written as:

$$\tilde{F}_v = \hbar\omega_0 / 2 + T_v \ln[1 - \exp(-\hbar\omega_0 / T_v)] ; \quad (8-8)$$

$$\tilde{S}_v = -k_B \frac{\partial F_v}{\partial T_v} = k_B \left[\frac{\hbar\omega_0}{T_v} \frac{1}{\exp(\hbar\omega_0 / T_v) - 1} - \ln[1 - \exp(-\hbar\omega_0 / T_v)] \right] \quad (8-9)$$

Specific (that is, per unit mass) vibrational entropy is: $S_v = \tilde{S}_v N / \rho$ [J/kg·K].

The vibrational excitation term, Q_v , can be expressed as a fraction η of the Joule heating rate:

$$Q_v = \eta j_y (E_y - uB_z) \quad (8-10)$$

The fraction $\eta \equiv \eta((E_y - uB_z) / N) < 1$ is determined on the basis of the solution of the Boltzmann kinetic equation for plasma electrons done in Ref. 12.

8.2.1.2 Governing Equations for Gasdynamic and MHD Processes

The vibrational energy Eq. (8-3) should be solved together with continuity, momentum, energy, and EOS equations, assuming an ideal Faraday accelerator:

$$\begin{aligned} d(\rho u A) / dx &= 0, \quad \rho u A = \text{const}, \\ \rho u du / dx + dp / dx &= j_y B_z, \\ \rho u d(\gamma \varepsilon + u^2 / 2) / dx &= j_y E_y - Q_v + [E_v - E_v^0(T)] / \tau_{vT}(T) + Q_b, \\ p &= R \rho T = (\gamma - 1) \rho \varepsilon \end{aligned} \quad (8-11)$$

where $A(x) = Z^2(x)$ is the cross-sectional area of the channel; $Q_b = \frac{2 j_b \varepsilon_b}{Z}$ is the rate of energy addition by the two ionizing e-beams injected from the opposite sides of the channel; ε_b and j_b are the e-beam energy (in eV) and current density; W_i is the ionization cost (in air, $W_i \approx 35$ eV); and Z is the channel width.

The transverse current density in an ideal Faraday accelerator is:

$$j_y = \sigma (E_y - uB_z), \quad \sigma = e \mu_e n_e \quad (8-12)$$

where σ is the electrical conductivity, μ_e is the electron mobility, and n_e is the plasma electron number density.

The plasma is modeled as consisting of electrons and positive and negative ions, whose number densities n_e, n_+, n_- obey the quasi-neutrality condition: $n_+ \approx n_e + n_-$. The set of equations for kinetics of charge species accounting for e-beam-induced ionization rate (q_i term), attachment of electrons to molecules with formation of negative ions (frequency ν_a), collisional detachment of electrons from negative ions (rate constant k_d), and electron-ion and ion-ion recombination (rate coefficients β and β_{ii} , respectively) is:

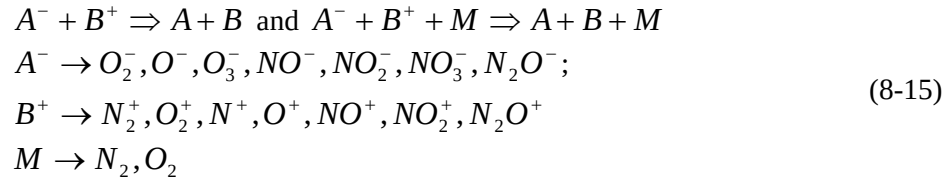
$$\begin{aligned}\frac{\partial n_e}{\partial t} + \frac{\partial \Gamma_e}{\partial x} &= q_i + k_d N n_- - \nu_a n_e - \beta n_+ n_e, \\ \frac{\partial n_+}{\partial t} + \frac{\partial \Gamma_+}{\partial x} &= q_i - \beta_{ii} n_- n_+ - \beta n_+ n_e, \\ \frac{\partial n_-}{\partial t} + \frac{\partial \Gamma_-}{\partial x} &= -k_d N n_- + \nu_a n_e - \beta_{ii} n_- n_+\end{aligned}\quad (8-13)$$

For 1-D stationary flow ($\partial n_{e,+,-} / \partial t = 0$) in the case of $E_x = 0$ (ideal Faraday accelerator), the fluxes of charged species can be written simply as $\Gamma_{e,+,-}(x) = n_{e,+,-} u$.

The approximation formula for the e-beam ionization rate is (Ref. 1):

$$q_i = \frac{2\varepsilon_b j_b}{e W_i Z} \quad (8-14)$$

Two- and three-body ion-ion recombination:



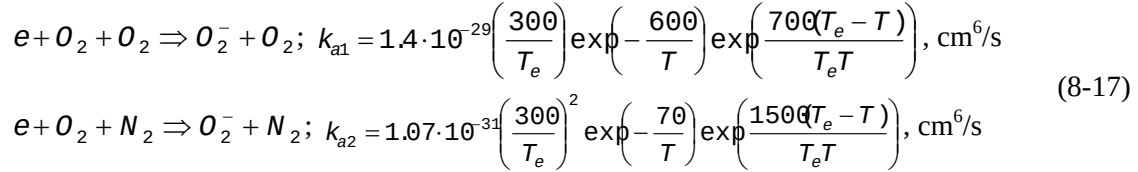
can be characterized by the rate coefficient (Ref. 13)
 $\beta_{ii} = 2 \cdot 10^{-7} (300/T)^{1/2} [1 + 1 \cdot 10^{-18} N (300/T)^2]$, cm³/s.

Electron-ion recombination is dissociative:



with the rate coefficient $\beta = 2 \cdot 10^{-7} (300/T_e)^{1/2}$ (Ref. 13), where T_e is the electron temperature.

The primary processes of three-body electron attachment and their rate coefficients (Ref. 13):



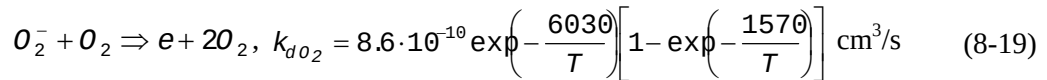
Since rate coefficients of processes Eqs. (8-17) depend on T_e , it is important to calculate the electron temperature in the modeling. In our computations, electron temperature was determined from the tabulated data on electron diffusion and mobility coefficients of Ref. 12. In that paper, the diffusion and mobility coefficients are listed as functions of E/N , determined from experimental data and extrapolation based upon solution of Boltzmann kinetic equation for electrons in air.

In principle, attachment could also be dissociative:

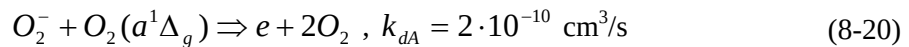


However, this process has a relatively high threshold, and its rate exponentially depends on T_e or E/N . In typical cases of interest for hypersonic MHD channels with e-beam ionization, the parameter E/N (where $E = E_y - uB_z$), is very small, and the process Eq. (8-18) for plasma electrons can be neglected. However, in future research it would be desirable to evaluate the role of process Eq. (8-18) with participation of high-energy beam electrons.

The dominant process of collisional detachment of electrons from negative ions and its rate constant (Ref. 14):



In many gas discharges, detachment can also occur in collisions with excited species, for example:



Detachment in collisions with other active particles has rate coefficients of the same order of magnitude as Eq. (8-20). Therefore, in general, the frequency of detachment is

$v_d = k_{dO_2} N_{O_2} + k_{dA} N_A$ where N_A is the number density of active particles. At sufficiently high concentration of active species, electron attachment could be balanced by detachment.

8.2.1.3 Computational Results

Recently developed quasi-1-D codes have been applied to assess the performance envelope of the hypersonic wind tunnel with UHP plenum, energy addition to the supersonic flow by lasers or e-beams, and MHD acceleration. The main purpose of this exercise was to establish reasonable inlet conditions at the MHD accelerator inlet. The model tunnel (Refs. 1, 5) is assumed to consist of three major parts: UHP plenum, laser or e-beam heating during supersonic expansion, and an MHD accelerator, and it must generate a flow of air with Mach 12 to 15 velocity and dynamic pressure of 2,000 psf (about 1 atm) continuously (or, at least, with a run time of many seconds).

As a benchmark, a case with a UHP plenum followed by e-beam heating and expansion without MHD acceleration is considered. This benchmark case (Ref. 15) has been computed previously by Anderson using a 1-D system code that includes a real-gas EOS and a model of energy addition by relativistic e-beams developed at SNL. The selected plenum pressure and temperature are 20,000 atm and 900 K, respectively. The heating by 1 to 3 MeV e-beams begins at Mach 2. The heating and expansion is optimized so as to add maximum energy to the flow, provided that the static temperature is not allowed to exceed about 2,600 K and the exit temperature (240 K) and dynamic pressure (2,000 psf) are given. The computational results indicate that the maximum Mach number achievable under these constraints is approximately Mach 12.2.

For the MARIAH II/RDHWT facility (UHP plenum plus heating by relativistic electrons in supersonic expansion, plus MHD accelerator), the energy addition by relativistic electrons was terminated at the point where the gas reaches its maximum temperature. Specifically, for the benchmark case, the static pressure at this point was 206.6 atm, static temperature = 2,590 K, and velocity = 2,829 m/sec. The gas was then isentropically expanded to the static pressure of 0.1 atm, at which point its static temperature and velocity became 373 K and 3,667.6 m/sec, respectively. These conditions were considered to be the initial conditions at the entrance of the MHD accelerator channel. With a mass flow rate of 10 kg/sec, the MHD channel is 17 cm square at the entrance; with Mach 14.5 at $T=240$ K at the exit (see below), the channel is approximately 47-cm² at its exit. A magnetic field of 20 T was used in the channel.

When optimizing MHD channel performance, several important constraints must be obeyed. In addition to the given exit dynamic pressure and static temperature, there are constraints on the electric field, loading parameter, and ionizing beam current.

The constraint on the electric field is related to ionization by plasma electrons and a possibility of short-circuiting between adjacent electrode segments. If this problem is considered for a Faraday channel, the key parameter determining ionization processes due to plasma electrons is E/N , which is proportional to the energy gained by an electron between collisions. In an ideal Faraday MHD accelerator, the effective electric field is $E = E_y - uB_z$, so that the parameter is $(E_y - uB_z)/N$. If the Hall parameter Ω in the plasma is large, then in the boundary layer near the segmented electrodes, the electric field is determined primarily by its x -component, which is imposed for the purpose of eliminating Hall current in the plasma: $E_b = E_x = \Omega (E_y - uB_z)$ (see Fig. 8-3a). Since

electrons in the boundary layer must move across the strong magnetic field at high Hall parameters, their effective mean free path is determined by spiraling around magnetic field lines rather than by collisions. Since the Larmor radius is proportional to the magnetic field and does not depend on density, it is the product $N_b \cdot \Omega_b$ (subscript “b” denotes boundary layer) that should be used instead of just N_b to determine the E/N parameter in the boundary layer near electrodes. However, since the Hall parameter is inversely proportional to density, the ratio $E_b/(N_b \cdot \Omega_b)$ is equal to $(E_y - uB_z)/N$. Thus, it is the parameter $(E_y - uB_z)/N$ that defines the intensity of the ionization processes induced by plasma electrons both in the core flow and near the electrodes.

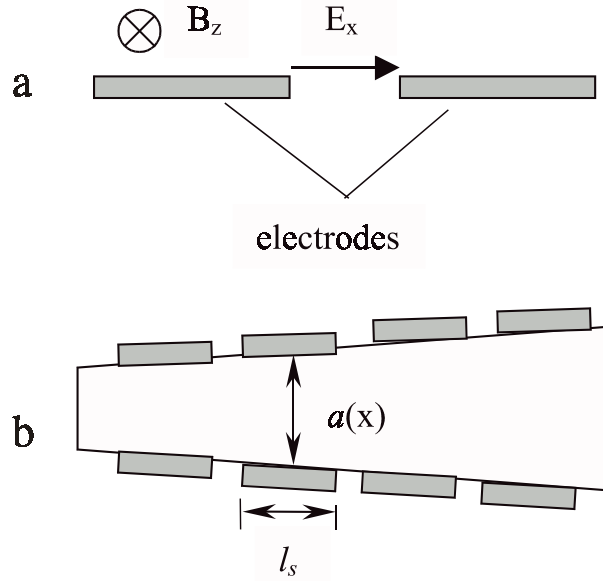


Figure 8-3. a – schematic of electric and magnetic field near electrode segments in a Faraday MHD channel; b – schematic view of an MHD channel consisting of several sections with different transverse electric fields (see the discussion in Section 6.2).

To avoid electric breakdown between the electrode segments (see Fig.8-3a), the $(E_y - uB_z)/N$ parameter should be kept low: $(E_y - uB_z)/N \ll 100 \text{ Td}$, where 1 Td (Townsend) = $10^{-17} \text{ V} \cdot \text{cm}^2$. However, there is a more restrictive condition imposed on $(E_y - uB_z)/N$. For stability, the plasma has to be non-self-sustained and fully controlled by e-beams, so the rate of ionization by plasma electrons has to be less than that provided by the beams. This condition can be approximately expressed as $(E_y - uB_z)/N < 20 \text{ Td}$ (Ref. 16).

For the best performance, mechanical work in the accelerator should be maximized, while Joule heating results in an entropy increase that should be minimized. Therefore, the loading parameter, $k = E_y/(uB_z)$, should be kept very close to 1. This, of course, makes the electric current and the $j \times B$ force small so that a longer channel is required to provide the necessary kinetic energy

augmentation. In addition, with k close to 1, gas velocity quickly reaches the limit E_y/B_z . For the special case of uniform and constant magnetic field, further acceleration would require an increase in the transverse electric field. However, from Maxwell's Equation [e.g., Eq (8-29) in Section 8.2.3.1] it is clear that E_x is independent of y only when the transverse field, E_y , is constant along the flow. The longitudinal field $E_x = \Omega (E_y - uB_z)$, created by independently biasing electrode segments is necessary to eliminate Hall current. Therefore, if the transverse electric field varies along the channel, the complete elimination of the Hall current becomes impossible, and the channel performance will deteriorate.

A solution to the problem of maximizing performance while keeping E_y constant along the channel is to have several consecutive MHD channels, each with its own E_y . At the end of the first channel, the flow would reach its maximum velocity E_y/B_z . Then, the flow would enter the second channel with slightly higher E_y and reach the new maximum velocity. Of course, if the loading parameter k is very close to 1, the channel length may become shorter than its width, which would lead to a nonuniform electric field, again reducing the channel performance. Therefore, k should not be too close to 1. Also, the requirement $l_s \ll a(x)$ is imposed to ensure E_y uniformity (Fig.8-3b).

Another important parameter is the current density of the ionizing e-beams. This current density should be kept low (about 1 mA/cm²) to minimize heating and entropy increase in the MHD channel. This relatively low beam current density also alleviates beam injection and foil heating problems. However, the resulting electrical conductivity in the channel is not high. To compensate for the reduced conductivity, very strong magnetic fields and very long channels may be needed.

With the constraints just discussed, Figs. 8-4 and 8-5 show the results for the set of parameters maximizing the exit Mach number. The ionizing beams were assumed to fill the entire sidewall of the channel. With a 20-T magnetic field, e-beam current density of 1.3 mA/cm², and a loading parameter $k=1.05$, the four-section MHD channel can generate (as a part of the overall facility with UHP plenum and energy addition upstream of the MHD accelerator) Mach 14.6 flow at 2,000-psf dynamic pressure. The required channel length is 3.2 meters.

As seen in Fig. 8-4d, vibrational temperature reaches almost 0.1 eV at the exit. Although this constitutes only a very small fraction of the total enthalpy, the vibrational-translational nonequilibrium is quite pronounced. To check how sensitive this result is to air chemistry that was not coupled with the gas dynamics, Fig.8-6 shows the variation of characteristic vibrational relaxation time along the channel at different mole fractions of atomic O₂. Since the residence time of molecules inside the channel is less than a millisecond, only a very large mole fraction of atomic O₂ (approximately 10 percent), could affect the relaxation. Since such mole fractions could hardly be expected to exist in the channel, removal of vibrationally excited molecules would proceed primarily by convection with the hypersonic flow. Since N₂ vibrational relaxation rate in collision with water molecules is comparable with that in collisions with O₂ atoms, it is also unlikely that a presence of water vapor would affect vibrational kinetics under these conditions.

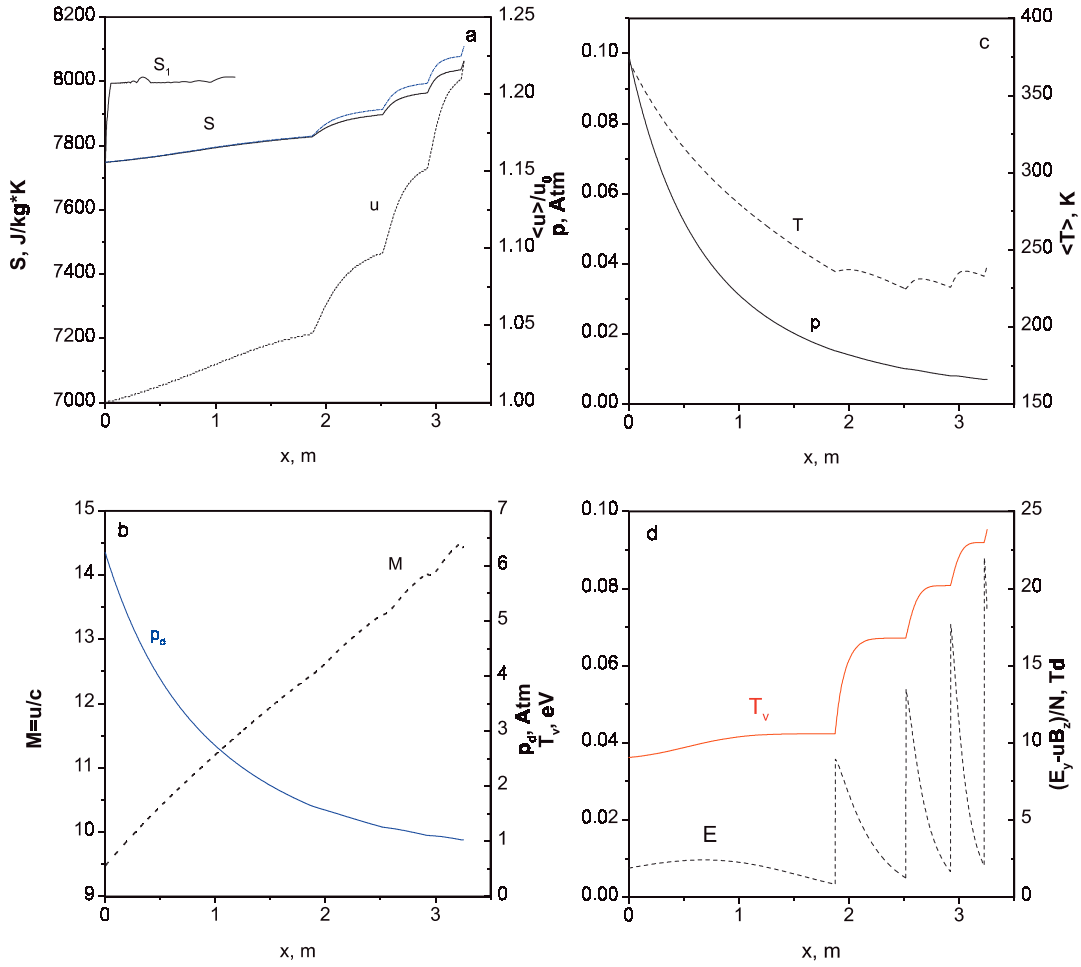


Figure 8-4. Computed profiles of gas parameters along an MHD accelerator channel (without ion slip).

- (a) S_1 – specific entropy variation for the case with energy addition by a relativistic e-beam with no MHD; S – specific entropy variation for the MHD case (solid line – translational-rotational entropy, dashed line – full entropy, including vibrational entropy); $\langle u \rangle / u_0$ – gas velocity averaged over the channel cross section, $\langle u \rangle$, relative to the initial velocity, u_0 . (b) p_d – profiles of dynamic pressure and M – Mach number. (c) T – temperature and P – pressure variation along the channel. (d) T_v – vibrational temperature and E – effective electric field strength variation along the channel. ($\langle \dots \rangle$ means averaging over the channel cross section.)

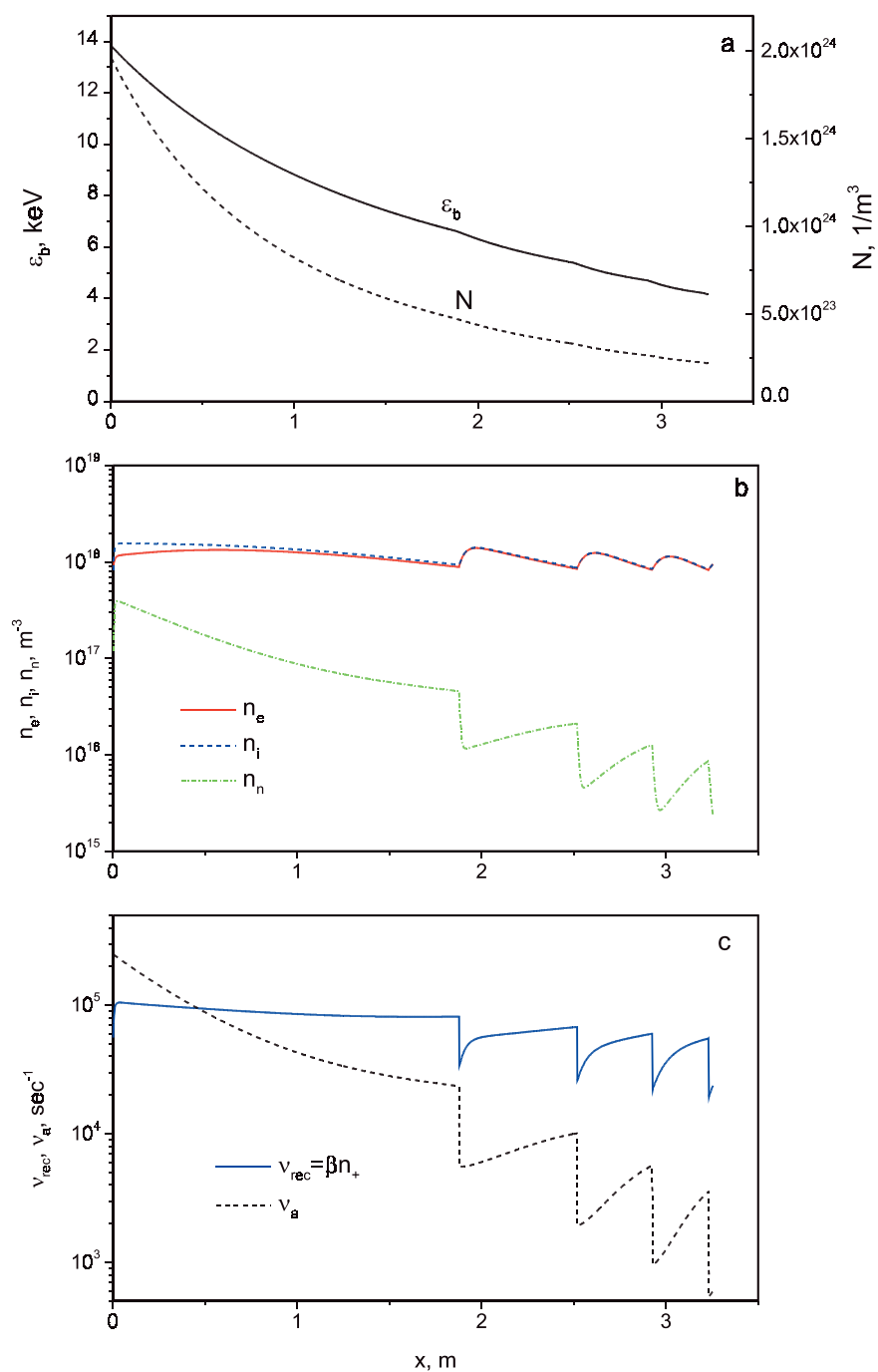


Figure 8-5. Profiles of e-beam energy, ϵ_b , gas number density, N , number densities of electrons and positive and negative ions, n_e , n_i , and n_n , and electron recombination and attachment frequencies, ν_{rec} and ν_a , for the case shown in Fig. 8-4.

Figure 8-7 shows the variation of electron attachment and detachment [Eq. (8-17, 8-19, and 8-20)] rates along the channel at two different mole fractions of active (for example, electronically excited) atomic O_2 . Note that since static temperature in the channel is very low, thermal detachment cannot play any role. As seen in the figure, only very high concentrations of excited species (approximately 1 percent) could affect the balance of electrons. Because high concentration is unlikely, the detachment can be neglected.

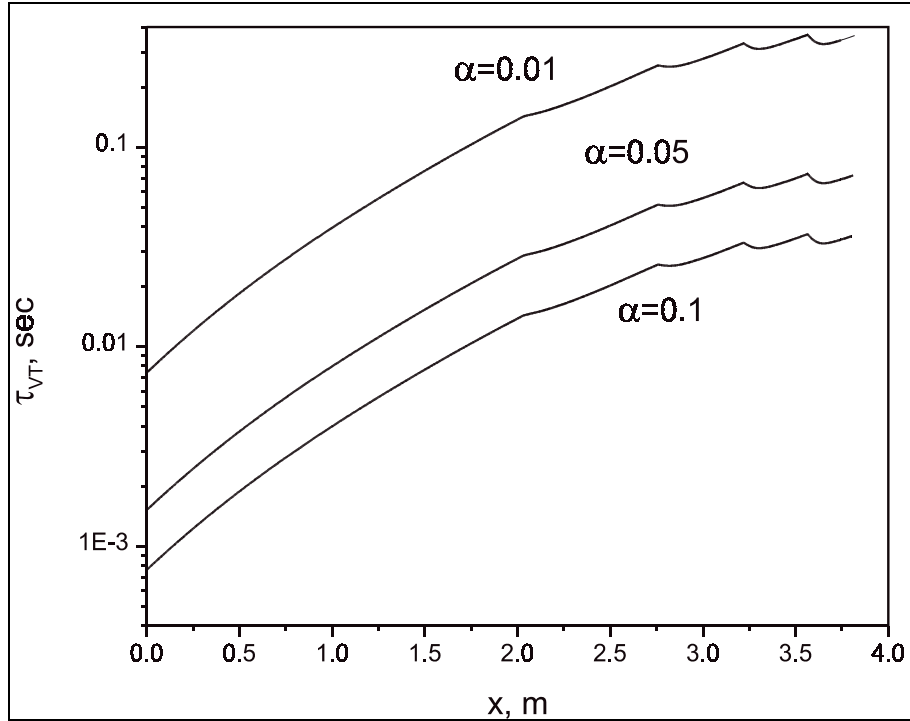


Figure 8-6. Variation of the vibrational relaxation time along the MHD channel for the case shown in Fig. 8-4, at different mole fractions, α , of atomic O_2 .

As can be seen in Fig. 8-5c, the rate of electron removal in the channel due to recombination and attachment is approximately 10^5 sec^{-1} . At flow velocities of 3,500 to 4,500 m/sec, it would take several centimeters for the plasma to decay if the ionization stops. Thus, it would be possible to employ windows for the beams similar to the strips shown in Fig. 8-1 with perhaps a few centimeters between the windows, which could allow reasonable mechanical strength and cooling of the windows and walls.

Figures 8-8 through 8-11 illustrate the computed results for the “periodic strips” e-beam injection process for the same MHD accelerator case. The width of each strip was taken as 0.5 cm, with 2-cm spacing between the strips. The current density of e-beams was increased to 3.5 mA/cm^2 —less than 3 times higher than the number required in the case with beams filling the entire wall. The best results were obtained with the loading parameter of 1.075 in the first section of the channel and 1.06 in subsequent sections.

As seen in Fig. 8-8, there is very little performance penalty compared with the case with beams filling the entire wall. The “periodic strips” method generates Mach 14.3 at 2,000 psf, and the channel length is 3.8 meters. Figures 8-9 through 8-11 show the variation of electron number density along the channel. Clearly, the number density of electrons that determines electrical conductivity stays close to 10^{12} cm^{-3} with relatively little variation, as expected.

Overall, the results predict an encouraging level of performance of the tunnel. Of course, a number of critical technical and engineering issues would have to be resolved in order to make the facility practical. At this time, two groups of issues appear to be the most important. The first is cooling of the walls, electrodes, e-beam pass-through windows, and the boundary layer. The second is developing a control system that will include monitoring key parameters of the channel and controlling e-beam parameters and voltages on multiple electrode segments.

For the near future, experimental studies of MHD channels with ionization by e-beams would be extremely valuable.

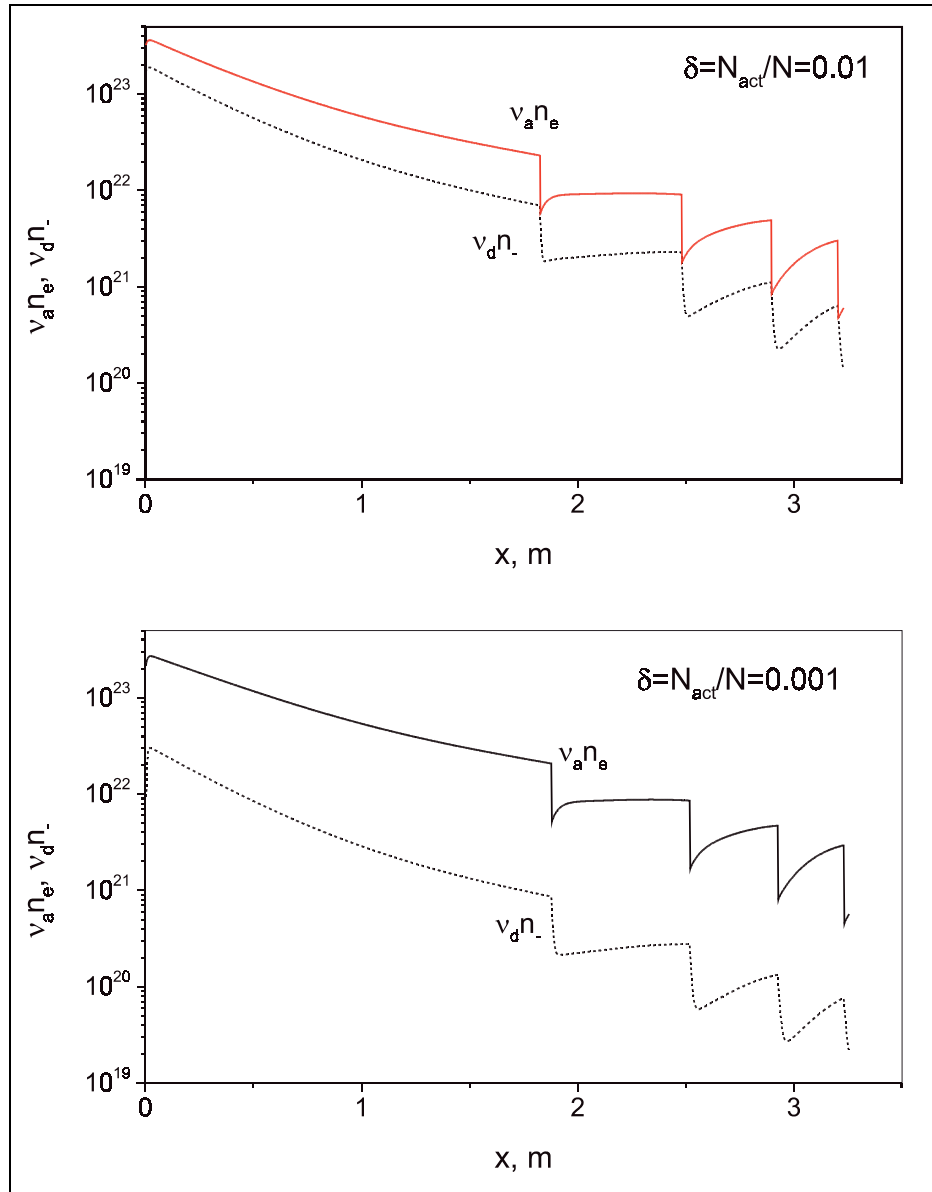


Figure 8-7. The computed variation of electron attachment and detachment rate along the MHD channel for the case shown in Fig. 8-4, at various mole fractions, $\delta = N_{act}/N$ of detachment-active particles. n_e and n_- are the electron and negative ion number densities, and v_a and v_d are attachment and detachment frequencies.

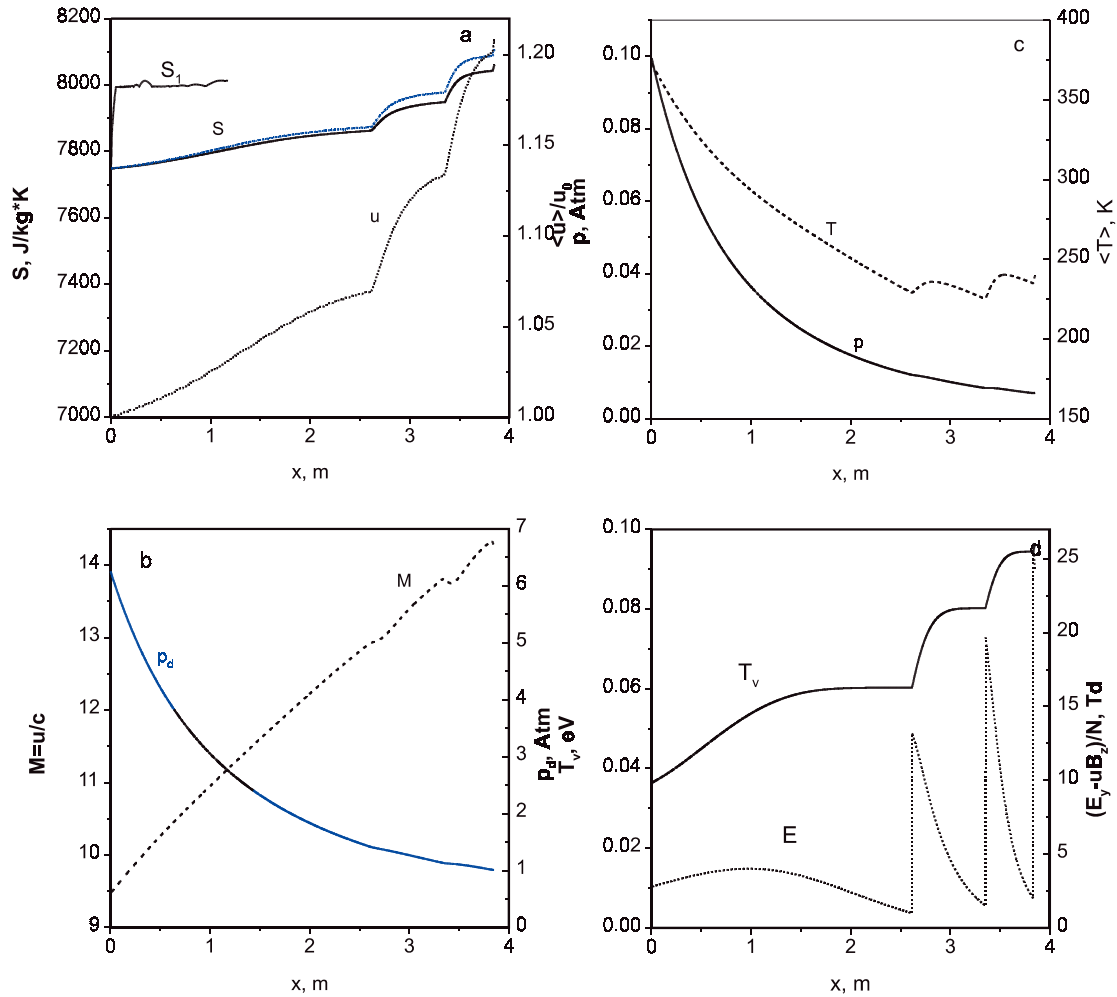


Figure 8-8. Computed profiles of gas parameters along an MHD accelerator channel (without ion slip).

- (a) S_1 – specific entropy variation for the case with energy addition by a relativistic e-beam with no MHD; S – specific entropy variation for the MHD case (solid line – translational-rotational entropy, dashed line – full entropy, including vibrational entropy); $\langle u \rangle / u_0$ – gas velocity averaged over the channel cross section, $\langle u \rangle$, relative to the initial velocity, u_0 . (b) p_d – profiles of dynamic pressure and M – Mach number. (c) T – temperature and P – pressure variation along the channel. (d) T_v – vibrational temperature and E – effective electric field strength variation along the channel. ($\langle \dots \rangle$ means averaging over the channel cross section.)

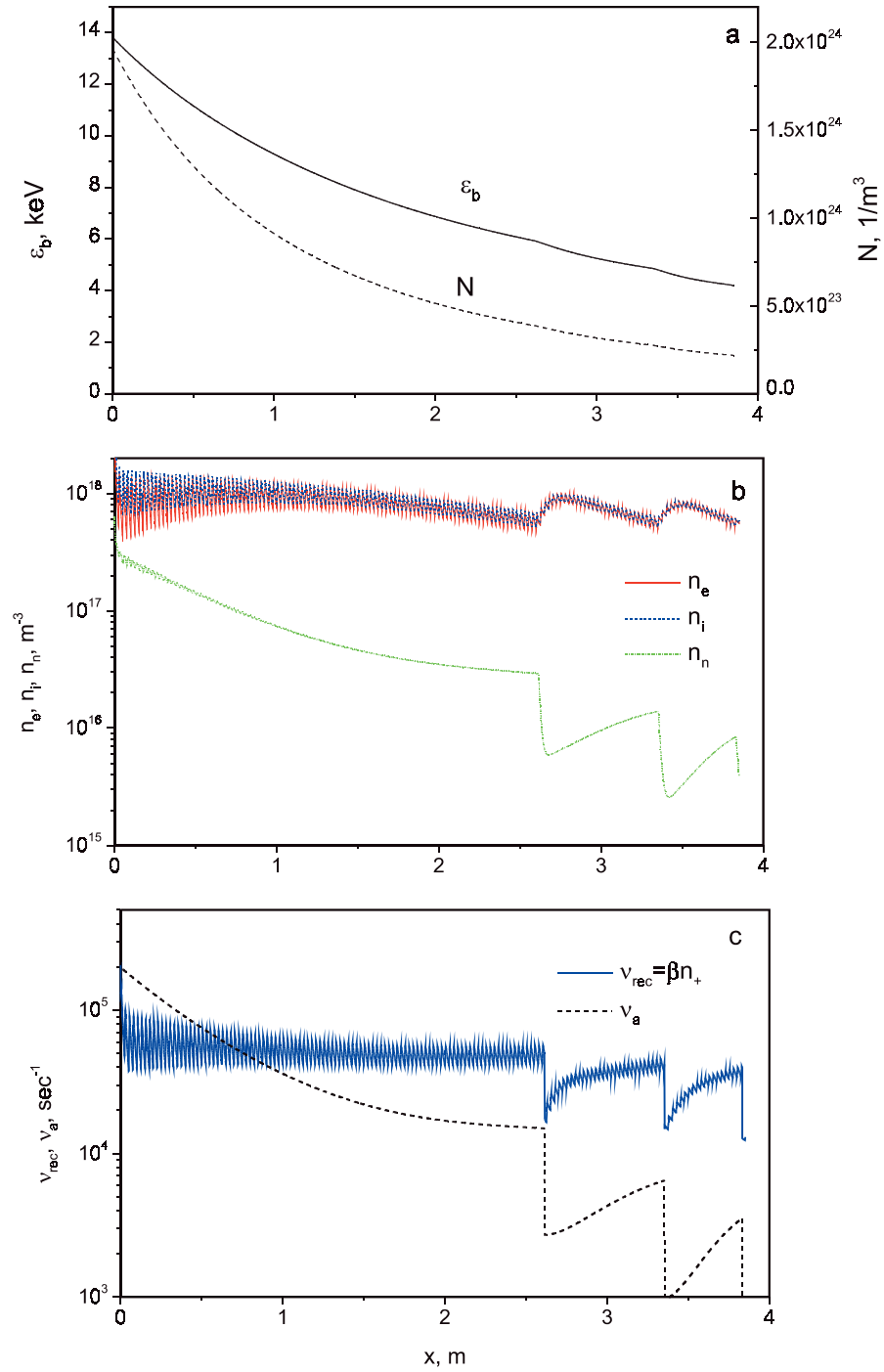


Figure 8-9. Profiles of e-beam energy, ϵ_b , gas number density, N , number densities of electrons and positive and negative ions, n_e , n_i , and n_n , and electron recombination and attachment frequencies, ν_{rec} and ν_a , for the case shown in Fig. 8-8.

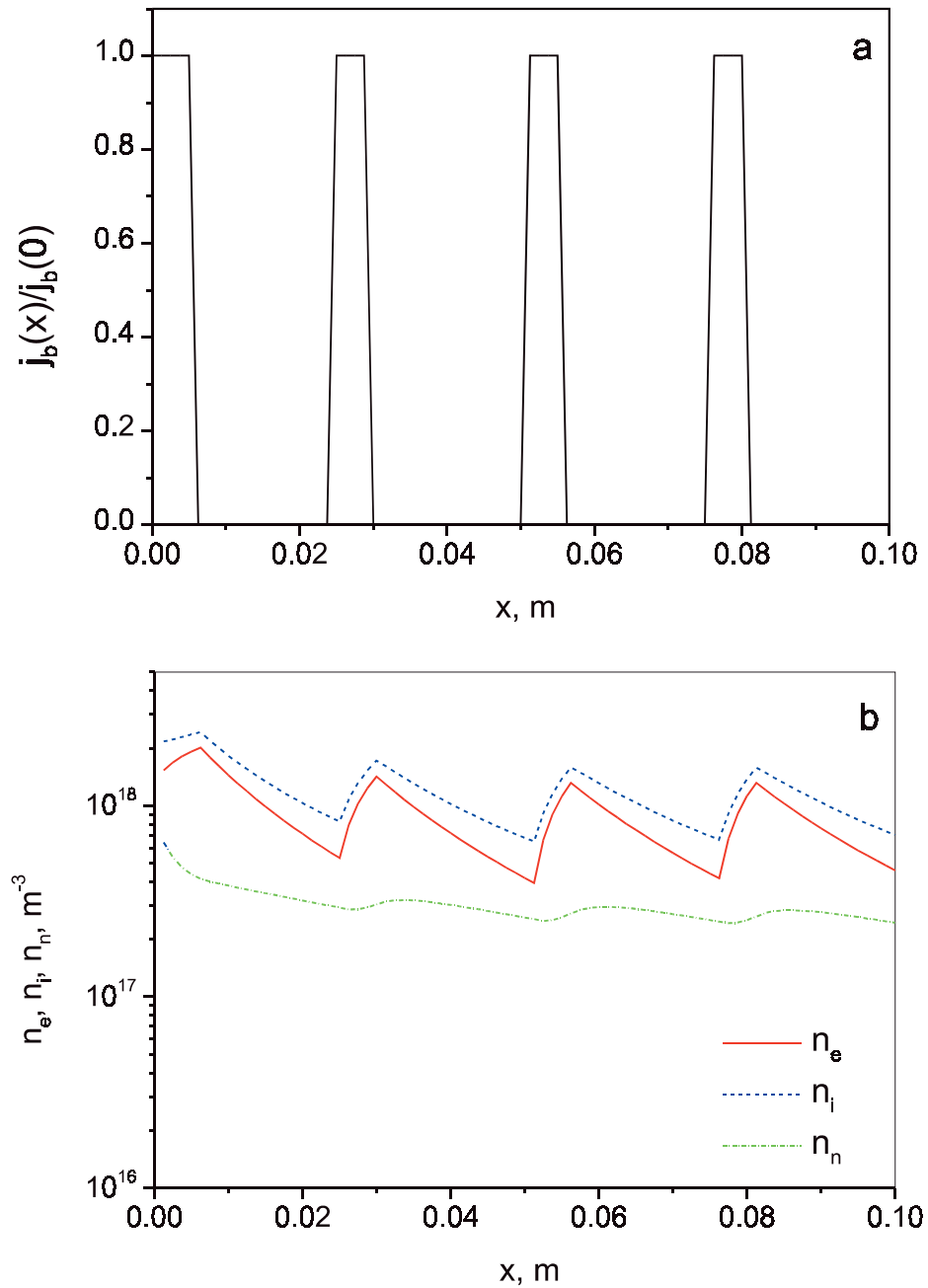


Figure 8-10. Normalized e-beam current density (a) and charged particle number densities (b) as functions of the x coordinate along the channel, from $x=0$ to $x=10$ cm, in the case shown in Fig. 8-8.

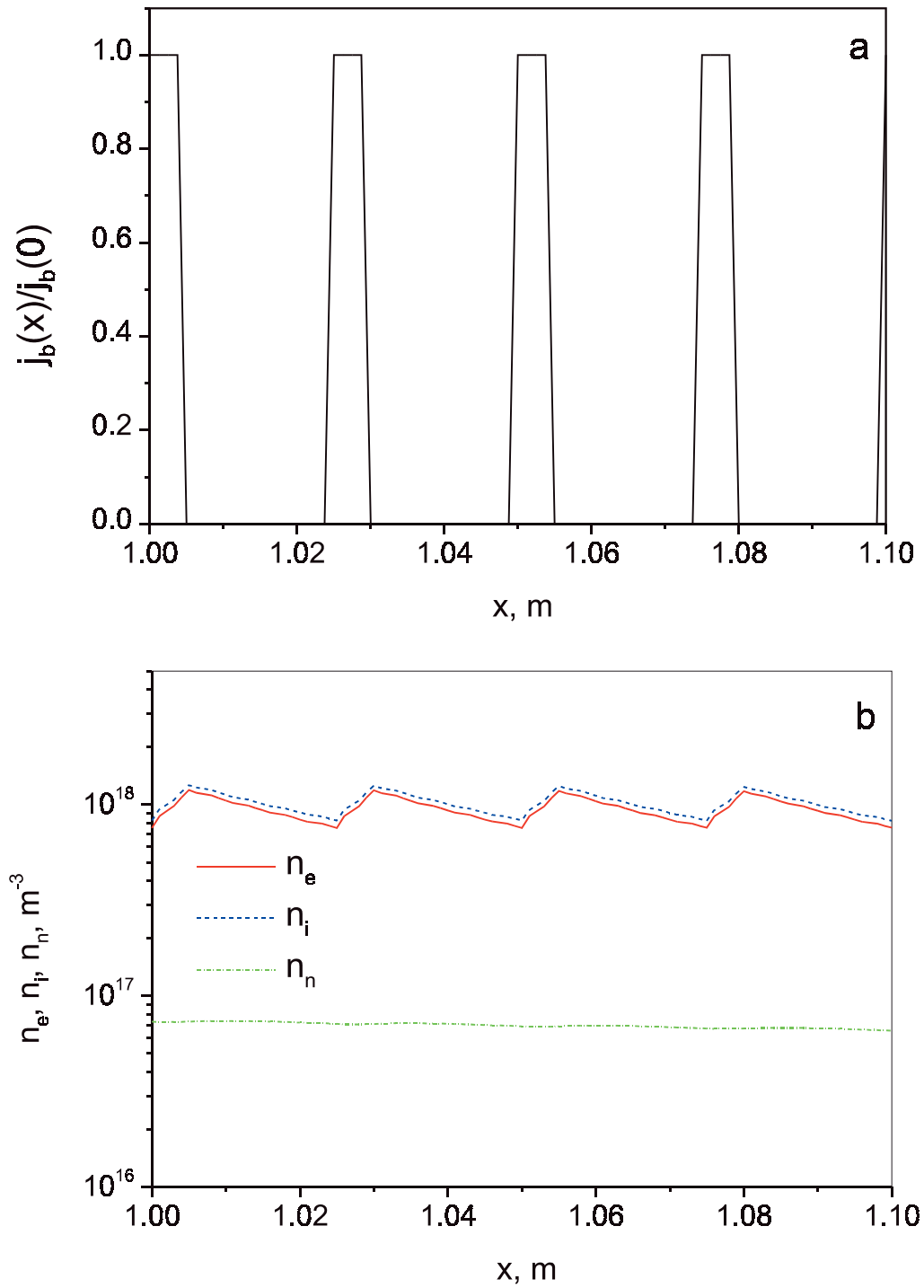


Figure 8-11. Number densities and beam current density vs. X at mid-channel for the “periodic strips” case described in Fig. 8-8.

8.2.2 Coupled Two-Dimensional Gas Dynamics Calculations with Beam Propagation

Two-dimensional gas dynamics models can be very useful for purposes of describing the interaction between an MHD boundary layer and an e-beam propagating across the channel. The initial steps in developing a comprehensive model of the hypersonic MHD channel with an e-beam as the ionizer are described in this section. First, a quasi-1-D model of the e-beam propagation along magnetic field lines is developed. The model is based on the recently developed “forward-backward” approximation, and it incorporates major inelastic collision processes. It is capable of predicting nonuniform ionization rates across the channel, and it can be used to guide the design of optimal configurations, such as placement of opposing beams for the purpose of creating more uniform ionization profiles across the channel. It is noted that because inelastic collision cross sections greatly exceed the momentum-transfer cross section, the “backward” part of the computation may be neglected. This leads to considerable simplification in the problem. The kinetics equations are not given here. For a detailed description of the model equations, the reader is referred to Ref. 5.

The e-beam propagation model is coupled to a set of 2-D viscous gas dynamic equations, producing a relatively simple 2-D model. The model incorporates MHD effects and nonuniform ionization profiles. In the present first-approximation form, the model neglects turbulence, flow separation instabilities, and detailed chemical, vibrational, and ionizational kinetics. Sample calculations that employ this code are shown to yield reasonable 2-D profiles of flow properties.

Computational Results

Coupled 2-D computations for a sample case were performed to illustrate the effects of a nonuniform ionization profile. A standard set of 2-D steady-state Navier-Stokes equations for a constant-area MHD accelerator was coupled with e-beam propagation across the channel and beam-generated ionization profiles. The effective electron-ion recombination rate was assumed to be $\beta = 2 \times 10^{-7} \text{ cm}^3/\text{s}$. An ideal Faraday accelerator was assumed, and the heat source term in the equations included both Joule heating and energy deposited by e-beams. The channel width was 15 cm, and the length was $L = 1 \text{ m}$. At the entrance, a uniform flow of air at $p_0 = 0.1 \text{ atm}$ and $T_0 = 300 \text{ K}$ with velocity $u_0 = 3,500 \text{ m/sec}$ was assumed. Flow boundary conditions at the wall were taken as: 1) zero tangential velocity (no slip), 2) zero normal pressure derivative, and 3) ideally cooled isothermal wall with $T_{\text{wall}} = T_0 = 300 \text{ K}$. The magnetic field in the channel was taken to be $B = 20 \text{ T}$, corresponding to the Hall parameter of about 10. The value of electric field $E = 770 \text{ V/cm}$ was chosen so that the loading parameter $K = E/(uB)$ equals 1.1 at the entrance and decreases as the flow accelerates in the channel. Two e-beams with initial energy 13.5 keV and current density $j_b = 0.1 \text{ A/cm}^2$ uniform across the entire side wall were each assumed to be injected from both sides of the channel along the z axis.

Figures 8-12 through 8-15 depict distributions of ionization rate, temperature, pressure, and density in the channel. The pronounced rise in temperature, density, and pressure near either sidewall is primarily a result of wall recovery processes. It is particularly strong in this case because of the very high core Mach numbers (of order 10 to 11) through the MHD channel.

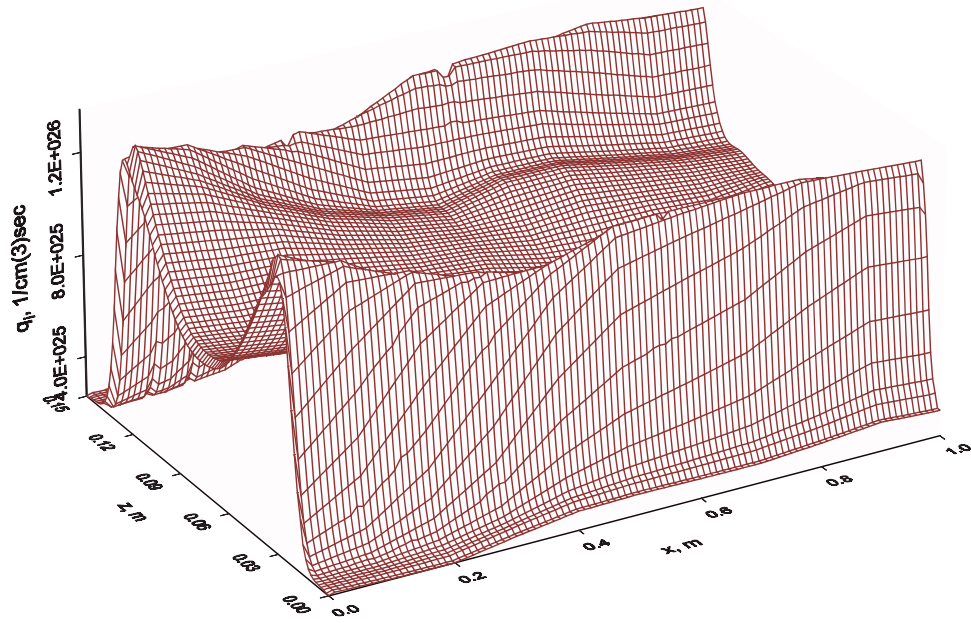


Figure 8-12. Ionization rate profile in the constant-area MHD channel for the test case (see text).

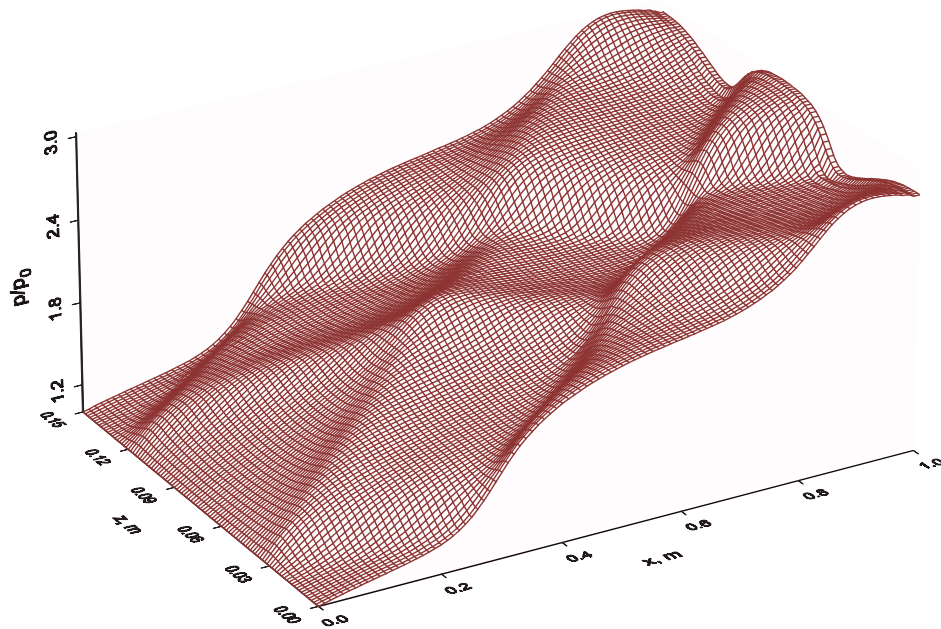


Figure 8-13. Pressure profile in the constant-area MHD channel for the test case (see text).

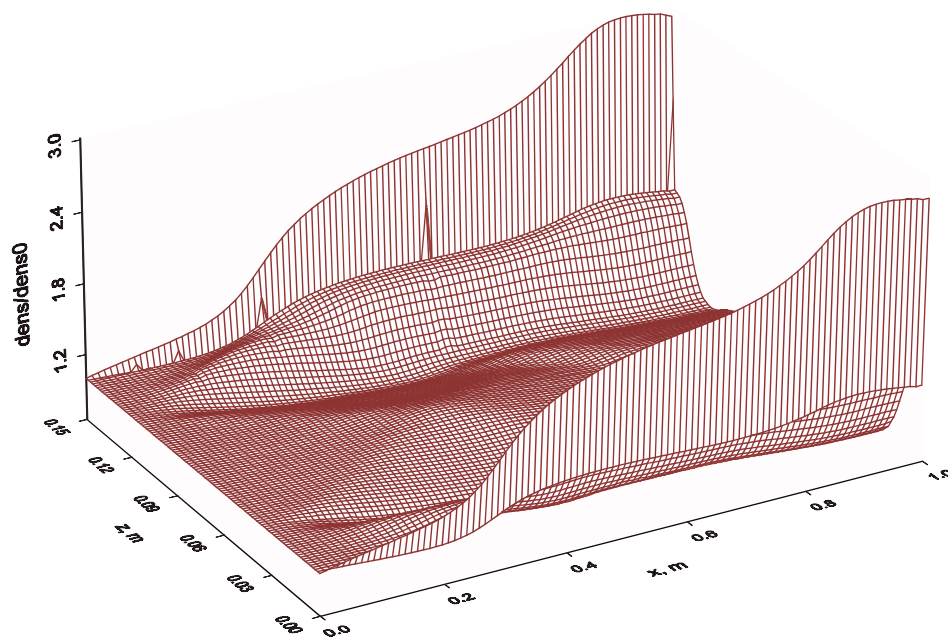


Figure 8-14. Density profile in the constant-areas MHD channel for the test case (see text).

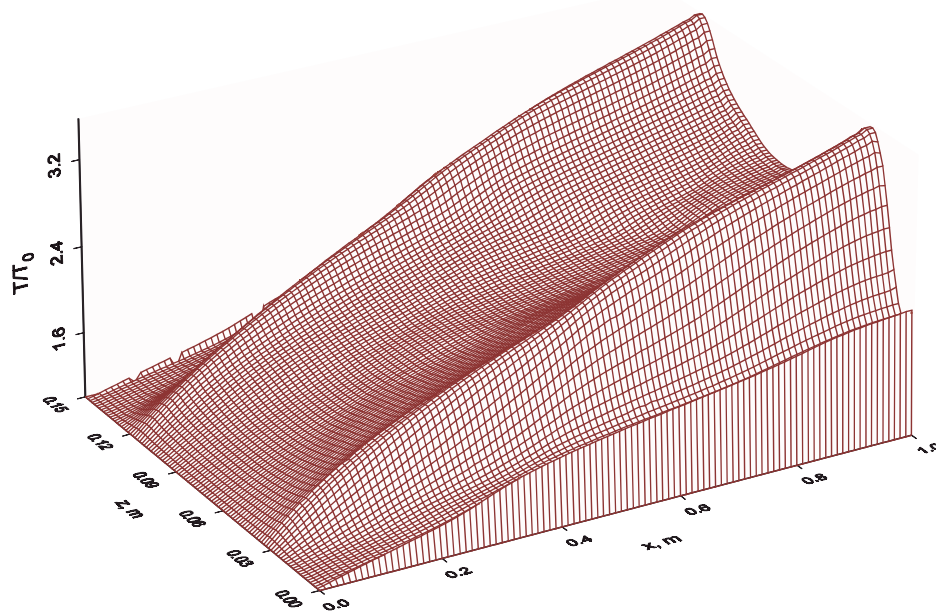


Figure 8-15. Temperature profile in the constant-area MHD channel for the test case (see text).

Because of the nonuniform ionization and heating rate, “hot spots” and shock waves can be seen in Fig. 8-16. This shows that multiple beams must be used, and special care should be taken in tuning the ionization profile to avoid shocks.

For this calculation, the e-beams were assumed to be monoenergetic. In fact, when a beam passes through a 50- to 100- μm -thick metallic foil, not only do the beam electrons lose on the average of 30 to 50 keV of energy, but the beam energy distribution spreads, and a low-energy tail appears (Ref. 6). Modeling of such nonmonoenergetic beams would be straightforward, thereby changing only the boundary condition (Ref. 17). Qualitatively, the energy spread could help in making the ionization profile more uniform.

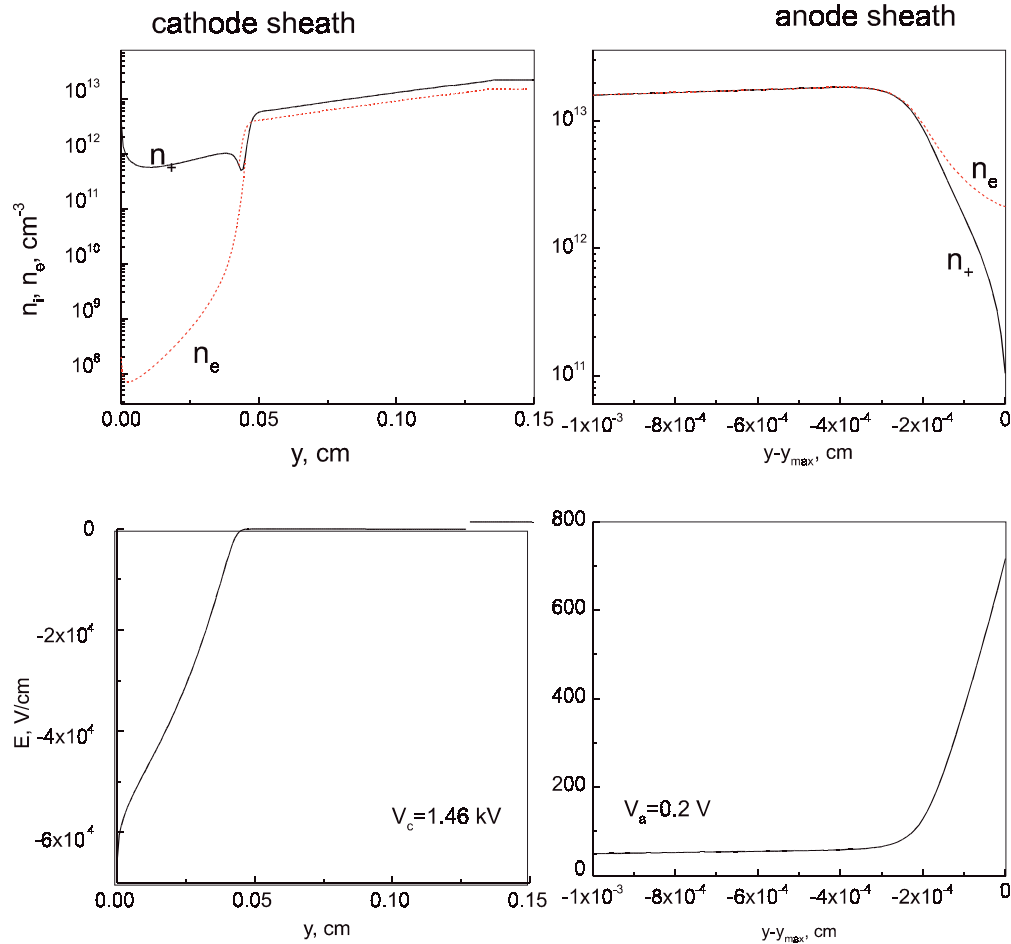


Figure 8-16. The computed cathode and anode sheath structure at 50 cm downstream from the MHD channel entrance, and the boundary layer parameters and the current density, j_y , corresponding to $B_z = 20$ T, but neglecting magnetic field effects on charged particle transport properties.

8.2.3 MHD Electrode Sheaths and Boundary Layers

Modeling of plasma flows in MHD power generators and accelerators is usually done within the framework of a single-fluid MHD model. For processes inside the plasma that are far from the walls and electrodes, this approximation is quite justified. However, because a strong transverse electric current must be sustained in the channel in order to give rise to accelerating ponderomotive (or $J \times B$) forces, pronounced cathode and anode charge sheaths are necessarily formed through which the current has to flow. In a strong transverse magnetic field, electron mobility is reduced, which can dramatically alter characteristics of the near-electrode sheaths, especially those of the anode sheath. The thickness of the sheaths can be comparable with that of the hypersonic fluid and thermal boundary layers. This can result in a strong coupling between the charge sheaths and fluid boundary layers. For example, characteristics of a charge sheath would be affected by the reduced density, high temperature, and turbulence in the hypersonic boundary layer, while the ponderomotive force could significantly increase or decrease the effective viscosity, thereby changing the boundary layer. The presence of such sheath effects clearly indicates that a multidimensional treatment is essential for understanding and predicting the performance of the MHD channel.

Two-dimensional modeling of ionized gas flow in an MHD accelerator depends substantially on the choice of the coordinate plane. In the (x, z) or (u, B_z) plane, there is no electric current, and the plasma is quasi-neutral everywhere except in near-wall regions with the thickness of the order of the Debye length. The Debye length is negligibly small in comparison with the boundary layer thickness, δ , and the voltage fall across the near-wall regions, $\Delta V_z \sim T_e$, can be neglected. Therefore, the flow in this plane can be treated with single-fluid MHD.

Much more complex is the flow in the (x, y) or (u, j_y) plane, where electric current, j_y , gives rise to the ponderomotive force directed along x . Near the electrode walls, charge separation occurs, forming the anode and cathode sheaths. It is well known that the anode voltage fall, V_a , and the anode sheath thickness, d_a , are negligibly small compared with the respective cathode-sheath values, V_c and d_c (see, for example, Ref. 18). The dramatic difference between the anode and cathode sheaths stems from the strong difference between electron and ion mobilities under normal conditions, $\mu_e / \mu_+ \sim 10^2$. However, in this case, electrode sheaths are “immersed” in hot and rarefied hypersonic boundary layers. Additionally, and very importantly, electric current in the sheaths has to flow across a strong magnetic field that substantially reduces electron mobility. Thus, one could expect boundary layers and electrode sheaths to be very different from those in conventional non-self-sustained transverse discharges.

A set of 1-D equations describing the physics of MHD electrode sheaths and e-beam kinetics is developed in the following sections. This model of the sheath/e-beam physics has been coupled to a 2-D gasdynamics solver to provide a quasi-2-D model of the MHD accelerator channel with e-beam seeding. The model of the electrode sheaths is described in Sections 8.2.3.1. The results of the 2-D computations are presented in Section 8.2.3.2.

To gain a first-order understanding of the multidimensional effects in MHD accelerators, let us determine how the presence of a strong magnetic field, B_z , and the nonuniform density profile in the boundary layer, $N(x, y)$, affects structure and parameters of cathode and anode sheaths in a hypersonic-flow transverse discharge supported by e-beams. Simple estimates show that viscous dissipation is the main heating source in the boundary layers and electrode sheaths (i.e., at all reasonable values of electric field in the sheaths), and the rate of work by viscous forces greatly exceeds the Joule heating rate:

$$|j_y E| \ll \eta u_{ext}^2 / \delta^2, (\eta + \eta_T) u_{ext}^2 / \delta^2 \quad (8-21)$$

This inequality allows one to analyze the sheath structure as an uncoupled overlay on the background of a steady flow field found from gas dynamic equations for the hypersonic boundary layer.

8.2.3.1 Charge Particle Kinetics with Inclusion of Induced Field Ionization

The transverse non-self-sustained discharge in gas flow was modeled with a standard set of continuity equations for electron and ion number densities, n_e and n_+ , plus the Poisson equation for the electric field $\vec{E}$:

$$\frac{\partial n_+}{\partial t} + d\vec{i}\vec{V}_+ = q + \alpha(E_{eff}/N) \left| \vec{\Gamma}_{e,dr} \right| - \beta n_+ n_e, \quad (8-22)$$

$$\frac{\partial n_e}{\partial t} + d\vec{i}\vec{V}_e = q + \alpha(E_{eff}/N) \left| \vec{\Gamma}_{e,dr} \right| - \beta n_+ n_e, \quad (8-23)$$

$$d\vec{i}\vec{E} = \frac{e}{\epsilon_0} (n_+ - n_e), \quad (8-24)$$

where $\vec{\Gamma}_e = n_e \vec{v}_e$, and $\vec{\Gamma}_+ = n_+ \vec{v}_+$ are the charged particle fluxes; $\vec{\Gamma}_{e,dr}$ is the “ionizing,” drift component of the electron flux (i.e., the flux without the convective component that does not contribute to electric current density); $q(y) = q_{ext} N(y) / N_{ext}$ approximates the rate of ionization produced by the e-beam; and gas density $N(y) \propto T^{-1}(y)$ is considered to be determined by the solution of the boundary layer problem. In the continuity Eqs. (8-22) and (8-23), account is also taken of electric-field-induced ionization, which may turn out to be substantial in those regions where the field is strong and the gas is rarefied. For the field-induced ionization, the conventional local Townsend approximation $\alpha = \alpha(E_{eff} / N)$ (Ref. 16) is used with the effective electric field in the case of crossed electric and magnetic field (Ref. 19):

$$E_{eff} = \left[\frac{E_x^2 + (E_y - uB_z)^2}{1 + \Omega^2} \right]^{1/2} \quad (8-25)$$

Here $\Omega = eB_z / mv_m \equiv \omega_c / \nu_m$ is the Hall parameter for electrons, $\omega_c = eB_z / m$ and ν_m are the electron cyclotron and collision frequencies. In what is to follow, we will use similar parameters for ions: $\Omega_+ = eB_z / M\nu_{in} \equiv \omega_c^+ / \nu_{in}$, where ν_{in} is the ion-neutral collision frequency. Taking into account that the strongest variation of charged particle fluxes in near-electrode sheaths occurs in the direction normal to the electrodes, an approximation $d\vec{I}\vec{V} \approx \frac{\partial \Gamma_y}{\partial y}$ can be used in Eqs. (8-22) and (8-23).

The boundary conditions at the electrode surface of the cathode are:

$$\vec{\Gamma}_e = -\gamma \vec{\Gamma}_+ \quad (8-26)$$

where γ is the effective coefficient of secondary emission and at the anode:

$$\vec{\Gamma}_+ = 0 \quad (8-27)$$

Quasi-neutral plasma density at the outer edge of the boundary layer ($y = y_{max}$) was determined by the ionization rate of $q_{ext} = 10^{20} \text{ cm}^{-3} \text{ sec}^{-1}$, which is close to the average ionization rate produced by the beam with the current density $j_b = 0.1 \text{ A/cm}^2$, initial electron energy $\varepsilon_b = 19.5 \text{ keV}$, and electron-ion dissociative recombination with the rate coefficient $\beta = 2 \cdot 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$ (that is, $n = n_{e,ext} \approx n_{+,ext} = \sqrt{q_{ext} / \beta}$).

Note that in the present research, a solution of the Poisson equation is sought along the transverse coordinate y . Longitudinal electric field is defined by the following. As is well known, for optimal performance of an MHD accelerator, Hall current should be compensated, that is, $j_x = 0$ (Ref. 20). This compensation is possible when the longitudinal electric field in the plasma is:

$$E_x = \Omega (E_y - uB_z) \quad (8-28)$$

For the conditions considered, the electric field is irrotational and therefore derivable from a potential function; the longitudinal and transverse electric field components are related by the Maxwell equation:

$$\nabla \times \vec{E} = 0, \text{ or } \partial E_x / \partial y - \partial E_y / \partial x = 0 \quad (8-29)$$

From Eq. (8-29), E_x does not vary with y when the transverse field, E_y , is constant along the flow. Ohm's law for the current density, j_y , then dictates that at $E_{y,ext} = \text{const}$, a condition $d(j_y / \sigma_{ext}) / du_{ext} = -B_z$ should be satisfied in a uniform magnetic field (Ref. 21). Thus, at quasi-constant conductivity $\sigma_{ext} \approx \text{cons}$, the current density, j_y , has to vary along the channel. In the computations, $E_x = \Omega (E_y - uB_z)_{ext}$ was assumed to be constant. This condition, of course, represents a rather crude approximation for the boundary layer and for near-electrode sheaths. A more realistic calculation of E_x would be possible only in the context of a formulation in which the electric field is determined by solving a 2-D or 3-D Poisson-type partial differential equation for the electric potential. The correct formulation and solution of this problem is the subject of an ongoing study. Results of the study will be presented in a future report.

8.2.3.2 Computational Results

Figure 8-16 (see Section 8.2.2) and Figures 8-17 through 8-20 show results from the 2-D sheath analyses. Figure 8-16 depicts the cathode and anode sheaths at 50 cm downstream from the MHD channel entrance for the boundary layer parameters and current density j_y corresponding to $B_z = 20$ T but neglecting magnetic field effects on charged particle transport properties. These magnetic field effects are included in Figures 8-17 and 8-18. As seen in these last two figures, the existence of a magnetic field perpendicular to the electric current substantially alters the structure of the sheath layers as well as the number density and electric field distributions within the sheaths. This is fundamentally due to the dependence of the charged particle mobilities on the magnetic field. The anode sheath is the one most affected since electrons that carry the current across the anode sheath experience a dramatic reduction in their mobility in the presence of a magnetic field. The thickness of the anode sheath becomes comparable to the cathode sheath, and the anode voltage fall, V_a , even exceeds the cathode fall, V_c , the effect becoming stronger with increasing B_z .

Figure 8-19 shows plots of velocity and temperature as a function of the transverse coordinate, Y . As one would expect, the accelerator ($B = +10$ T) exhibits a rapid rise in velocity, whereas the generator ($B = -10$ T) has a retarding effect on the flow stream. For the accelerator, it would appear that the velocity is very close to its maximum value at a distance of about 0.25 m, or one-half the assumed channel length. This suggests that an optimally designed MHD channel might be significantly shorter than 0.5 m.

Figure 8-20 shows the effects of two different limiting assumptions on the wall heat transfer. In the case of an adiabatic wall, the temperature reaches $\sim 4,500$ K at either electrode wall, whereas the isothermal wall is maintained at the relatively cool temperature of 300 K. The very high peaks in both of the temperature profiles are due to the wall recovery processes and the very high channel Mach number ($M = 14.5$) at the exit. To maintain a wall temperature of 300 K (isothermal wall case), it will be necessary to provide active cooling in or along the electrode walls.

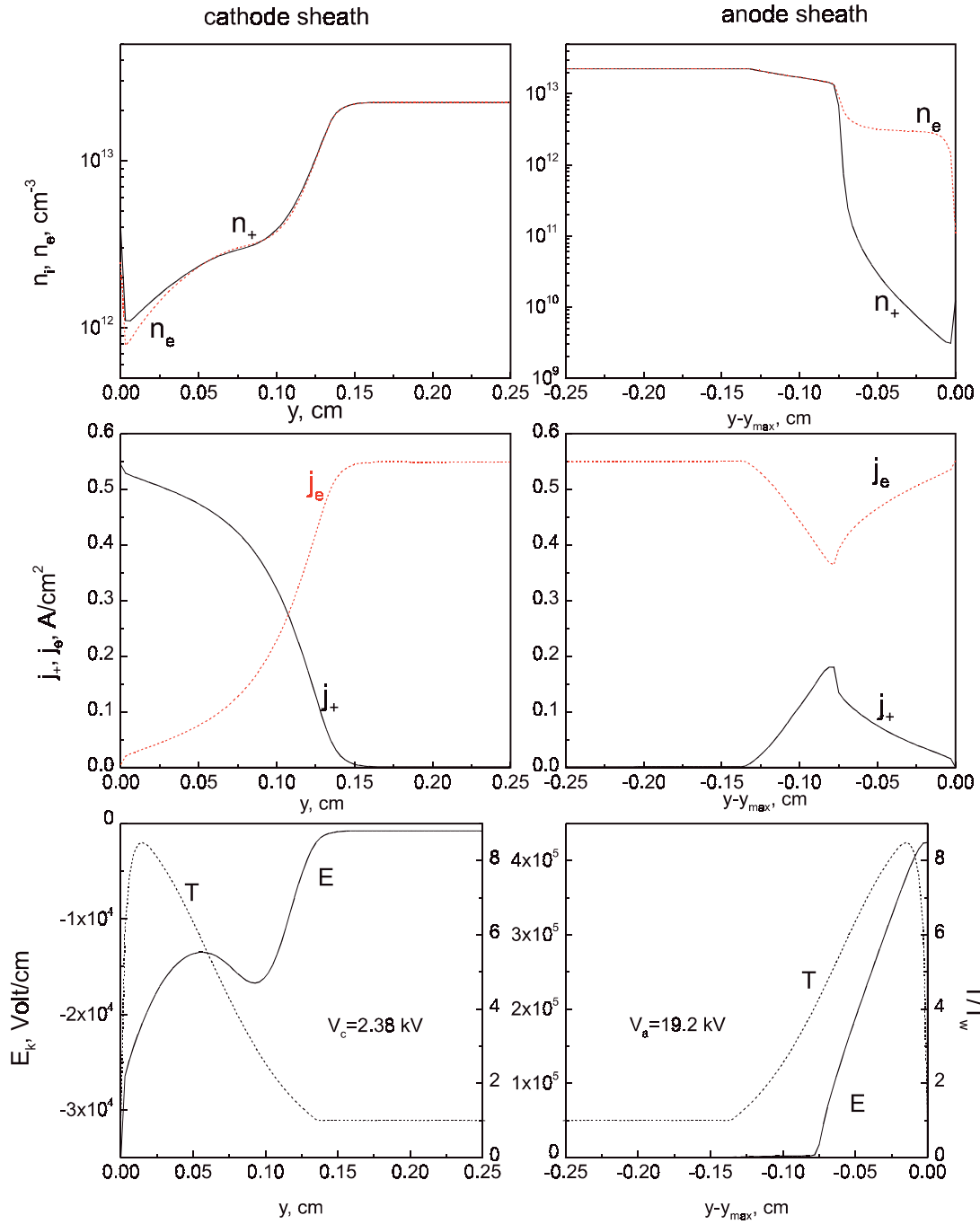


Figure 8-17. The computed cathode and anode sheath structure at 50 cm downstream from the MHD channel entrance, and a magnetic field $B_z = 20$ T, including the magnetic field effects on charged particle transport.

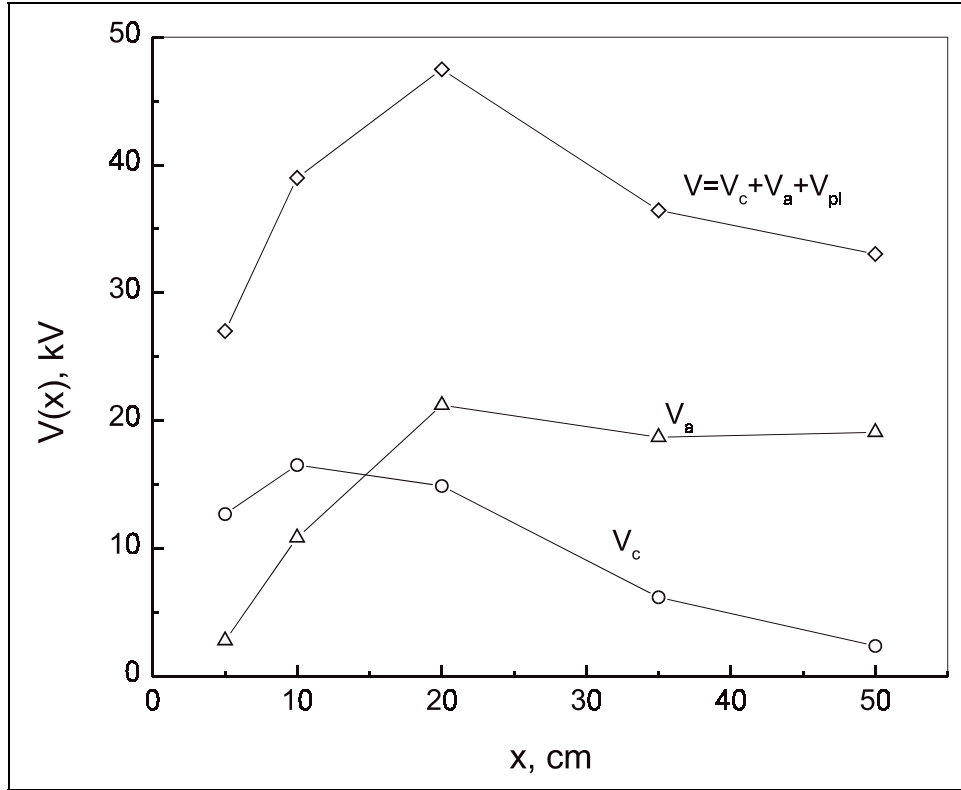


Figure 8-18. Cathode and anode (V_c and V_a) voltage falls and the total voltage V across the constant-area MHD accelerator channel versus the longitudinal coordinate for the conditions: air, $p=76$ Torr, ionization rate $q_0=10^{20} \text{ cm}^{-3}\text{sec}^{-1}$, $u_0=3,500$ m/s, $k=1.1$. A uniform magnetic field $B_z=20$ T, and uniform transverse electric field $E_y=ku_0B_z=770$ V/cm=const are assumed. (The electric current j_y varies along the channel).

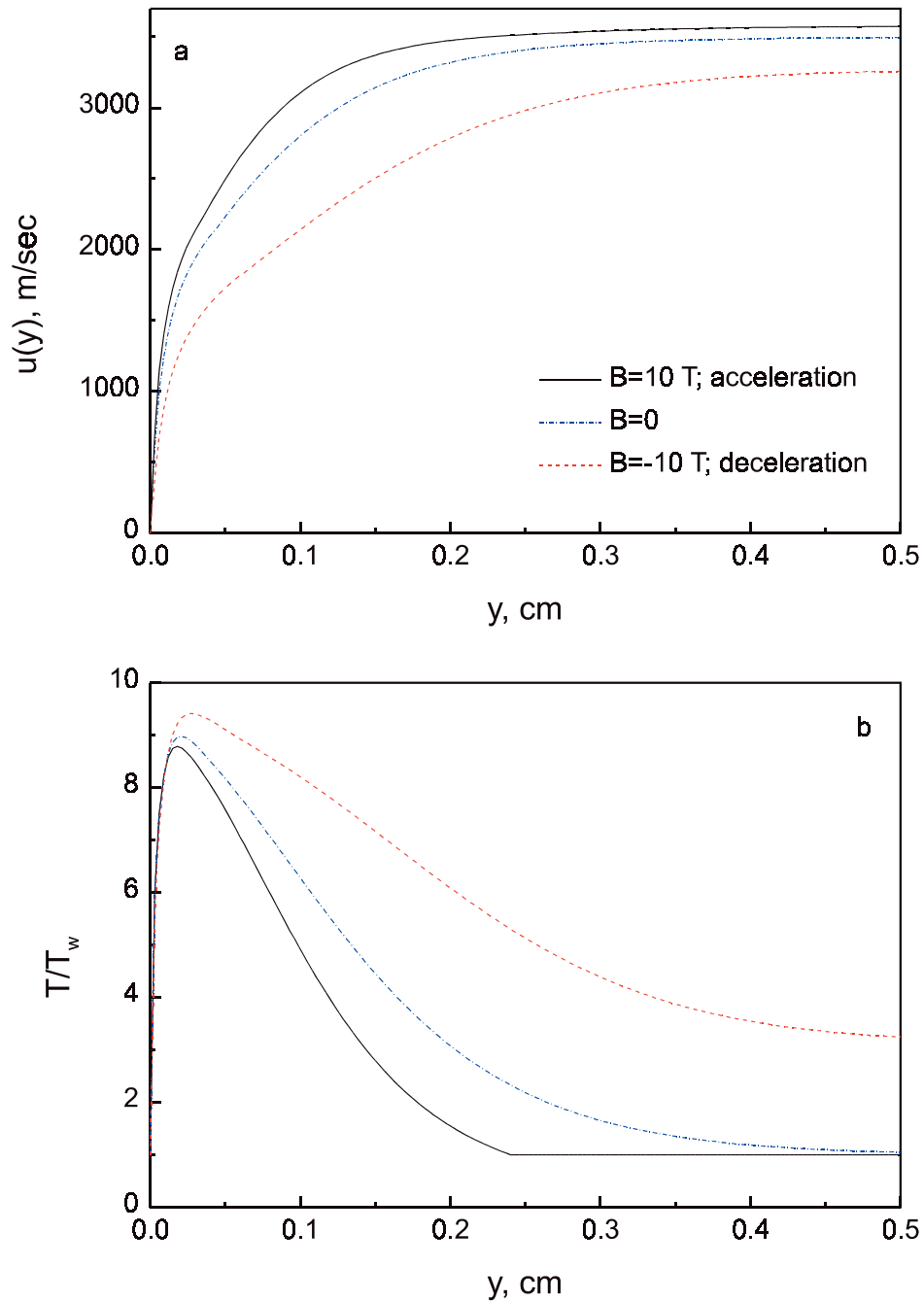


Figure 8-19. Fluid and thermal boundary layer profiles at a fixed location $x=0.5$ m from the channel inlet for a channel without a magnetic field ($B_z=0$), accelerator (positive B_z), and power generator (negative B_z). Pressure $p=p_0=const$; conductivity and transverse electric field are assumed uniform along the channel; loading parameter $k=1.1$. Free stream velocity is $u_0=3,500$ m/sec.

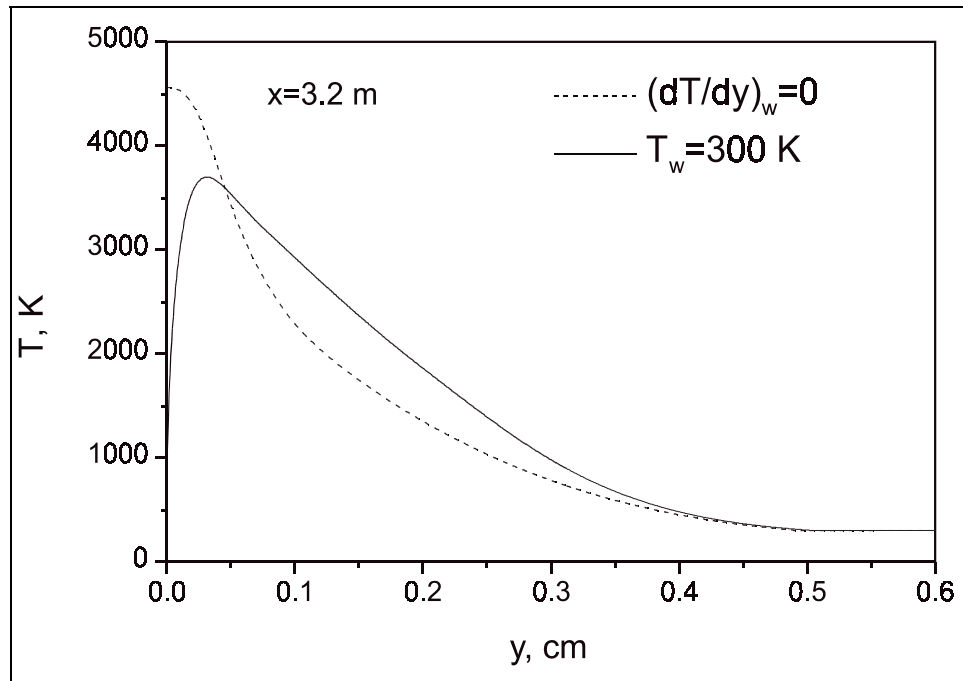


Figure 8-20. The computed temperature profile in the boundary layer at the exit of the Mach 14.5 MHD accelerator. Solid line— ideally cooled isothermal wall; dashed line—adiabatic wall.

8.2.4 Monte Carlo Methods For Analyzing Electron Beam Kinetics In MHD Accelerators

The most accurate way to compute ionization profiles generated by e-beams is to use the CYLTRAN code developed at SNL as a part of the ITS codes. CYLTRAN is a Monte-Carlo-type code computing many individual trajectories and incorporating elastic and inelastic scattering. The code was exercised (Ref. 5) for typical conditions expected in hypersonic MHD channels. Figure 8-21 shows the individual electron trajectories for 10 separate 23-keV electrons injected from the left side of the graph at $z = 0$. Note how the 7-T field overcomes the scattering from collisions with the air and keeps the electrons traveling straight across the channel. Note also how the electrons come to rest at different final locations. This effect is called straggling.

Figure 8-22 shows the energy deposition rate (in W/cm^3) for a uniform beam (which in this case means it is uniform in the x and y direction for at least several mm since that is the zone to which the magnetic field confines the beam). The solid line shows the deposition rate for a beam injected from the left side of the graph. Note how the deposition rate increases as the beam progresses and loses energy. (Lower-energy electrons deposit energy more rapidly.) However, the total deposition rate then starts to fall off due to straggling since some of the electrons come to a stop before others.

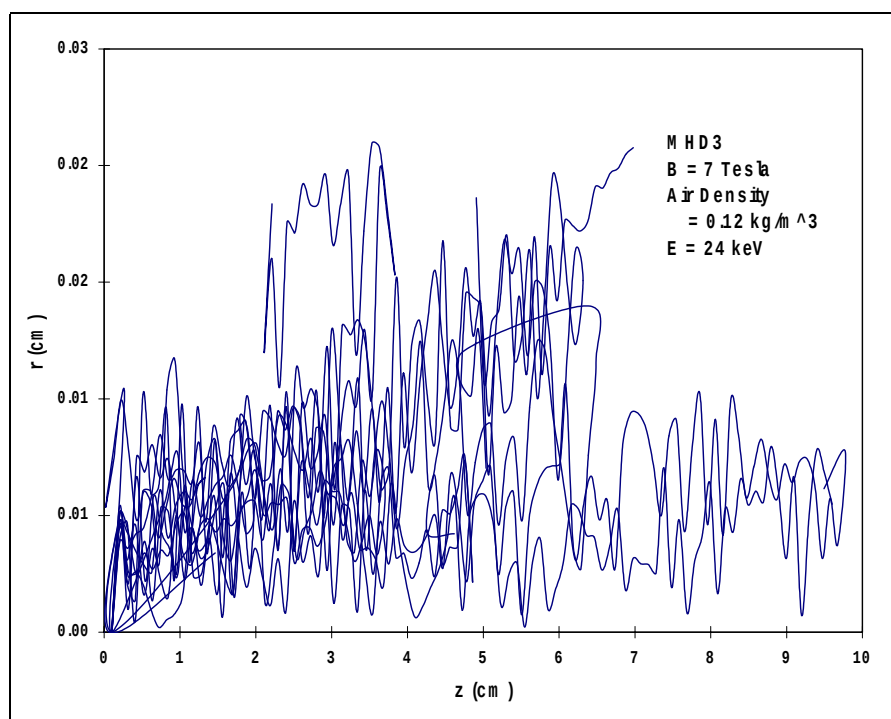


Figure 8-21. Electron trajectories from a point source. Confinement is about 0.1 mm.

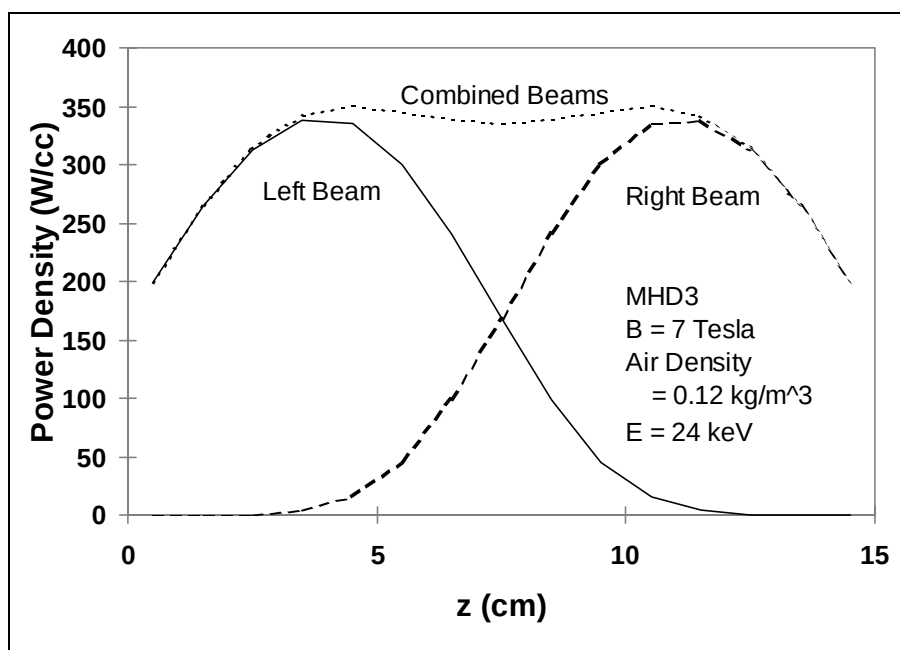


Figure 8-22. Power deposition for a uniform e-beam injected from the left (solid), right (dashed) and combined (dotted) line.

The power deposition profile will match the induced conductivity profile, so a more uniform deposition is preferred over what is shown in Fig. 8-22 by the solid line. A solution is to have another beam injected from the other side in the opposite direction. This is shown in the figure as a dashed line. The total deposition will be the sum of the two and is shown as a dotted line. It is reasonably uniform if the initial energy for both beams is 23 keV.

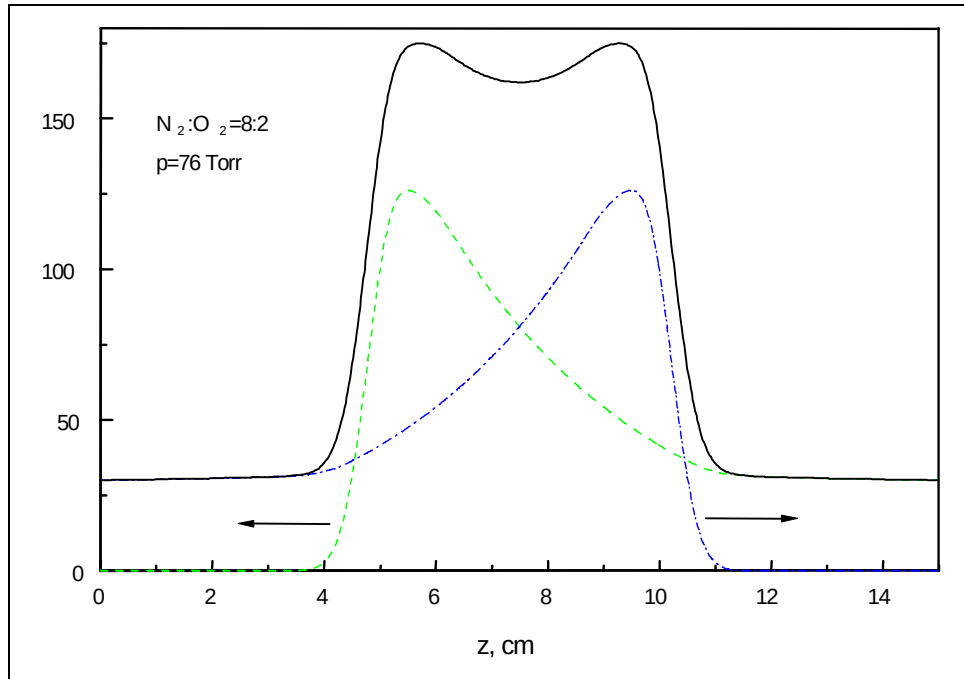


Figure 8-23. Total ionization rate across the channel q in $\text{cm}^{-3}\text{s}^{-1}$, for the unit beam flux $\Gamma(0)=1$, with two beams injected from the opposite sides.

Figure 8-23 shows the total ionization rate from the two oppositely directed beams. The conductivity profile would have essentially the same shape as the ionization rate profile.

The CYLTRAN trajectory code is capable of predicting the beam energy deposition and ionization rate profiles across the channel provided that the density profile is known. However, to build a comprehensive computational model, the beam propagation code must be coupled with 2-D or 3-D viscous gas dynamics, electrodynamics, and ionization-recombination kinetics. Monte Carlo trajectory codes are very computationally intensive, and their inclusion into full models could be done only at the expense of oversimplified kinetics and MHD.

It is noted here that the ionization rates depicted in Fig. 8-23 are based on use of the forward approximation. This approximation is equivalent to assuming that the effect of all collisions between electrons and heavy particles is to scatter electrons only in the forward direction parallel to magnetic field lines. This approximation is not an intrinsic assumption of the kinetics model but is made primarily for the purpose of reducing the computational burden and obtaining solutions within reasonable computational time. By contrast, the Monte Carlo simulations

depicted in Figs. 8-22 and 8.24 allow for electron scattering in all directions while requiring substantially greater computational time to execute. The net result is that the Monte Carlo simulations will more accurately predict the energy deposition profiles than will computations based on the forward approximation. Note that Figs. 8-22 and 8.24 (Monte Carlo/ITS simulations) depict somewhat flatter profiles with a more gradual rise from the wall regions than is shown in Fig. 8-23. It can be assumed that the ITS calculations are, in this case, somewhat more faithful to reality.

The MHD section of the MSHWT requires a broad beam of electrons passing perpendicularly through the airflow to create a high conductivity in the air that will allow it to interact with the magnetic field of the MHD accelerator. The amount of conductivity that can be produced is a function of the energy deposited by the broad e-beam, which is in turn a function of the initial beam voltage, air density, and MHD channel width. Typical conditions are 0.1-atm, 15-cm channel width, and 7-T magnetic field. The beam direction must be parallel to the magnetic field.

For such a channel width and air density, the electron energy must be around 20 keV. At this low energy, the energy deposition rate is not independent of energy (as is the case for relativistic electrons). Thus, the beam tends to deposit more energy per path length as it slows down, peaks, and then deposits less energy as individual electrons come to a stop at different locations.

The ITS electron transport simulation code was used to simulate such energy deposition. Figure 8-24 shows the results. By choosing the correct voltage for the beams, the sum can be made to be very flat. This is the proposed mode of operation for this MHD channel conductivity enhancement. It should be noted that the strong magnetic field across the channel for MHD purposes also strongly confines the electrons in the beam. It keeps them from spreading out as they travel across the channel. Figure 8-21 shows the trajectories of several electrons. Generally, they follow the field lines within about 0.1 mm.

Running the ITS code can be a tedious process. In order to have a convenient tool for modeling the beam deposition behavior, an empirical formula for e-beam energy deposition was derived. Several ITS calculations were done to determine the energy deposition profiles for a range of e-beams penetrating an MHD channel to enhance the gas conductivity. A series was run with a gas density of 0.00012 g/cm^3 (0.1 atm at 300 K) with a guiding magnetic field of 7 T perpendicular to the MHD channel wall. The beam electrons were assumed to be injected parallel to the field lines without any initial divergence.

Figure 8-24 shows the resulting energy deposition rates (solid curves) for electrons with initial energies of 20, 30, 40, 50, and 70 keV. (These are typical energies needed to penetrate an MHD channel from the side.) The deposition is given in terms of MW/cm^3 for each A/cm^2 of beam current.

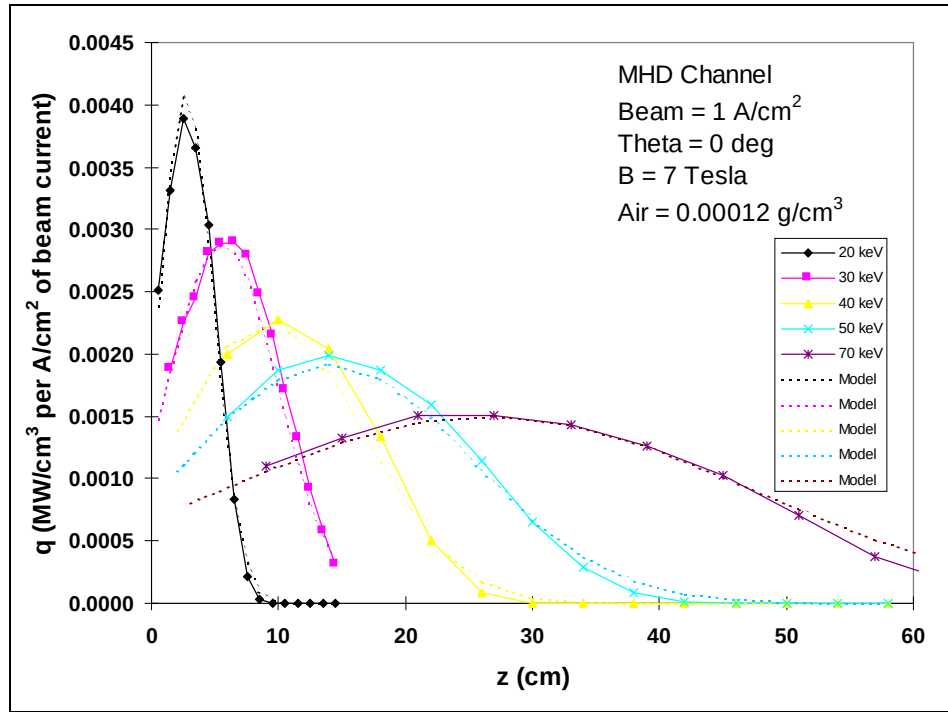


Figure 8-24. Energy deposition in MHD channel with 7-T applied field in 0.00012-g/cm³ air.

The volumetric energy deposition rate decreases, and the range increases as the initial electron energy increases. The curves may be fitted with an empirical formula in similar fashion to that shown in Section 7 (using different values of the derived constants) for the deposition rate “q,” given in terms of MW/cm³:

$$q = \left(1 \text{ MW/cm}^3\right) \left(\frac{j}{1 \text{ A/cm}^2}\right) \left(\frac{\rho}{1 \text{ g/cm}^3}\right) \left(C1 + \frac{C2}{E_0}\right) \exp\left(-\frac{(w - w_0)^2}{w_1^2}\right) \quad (8-30)$$

where

$$w = \int \rho \, dz = \rho z$$

$$w_0 = C3 \left(\frac{E_0}{1 \text{ MV}} + C4 \left(\frac{E_0}{1 \text{ MV}} \right)^2 \right) \quad (8-31)$$

$$w_1 = C5 \left(\frac{E_0}{1 \text{ MV}} + C6 \left(\frac{E_0}{1 \text{ MV}} \right)^2 \right)$$

and where E_0 is the initial electron energy (in MeV) and w , w_0 , and w_1 are in units of g/cm². There is no obvious physical basis for the formula (except possibly the Gaussian form); however, it fits the calculated curves with convenient functions.

For the range of 20 through 70 keV, the algebraic model fits the simulation reasonably well with:

$$\begin{aligned}
 \rho &= 0.00012 \text{ g/cm}^3 \\
 j &= 1 \text{ A/cm}^2 \\
 C1 &= 4 \\
 C2 &= 0.6 \text{ MeV} \\
 C3 &= 0.0045 \text{ g/cm}^2 \\
 C4 &= 130 \\
 C5 &= 0.005 \text{ g/cm}^2 \\
 C6 &= 130
 \end{aligned} \tag{8-32}$$

The results generated by this algebraic model are shown as the dotted line curve in Figure 8-24.

This formula then allows a simple way to determine the local power deposition of the beam. One keeps track of the total accumulated number of g/cm^2 the beam has passed through (w), and uses this in the above formulae along with knowledge of the current and air densities.

A computer simulation was made for a gas density 10 times higher, and the results agreed with the model well (that is, the curve fit scales correctly with gas density). Another simulation was made for a 10-T field, and the results were identical. A third simulation was made for a beam injection angle of 45 deg relative to the magnetic field, which made a significant difference. The results are shown in Figure 8-25. The energy absorption rate is increased because the path length of the beam electrons is longer due to the fact that they are spiraling more. One might expect the deposition rate to increase with $1/\cos\theta$, but it appears to be somewhat stronger. This should have some impact on the design approach.

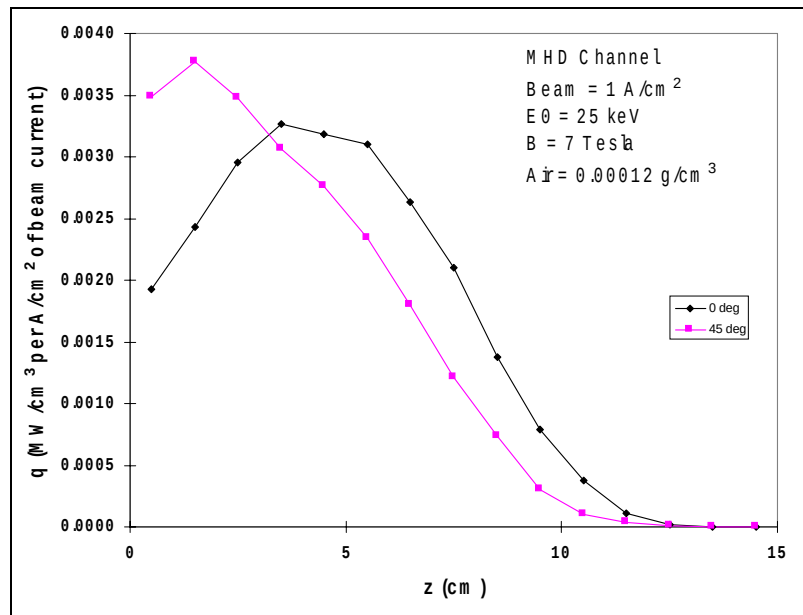


Figure 8-25. Comparison of deposition rate for 25-keV e beam injected at different angles relative to a 7-T magnetic field.

8.3 ELECTRICAL CONDUCTIVITY EXPERIMENTS

The following subsections describe experiments conducted at SNL for validating a simplified theoretical model of e-beam ionization in air. The first phase of these experiments consisted of measuring the bulk electrical conductivity of static air in a confined volume, which is uniformly irradiated by an e-beam. The experimental method is described below, preliminary data is presented, and the results are interpreted in the light of an analytic model for conductivity. The preliminary results reported below represent the first phase of a planned multiyear experimental effort to demonstrate an alternative mode of MHD accelerator operation that can potentially obviate some of the limitations of conventional MHD accelerators. Many of the results discussed below were reported in Ref. 22. However, some of the analytical results discussed below are more recent and replace much of the preliminary analysis reported in Ref. 22.

8.3.1 Objectives

The objectives of the conductivity experiments were two-fold:

- Measure the scalar electrical conductivity, σ , as a function of e-beam current density, e-beam energy, and cell static pressure.
- Use the conductivity data to validate a simplified model for conductivity. This model incorporates a very simple model for e-beam-induced conductivity and is described in some detail below.

Because of limitations in the operation of the SNL HAWK accelerator, it was not possible to adjust either the current density or the beam energy during the course of the experiment. Therefore, the only one of the three control variables that was varied in this initial set of experiments was the static pressure. For purposes of evaluating the severity of O_2 attachment, some conductivity data was also taken in N_2 . In the case of N_2 , electron attachment should be entirely negligible.

Conductivity was measured by imposing a known voltage amplitude at a specified frequency across the electrodes of a static cell that contained air at near-atmospheric pressure. To date, data has been collected at two pressures, 0.1 atm and 0.5 atm, in both N_2 and air. This data will be used to validate a particular model for the ionization kinetics in e-beam seeded air described in Ref. 22 and referred to hereafter as the e-beam-induced conductivity model, or, more simply, as the nonequilibrium conductivity model. This model was adopted as the working hypothesis for purposes of these experiments. The governing kinetics equations in the model include terms for attachment of electrons by diatomic O_2 . However, the only analytic solutions to these equations developed to date involve the simplifying assumption that attachment effects can be neglected. Because there was concern that O_2 attachment could be a significant factor in the SNL experiments, an improved solution for electron number density was developed that incorporates attachment effects. This is presented below.

The experimental apparatus consisted of an e-beam source, a specially constructed static cell through which the e-beam passed, and a high frequency multichannel oscilloscope. A signal generator, which was capable of imposing high frequency voltages across the electrodes of the cell, was also used. This made it possible to separate the applied voltage across the cell electrodes from the substantial electrical noise induced by the passage of the beam and subsequent impingement in the anode collector. The experimental apparatus is explained more fully in the following section.

8.3.2 Experimental Method

Electron beam induced conductivity measurements were performed using the HAWK accelerator at SNL. The HAWK accelerator is a Van de Graaff generator (see Fig. 8-29) that was adjusted to produce a 170.5 keV e-beam at 30 mA/cm² in a 50 μ s duration pulse. This beam energy was chosen because it was as low as HAWK would operate and still maintain a stable e-beam. It was not the optimum energy for the experiment.

The primary requirement defining the optimal beam energy is that most of the beam energy should be absorbed by the air and very little by the opposite wall. The analysis presented in Section 8.2.4 suggests that for nominal MHD channel widths of 15-25 cm, e-beam energies in the range 25–50 keV would be close to optimal at a density of 1.2 kg/meter³. Lower densities will imply somewhat lower beam energies.

The test cell, Fig. 8-26, was mounted on the output end of the HAWK beam tube.



Figure 8-26. The HAWK Accelerator.

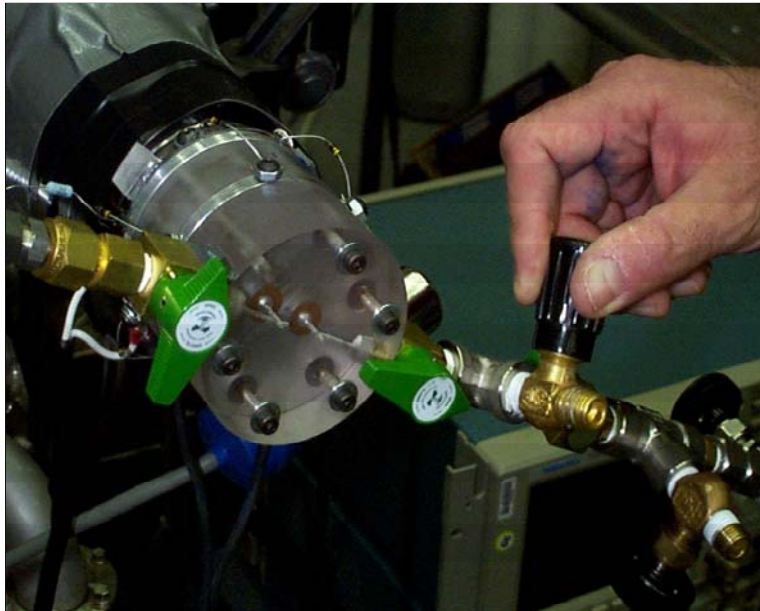


Figure 8-27. Test cell at output end of the HAWK beam.

Data was collected for dry air and dry nitrogen at 0.1 atm and 0.5 atm. The e-beam entered the test cell through a 0.01-cm-thick grounded Be foil that formed the front face (cathode) of the cell (Fig. 8-27). Since there is a vacuum inside the HAWK beam tube, the Be foil is concave inside the test cell. Therefore, the conductance of the cell is the integral of the annuli centered on the axis of the cell. The cell is 0.217 cm long from the aluminum foil anode to the chord of the arched Be foil and 0.03 cm from the center of the chord to the center of the Be foil. The radius of curvature of the foil is 4.116 cm and the diameter of the aperture in the test cell is 1.0 cm. With these dimensions, the annular conductances may be integrated to yield:

$$\sigma = 29.4/R \text{ [mhos/meter]} \quad (8-33)$$

where σ is the e-beam induced conductivity of the gas in mhos/meter and R is the measured resistance of the cell in ohms. For this relationship to be accurate, the e-beam must uniformly ionize the gas in the test cell. In part, this means that the e-beam must not vary in energy or intensity as it passes through the test cell.

A Monte Carlo-based coupled electron/photon radiation transport code, CYLTRAN (Ref. 10), was used to verify that the test cell was short enough in the beam direction to allow essentially all of the beam to pass through and retain most of its energy. Estimates of beam energy deposition based on Fig. 8-25 indicated that less than 1 percent of the incident beam energy would be absorbed within the cell. After passing through the 0.01-cm Be foil, the beam has an extremely large divergence. Some of the emerging electrons go almost tangent to the surface of the foil. In order to force as much of the e-beam as possible to pass through the test cell, the cell was made short in the axial direction. Transverse beam uniformity was also an issue. Since the intensity cross section of the beam inside the HAWK beam tube is intrinsically Gaussian, it was necessary to spread the diameter of the beam much larger than that of the test cell aperture. By using just the

central part of the beam, much of the current was lost, but the intensity was uniform over the cross section to within ± 6 percent. Initially, a measurement was attempted of the current into the test cell by applying a DC test voltage to the cell. At the time it was thought that electron sweep-out would not be a problem if this applied voltage were kept below 5 volts (it is now known that it is a problem). In addition, the carbon beam-stop was located adjacent to the diagnostic anode. When the e-beam struck the anode, it caused a -15 volt offset, resulting in a net -10 volt offset on the anode foil relative to the cathode foil. This DC offset caused the cell resistance to be several thousand ohms due to electron sweep-out, so that the current flowing in the current viewing resistor (CVR), due to the conduction current induced in the test cell was only about 1 mA, while the beam current contribution was close to 30 mA. Under these conditions and in the presence of noise, it was impossible to measure the induced conduction current in the test cell.

This problem was solved by adopting the experimental configuration shown schematically in Figs. 8-28 and 8-29. First, a sinusoidal diagnostic signal was applied in order to distinguish it from the pulse caused by the arrival of the beam at the anode. Second, the amount of beam current flowing through the CVR was reduced by using a 0.0013-cm thick aluminum foil diagnostic anode and a separate carbon beam-stopping anode. The aluminum foil anode is referred to as the diagnostic anode because the test cell resistance is measured between it and the Be foil cathode. Since the diagnostic anode foil is thin and fabricated from a low-density material, most of the beam that passes through the test cell also passes right through the anode foil and is intercepted by the carbon beam-stop anode. The beam current that is captured by the carbon beam-stop is returned to the ground of the HAWK accelerator through another CVR, so it functions as a Faraday-Cup probe, which allows for the monitoring of the beam current that passes through the test cell.

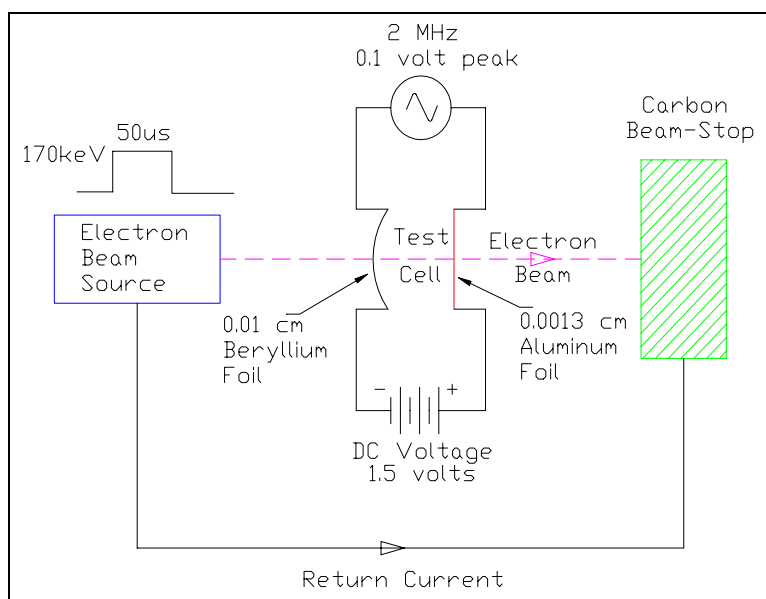


Figure 8-28. Block diagram of static cell test rig.

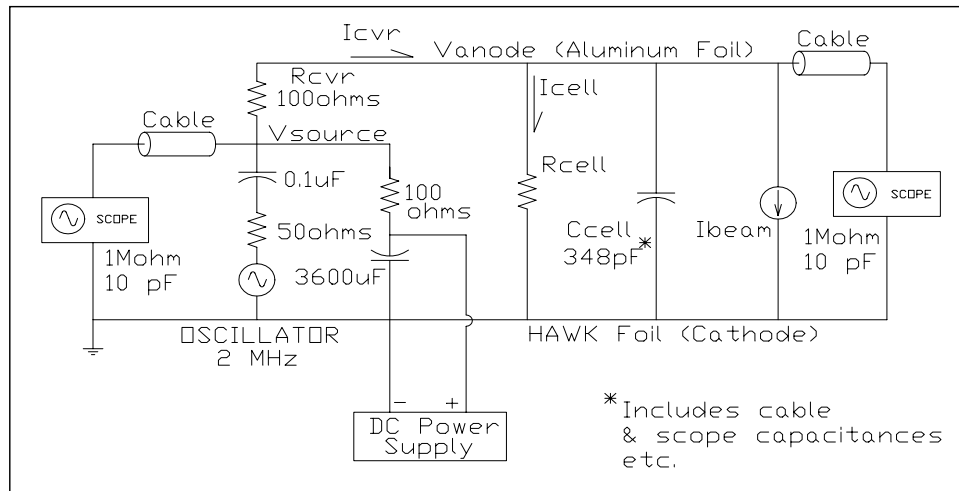


Figure 8-29. Circuit diagram of the experimental set-up used to determine the test cell resistance foil.

The circuit diagram (see Figure 8-29) was developed to model the experimental set-up. The capacitance of the diagnostic cable (which includes the oscilloscope input capacitance) and the capacitance of the test cell itself appears across the test cell and must be included in this model for correct results. Since one of the oscilloscope channels was applied directly across the test cell, the oscilloscopes were operated in the high impedance mode so as not to short out the test cell. This made the capacitance of the diagnostic cable and the oscilloscope input critical. As seen in this circuit diagram, a CVR was located between the sinusoidal excitation source and the diagnostic anode. The excitation current that flowed into the test cell was determined by vectorially subtracting the voltage across the cell from the source excitation voltage and dividing the amplitude of the resultant sine wave by the value of the CVR. Part of this current flows into the capacitances across the test cell, and part of it flows through the cell resistance. A simple calculation yields the part of the current that flows through the cell resistance. This current is divided into the voltage measured across the test cell to obtain the resistance that is used in Eq. (8-33) to calculate the conductivity of the ionized gas. All of these calculations were implemented in a Microsoft Excel spreadsheet.

To avoid problems with electron sweep-out, the peak amplitude of the diagnostic sinusoid was limited to approximately 0.1 volt, and the DC power supply was adjusted so that it would cancel the voltage offset caused by the e-beam hitting the anode. Since the resistance of the ionized test cell is approximately 100 ohms, the current in the cell with the CVR is only about 1 mA. Consequently, the vector voltage difference across the CVR is very noisy and it is difficult to determine its peak amplitude. To solve this problem, the voltage data was fit to an ideal sinusoid having the same frequency as the signal generator. A least-squares algorithm was used to determine the amplitude and phase, and then the amplitude of the ideal sinusoid was used to calculate the cell resistance in the Microsoft Excel spreadsheet.

The test cell was prepared for each shot by keeping it evacuated to 150 millitorr until the leak rate produced less than a 6 Torr/hour rise. The vacuum port was then closed and the test gas valve

opened slightly until the partial vacuum in the test cell reached the desired value. The partial vacuum in the test cell was measured using a digital Granville-Phillips™ 275 convectron gauge.

A four channel digitizing oscilloscope was used to simultaneously measure the sinusoidal oscillator output, DC and sinusoidal voltage across the test cell, beam current captured by the beam stop, and the beam current inside the HAWK accelerator beam tube. This oscilloscope was externally triggered 20 μ s after the trigger pulse to the HAWK accelerator. The delayed trigger sampled the test cell parameters well after from the transients that occurred at the both onset and cutoff of the e-beam. The frequency of the diagnostic oscillator was chosen so that at least 25 cycles would occur in the 50 μ s duration of the beam. Only a single cycle was used to calculate the test cell resistance.

8.3.2.1 Calibration

A number of factors affect the calibration of the data acquisition system (DAS). These include data cable connectors, attenuator calibration factors, oscilloscope input impedance, and oscilloscope channel gains. All were accounted for by using the DAS and computational algorithms to measure known carbon resistors connected across the test cell electrodes, with the HAWK accelerator not energized. As is shown in Figure 8-30, data was taken across a number of shots to demonstrate that the apparatus could correctly measure a 199.3-ohm resistor, which was placed in the circuit. As the figure indicates, all of these measurements are within ± 3 percent of the exact value of 199.3 ohms, and this was considered an adequate calibration for the purposes of this experiment.

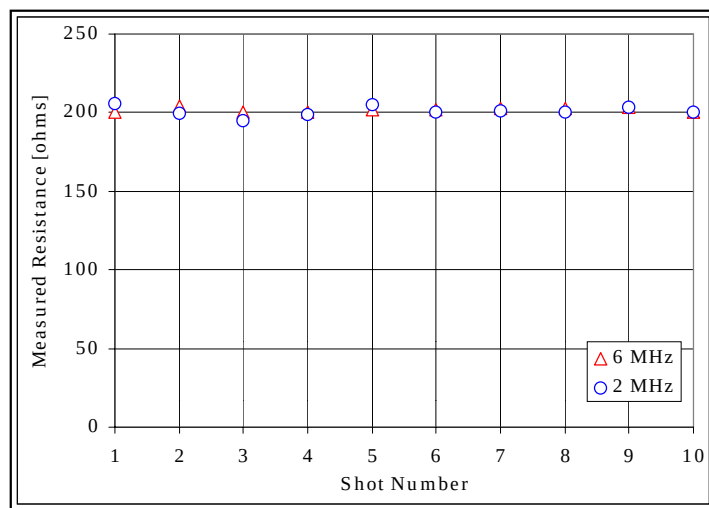


Figure 8-30. Measurements of a 199.3 ohm resistor at 2 and 6 MHz.

The objective of these experiments was to determine the e-beam induced conductivity in the absence of electron sweep-out. Sweep-out is most likely to be a problem at lower pressures, since there are fewer electrons available to sweep-out. In addition, when the gas in the test cell contains O₂, sweep-out is more likely to be a problem, since electron/O₂ attachment reduces the number of

available electrons. For this reason, all tests for sweep-out were performed with dry air at 80 Torr. Measurements were taken with various voltage offsets, see Fig. 8-31, and it was found that the offset must be as small as possible or sweep-out would be an issue. Reducing the voltage offset from 1.8 volts to 0.15 volts while holding the pressure at 80 Torr and the diagnostic frequency at 1 MHz causes the resistance of the test cell to go from 290 ohms to 184 ohms, thereby indicating that the voltage offset was causing electron sweep-out. To determine if sweep-out was affecting the measurements with zero voltage offset, the frequency was varied. If sweep-out was occurring, then the resistance of the test cell would go down as the frequency is increased, since the test cell voltage spends less time at either polarity at higher frequencies.

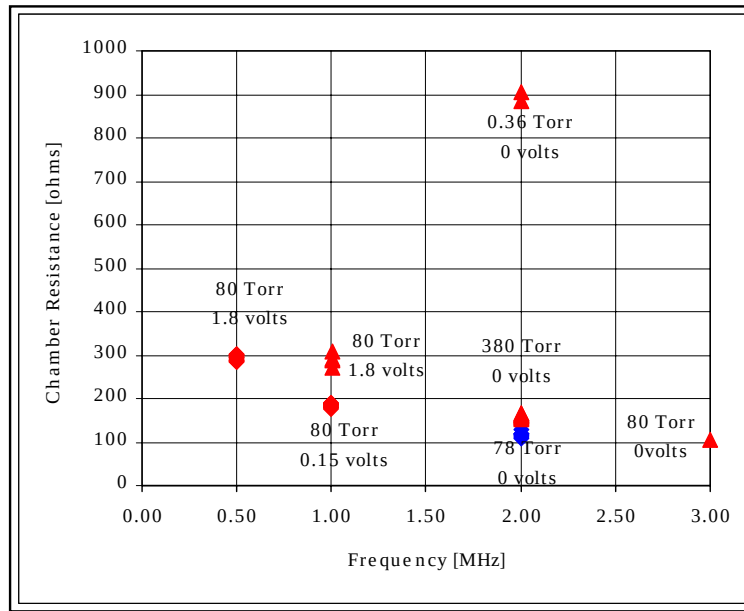


Figure 8-31. Variation of cell resistance as a function of frequency, pressure and DC offset.

It was determined that with a 0.1-volt peak sine wave and zero voltage offset on the test cell, measurements taken at both 2 MHz and 3 MHz yielded the same resistance at 80 Torr. Therefore, sweep-out was probably not occurring at frequencies at or above 2 MHz.

As a final test, measurements were taken with the test cell pressure reduced to 0.36 Torr to verify that the resistance would be high.

8.3.3 Analysis of Electrical Conductivity and Ionization Kinetics

The MHD process requires that free electrons be present to interact with the static electric and magnetic fields. Moreover, the electrical conductivity, which is proportional to the electron number density, must be sufficient to permit substantial acceleration to be achieved in a reasonable duct length. In general, if we assume that ion slip can be neglected, the generalized Ohm's Law takes the form:

$$\underline{J} = \underline{\Sigma} \left(\vec{E} + \vec{U} \times \vec{B} \right) \quad (8-34)$$

where $\underline{\Sigma}$ is the conductivity tensor. For an applied magnetic field $\vec{B}$ in the z-direction, the tensor takes the form:

$$\underline{\Sigma} = \sigma \begin{bmatrix} \frac{1}{1 + \beta^2} & \frac{-\beta}{1 + \beta^2} & 0 \\ \frac{\beta}{1 + \beta^2} & \frac{1}{1 + \beta^2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (8-35)$$

In the above relation, β is the Hall Parameter, $\beta = \mu B_z$, where μ is the electron mobility. The parameter σ is the scalar conductivity. Note that in the limit of zero magnetic field, the conductivity tensor becomes equal to the scalar conductivity multiplied by the identity tensor (that is, the conductivity tensor reduces to a scalar multiplier of the electric field).

In planning the overall test campaign, the form of the conductivity tensor has served as a guide to the testing. Thus, in the initial test series, referred to as Phase 1, a static test cell was used with no applied magnetic field (that is, both the magnetic field, B , and the flow velocity, U , were set to zero). In this limit, the experimental apparatus could be kept conceptually simple while still permitting a measurement of σ . The experimental apparatus for these early tests consisted of a sealed, static test cell with thin metallic foils on each of two sides of a short Lexan cylinder. By applying a known field E across the two foils and measuring the current due to thermalized electrons, the scalar conductivity could be inferred. This is described in greater detail in the following sections.

In the second phase of tests, it is planned that a magnetic field will be imposed while maintaining a zero flow velocity. Finally, it is ultimately planned that data will be taken in an operational MHD channel, for which both the flow velocity and the magnetic field are nonzero. The above relationships for conductivity require a model for σ and μ be specified. For conventional MHD processes in which thermal equilibrium determines the degree of ionization, a model based on the Saha Equilibrium Equation for electron number density is adequate. In the present case, where impact ionization by e-beams is the dominant ionization process, a finite rate kinetics model is necessary. Such a model has been developed by Macheret et al. (Ref. 1). Because the model is central to the experimental effort, it is summarized below.

The assumptions of the kinetics model are: 1) impact ionization is the dominant process creating free electrons; 2) free electrons are annihilated through several other kinetics processes such as attachment by diatomic O_2 and dissociative recombination with NO molecules; and 3) other kinetic processes, namely detachment processes involving O_2^- and production of NO_2 , contribute to the production of free electrons.

These processes give rise to a set of kinetics equations for number densities of electrons, positive ions, and negative ions. These governing kinetics equations are:

$$\dot{n}_e = \frac{j_b Y \rho}{e W_i} - k_{dr} n_e n_+ - k_a n_e [O_2]^2 + k_{d,eff} n_- n \quad (8-36)$$

$$\dot{n}_+ = \frac{j_b Y \rho}{e W_i} - k_{dr} n_e n_+ - k_r n_+ n_- \quad (8-37)$$

$$\dot{n}_- = k_a n_e [O_2]^2 - k_{d,eff} n_- n - k_r n_+ n_- \quad (8-38)$$

From these equations, it was shown by Macheret (Ref. 1) that for steady conditions in the MHD channel, the electron number density, designated as n_{e0} , is given by:

$$n_{e0} = \sqrt{\frac{j_b Y \rho}{e W_i k_{dr}}} \quad (8-39)$$

The expression for conductivity is then given by:

$$\sigma = \frac{e^2 n_{e0}}{m v_c} = \frac{M}{k_{en} m} \sqrt{\frac{j_b Y}{W_i k_{dr} \rho}} \quad (8-40)$$

The derivation of the above expression depends critically on the assumption that attachment of electrons by O_2 can be neglected. For some representative conditions prevailing in MHD channels, this assumption may be questionable. More general expressions for electron density and conductivity, which include attachment effects, are developed below. The analysis proceeds on the basis of two assumptions: 1) the terms proportional to $k_{d,eff}$ can be neglected on the grounds that the impact ionization process dominates over detachment of electrons from negative ions; 2) the overall kinetics comes to steady conditions very rapidly, so that the left-hand side of Eqs. (8-36) through (8-38) can be set to zero. This is equivalent to assuming quasi-steady conditions at all times. In solving the above set of rate equations, note that the three rate equations presented above are linearly dependent, although any two of them are linearly independent. This situation derives from the constraint of charge conservation:

$$n_e + n_- = n_+ \quad (8-41)$$

For this reason, Eqs. (8-36) through (8-38) are replaced by Eqs. (8-36), (8-37), and (8-38). This revised equation set constitutes a linearly independent, closed set of equations that determine the number densities. It is convenient to introduce three dimensionless parameters α , γ , χ defined by:

$$\begin{aligned}
\alpha &= n_{e1} / n_{e0} \\
\gamma &= k_{dr} / k_r \\
\chi &= n_e / n_{e0}
\end{aligned}
\tag{8-42}$$

Where n_{e1} is a characteristic number density based on attachment and dissociative recombination:

$$n_{e1} = \frac{k_a [O_2]^2}{k_{dr}} \tag{8-43}$$

The above nondimensionalization scheme, along with the assumption that Π is a fixed numerical constant, enables the set of three algebraic equations to be reduced to a single equation that expresses the electron density χ implicitly as a function of α . The parameter Π is the dimensionless electron number density, and α is a dimensionless measure of the importance of electron attachment by O_2 . The following values of the rate constants were taken from Raizer (Ref. 16):

$$\begin{aligned}
k_r &= 3.0 \times 10^{-7} \text{ cm}^3/\text{s} \\
k_{dr} &= 1.5 \times 10^{-7} \text{ cm}^3/\text{s} \\
k_a &= 2.5 \times 10^{-30} \text{ cm}^6/\text{s}
\end{aligned}
\tag{8-44}$$

These yield the value $\Pi = 0.5$. Algebraic reduction of Eqs. (8-36), (8-37), and (8-38) with the left-hand side of Eqs. (8-36) and (8-37) set to zero yields the following implicit equation for χ as a function of α :

$$1 - \alpha\chi - \frac{\chi^2}{2} \left[1 + \sqrt{1 + 2\alpha/\chi} \right] = 0 \tag{8-45}$$

Equation (8-45) was solved numerically using a standard root solver subroutine. The resulting plot of χ vs. α is shown in Fig. 8-32. The figure shows that when attachment is negligible ($\alpha \ll 1$), the solution is (to good approximation) $\chi = 1$ or $n_e = n_{e0}$, which is in agreement with the analysis of Macheret. When attachment is the dominant mechanism ($\alpha \gg 1$), the solution is $\chi = 0$, which is consistent with the fact that nearly all electrons released by ionization have been attached to O_2 molecules. The region $0.1 < \alpha < 10$ can be described as a transition zone, in which attachment is becoming an increasingly important effect.

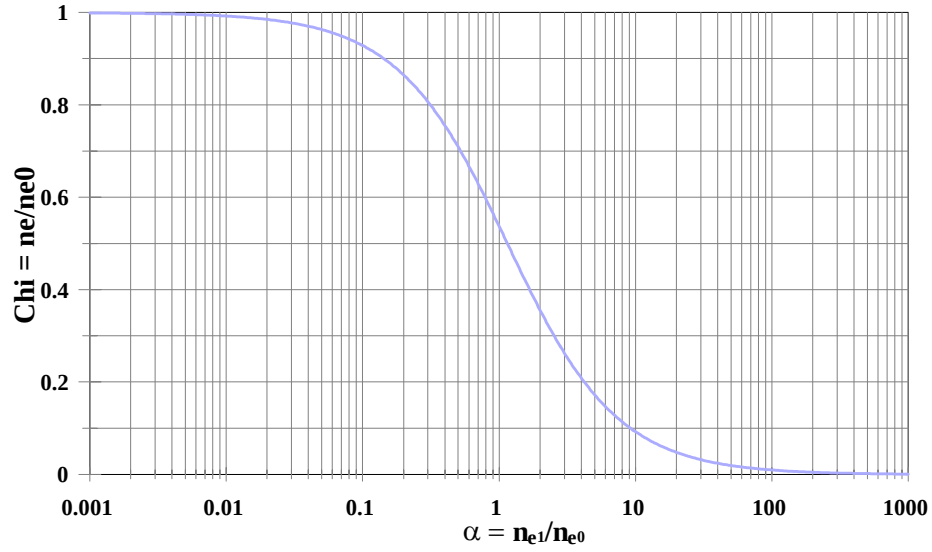


Figure 8-32. Solution to the e-beam kinetics equations.

Electrical conductivity is now given by a slightly generalized form of Eq. (8-40), namely:

$$\sigma = \frac{e^2 n_{e0}}{m v_c} \chi(\alpha) \quad (8-46)$$

Some care must be taken in the interpretation of the collision frequency v_c . For the case considered here where there is no applied magnetic field, the collision frequency is obtained by averaging over a distribution function, which is isotropic in velocity space. When a magnetic field is present, the collision frequency, v_c , must be replaced by the momentum collision frequency, v_m , defined by:

$$v_m = v_c [1 - \overline{\cos(\theta)}] \quad (8-47)$$

The bar in the equation denotes an averaging over all directions, noting that the distribution function is no longer isotropic. In the present research, v_c was evaluated from the electron mobility, μ_e :

$$v_c = \frac{e}{m \mu_e} ; \mu_e = \left(\frac{6000 \text{ pa}}{P} \right) \left(\frac{T}{300 \text{ K}} \right) \frac{\text{meter}^2}{\text{volt sec}} \quad (8-48)$$

The expression for electron mobility was obtained from Raizer (Ref. 16) but has been corrected for temperature effects.

Since the objective of the Phase 1 experimental effort was to measure conductivity as a function of pressure, it is of interest to develop plots of conductivity vs. pressure based on the kinetics model just described. Equations 8-44 through 8-48 were used as the basis of a spreadsheet calculation to compute conductivity as a function of pressure for specified beam current density and beam energy. The results are shown in Fig. 8-34. It should be emphasized that ∇ is a quadratic function of diatomic O_2 concentration; thus, as pressure increases, attachment effects are expected to increase dramatically and conductivity is expected to be correspondingly depressed. Pressure also influences the collision frequency ν_c , as shown in Eq. (8-48).

Note these results are obtained only in the low temperature limit, where dissociation is minimal. In Fig. 8-33 experimental data for air and for nitrogen are compared to a theoretical prediction of the electrical conductivity in air with no correction for electron attachment. Figure 8-34 shows the predicted conductivity for air at 300 K for an e-beam having a current density into the test cell of 35 mA/cm^2 and a beam energy of 120 keV. The same figure shows the theoretical predictions for electrical conductivity of air corrected for electron attachment and without electron attachment, compared to the experimental data for air. The shaded rectangles in the figure represent the range of experimental bulk conductivities computed from the current and voltage data collected to date by SNL research staff.

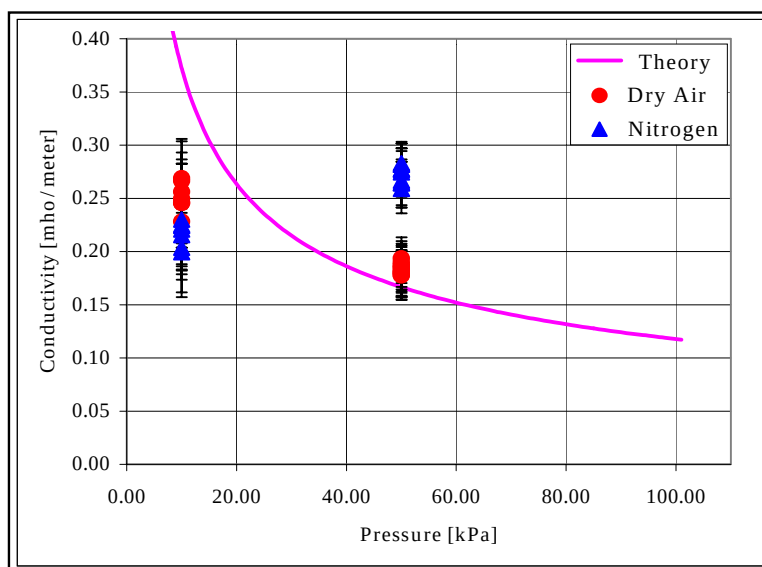


Figure 8-33. Comparison of experimental measurements to theory for dry air and nitrogen at 0.1 and 0.5 atm, 300 K.

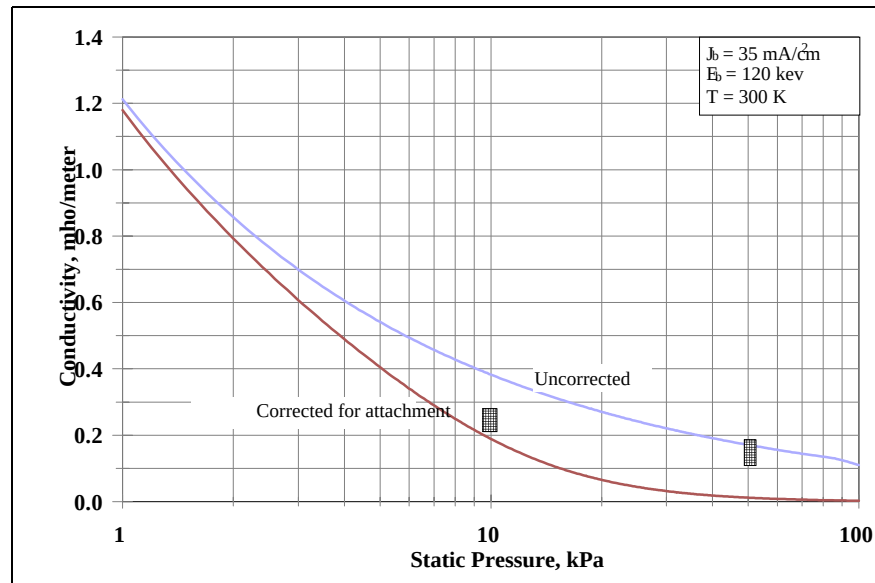


Figure 8-34. Predicted conductivity vs. pressure for air at a temperature of 300 K under conditions representative of the SNL conductivity experiments. (Note: the shaded rectangles denote the range of data collected for air in the SNL experiments.)

The significant conclusion to be drawn from this plot is that the two theoretical curves provide upper and lower bounds for the experimental data. These results provide at least preliminary confirmation of the conductivity model described above.

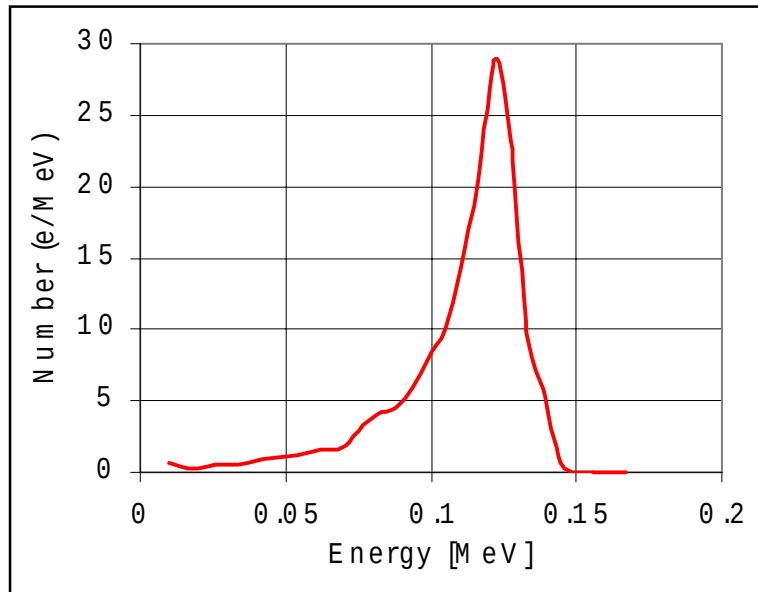


Figure 8-35. Energy distribution of e-beam.

8.3.4 Results

The goal of these experiments was to collect data for e-beam induced electrical conductivity in dry air and dry nitrogen at 0.1 atm and 0.5 atm at 300 K. Data was obtained at different pressures, frequencies, and voltage offsets in order to verify that electron sweep-out was not occurring. It was determined that electron sweep-out would not occur even at 0.1 atm in air if the voltage offset is 0 ± 0.05 volts, the frequency is equal or greater than 2 MHz, and the peak voltage amplitude is equal or greater than 0.1 volt. For this reason, the four data sets were measured under these conditions.

The energy of the e-beam in the vacuum at the output end of the HAWK accelerator was 170.5 keV. Analysis using the CYLTRAN code indicates that after passing through the 0.01-cm thick Be foil and into the test cell, the beam energy peaks at 120 keV and is approximately 20 keV wide at the half maximum. The beam current density as measured in the test cell using the beam-stop Faraday probe was 30 ± 4.2 mA/cm² the test cell.

The measured conductivity data is compared to the theoretical conductivity for dry air and nitrogen as a function of pressure in Fig. 8-33. The theoretical curve shown is for dry air and does not include the corrections for O₂ attachment discussed above. The sources of uncertainty in the measurements are summarized in Table 8-1. The uncertainty in these measurements were considered to be the same for both gasses. A pressure uncertainty of approximately ± 2.5 percent at both 0.1 atm and 0.5 atm was estimated. This variation was put into the theoretical model to determine the uncertainty in conductivity given in Table 8-1 below. The parasitic capacitance C across the test cell could be determined to within ± 10 percent. Electron beam current density J could be controlled to within ± 4 percent and the uniformity to within ± 6 percent. The theoretical model was used to estimate the resultant uncertainty in the conductivity.

Sine wave distortion from the diagnostic oscillator and noise were each estimated to cause an uncertainty in conductivity of about 10 percent. Since the test chamber had an O-ring on the front face (HAWK side), the chamber length could vary from 0 cm to +0.025 cm. The effect of this variation on conductivity is determined in the calculation of the proportionality constant between R and σ in Eq. (8-33). As mentioned earlier, the uncertainty in the measurement of the cell resistance caused by DAS calibration is approximately ± 3 percent. The corresponding variation in the measured conductivity is calculated from Eq. (8-47). The overall error bars are obtained from the square root of the sum of the squares of the individual uncertainties.

Table 8-1. Estimated variation in conductivity (mhos/m) due to uncertainty in various parameters.

Operating Pressure (atm)	Pressure	C	J	Distortion	Noise	Chamber Length	DAS Calibration	Error Bars
0.1 atm	0.0045	0.006	0.035	0.003	0.003	0.003	0.009	0.037
0.1 atm	-0.0045	-0.010	-0.040	-0.003	-0.003	0	-0.009	-0.042
0.5 atm	0.007	0.006	0.015	0.003	0.003	0.003	0.009	0.020
0.5 atm	-0.007	-0.010	-0.018	-0.003	-0.003	0	-0.009	-0.023

8.3.5 Conclusions

Several conclusions may be drawn from the above analysis of the experimental data and the kinetics model. First, an analysis of the kinetics equations enables one to identify a parameter χ that characterizes the regime in which attachment of electrons by diatomic O_2 will be important. For air close to standard temperature, O_2 attachment appears to be an important, even dominant, process with respect to e-beam kinetics at static pressures in excess of 0.1 atm. This agrees generally with other analyses of the same problem (Ref. 23). This conclusion has important implications for the demonstration of e-beam-seeded MHD acceleration. It appears that for such a concept to be feasible, it will be necessary to operate at subatmospheric pressures in the MHD channel, at pressures as low as 0.1 atm. An important point relevant to this discussion is that operating the MHD channel at subatmospheric pressures necessarily implies operation at high channel Mach numbers. This is due to the very high total enthalpy and high static pressures upstream of the MHD channel. In addition, if the Joule heating is to be kept small (a desirable mode of operation), then it will be necessary to operate at low current densities and high magnetic fields in order to obtain significant body force acceleration ($J_y B$). This reasoning is confirmed in the recent analytical study by Macheret et al. (Ref. 5) in which current densities of approximately 100 mA/cm^2 were specified with magnetic fields as high as 20 Tesla. These high field strengths were required to obtain substantial acceleration of the air through the MHD channel while minimizing Joule dissipation.

With respect to the static cell conductivity measurements, preliminary data taken in air using the HAWK e-beam accelerator appear to agree with the first order kinetics model developed by Macheret (Ref. 1). The predictions of the theory agreed to within 40 percent–50 percent with the conductivities inferred from the static cell resistance measurements. The experimental conductivity data was consistently bracketed by the two limiting theoretical curves representing conductivity vs. pressure with and without corrections for O_2 attachment. This statement holds only for air. For nitrogen, there appears to be an anomalous trend in the conductivity/ pressure relationship, inasmuch as the measured conductivity increases in passing from 0.1 to 0.5 atm of cell pressure. This was unexpected and is at this point unexplained.

8.3.6 Recommendations for Future Research

As noted in Section 8.3.1, it was not possible to collect conductivity data for varying current densities or varying beam energies. This is due to limitations in the mode of operation of the HAWK accelerator and to some extent, the limitations in the e-beam foil. It is recommended that MSE conduct a study to determine whether it is economically feasible to acquire an alternative e-beam source with greater flexibility in terms of beam energy. It would be desirable to control beam energy over the range 20–100 keV, with currents in the range $1\text{--}50 \text{ mA/cm}^2$.

Near term efforts should be focused on collecting a more comprehensive set of conductivity data for zero magnetic field and velocity. Specifically, additional conductivity data should be collected at several additional pressure values, beam energies, and current densities for the purpose of providing further validation in the kinetics models. In the long term, data should be taken with a magnetic field applied both parallel and transverse to the beam current. This could provide validation for more sophisticated models of MHD interactions.

8.4 MHD INTEGRATED SIDEWALL AND WINDOW DESIGN

The purpose of this phase of the research is to develop a technically credible design for an integrated MHD sidewall and e-beam window. The requirements of the MHD sidewall are quite stringent. It is required that multiple e-beams be admitted through the wall (most likely through both sidewalls), while at the same time, the wall must confine a very high velocity gas at pressures greatly in excess of the near-vacuum conditions in the beam accelerator. This must be accomplished in the presence of a strong applied magnetic field. Either the e-beam must be created and injected within the magnet bore, or the beam must be created outside the magnet and then injected through the core of the magnet and across the sidewalls. Novel accelerator designs might alleviate the beam injection problem. For example, it has been suggested that an azimuthally directed magnetic field could be used to create the Lorentz interaction. The MHD accelerator would then have an annular cross section, with the air stream confined within the cylindrical annulus. This would provide the additional benefit of eliminating the sidewalls. In this case, the e-beams could be injected at a grazing angle into air stream. In any case the interface between the e-beam generator and the sidewall (or cylindrical outside wall) constitutes a serious engineering challenge.

As is shown in Section 8.3.3, electrical conductivity scales as the square root of the e-beam current density. This gives the designer an incentive to work at high beam current densities. There are fundamentally two options available: 1) use conventional metal foils along the sidewalls as windows for the electrons, or 2) use an open aperture concept such as the recently developed plasma porthole concept (Refs. 7, 8). The advantage of metal foil technology is that it is a mature technology for which the limits of performance are well known. This is also its weakness, inasmuch as the upper limit of current density for cooled metal foils is approximately 35 mA/cm^2 . If the e-beam current exceeds this limit, the energy deposited per unit time within the foil will exceed the rate at which heat can be transferred away by cooling, and the foil will vaporize in very short order. The advantage of the plasma porthole technology is that it offers a way to circumvent this rather low limit on current density. In principle, current densities of several amp/cm^2 or more could be admitted through the porthole. However, this technology is quite novel and has not been demonstrated for the application envisioned here. A more detailed evaluation of these two options is one of the tasks assigned to MSE and SNL during the third quarter of calendar year 1999. The issues associated with each of these options, as well as some preliminary sidewall/window design concepts, are discussed in the following sections.

8.4.1 Approach

The relatively low-voltage (25–50 keV) e-beam for the MHD channel must be extracted from the vacuum of the accelerator into the relatively high pressure (0.1 atm) of the MHD channel. This requires an e-beam "window" (that might be empty space or a thin foil). Literature searches on e-beam windows led to two possible concepts for the MHD e-beam window. The goal is to inject a 25–50 keV e-beam into a flowing MHD channel with about 0.1 atmosphere in the channel and a vacuum in the accelerator for durations of about a second. Power deposition in the window material by the beam will be substantial. For example, a 0.1-A/cm^2 , 50-keV beam passing through a 5-mil Be window will deposit approximately 14 kW/cm^2 . Removal of such a large heat flux is very challenging.

In a recent paper, Vidmar and Barker (Ref. 24) present a very comprehensive analysis of various foil window designs. They also report on heat removal using an array of very small stainless-steel capillary tubes with an internal diameter of only 0.131 mm. (The heat in these experiments was generated by Joule heating rather than an e-beam.) Figure 8-36 shows a sketch of a generic arrangement. From these experiments and from their analyses, they conclude that they could construct an e-beam window consisting of a thin foil backed by an array of such tubes that could remove the heat deposited by a 0.03-A/cm^2 , 500-keV e-beam. The beam would pass through the foil, the tube walls, and the water coolant. The analysis took into consideration the beam voltage, the deposition rate for the specific materials involved, the pressure needed to drive the coolant flow, and the fluid properties of the coolant.

If one extrapolates down to a 50-keV beam (which deposits more energy per unit length), Vidmar's window design could support up to 0.01 A/cm^2 (a bit short of the desired 0.1 A/cm^2). However, by using lower-Z materials and a coolant capable of higher temperatures (for example, lithium) one might be able to approach the desired 0.1 A/cm^2 .

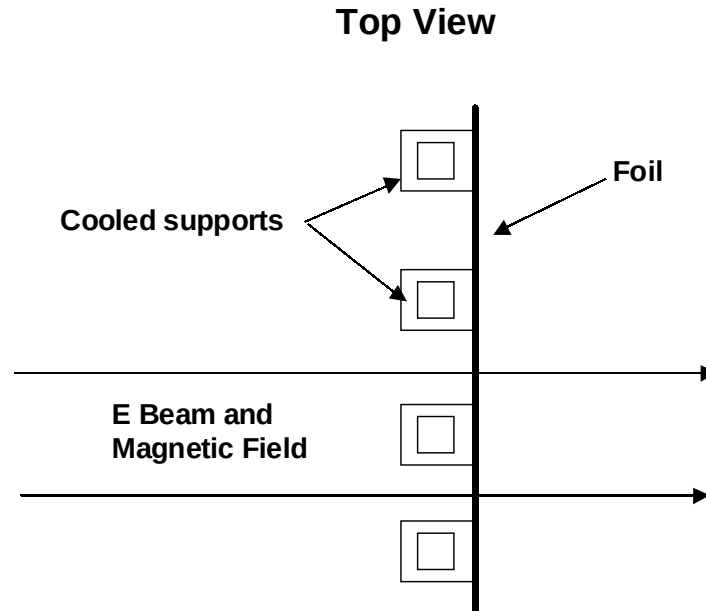


Figure 8-36. Top view of a possible MHD e-beam window (foil cooled by an array of supports).

The difficulty with foil heating could be overcome if there were no foil. This approach has been developed within the high-power accelerator industry and is called differential pumping. The beam is made to pass through a series of small-diameter apertures separated by chambers large enough to allow attachment of a pumping port. Each stage allows a pressure reduction factor equal to the ratio of the areas of the pumping port to the beam aperture divided by the ratio of their respective lengths. The first stage in this process (at the high-pressure end) is usually the most power intensive since it must pump a large mass flow. The difficulty with this approach for the MHD window is that the beam is injected parallel to a very strong (multi-Tesla) magnetic

field. Previous calculations have shown that the beam electrons stay within a millimeter of the magnetic field across the channel. Therefore, an array of very closely spaced beamlets will be needed (or many sheets of electrons oriented parallel to the driving electric field for the MHD channel). It would be perhaps feasible, but very awkward to achieve this with multiply pumped volumes in the standard differential-pumping mode.

Hershcovitch reports in a recent paper an improvement to the traditional differential pumping approach (Ref. 8). He adds a plasma discharge along the length of the first-stage aperture. The gas is heated in a small discharge tube to approximately 12,000 K. Since pressure increases linearly with temperature, this allows the high pressure of the outside air to be held off with low-density gas in the aperture. In addition, viscosity also increases with temperature (slightly more than linearly). This also adds to the pressure drop through the aperture. This technology has been successfully demonstrated to yield a first stage pressure drop to 360 mTorr from atmospheric (a factor of 3,000) using a 2.4-mm diameter discharge tube which was 6-cm long. In a subsequent paper with Gerber, et al. (Ref. 25) Hershcovitch refers to this as a “plasma porthole” and reports on a first-stage pressure drop to 32 mTorr from atmospheric by adding a venturi entrance to the aperture. The aperture was 3 mm.

A thermionic cathode needs approximately 10^{-7} Torr to operate. To reach this pressure with either approach will require several pumping stages. However, a hollow cathode can produce an e-beam in a much higher-pressure background. Mytnikov, Oks, and Chagin from Tomsk State University in Russia report (Ref. 26) on a hollow-cathode driven device that has produced a 400-mA beam at 8 kV in a background gas at 100 mTorr. This pressure could be achieved in a single stage with a short plasma porthole. The cathode for this particular device was 5.5 cm in diameter and 10 cm long, but it drove seven 3-mm diameter beamlets in a small array. These beamlets merged into a single beam with a moderately small divergence of about 15 deg. However, if the device were embedded in a strong axial magnetic field, the beamlets would have remained separate and follow the field lines. It may be possible to combine these two advances (plasma porthole and multibeam hollow cathode) to produce a broad e-beam window suitable for the MHD application.

There is presently a large uncertainty in the amount of beam current per unit area needed for the conductivity enhancement in the MHD channel. Calculations are progressing integrating the channel results with the upstream energy-addition calculations to reach the desired conditions behind a 5-deg wedge in a Mach 15 flow with a dynamic pressure of 2,000 psf. At present, the possibilities range from approximately 5 mA/cm² to 1 A/cm². A cooled foil beam-extraction window can work up to approximately 10 mA/cm² and would be the simplest approach it provides sufficient current density. A different approach would be needed for higher current densities.

To prepare for the possibility that a high current density would be needed, a rough configuration for the e-beam conductivity-enhancement accelerator and extraction window was developed. It is shown in Figs. 8-37 through 8-39. Figure 8-37 shows an overview of the MHD channel with an array of tall, narrow plasma portholes through which the e-beams will pass. The plasma portholes are based on the designs of Ady Hershcovitch, Brookhaven National Laboratory (Refs. 7, 8), except that it uses an array of rectangular apertures rather than square apertures. The e-beams will be the same shape as the portholes (tall and narrow) and will generate a series of parallel slabs of enhanced conductivity. The driving MHD current will pass from top to bottom along each slab.

Figure 8-41 shows one of the tall narrow plasma portholes with a tall narrow hollow cathode accelerator behind it. The accelerator is based on a hollow cathode design by Mytnikov, Oks and Chagin of Tomsk State University in Russia (Ref. 26), except that it is tall and narrow, rather than small and circular. Their hardware has demonstrated a 400-mA beam at 8 kV in a background gas at 100 mTorr. The areas and applied voltages in the MHD design are similar (per unit length or area) to the Russian design, but verification that voltage breakdown levels are not exceeded is required. The gas in the hollow cathode is heated by discharge and creates a plasma that provides the electrons for the beam. The first electrode extracts the beam from the plasma, and the second accelerates that beam toward the plasma porthole. The entire accelerator is embedded in the strong (5–10 Tesla) magnetic field of the MHD channel, so the beam will follow the field lines closely. The advantage of the hollow cathode is its ability to operate at relatively high pressure (100 mTorr).

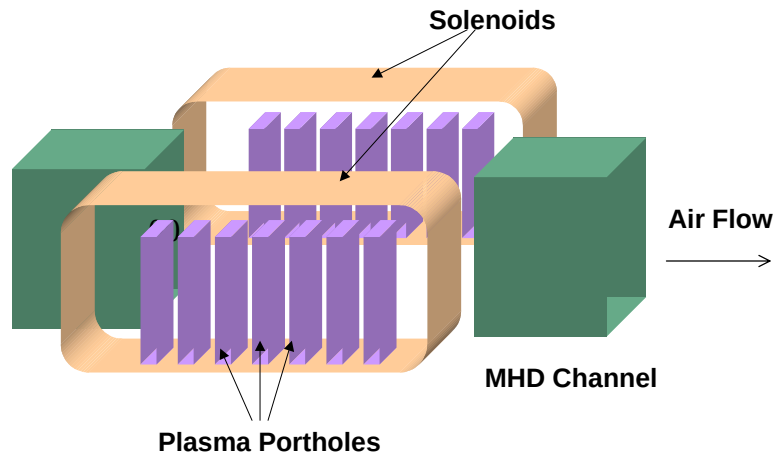


Figure 8-37. Overview of the MHD channel with an array of tall narrow plasma portholes.

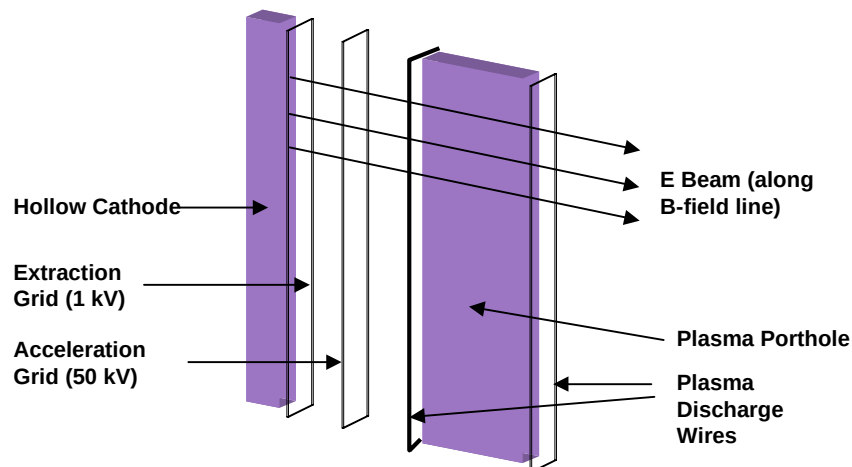


Figure 8-38. One tall narrow plasma porthole with a tall narrow hollow cathode accelerator behind it.

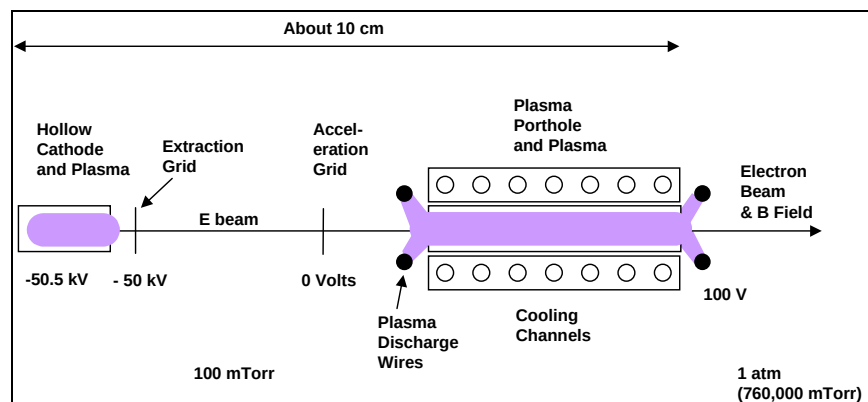


Figure 8-39. Top view of one hollow-cathode accelerator section and plasma porthole.

Figure 8-39 shows a top view of one hollow-cathode accelerator section and plasma porthole. The plasma in the porthole is created by a discharge (approximately 100 V) through the gas in it. This hot plasma keeps out the air from the MHD channel out by high-temperature pressure and high viscosity. The plasma porthole walls are actively cooled and keeps the plasma away from the wall. Another plasma is generated inside the hollow cathode and provides the electrons for the beam current.

This design will be further developed in the near future if it is determined that current densities above 10 mA/cm^2 are required.

8.5 CONCLUSIONS

8.5.1 Modeling

Models of charged particle kinetics and vibrational relaxation were coupled with a quasi-1-D flow code, resulting in an efficient tool for analyzing and optimizing system performance. The quasi-1-D code generally agreed with more sophisticated 2-D modeling. Modeling helped to identify the optimal range of e-beam parameters and to suggest injection of the beams through foil-covered slots spaced periodically along the channel. Performance calculations employing the 1-D code showed that in a MARIAH II/RDHWT-type facility was assumed to have an air supply system operating at 20,000 atm plenum pressure and an e-beam energy addition section employing relativistic e-beams. This was followed by an MHD channel operating at low temperature and using 10 keV range e-beams for ionization. The calculations showed that it would be possible to achieve a test section Mach number of 14.3 flow at a dynamic pressure of 2,000 psf

The analysis of hypersonic boundary layers in MHD channels revealed that a strong coupling exists between the thermal boundary layers and the near-electrode, space-charge sheaths. The anode sheath was shown to be extremely important for the device performance. Anode voltage fall, affected by the reduced mobility of electrons across a magnetic field and the reduced density

in the boundary layer, can be comparable with the total voltage across the channel. Other simulations using a 2-D gas dynamic code coupled to a beam propagation model showed that the temperature, density, and pressure profiles along the Z direction are all highly nonuniform and are strongly affected by the wall recovery physics.

More recent simulations (not discussed in Section 8.2) have suggested that ion slip may also play an important role in the current transport, especially at high magnetic fields. As noted by Rosa (Ref. 18), the condition for ion slip to be important is that the parameter $(\omega_e \tau_e)^2 (m_e/m_i)^{1/2}$ must be of order 1 or greater. If this relation holds, then the effective conductivity is given by the expression $\sigma/(1 + \omega_e \tau_e \omega_i \tau_i)$. A first-order analysis indicates, assuming O_2^+ is the positive ion, that ion slip effect becomes significant when the magnetic field reaches a value of approximately 10 Tesla.

The CYLTRAN trajectory code is a Monte Carlo type of code, which is capable of predicting the beam energy deposition, and ionization rate profiles across the channel provided that the density profile is known. A series was run with a gas density of 0.00012 g/cm^3 (0.1 atm at 300 K) with a guiding magnetic field of 7 Tesla perpendicular to the MHD channel wall. The beam electrons were assumed to be injected parallel to the field lines without any initial divergence. These calculations have been used as the basis for developing accurate curve fits for beam energy absorption as a function of beam distance.

8.5.2 Conductivity Experiments

Several conclusions may be drawn from the analysis of the experimental data and the kinetics model. First, an analysis of the kinetics equations enables one to identify a parameter χ that characterizes the regime in which attachment of electrons by diatomic O_2 will be important. For air close to standard temperature, O_2 attachment appears to be an important, even dominant, process with respect to e-beam kinetics at static pressures in excess of 0.1 atm. This agrees generally with other analyses of the same problem. This conclusion has important implications for the demonstration of e-beam-seeded MHD acceleration. It appears that for such a concept to be feasible, it will be necessary to operate at subatmospheric pressures in the MHD channel, perhaps at pressures as low as 0.1 atm. Increasing the static temperatures substantially above ambient in the channel, to levels on the order of 1,000–1,200 K would help reduce the concentration of atomic O_2 (at a fixed pressure) and could enable operation at somewhat higher channel pressures. An important point relevant to this discussion is that operating the MHD channel at subatmospheric pressures necessarily implies operation at high channel Mach numbers. This is due to the very high total enthalpy and high static pressures upstream of the MHD channel. In addition, if the Joule heating is to be kept small (a desirable mode of operation), then it will be necessary to operate at low current densities and high magnetic fields in order to obtain significant body force acceleration ($J_y B$). This reasoning is confirmed in the recent analytical study by Macheret et al. (Refs. 1, 21) in which current densities of a few mA per square cm were specified with magnetic fields as high as 20 Tesla. These high field strengths were required to obtain substantial acceleration of the air through the MHD channel while minimizing Joule dissipation.

With respect to the static cell conductivity measurements, preliminary data taken in air using the HAWK e-beam accelerator appear to agree with the first order kinetics model developed by Macheret (Ref. 1). The predictions of the theory agreed to within 40–50 percent with the conductivities inferred from the static cell resistance measurements. This statement is true only for air. For nitrogen, there appears to be an anomalous trend in the conductivity/pressure relationship, inasmuch as the measured conductivity increases in passing from 0.1 to 0.5 atm of cell pressure. This was unexpected and is at this point unexplained.

8.5.3 Integrated MHD Sidewall and Window Design

Two concepts for the MHD sidewall design have been considered. The first is to use cooled foils as apertures for injection of the e-beams. This method appears to be promising providing the beam current densities can be maintained below approximately 30 mA/cm². At currents above this value, the heating of the foil due to absorption of the beam becomes an issue. If it is necessary to work at higher currents, the plasma porthole concept is a possible solution. An essential requirement is that most of the area of the sidewall must be irradiated with e-beam radiation. This implies that a large number of e-beams will be required. For either the plasma porthole or the cooled foil options, this requirement will complicate the design due to the cooling requirements. In the foil option, active cooling of the foil is required. In the case of the plasma porthole, each individual discharge tube must be cooled. These are the technical challenges to be solved as part of the design effort.

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9.0 SYSTEM INTEGRATION

9.1 OBJECTIVES

The systems integration objectives are to ensure that the major components of the MSHWT are compatible in terms of scale, operating regime, interfaces, and stability of operation; most importantly, the total MSHWT system must meet its performance, operability, reliability, maintainability, and capital and operations cost requirements. Requirements for the MSHWT are being determined through the Hypersonic Facilities Requirements Study (see Section 3). Specific performance requirements are derived from the hypersonic test requirements provided by this study. Another systems integration objective is to ensure environmentally acceptable and safe operation of the MSHWT through compliance with ES&H requirements and safe design and siting practices. Systems integration issues must be considered in the development and definition of experiments throughout Phases I and II of the program.

To meet these objectives, computational models of subsystem components (such as the UHP air supply, nozzle, thermal energy addition, and MHD subsystems) are being used to investigate system performance and subsystem interface issues. Experiments are being designed to evaluate subsystem interface issues while investigating and demonstrating component performance. Where necessary, other systems integration experiments will be performed to demonstrate interfaces and performance and to acquire essential data for preparing the MSHWT system design criteria. Integrated system-level cost models will also be used to analyze tradeoffs between system cost and performance as well as estimate integrated MSHWT system costs.

9.2 APPROACH

To ensure the systems integration issues are properly addressed and resolved during this research program, several activities that must be undertaken are defined in the MARIAH II/RDHWT Research Plan. System integration activities to be pursued during the Phase I and II programs include:

- Develop performance predictions for the overall system and for the interaction of major subsystems.
- Characterize the design and off-design performance of candidate or baseline wind tunnel systems concepts.
- Perform subsystems design concept, performance, and cost trades to establish subsystem and total system concept, performance, and cost.
- Demonstrate the effects of scale on the interaction of system components through a program of subscale testing and computer simulation. Because testing will be limited to power levels of a few megawatts or less, scaling issues will be a significant challenge in the Phase I and II R&D programs. The subscale testing may take the form of tests on partially integrated subsystems (for example, an energy addition/nozzle/ high-pressure driver) at power levels and mass flow rates below that of the MSHWT. Validated computational models can then bridge the gap between the demonstrated scale and that of the MSHWT.

- Ensure operational reliability of the total system through analytical studies and experimental demonstrations at the system level.

Systems integration activities during the FY98 reporting period have consisted primarily of planning, preparation of the research plan, and initiation of a preliminary performance characterization study at Princeton University (see Section 9.6). Environmental, safety and health planning activities were also initiated at LLNL. Systems integration tasks planned for the FY99 reporting period include the following:

- Completion of the preliminary analytical performance characterization for the MSHWT using e-beam heating both with and without MHD augmentation.
- Completion of a plan that outlines and defines the approach of system cost trades for the MSHWT.
- Preliminary definition of component interface issues.
- Completion of Version 1 of the system simulation model.

9.3 EXPERIMENTAL APPARATUS

System integration experiments will first be explored using the A-2 UHP air supply system, described in Section 5, coupled to a megawatt-class e-beam energy source for the megawatt-level energy addition experimental demonstration. The issues associated with these experiments are discussed further in the design subsection below.

Critical technical issues have been defined in the systems integration section of the MARIAH II/RDHWTT Research Plan. These include performance, interface, and scale issues. Wherever necessary, experimental demonstrations will be used to resolve these issues. Some of these issues will be addressed in the A-2, megawatt energy addition experiments as discussed below. Further systems level experiments will be defined as necessary to investigate and/or resolve interface and system performance issues.

Three key systems demonstration experiments are planned. These would be experiments at a scale below that of the MSHWT to establish the credibility of the analytical simulations and partially resolve the scaling and performance issues prior to the design of the MSHWT system. The three identified experiments are:

- Design verification testing of the A-2 UHP nozzle system.
- Demonstration of a specific configuration consisting of a high-pressure driver, nozzle, and energy addition unit.
- Demonstration of an MHD accelerator driven by a high-pressure driver.

The first experiment will be satisfied by planned energy addition experiments with the A-2 air supply system and nozzle. The second may take the form of testing of an MHD accelerator in an impulse facility. The third test series will be conducted to verify that the A-2 system meets all design objectives, including ES&H requirements.

9.4 ANALYTICAL METHODS

Several system and subsystem component performance models have been under development during the reporting period. Both 1-D and 2-D gasdynamic, energy addition computational models have been developed at Princeton University and are described in Section 7. In addition, a 1-D, inviscid code, which includes both laser and e-beam energy addition models, was developed and used exclusively for system and performance envelope studies during this reporting period. A detailed, unsteady, 2-D, axisymmetric code is used to model energy addition by either lasers or e-beams through coupling to the appropriate energy deposition codes. The laser model is fully integrated into the fluid code while the e-beam modeling requires manual coupling to an external e-beam trajectory analysis and deposition model. Details of these models are discussed in Section 7.

One-dimensional MHD computational models have been developed at both Princeton University and MSE. Simple e-beam electrical conductivity enhancement models have been incorporated in these MHD codes to predict the conductivity enhancement in the low-pressure, low temperature MHD operating regime. These codes were used to predict the MHD channel performance for the system studies conducted during the FY98 reporting period. Future versions of these codes may require modification to simulate the nonequilibrium modes of MHD interaction.

An essential element of the computational modeling is the high-pressure EOS for air. An EOS database for air (also for N_2) at temperatures up to 1,800 K and pressures up to 2,220 MPa was obtained from NIST for use in the MARIAH II/RDHWI Program. Subroutines were developed at LLNL to access this database from within the various modeling codes. The air and nitrogen EOS databases are discussed in Appendix D.

The UHP air supply system has been modeled at LLNL using the NIST air EOS database (see Section 5). Heat transfer analysis (predicting heat loss from the UHP dynamically compressed gas) is an important element of this modeling. Dynamic modeling of the UHP dynamic intensifier air supply system provides predictions of the steadiness and uniformity of the air supply from the plenum and the variation of thermodynamic conditions with time. This modeling has been initiated at LLNL and will be continued as necessary to provide predictions of flow quality in the nozzle.

Additionally, there is a need for a simplified (i.e., 1-D/algebraic) model of the facility system. Plans are to use this code to conduct performance sensitivity and cost trade studies. For example, this code should simulate the effect of adding power in the MHD accelerator versus adding additional power in the thermal energy addition section on the final test section conditions. In addition, it could also simulate the effect of MHD energy addition on the required reservoir pressure. Such a code will be useful for predicting overall system performance to first-order approximation. Development of this code should draw freely upon experimental data from subsystem/component testing as well as algorithms and models developed for simulation codes that model individual subsystems.

9.5 SYSTEM INTEGRATION DESIGN ISSUES

Systems integration issues will significantly influence the design of the MSHWT as well as the design of subscale experiments for testing and demonstrating components and component interfaces. MSHWT systems requirements and interface issues will be critical factors in the design of the A-2 air supply system that is to be used for nozzle survivability research and megawatt-level energy addition experiments.

These experiments will provide a unique opportunity for investigating, testing, and demonstrating systems integration and interface issues. For example, the multi-megawatt energy addition experiments can be designed to provide near-MSHWT-scale enthalpy in the air after energy addition, thus demonstrating the coupling of the UHP air supply subsystem, the energy addition subsystem, nozzle cooling/survivability subsystems, and other equipment such as the focusing magnets and the e-beam accelerator. If properly designed, the A-2 will also demonstrate other systems integration concepts and issues such as the method for nozzle replacement and injection of cold gases or liquids in the boundary layers.

MHD sidewall experiments will demonstrate the integration of several subsystems, including the MHD channel, e-beam accelerators, beam ports or windows, and the MHD magnet. These may also be designed to demonstrate the transition from the energy addition section to the MHD channel inlet. System integration will enter into the design of most experiments and demonstrations for the MARIAH II/RDHWT Program and will be essential in the development of design criteria for the MSHWT.

9.6 SYSTEM PERFORMANCE ANALYSIS RESULTS

The operating performance characteristics of the MSHWT facility will be critically dependent on the thermodynamic path followed by the air as it passes through the nozzle. In a conventional wind tunnel, there is only one path that is an adiabatic constant entropy expansion where the total enthalpy in the plenum is converted to kinetic energy and residual static enthalpy in the test chamber. Since energy is added downstream of the throat, there are an infinite number of thermodynamic paths that can be taken before the air arrives in the test section in the MSHWT facility. The design challenge is to determine which of these thermodynamic paths optimize wind tunnel performance and how closely these paths can be followed given the practical considerations of the nozzle contour, boundary layer growth rates, heat transfer to the walls, and thermal energy addition with or without MHD augmentation. Figure 9-1 shows a Mollier diagram with an example of such a thermodynamic path. Any thermal energy addition process increases the enthalpy, Δh , while simultaneously increasing the entropy, $\Delta s = \Delta h / T$. The selected operating point in the test facility can be represented as a single point on this diagram. Since the entropy of the flow cannot be reduced (heat cannot be extracted from a hypersonic flow except by radiation), any energy addition requires that the initial flow must have entropy lower than the final state. It is this low initial entropy requirement that moves one as far as possible to the left on this Mollier diagram and necessitates a UHP driver to achieve the needed test conditions.

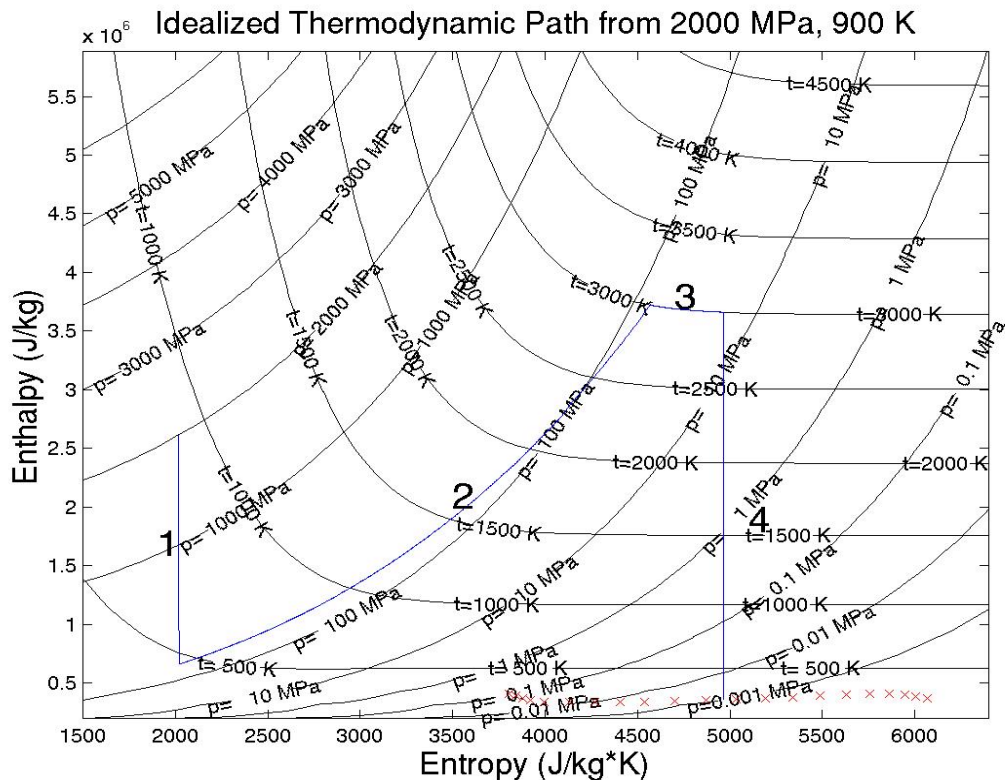


Figure 9-1. Mollier diagram showing idealized thermodynamic path from 2,000 MPa, 900 K.

The design of the nozzle then follows a process, which begins with the selection of an ideal thermodynamic path that the design will target. For illustration purposes and neglecting the compression process, ideally that path begins with a first step, which is an adiabatic constant entropy expansion (path 1 on the diagram) from the UHP plenum through the throat. This expansion continues to a Mach number somewhat greater than 1, usually chosen for the purpose of these calculations to be Mach 2. In order to deposit the maximum amount of enthalpy into the flow, it is important to heat the gas as rapidly as possible downstream of the throat to minimize the increase in entropy. The maximum heating rate is limited by choking, and for the purposes of this calculation, the initial heating is assumed to occur at constant Mach number. In order to keep the entropy rise to a minimum during energy addition, the flow temperature should be maintained as high as practical (see entropy change equation in the previous paragraph). This implies a low Mach number; therefore, a Mach number in the energy addition region approaching unity is desirable. However, Mach 2 is chosen for these analyses in order to ensure that choking conditions are avoided.

Heating at constant Mach number 2 (path 2) continues until the maximum allowable temperature is achieved. That temperature is determined by constraints on the chemical composition of the flow and may, in some cases, exceed the temperature that would be associated with equilibrium concentrations due to the fact that the residence time at this temperature is relatively short. For

this sample calculation, the maximum temperature is assumed to be 3,000 K. Heating then proceeds at constant temperature until the entropy in the test section is reached (path 3). At that point, the flow is expanded into the test chamber through an adiabatic, isentropic expansion (path 4). When MHD augmentation is added, the flow may be expanded at an earlier stage and passed into the MHD acceleration section before entering the test chamber.

This particular idealized path has been used to estimate operational performance limits of the MSHWT wind tunnel with thermal energy addition. Figure 9-2 shows the idealized operating conditions as a function of plenum pressure and temperature for atmospheric flight conditions at a dynamic pressure of 2,000 psf. The thermodynamic path assumed for this diagram is shown in Fig. 9-1 (i.e., expansion to Mach 2, constant Mach number energy addition to 3,000 K, constant temperature energy addition followed by a final isentropic expansion to the operating point). Also shown in Fig. 9-2 are the minimum throat diameters in millimeters per meter test section diameter and the thermal energy addition requirements in megawatts per square meter of test section area. Required throat diameters may be larger than these when allowance is made for boundary layers, film cooling, or heating in only the core of the flow.

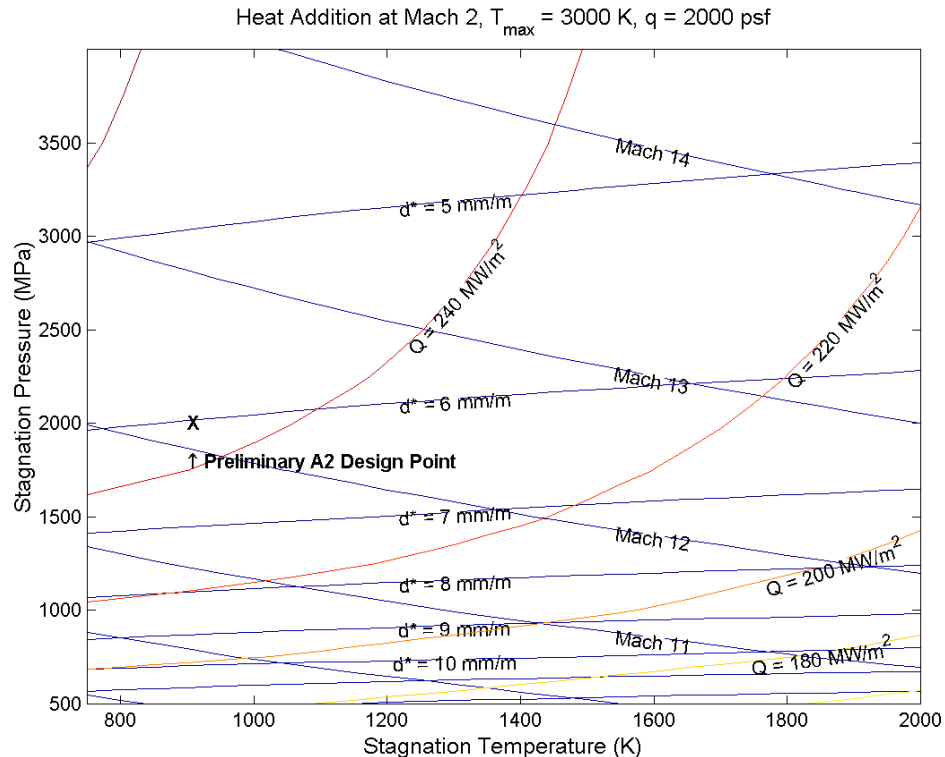


Figure 9-2. Idealized operating conditions as a function of plenum pressure and temperature for atmospheric flight conditions at a dynamic pressure of 2,000 psf.

Figure 9-2 shows the predicted ideal performance of a wind tunnel for a multiplicity of test Mach numbers assuming an idealized thermodynamic path like that shown in Fig. 9-1. In practice, that path can only be approximated based on the physics of the energy deposition mechanism. A

better estimate of the true path that can be achieved is found using a 1-D iterative design code, developed at Princeton University, in conjunction with either laser or e-beam energy deposition codes. This code incorporates the real gas EOS for air and computes the nozzle contour that is required in order to come as close as possible to the ideal performance target. Energy is deposited through either high power laser radiation or e-beams, which are focused into the nozzle energy addition section from downstream. (The very high power required (hundreds of megawatts) and the high pressures in the energy deposition region (hundreds of atm) preclude passing the energy through the wind tunnel walls. In practice, laser beams can be steered into the nozzle through naturally occurring index-of-refraction gradients and e-beams can be focused along magnetic field lines.)

Electron beam energy absorption is computed using the DOE CYLTRAN Monte Carlo code at SNL. This code is iterated with the 1-D design code until a steady-state solution is found, thereby giving the energy deposition as a function of axial position along the nozzle and the nozzle contour that is required to achieve that solution. The MSHWT is projected to operate with a ½-m-diameter test section at Mach 12.2 and $q=2,000$ psf. This will require the deposition of 52 MW of power from a 3-MeV e-beam generator.

The predicted thermodynamic path for such a calculation is compared to the ideal thermodynamic path in Fig. 9-3. Figure 9-4 shows the results of calculations for the nozzle contour that is required to accomplish this heating profile and the power deposition as a function of axial position. In this example calculation, the throat diameter is only 3 mm, and the UHP driver forces the air through that throat at 9.8 kg/sec. The energy deposition region is only a half a centimeter to a few centimeters downstream, depending upon the energy of the e-beam.

A similar thermodynamic path can be established for other MSHWT operating conditions. Figure 9-5 shows the idealized operational conditions as a function of plenum pressure and temperature for a flight dynamic pressure of 500 psf with a constant Mach number ($M=2$) and constant temperature ($T=3,000$ K) energy addition path. This configuration reaches a final Mach number of 12.2 assuming the plenum stagnation conditions of 2,000 MPa pressure and 900 K temperature.

If the limit of 3,000 K is removed, the thermodynamic path is changed to allow heating at constant Mach number up to the final flight entropy. In this case, the Mach number performance of the tunnel is slightly increased at the expense of degraded flow quality (more nonequilibrium species such as NO and O_3). For example, for a dynamic pressure of 500 psf, the final Mach number is 13.44 and the core flow reaches a temperature of 5,074 K before the final expansion. For a dynamic pressure of 2,000 psf, the final Mach number is 12.36, and the core flow reaches a temperature of 3,746 K.

The last iteration in the design process is to implement a time-accurate, 2-D Navier-Stokes solver to examine the stability of the flow and to predict radial variations in flow properties. Also of great importance is the question of heat transfer to the wall and boundary layer thickness. In the case of laser energy addition, the 2-D code incorporates a ray-tracing algorithm that permits the dynamic interaction of the laser with the flow field. In this case (Ref. 1), it is clear that the laser beams are steered by small density variations in the flow in such a manner that, on average, the

laser beams uniformly fill the volume. The high temperature, low density, low index-of-refraction boundary layer refracts the laser beams back toward the core of the flow and serves to minimize wall heating by laser irradiation. This effect may be further enhanced by He injection along the wall, a step that may need to be taken in any case to suppress heat transfer from the high enthalpy air.

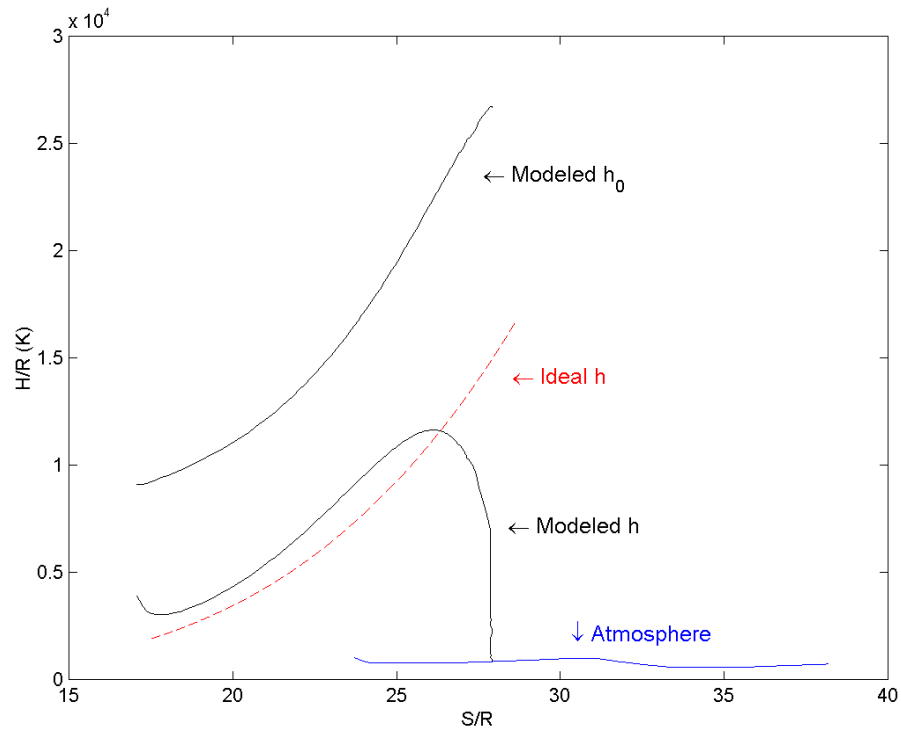


Figure 9-3. Predicted thermodynamic path vs. ideal thermodynamic path.

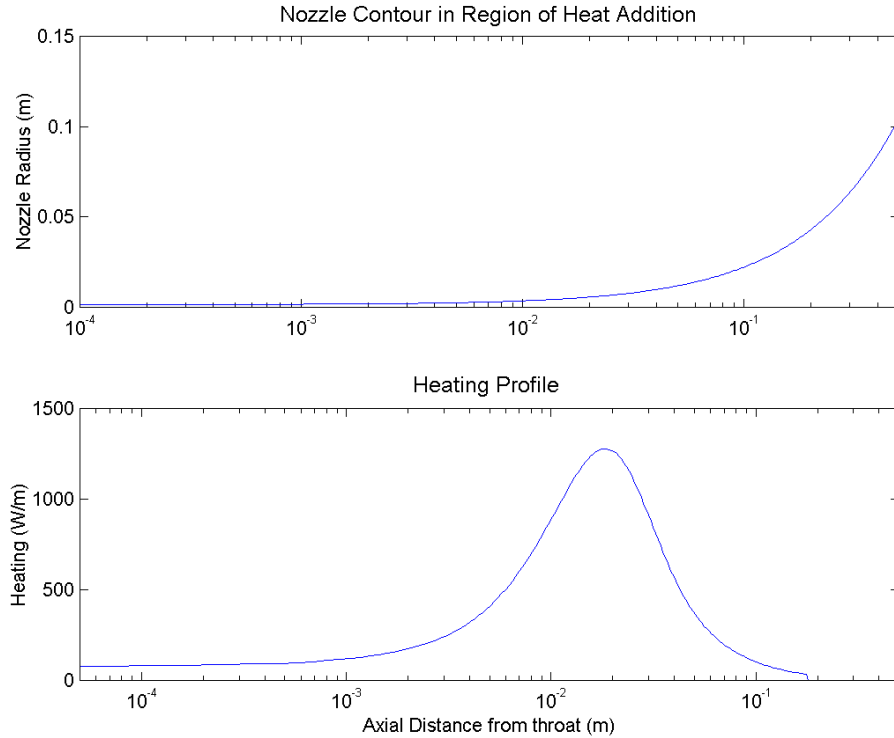


Figure 9-4. (a) Nozzle contour for heating profile, and (b) power deposition as a function of axial position.

In the case of the e-beam, the radial heating profile is largely driven by the profile of the e-beam itself. This profile may be controlled to some extent through the e-beam formation process and the magnetic field. In any case, the e-beam must be contoured to keep it from directly heating the walls of the nozzle. Current research is underway exploring the possibility of using a contoured e-beam to heat the core of the flow while leaving a cold annulus of air surrounding that core in order to protect the nozzle wall from excessive heat transfer.

Calculations show that the addition of an MHD accelerator section immediately following the e-beam energy addition region further enhances the performance of the MSHWT. These calculations indicated that the Mach number can be extended from Mach 12.4 up to greater than Mach 13, and perhaps, as far as Mach 14 at a dynamic pressure of 2,000 lb/ft² depending upon the severity of a phenomena called ion slip discussed later in this section. While research is underway developing an understanding of the physical processes that limits the performance of the MHD augmentation, preliminary results are shown in Fig. 9-6. In this case, the flow is expanded into the MHD section from a pressure of 206.6 atm and a temperature of 2,590 K, down to a pressure of 0.1 atm at temperature of 373 K. This expansion increases the flow velocity from 2,829 m/sec to 3,667 m/sec at the entry of the MHD section. The pressure at the end of the section is 0.006 atm and the temperature is 240 K, which closely approximates atmospheric conditions at 35,000 m (114,000 ft) and corresponds to a flight Mach number of 14.4 and a flight dynamic pressure of 2,000 psf. It is presumed that the electrons are injected through a series of 0.5-cm-wide slots at

2-cm intervals along the 4-m MHD channel. The e-beam current density in the strips is 3.5 mA/cm^2 . The loading parameter, k , is 1.075 for the first channel section and 1.06 for subsequent sections. The magnetic field for this analysis is 20 T.

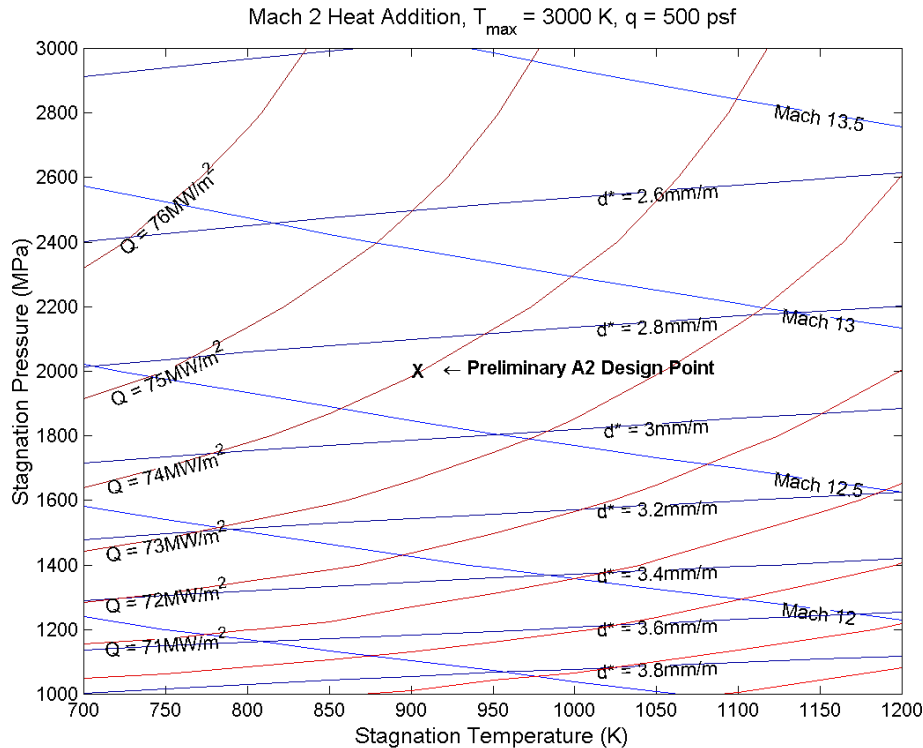


Figure 9-5. Theoretical performance, Mach 2 heat addition to $T_{\max}=3,000 \text{ K}$, $q=500 \text{ psf}$ atmospheric conditions.

Profiles of the e-beam energy, gas number density, the number density of electrons and ions, and the electron recombination attachment frequencies are shown in Fig. 9-7. The electrons are used to maintain the conductivity at approximately $10^{18} \text{ electrons/m}^3$. These electrons follow the magnetic field lines very closely, even as they scatter since the magnetic field strength is assumed to be 20 T. The negative ion concentration closely follows the electron density, thereby maintaining charge neutrality. The analyses presented in Figures 9-6 and 9-7 were computed assuming ion slip does not occur in the MHD accelerator.

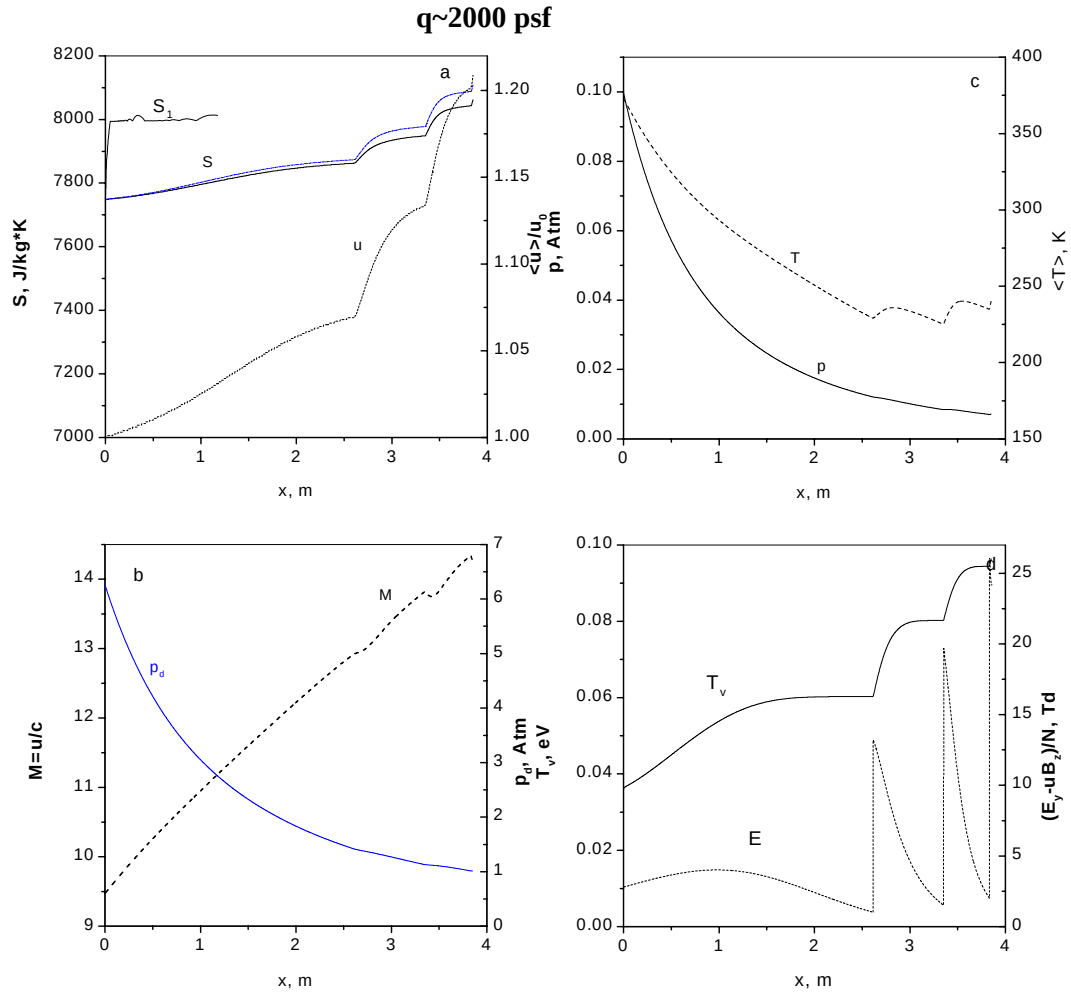


Figure 9-6. Computed profiles of gas parameters along an MHD accelerator channel without ion slip. (a) S_1 – specific entropy variation for the case with energy addition by a relativistic e-beams with no MHD; S – specific entropy variation for the MHD case (solid line – translational-rotational entropy, dashed line – full entropy, including vibrational entropy); $\langle u \rangle / u_0$ – gas velocity averaged over the channel cross section, $\langle u \rangle$, relative to the initial velocity, u_0 . (b) p_d – profiles of dynamic pressure and M – Mach number. (c) T – temperature and P – pressure variation along the channel. (d) T_v – vibrational temperature and E – effective electric field strength variation along the channel. ($\langle \dots \rangle$ means averaging over the channel cross section.)

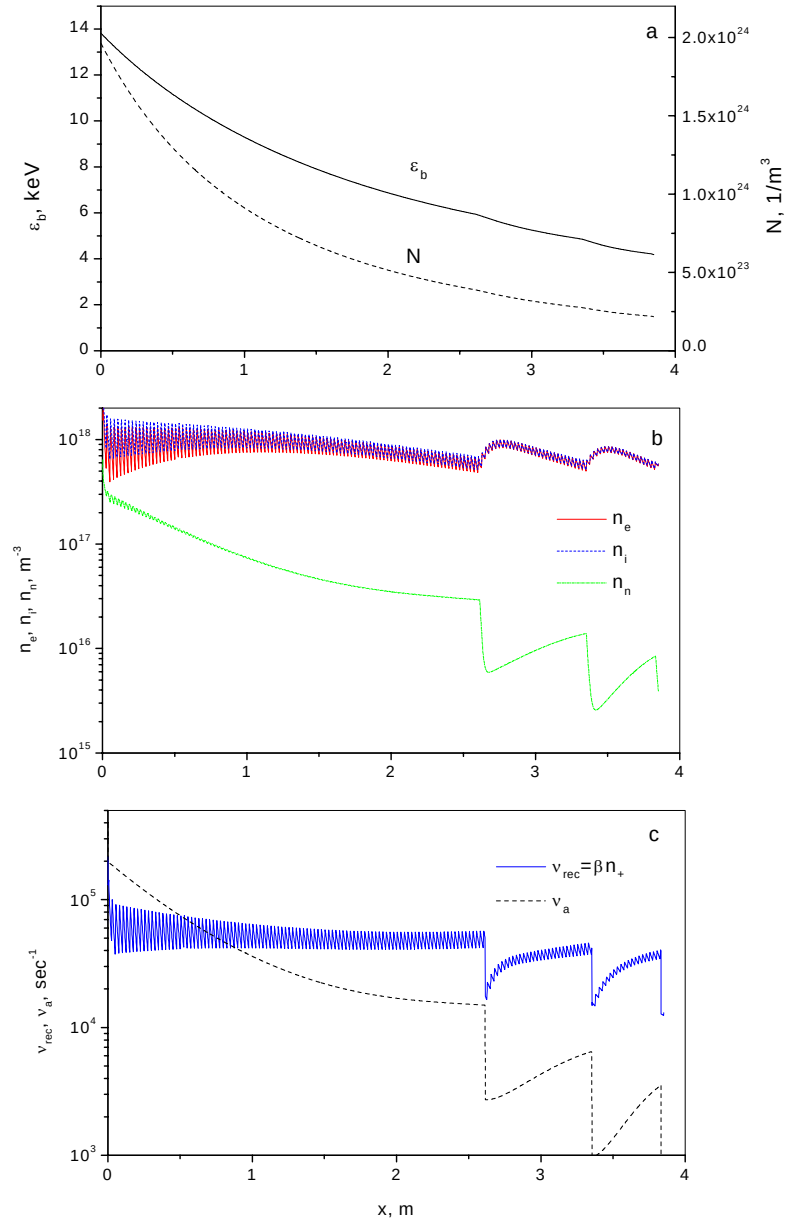


Figure 9-7. a – c. Profiles of e-beam energy, ε_b , gas number density, N , number densities of electrons and positive and negative ions, n_e , n_i , and n_n , and electron recombination and attachment frequencies, ν_{rec} and ν_a , for the case shown in Fig. 9-5.

It was recently found that ion-slip phenomena may degrade the projected performance of the MHD section. This arises because the MHD channel is being operated at very low conductivity and high magnetic field in order to avoid excess flow heating. This leads to a weak coupling between the ions and the neutrals in the flow and significant lag in the acceleration of neutrals compared to the standard strong coupling approximations. Taking this effect into account causes a reduction of the exit Mach number for the q of 2,000 psf case to a value of Mach 13.55. The e-beam current density is also increased in order to provide somewhat higher conductivity to mitigate this effect. Modified curves are shown in Figs. 9-8 and 9-9. These are similar to those of Figs. 9-6 and 9-7, except incorporating the ion-slip effect. Again, the electrons are assumed to be injected through a series of 0.5-cm-wide slots at 2-cm intervals along the 4-m MHD channel. The e-beam current density in the strips is 6 mA/cm². The loading parameter, k , is 1.15, and the magnetic field is 20 T for this analysis.

If the dynamic pressure is reduced, a higher Mach number can be achieved (as shown in Figs. 9-10 and 9-11 for a dynamic pressure of 540 psf). In this case, the Mach number extends beyond 14, but the e-beam current density has increased to as high as 10 mA/cm². The loading parameter, k , for this case is 1.155 and the magnetic field is 20 T.

The final design must incorporate a model for the boundary layer growth rate as well as an understanding of heat transfer mechanisms under these ultrahigh Reynolds number, nonideal gas conditions. Experiments are currently underway at Princeton University using a 275-MPa, atmospheric temperature, high pressure, blowdown facility to study these questions. The Reynolds number of that facility is near that of the medium- and full-scale facilities, largely because of the relative incompressibility of the air at these pressures and the variation of viscosity with temperature. A major question that needs to be resolved is the recovery temperature at the wall, even in the absence of thermal energy addition. In the non-ideal gas regime, the total enthalpy has a significant dependence on pressure. This is an important feature of the MARIAH II/RDHWI concept since high enthalpy can be achieved in the plenum at relatively low temperatures. As the flow passes through the throat, the total enthalpy remains constant. In the core of the flow, the entropy is unchanged, but entropy increases across the boundary layer at the walls. Assuming the transverse pressure is uniform, this could lead to a significant temperature increase with temperatures achieving levels well beyond the plenum temperature. For example if the MSHWT plenum is at 20,000 atm at a temperature of 900 K, the recovery temperature in the throat could be as high as 2,000 K. This will have a significant impact on nozzle and throat survivability and may lead to the requirement that active nozzle cooling strategies be implemented.

$q \sim 2000$ psf;

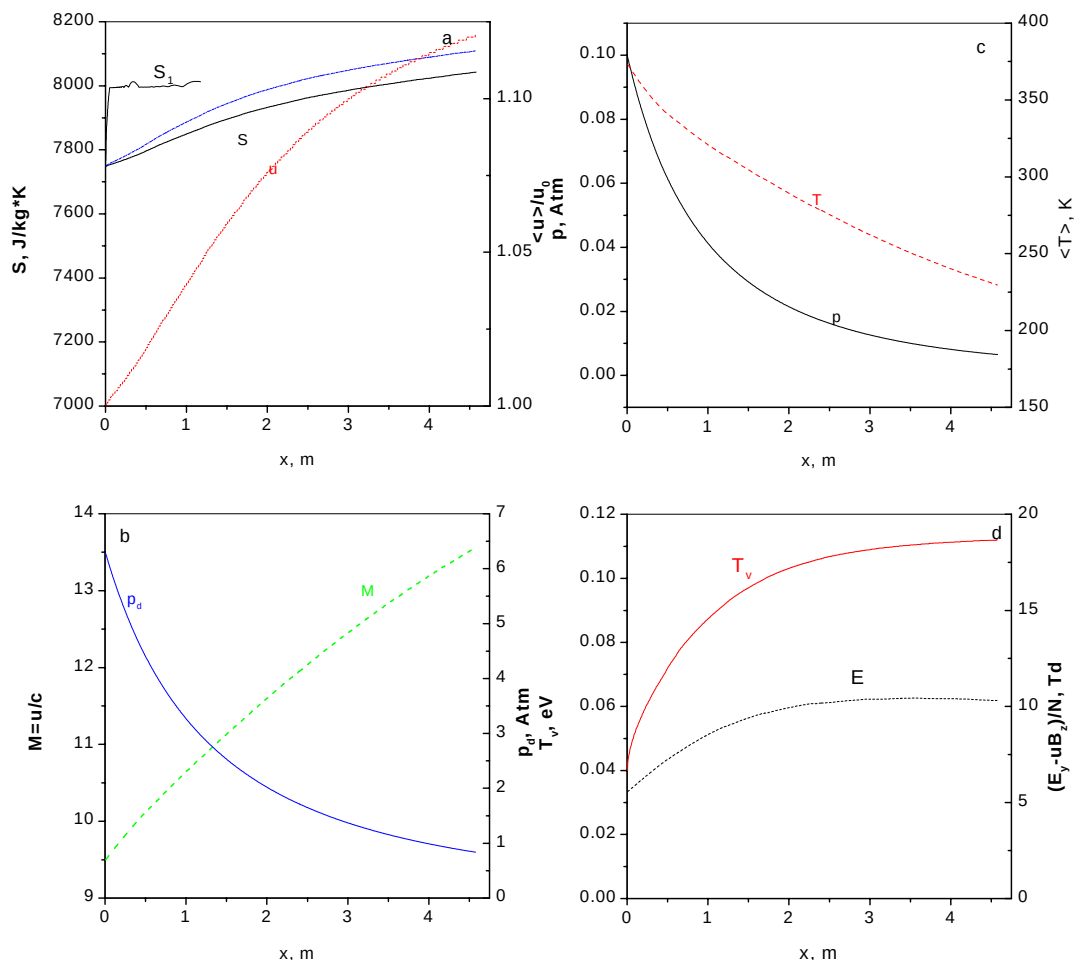


Figure 9-8. Computed profiles of gas parameters along an MHD accelerator channel with ion slip for a simulated dynamic pressure of 2,000 psf.

- (a) S_1 – specific entropy variation for the case with energy addition by a relativistic e-beams with no MHD; S – specific entropy variation for the MHD case (solid line – translational-rotational entropy, dashed line – full entropy, including vibrational entropy); $\langle u \rangle / u_0$ – gas velocity averaged over the channel cross section, $\langle u \rangle$, relative to the initial velocity, u_0 . (b) p_d – profiles of dynamic pressure and M – Mach number. (c) T – temperature and P – pressure variation along the channel. (d) T_v – vibrational temperature and E – effective electric field strength variation along the channel. ($\langle \dots \rangle$ means averaging over the channel cross section.)

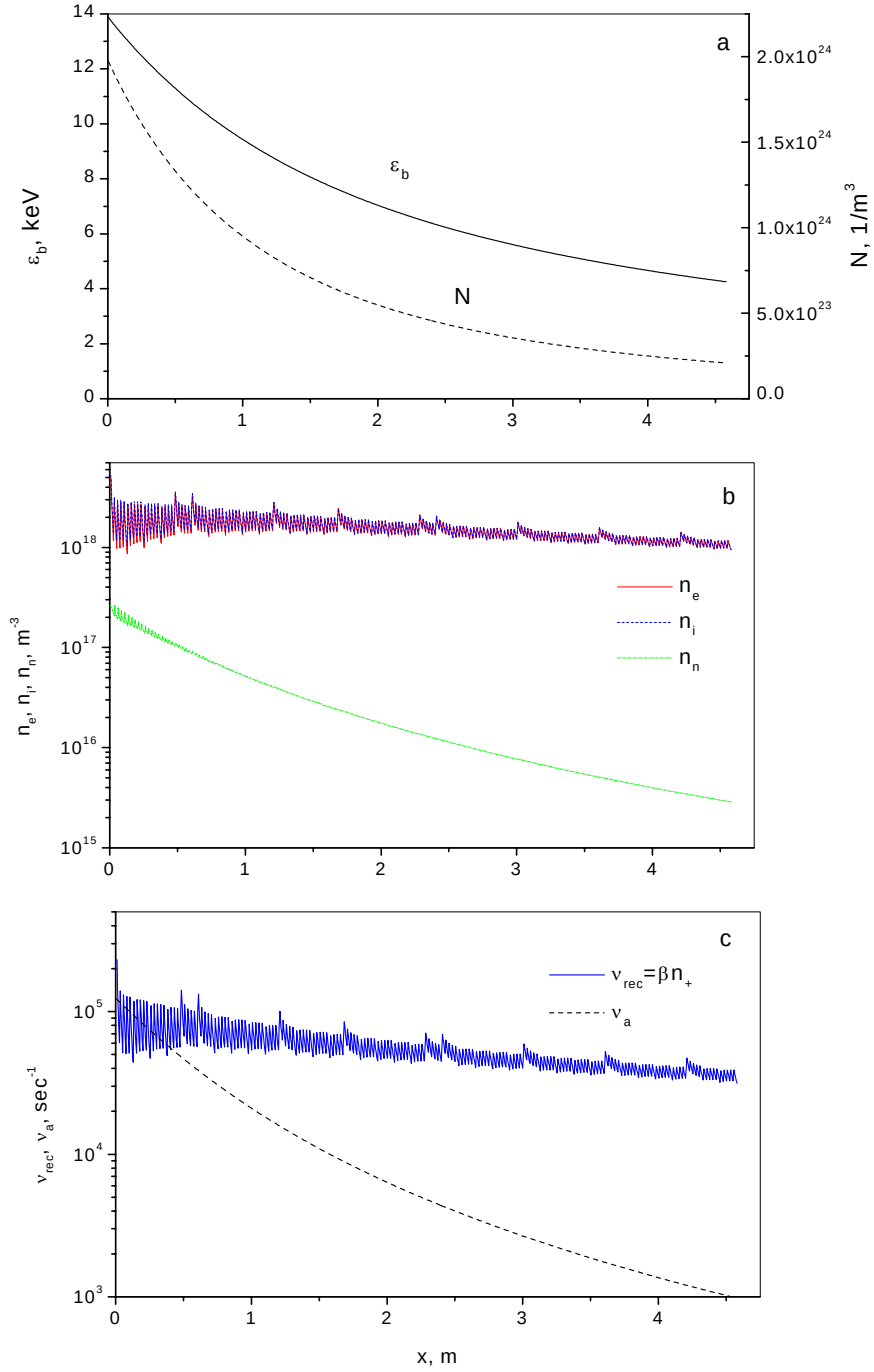


Figure 9-9. a – c. Profiles of e-beam energy, ε_b , gas number density, N , number densities of electrons and positive and negative ions, n_e , n_i , and n_n , and electron recombination and attachment frequencies, ν_{rec} and ν_a in the case shown in Fig. 9-7.

$q=540$ psf

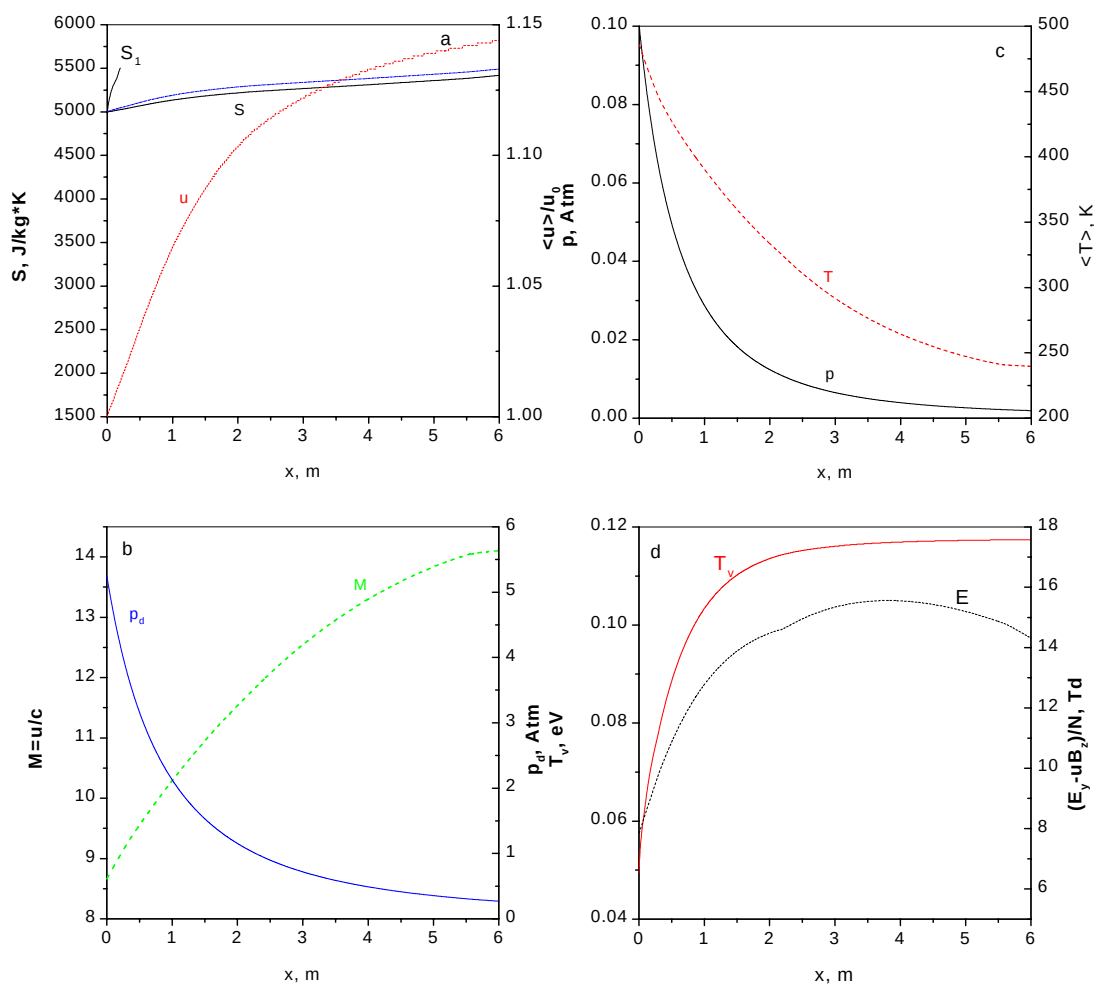


Figure 9-10. Computed profiles of gas parameters along an MHD accelerator channel with ion slip for a simulated dynamic pressure of 540 psf. S_1 – specific entropy variation for the case with energy addition by a relativistic e-beams with no MHD; S – specific entropy variation for the MHD case (solid line – translational-rotational entropy, dashed line – full entropy, including vibrational entropy); $\langle u \rangle / u_0$ – gas velocity averaged over the channel cross section, $\langle u \rangle$, relative to the initial velocity, u_0 . (b) p_d – profiles of dynamic pressure and M – Mach number. (c) T – temperature and P – pressure variation along the channel. (d) T_v – vibrational temperature and E – effective electric field strength variation along the channel. ($\langle \dots \rangle$ means averaging over the channel cross section.)

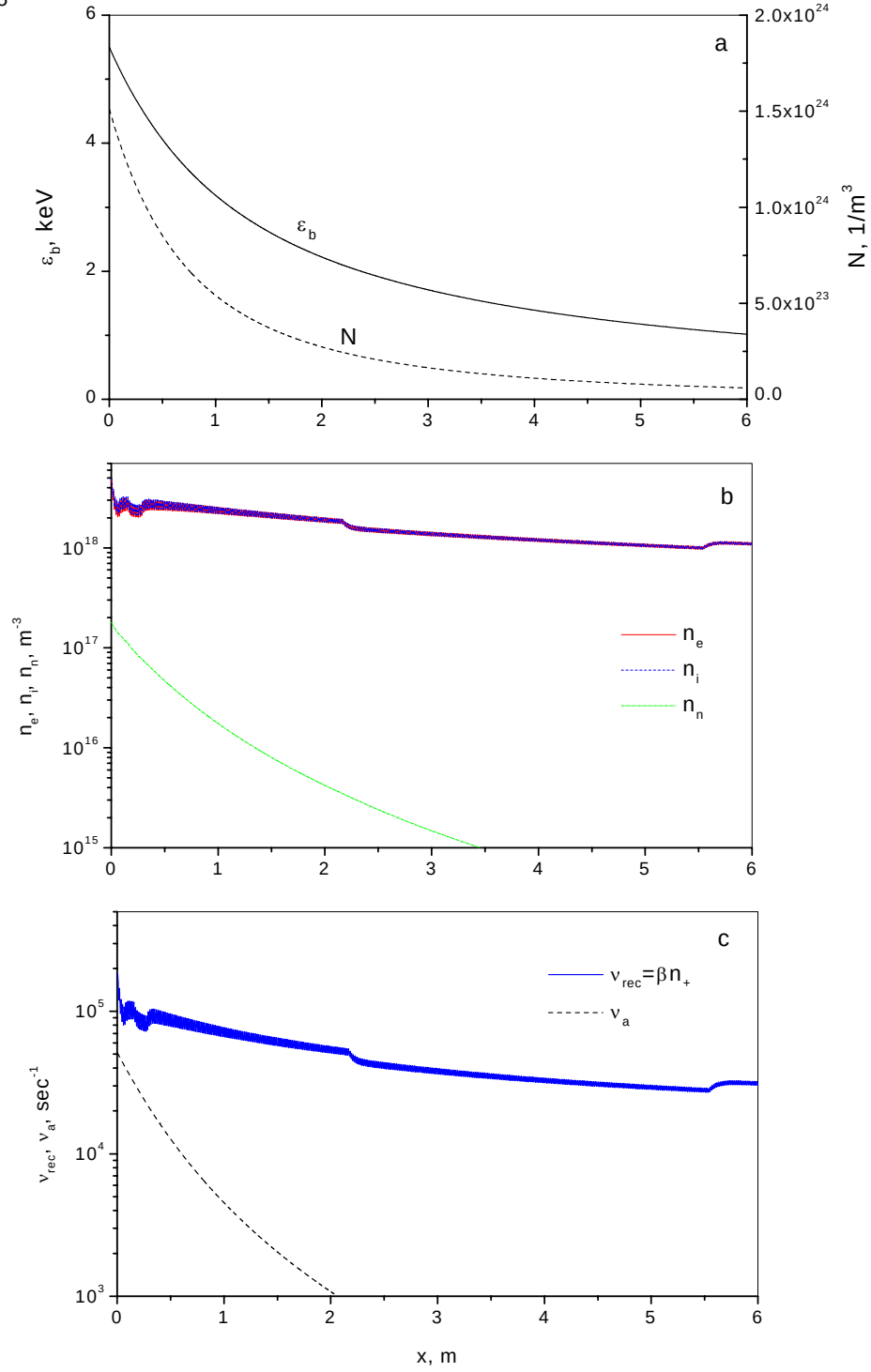


Figure 9-11. a – c. Profiles of e-beam energy, ε_b , gas number density, N , number densities of electrons and positive and negative ions, n_e , n_i , and n_n , and electron recombination and attachment frequencies, ν_{rec} and ν_a , in the case shown in Fig. 9-9.

9.7 CONCLUSIONS

System modeling, analysis, and planning have been initiated in FY98. Although this research was at the component and subcomponent level, systems integration and interface issues were addressed in the planning of experiments, preliminary design concept of the A-2 air supply system, and various other areas of the program. These issues will be elevated to a much higher level of importance and visibility in the FY99 and future years as the program focuses to a greater degree on the development of a functional MSHWT system.

A preliminary system analysis of a MSHWT has been performed at Princeton University. The results are encouraging and indicate that the system goals can possibly be met with e-beam energy addition for the Mach 12 flight conditions and with MHD augmentation for the Mach 15 conditions. With only e-beam heating, the MSHWT is estimated to be capable of test conditions to Mach 12.2 for the 2,000-psf dynamic pressure and Mach 12.7 for a 500-psf dynamic pressure. When the temperature in the heating region is allowed to extend beyond the 3,000 K temperature limit imposed for these estimates, the test conditions become Mach 12.36 for 2,000 psf and Mach 13.44 for 500 psf. With MHD augmentation, the analysis was not as definitive but indicated possible Mach numbers in excess of 14. Including ion slip in the analysis reduced the Mach number some and resulted in a Mach number of 13.55 for a dynamic pressure of 2,000 psf and a Mach number beyond 14 for 500 psf.

9.8 RECOMMENDATIONS

The results of the preliminary performance analysis for a MSHWT were very encouraging. However, a potential “show stopper” for these performance estimates is the nozzle survivability issue, primarily for the nozzle throat. This issue should be addressed as soon as possible. Further performance analysis and optimization of the solutions should be accomplished in FY99 and future years. A systematic study of the systems integration and interface issues should be conducted to identify the issues, propose conceptual solutions, demonstrate resolution of key issues, and test/demonstrate integrated subsystems. Systems integration must be considered in the development of all components and concepts for the remainder of the program leading to the design criteria for the MSHWT.

9.9 REFERENCES

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10.0 CONCLUSIONS

The MARIAH II/RDHWT goals during this past year have been to 1) study the potential of using a high-power, megaelectronvolt, e-beam as a thermal energy source for the wind tunnel, 2) explore preliminary concepts for the design of a UHP driver system, 3) address nozzle boundary layer phenomena, and 4) explore the performance of an MHD accelerator. This research has been undertaken with the focus of building both medium- and large-scale wind tunnel facilities capable of running at Mach numbers up to the Mach 12 regime and up to Mach 15 with MHD augmentation, reflecting true atmospheric temperature and pressure conditions and dynamic pressures up to 2,000 psf.

The UHP air supply subsystem uses a technology that in many ways echoes the hydraulically driven A-1 facility at the Institute of Hydrodynamics in Novosibirsk, Russia. For that reason, this facility has become known as the A-2. The high-pressure air is passed through a throat and enters the expansion nozzle section where thermal energy addition occurs. Details of the fluid dynamics in the throat and nozzle sections are critical for understanding issues related to wall heating and for taking into account boundary layer growth rates for proper nozzle contouring. Experiments indicate that energy addition can be accomplished in the expansion section by either using high power lasers or high power e-beams. Technical complexities with microwaves led to the decision not to pursue that technology further during this fiscal year. The focus of the energy addition research this year has been on e-beam technology. The use of MHD augmentation following the e-beam energy addition section will allow the facility to operate at an even higher Mach number, and progress in modeling MHD processes and some initial experiments on conductivity were performed to develop a more detailed understanding of that potential.

10.1 ULTRAHIGH-PRESSURE SUBSYSTEM

The objective of the UHP portion of the MARIAH II/RDHWT Program is to demonstrate the science and technology requirements of an air source for a full-scale hypersonic ground test facility. This objective is accomplished by 1) developing a UHP air source design concept that can credibly meet the performance requirements for a full-scale facility and 2) operating a device based on this design concept but sized to match MW-scale energy addition experiments. These objectives are accomplished by developing a UHP apparatus, called the "A-2." The successful A-2 proves the UHP technologies required for the full-scale facility and provides the air source for the multi-megawatt experiments that will demonstrate the science and technology of energy addition to reach full enthalpy. The A-2 subsequently will be scaled in volume to meet the air source requirements for the MSHWT, a user hypersonic test facility with performance similar to the full-scale facility but with a test section dimension of 0.5 to 1 m. A UHP driver that provides specific enthalpy and entropy conditions in the plenum to match supersonic radiant energy addition requirements for achieving Mach 12 flight conditions and that is scalable in volume to meet test article size and dynamic pressure conditions appears to be achievable with moderate R&D risk.

A major accomplishment in FY98 was the preliminary definition of the design objectives for the A-2 UHP air supply system. This is to be an R&D device having the following preliminary performance goals:

- Plenum pressure – 2,000 MPa
- Plenum temperature – 900 K
- Mass flow rate – 10 kg/sec
- Run time – 1 sec
- Test medium – Pure air
- Flow quality – <5 percent variation in plenum pressure over the run duration.

These performance goals are selected to achieve a Mach number of approximately 12.2 and a dynamic pressure of 2,000 psf at the exit of a radiatively driven facility, with the potential of extending the Mach number up to 15 with MHD augmentation. Modeling results indicate that there is a range of plenum conditions that can meet the same Mach number and dynamic pressure goals, and the actual operating parameters of the A-2 may vary somewhat based on engineering tradeoffs. For example, a similar performance can be achieved by operating at a pressure of 2,300 MPa and a plenum temperature of 750 K. The final design point for plenum pressure and temperature and for mass flow rate will evolve as system performance, cost, and technical risk tradeoffs are identified and understood.

Significant progress has been made in defining a conceptual design for the A-2 system. Based on the above preliminary design criteria and on ES&H considerations, the dynamic intensifier approach was selected as having the highest potential for meeting the MARIAH II/RDHWT Program performance requirements. This approach was selected because it has low-to-moderate R&D risk, a credible means to expand the subsystem to full-scale facility run time and mass flow rate requirements, and an acceptable ES&H risk. Alternative approaches failed to meet one or more of the UHP driver performance objectives. The radially arrayed dynamic intensifier scheme provides connected volumes of UHP air that are scalable to meet mass flow rate and run time requirements of the full-scale facility. Use of a variable radial support design permits plenum conditions with pressures greater than 2,000 MPa at temperatures greater than 700 K. While much of the technology is well understood, the construction, proof testing, and operation of the UHP air source remains a formidable task. A detailed description of this design approach is given in Section 5.

10.2 NOZZLE

The UHP nozzle section is a high technical risk component in the UHP driver subsystem. A preliminary geometrical design concept has been developed that appears to be consistent with UHP, energy addition, and fluid dynamics subsystem integration. The design concept also appears to support acceptable operational costs. Significant effort is required in the literature survey of high strength nonmagnetic materials, chemical reactivity at high temperature and O₂ fugacity, and thin film thermal and chemical barrier layers. Research is required in mass diffusion rates of O₂ across the boundary layer, heat transport across the fluid wall interface, chemical reactivity at high temperature and O₂ fugacity, and mechanical surface erosion in hot/high Reynolds number flows.

The present concept for the UHP nozzle is a compound pressure vessel, approximately 10 cm in OD, having at least three layers. The nozzle must be long enough to be inserted into the UHP axial manifold at least 1 diameter and to permit a magnetic field having the required field strength

and uniformity at the throat. In the conceptual design, the magnet has an assumed aperture of at least 10 cm and a depth of 60 cm. If the symmetry plane of the magnet is at the throat, the overall UHP nozzle length is approximately 80 to 100 cm. All layers of the nozzle must be made of materials that are compatible with the time-dependent magnetic field strength and uniformity required at the throat. Details of the design approach are given in Section 6.

A promising approach to fabricating nozzles for the MARIAH II/RDHWT Program has been developed. The approach appears to meet the several requirements for research on high Reynolds number supersonic flows near room temperature, *viz.*, precise control of the nozzle cross-sectional area, surface smoothness of the order of hundreds of nanometers, and economical fabrication. The flexibility to lay down “designer” layers on the internal surface of the nozzle to serve as thermal, chemical, and diffusion barriers; to control surface erosion; and to match thermal expansion coefficients will be important to the high O₂ fugacity, high temperature, high shear stress environment in the A-2 and successor devices.

Heat transfer and boundary layer growth rate in the nozzle section must be predictable, both for nozzle survivability and for proper design of the nozzle contour. In this high density, real gas regime, the recovery temperature at the wall of the nozzle is expected to be significantly higher than the temperature in the plenum. This may lead to the requirement of thin film cooling, or some other approach, to avoid nozzle degradation. A 275-MPa, room temperature, blowdown device has been built to study boundary layer growth phenomena and heat transfer at Reynolds numbers equal to those of the full-scale facility. The installation of this blowdown apparatus and associated safety protection barriers has been completed during this fiscal year, along with the fabrication of a high quality throat and nozzle section.

10.3 ENERGY ADDITION

The major focus of the energy addition studies during this fiscal year has been on the e-beam concept. Initial experiments in the 23- to 123-kW regime were conducted at SNL to test whether the e-beam could, in fact, be used as a source for controllable thermal energy addition into the supersonic flow. These results showed controllable energy addition with no indication of flow instability. As such, they complemented the earlier results with laser energy addition, and much of the same diagnostic technology was used in this set of experiments. Although some difficulty was encountered with the magnetic focusing, the last set of experiments indicated that this difficulty could be overcome with better magnetic shielding. It was also observed that classical probes did not function properly, due to interference from x-rays, but that optical probes provided adequate information for performance analysis. This work formed the foundation for follow-on experiments using an e-beam with an expanded set of optical diagnostics, including embedded optical pressure sensors as well as measurements of chemical composition. These follow-on experiments are also expected to have more efficient energy coupling to the flow using improvements in the magnetic focusing technology.

Research on laser energy addition has continued in the modeling of boundary layer interactions; however, experimental work on laser energy addition has not been conducted during this fiscal year, primarily because of the lack of available funds to support both e-beam and laser research simultaneously. Recent e-beam experiments have led to an important conclusion that, should the

chemical composition in the e-beam thermal energy experiments be satisfactory, the potential of scaling an e-beam source up to the scale required for an MSHWT appears to be within the projected state-of-the-art.

For microwaves, the phenomenon of breakdown at low density severely complicates strategies for coupling microwave energy into the energy addition section of the wind tunnel. Bringing the microwaves in from downstream, as is proposed for both e-beams and lasers, is not feasible since breakdown will occur well before the microwaves reach the desired energy addition region. In addition, there are large uncertainties associated with the absence of a compelling energy coupling mechanism by which that energy will be deposited into air as well as complexities in beam coupling into the flow facility itself. These difficulties were a primary factor in choosing e-beams as the primary radiant energy addition source.

While neither microwaves nor laser energy addition have been excluded from the program, R&D cost constraints will preclude substantial R&D from being accomplished in either of these areas unless it is demonstrated that the e-beam option is not feasible.

10.4 MHD

For MHD, significant progress was made in developing the necessary computational tools for analyzing and predicting the performance of MHD accelerators. The most promising accelerator configuration appears to be one that operates at low to moderate temperatures (below 1,800 K), employs e-beams to provide a nonequilibrium level of conductivity, and operates at low current densities. Projected channel lengths are of the order of 3 to 4 m. With such technology, it appears possible to obtain significant acceleration and enthalpy augmentation through the MHD channel.

Progress in the experimental area includes preliminary conductivity measurements accomplished in a static cell. The results of these measurements agreed approximately with predictions of the conductivity model discussed in Section 8.3. Progress in the design of an MHD sidewall was reported in Section 8.4.

10.4.1 MHD Modeling

Models of charged particle kinetics and vibrational relaxation were coupled with a quasi-1-D flow code, resulting in an efficient tool for analyzing and optimizing system performance. The quasi-1-D code generally agreed with more sophisticated 2-D modeling. Modeling helped to identify the optimal range of e-beam parameters and to suggest injection of the beams through foil-covered slots spaced periodically along the channel. Performance calculations employing the 1-D code were applied to an MSHWT-type facility that was assumed to have an air supply system operating at 20,000-atm plenum pressure and an e-beam energy addition section employing relativistic e-beams. Exit Mach numbers of 14.5 and exit total enthalpies approaching the Mach 15 with a dynamic pressure of 2,000 psf appear to be feasible assuming channel inlet conditions compatible with the performance of the upstream components (UHP air supply, nozzle, and e-beam energy addition). However, these calculations were performed under the assumption that ion slip effects are negligible. More recent computations (not reported in Section 8) indicate that, at low mass densities (below 1.2 kg/m^3) and high magnetic fields (above approximately 10 T),

ion slip will have a significant effect on MHD performance (see discussion below and in Section 9.6). A first-order analysis indicates, assuming O_2^+ is the positive ion, that the ion slip effect becomes significant when the magnetic field reaches values of approximately 10 T or greater.

The analysis of hypersonic boundary layers in MHD channels revealed that a strong coupling exists between the thermal boundary layers and the near-electrode, space-charge sheaths. The anode sheath was shown to be extremely important for the device performance. Anode voltage fall, affected by the reduced mobility of electrons across a magnetic field and the reduced density in the boundary layer, can be comparable with the total voltage across the channel. Other simulations using a 2-D gas dynamic code coupled to a beam propagation model showed that the temperature, density, and pressure profiles along the Z direction (magnetic field direction) are all highly nonuniform and are strongly affected by the wall recovery physics.

The CYLTRAN trajectory code is a Monte Carlo-type of code that is capable of predicting the beam energy deposition and ionization rate profiles across the channel provided the density profile is known. A series of calculations was run with a gas density of 0.00012 g/cm^3 (0.1 atm at 300 K) with a guiding magnetic field of 7 T perpendicular to the MHD channel wall. The beam electrons were assumed to be injected parallel to the field lines without any initial divergence. The results of these calculations have been used as the basis for developing accurate curve fits for beam energy absorption as a function of beam distance.

10.4.2 Conductivity Experiments

Preliminary static cell tests were conducted in air and N_2 at SNL for the purpose of measuring the electrical conductivity induced by e-beams. The experimental results were in approximate agreement with theoretical models developed by the MARIAH II/RDHWT Program team. The preliminary data taken in air using the HAWK e-beam accelerator appears to agree with the first-order kinetics model described in Section 8.3. For air, the predictions of the theory agreed to within 40 to 50 percent with the conductivities inferred from the static cell resistance measurements. The two limiting theoretical curves, one representing inclusion of electron attachment effects and the other neglecting attachment, provide consistent lower and upper bounds for the experimental conductivity data. These results provide at least preliminary confirmation of the conductivity model described in Section 8.3. For N_2 , there appears to be an anomalous trend in the conductivity/pressure relationship, inasmuch as the measured conductivity increases in passing from 0.1 to 0.5 atm of cell pressure. This was unexpected and is at this point unexplained.

Several conclusions may be drawn from the analysis of the experimental data and the kinetics model.

First, an analysis of the e-beam kinetics equations enables one to identify a dimensionless parameter $\alpha = (k_a/k_{dr})[O_2]^2$ that characterizes the regime in which attachment of electrons by diatomic O_2 will be important. For $\alpha \ll 1$, attachment is negligible, whereas for $\alpha \gg 1$, it dominates the kinetics. Since the effect of attachment is to remove free electrons and reduce the gas conductivity, it will be essential to operate the MHD accelerator at a condition of $\alpha < 1$. The

analysis given in Section 8.3 indicates that to ensure this condition, it will be necessary to operate at subatmospheric pressures in the MHD channel, probably at pressures as low as 0.1 atm. An important point relevant to this discussion is that operating the MHD channel at subatmospheric pressures necessarily implies operation at high channel Mach numbers. This is due to the high total enthalpy and high static pressures upstream of the MHD channel. In addition, if the Joule heating is to be kept small (a desirable mode of operation), it will be necessary to operate at low current densities and high magnetic fields to obtain significant body force acceleration ($J_y B$). This reasoning is confirmed in the analytical study summarized in Section 8.2 in which current densities of a few milliamps per square cm were specified with magnetic fields as high as 20 T. These high field strengths were required to obtain substantial acceleration of the air through the MHD channel while minimizing Joule dissipation.

10.4.3 Integrated MHD Sidewall and Window Design

Two concepts for the MHD sidewall design have been considered. The first is to use cooled foils as apertures for injection of the e-beams. This method appears to be promising, providing the beam current densities can be maintained below about 30 mA/cm². At currents above this value, the heating of the foil due to absorption of the beam energy becomes a serious materials challenge. If it is necessary to work at higher currents, the plasma porthole concept is a possible solution. An essential requirement is that a large fraction of the total sidewall area must be irradiated with e-beam radiation. This implies that a large number of e-beams will be required. For either the plasma porthole or the cooled foil options, this requirement will complicate the design due to the cooling requirements. In the foil option, active cooling of the foil window is required. In the case of the plasma porthole, present design configurations require each individual discharge tube to be cooled.

10.5 SYSTEMS INTEGRATION

One-dimensional analyses of overall system performance were accomplished to evaluate the potential of this system concept to achieve the objectives of a Mach 12, 2,000-psf dynamic pressure flight condition with radiant heating alone and a Mach 15, 2,000-psf flight condition with MHD augmentation. These analyses identified feasible, idealized thermodynamic paths for the UHP and nozzle subsystems. The basic, idealized thermodynamic path consists of the following processes: 1) an adiabatic compression of air-to-plenum pressure of 2,000 MPa; 2) adiabatic expansion in the nozzle to Mach 2; 3) radiant energy addition at constant Mach number to a temperature of 3,000 K; and 4) constant temperature radiant energy addition up to the final total enthalpy. As required for the higher Mach number test conditions, an MHD accelerator would follow the radiant heating in the nozzle to provide the final stage of energy addition prior to the final isentropic expansion into the test section.

Analysis of e-beam heating of the supersonic air in the nozzle concluded that a test section Mach number of 12.2 at a dynamic pressure of 2,000 psf could be achieved without MHD acceleration. This would require 52 MW of power from a 3-MeV e-beam source. Analysis for a simulated flight dynamic pressure of 500 psf concluded that a test section Mach number of 12.7 could be achieved. These analyses were based on initial plenum conditions of 2,000 MPa and 900 K and a maximum temperature of 3,000 K in the e-beam heating region of the nozzle. If the 3,000 K

temperature limit is removed and all of the heating occurs at a constant Mach number of 2, the system performance is improved slightly, producing test section Mach numbers of 13.44 for a 500-psf dynamic pressure and 12.36 for 2,000 psf. However, for these cases, the air temperature rises to 5,074 K and 3,746 K respectively during e-beam heating in the nozzle. Allowing the temperature to reach these high values would undoubtedly result in a degradation of flow quality (dissociation and formation higher concentrations of undesirable species such as NO and O₃), although the degree to which this will occur for the very short residence times at these temperatures is unknown at present.

Further analysis including MHD acceleration following the e-beam heating in the nozzle was not as definitive but indicated that Mach numbers in excess of 14 may be possible at a dynamic pressure of 2,000 psf. One analysis concluded that a Mach number of 14.4 was achievable with a dynamic pressure of 2,000 psf. However, with low density flow and a high magnetic field in the MHD channel, the ion-slip phenomena has been identified as a potential problem that may reduce the MHD performance. An analysis for similar conditions taking this effect into account concluded that a test section Mach number of 13.55 might be achievable. It should be noted that the analyses including MHD acceleration have not been optimized and are only preliminary, rough estimates of the performance. Further analyses optimizing the system performance and with improved MHD models must be conducted. For instance, the performance should be evaluated with the fractions of the enthalpy added by e-beam heating and MHD varying. Optimum operating conditions for the MHD accelerator channel should also be investigated. The ion-slip phenomena may be avoided by operating the MHD accelerator in a different flow regime, for example, higher density and lower magnetic field. Further details of these analyses may be found in Section 9.6.

System modeling, analysis, and planning have been initiated in FY98. Although this research was at the component and subcomponent level, systems integration and interface issues were addressed in the planning of experiments, preliminary design concept of the A-2 air supply system, and various other areas of the program. These issues will be elevated to a much higher level of activity and visibility in the FY99 and future years as the program focuses to a greater degree on the development of a functional MSHWT system.

In conclusion, results from preliminary system analysis of an MSHWT are very encouraging and indicate that the system goals can possibly be met with e-beam energy addition for the Mach 12 flight conditions and with MHD augmentation for the Mach 15 conditions. To date, no technical issues have been identified that would prevent this objective from being realized.

11.0 RECOMMENDATIONS FOR FUTURE RESEARCH

The continued development of individual subsystems, as well as the integration of those subsystems into a large-scale facility, forms the focus of the future research for the MARIAH II/RDHWT Program. The program team recognizes that the subsystem integration issues are of first-order importance and will affect the capabilities of the subsystems themselves. Future research will continue to focus on a medium-scale hypersonic wind tunnel facility capable of operating in the Mach 12 to 14 regime at a dynamic pressure of 2,000 psf. The objective is for this facility to have a run time on the order of seconds and produce a hypersonic air flow that closely matches true flight conditions in static temperature, pressure, and chemical composition. Major issues to be addressed for the subsystems are summarized below:

11.1 ULTRAHIGH-PRESSURE AIR SUPPLY SYSTEM

As noted in Section 5, system requirements such as test section size, Mach number, dynamic pressure, flow quality (both chemical and thermodynamic), and run time define the limits of tradeoffs between the air supply and energy addition subsystems. In general, the more energy provided by the UHP subsystem, the less required of the energy addition subsystem. In both subsystems, operation at and beyond current industrial limits results in increased risk and cost along steeply increasing curves. The MARIAH II/RDHWT R&D strategy is to accept moderate technical risk in the UHP subsystem. The UHP subsystem concept is constrained by an existing materials and technology envelope that may be somewhat beyond current industrial practices.

Environmental, Safety, and Health must be integrated continuously with the science and technology analysis, engineering design, procurement, fabrication, testing, and operation of the UHP air source. Both ES&H specialists and program management must play an active role in the development of the UHP air source design and deployment. The primary hazards presented by the considerable (approximately 10^8 J) total stored energy in the UHP air source are blast overpressure, static overpressure, shrapnel, noise (both in normal operation and upon catastrophic failure), and asphyxiation.

Consistent with these requirements, the MARIAH II/RDHWT Program team recommends that a UHP air supply system (designated the A-2 facility) be designed, fabricated, and demonstrated during the next 2 years. The purpose of this facility is two-fold: 1) demonstrate a design concept that meets all of the design requirements for the MSHWT air supply system, and 2) provide a UHP driver system that can support future experiments in the areas of energy addition and nozzle boundary layer characterization. A planning assumption is that the A-2 facility will be sited at the location of the energy addition source since it is likely to be the center of mass of organizational, energy, and plant infrastructure of the experiments. The A-2 UHP driver will be designed and built at the LLNL and is likely to be sited at the e-beam energy source at SNL. Both laboratories are operated by the DOE and must meet its ES&H requirements.

11.2 NOZZLE

At present the nozzle represents the least understood and, potentially, the most critical component of the system. As previously mentioned, in the real gas regime, the recovery temperature at the

wall of the nozzle will be far in excess of the plenum temperature. For example, an air flow originating in a plenum at 20,000 atm and 900 K may reach temperatures as high as 2,000 K at the wall of the throat. As energy is added to the flow in the expansion section, these stagnation wall temperatures can increase even further. Understanding what the actual recovery temperature will be at the wall in the throat region, and possibly controlling that temperature with thin-film cooling, become critical components of the research program. It is particularly important to keep O_2 away from the surface to avoid oxidation of surface material, and at these temperatures, combustion. The most promising approach appears to be the injection of a He layer that is entrained along the wall just upstream of the throat. Research to study the feasibility of injecting a thin layer of He and its stability while passing through the throat and into the nozzle section needs to be undertaken.

A second issue of critical importance is the growth rate of the boundary layer under these conditions. Even downstream of the throat the gas is at very high pressure and, therefore, far from an ideal gas. Due to the relative incompressibility of the gas, small changes in the throat area lead to large changes in Mach number. This suggests that the nozzle contour must be very carefully controlled to optimize the expansion through the thermal energy addition section. Knowledge of the boundary layer growth rate, therefore, becomes critical for the proper design of that expansion section. The initial work on the study of boundary layer growth rate, as well as wall heating and cooling strategies, will use a 275-MPa, room temperature, blowdown facility that reaches approximately the same Reynolds number as the UHP nozzle for the medium-scale hypersonic wind tunnel facility. Research must also be undertaken on the integration of a high-pressure nozzle into the high-pressure driver in such a manner that film cooling can be accomplished and the high field strength magnet can be properly situated.

During FY99 and future years, the UHP nozzle section effort must focus on:

- Integration of the UHP nozzle with the UHP driver, energy addition, and fluid dynamics subsystems.
- Literature survey to determine mechanical and chemical reactivity properties of candidate UHP nozzle materials.
- Experimental effort to understand the mechanical and chemical survivability of candidate nozzle materials and configurations under the hot, high Reynolds number flow conditions.
- Experimental and theoretical effort to determine O_2 transport across the boundary layer.
- Experimental and theoretical investigation into the feasibility of using He injection in a thin layer upstream of the throat.
- Experimental effort to determine the UHP nozzle wall temperature and heat transfer coefficient across the fluid-wall interface.
- Experimental and theoretical study of the boundary layer growth rate and wall cooling strategies in the high-pressure, high-Reynolds number nozzle.

11.3 ENERGY ADDITION

Continuing research will focus on e-beam technologies since those appear to be scalable to the MSHWT level in the near term without significant development risks. The preliminary tests conducted at the 23- to 123-kW level indicated that the e-beam can be properly focused into a supersonic air flow and can deposit thermal energy into that air flow with no apparent instabilities. Significant technical issues that remain to be resolved are:

1. The air chemistry created by such a beam.
2. The potential of contouring the e-beam with a top-hat profile to avoid heating the flow near the wall.
3. The stability of the energy deposition process at higher pressures where dynamic interactions between the flow field and the e-beam may arise.
4. The development of window technologies and magnetic field designs to properly couple the e-beam into the flow.

A continuing series of experiments are required in order to move to e-beam power levels, flow densities, and Reynolds numbers that reflect conditions required for a test facility. Improved beam focusing techniques and new diagnostic technologies are currently being tested using the e-beam at the 100- to 150-kW level with plenum pressures up to 2,000 psi. Follow-on experiments at the megawatt level are projected for the following years, and will require the development of a gas dynamic window technology in order to couple the beam out of the accelerator and into the flow. These experiments will also require a high-pressure blowdown driver technology to achieve the plenum conditions. The megawatt-level tests will have the objectives of demonstrating scalability and stability of the energy deposition process, as well as further characterization of air chemistry and other flow quality-related issues. With the aerodynamic window and blowdown driver technology, the megawatt-level experiments set the stage for follow-on experiments at the 10-to 50-MW level, which are expected to reach the operating power and Reynolds number regime of the MSHWT facility.

11.4 MHD ACCELERATOR

Planned MHD technology experimental research during the coming year will focus on the completion of the static cell conductivity tests (both with and without a magnetic field) and the design and demonstration of an MHD sidewall section capable of supporting e-beam injection. Another major planned activity is to begin the development of a multidimensional MHD accelerator model that would be capable of simulating the 2-D and 3-D effects of electrode geometry. Such a code would also in principle be capable of calculating the electromagnetic field quantities given an applied magnetic field and a specified array of applied voltages along the electrode walls. A more detailed discussion of the technical issues and the approach is given below.

11.4.1 MHD Accelerator Modeling

Presently, the status of the MHD accelerator models is that reasonably comprehensive models for simulating the e-beam ionization kinetics have been developed, but the computation of the

electromagnetic field quantities (current density, electric potential, and electric field) are essentially one-dimensional. As such, they cannot properly account for the geometry of the duct or the geometry of individual electrodes. Accounting for the effect of a specified pattern of applied voltages along the electrode walls is also quite problematic with existing codes. Therefore, it is recommended that a multidimensional MHD code be developed for the purpose of addressing these issues. Such a code, if it were coupled to a multidimensional flow solver, would be very useful for understanding the behavior of the MHD boundary layer under a variety of different scenarios, including varying magnetic fields, specified external voltages, and different (possibly nonuniform) MHD inlet flow conditions.

As presently envisioned, this code would be based on a solution to a governing partial differential equation of Poisson type for the electric potential. The problem can be formulated in terms of a generalized Ohm's law that includes ion slip. This formulation leads to a single partial differential equation for the electric potential. A multidimensional flow solver would also be required. Such algorithms are now available (see the discussion in Section 8.2). This code development will also require the e-beam kinetics models to be generalized from one dimension to two or three. A major issue in developing such a code will be the long computational times required for solving the multiple differential equations. To ensure success, it is recommended that the code be developed as several different modules (kinetics module, elliptic equation solver, and flow solver, for example), each of which can be run in a "stand-alone" mode for purposes of code validation. These codes will then lead to models that will be incorporated into a single multidimensional MHD accelerator model.

It is also recommended that the e-beam kinetics models be upgraded by generalizing them to two dimensions. The feasibility of implementing a Boltzmann solver for the electron energy distribution function should also be evaluated.

11.4.2 Conductivity Testing

As noted in Section 8.3, it was not possible to collect conductivity data for varying current densities or varying beam energies. This is due to limitations in the mode of operation of the HAWK accelerator and to some extent the limitations in the e-beam foil. It is recommended that a study be conducted to determine whether it is economically feasible to acquire an alternative e-beam source with greater flexibility in terms of beam energy. It would be desirable to control beam energy over the range of 20 to 100 keV with currents in the range 1 to 50 mA/cm².

Near-term experimental efforts should be focused on collecting a more comprehensive set of conductivity data, both with and without an applied magnetic field. As shown in Section 8.2, transport properties such as electron mobility, ion mobility, and electrical conductivity will in general depend on the magnetic field. It appears feasible to measure electrical conductivity and perhaps Hall parameters (using a static cell) in the presence of a magnetic field. Such experiments would be very valuable for verifying the prediction of transport properties carried out thus far. Specifically, data on conductivity and Hall parameter should be collected across a spectrum of pressures, beam energies, and current densities, with and without an applied magnetic field. The data should be compared against more sophisticated analytical models for conductivity and Hall parameter that incorporate the effects of an applied magnetic field on the transport properties. This will require additional MHD model development, as is discussed above.

11.4.3 Integrated MHD Sidewall/Electron Beam Window Design and Demonstration

The goal of the MHD sidewall demonstration tests is to demonstrate the injection of multiple beams and to demonstrate a credible design for e-beam windows. To be credible, these tests should be done in a high speed flow facility. Based on modeling studies, a recommendation has been made to design the MHD sidewall section using cooled metallic foils rather than an open aperture concept. This recommendation was made based on analyses that showed that the MHD accelerator must operate at low current densities in order to minimize Joule dissipation. The cooled foil technology appears to be capable of sustained operation at the required current densities. Another factor in this recommendation was the perceived higher technical risk associated with the plasma porthole technology.

11.5 SYSTEMS INTEGRATION

To date, each system including the UHP driver, the nozzle, the thermal energy addition, and the MHD has been addressed separately with a large portion of the effort directed toward the thermal energy addition part of the problem. The preliminary outcome of these individual research efforts has now led to a strawman design for a MSHWT facility. This design includes a UHP air supply system driven by hydraulic pressure intensifiers, a film-cooled nozzle and throat assembly housed inside a magnet with a field strength that might be as high as 20 T, thermal energy addition using quasi-“flat-top” e-beams that are steered into the nozzle through aerodynamic windows in the sidewall, and an MHD acceleration section with conductivity sustained by an array of e-beams propagating across the flow along magnetic field lines. The MHD section will be several meters long, and the flow will exit from it directly into the test section. Numerous technical issues regarding system integration and overall system performance remain to be addressed. Some of these are:

- A requirements study needs to be conducted to determine the preferred operational range of the facility, such as run time, Mach number, dynamic pressure, and test article size. The flow quality requirements must also be quantified. Of particular importance for the e-beam-driven facility is the question of chemical composition of the air. Both the thermal energy addition section and the MHD accelerator will cause some chemistry to occur in the air. The impact of small amounts of nitric oxide and other nonatmospheric species must be understood.
- The integration of subsystem components needs to be examined. The issues include the following:
 - integration of wall cooling into the UHP driver and nozzle assembly;
 - integration of the high field strength beam focusing magnet into the high-pressure nozzle configuration;
 - design of the high-power e- beam path and entry window technology;
 - design of transition from circular to rectangular cross section for the MHD accelerator;
 - integration of the MHD accelerator section into the expansion nozzle considering the conflicting magnetic field requirements;

- development of a credible design for an MHD sidewall. The major technical challenge is to demonstrate an acceptable e-beam window design capable of admitting multiple e-beams. Design of the e-beam array is an integral part of this effort; and
 - design of the run time and run repetition rate compatibility for all subcomponents.
- ES&H issues must be examined for the entire facility, particularly including protection from catastrophic explosive failures in the UHP air supply system and protection from x-rays and other radiation generated by the e-beams.
 - Design risk should be minimized by choosing UHP technologies and source technologies that fall well within the projected state-of-the-art, and consequently, limiting the high risk areas to new technologies including thermal energy addition to supersonic air, wall cooling, and MHD acceleration of unseeded low temperature air.

One of the highest priority system integration issues that must be addressed in the near term is nozzle throat survivability. The UHP and moderately high temperature required in the plenum to achieve the system performance objectives results in high recovery temperature in the nozzle throat which, combined with high mechanical stress in the nozzle, can result in severe mechanical erosion and possible chemical combustion of the nozzle throat material. Investigation of methods to mitigate this potential problem must be initiated immediately. Recommendations on near-term research into nozzle throat survivability issues are addressed above in Section 11.2

Further system performance analyses and optimization should be accomplished in FY99 and future years. Improvements to the e-beam heating models including multidimensional fluid dynamics and the use of realistic e-beam profiles are recommended. Acquisition of nozzle boundary layer data in the 275-MPa blowdown facility is also recommended. (See also recommendations in Section 11.3.) The improved models and data will allow improved system analysis and optimization, which is also recommended. MHD model improvements are recommended to allow the investigation of multidimensional phenomena, ion slip, and nonequilibrium e-beam ionization. (See also recommendations in Section 11.4.) Improved system analysis and optimization with MHD augmentation is recommended for initiation in FY00.

A systematic study of the systems integration and interface issues should be initiated in FY99 to identify the issues, propose conceptual solutions and resolution of key issues, and to test/demonstrate integrated subsystems. Systems integration must be considered in the development of all components and concepts for the remainder of the program leading to the design criteria for the MSHWT.

Key systems demonstrations and analysis are identified in the MARIAH II/RDHWT Research Plan (see attached). The demonstrations will have the objectives of 1) establishing the credibility of the analytical simulations and 2) partially resolving scaling and performance issues.

11.6 FACILITY REQUIREMENTS

A hypersonic facilities requirements study will be initiated in FY99. Critical technical issues to be considered in this study have been identified as test duration, test section size, air chemistry, and

flow quality. The requirements for the national hypersonic T&E facility will be driven by the types of vehicles anticipated to be developed over the next 25 to 30 years and the test methodologies that will be utilized. These vehicles include advanced tactical missiles, interdiction/reconnaissance vehicles, and fully reusable space lift vehicles. To support the T&E of such vehicles will impose broad requirements on any such facility. Current T&E capabilities are inadequate in several areas, including aerothermodynamics, aeropropulsion, and materials/structural testing needs. These issues are described in more detail in Section 4.4.

NOMENCLATURE

a	speed of sound, m/sec
A	test section area, m^2
Bi	Biot number
$B_z, \vec{B}$	magnetic field, Tesla
$C_i, i=1-6$	constants in energy deposition rate equation, (Equation 8-30)
c_p	coefficient of specific heat, J/kg-K
d	nozzle diameter, mm (Section 6.3.2)
D	diameter, m
$\vec{E}$	electric field, V/m
E_b	e-beam energy, MeV
E_0	initial electron voltage, MV (Equations 7-1 and 8-30)
F_0	Fourier number
f_0	fugacity, Pa
h	convective heat transfer coefficient, W/m^2-K
$j, \vec{J}$	current density, amp/m^2
j_b, J_b	e-beam current density, amp/m^2
j	current density, A/cm^2
k	thermal conductivity, $W/m-K$
k_a	rate coefficient for attachment of electrons by oxygen, cm^6/sec
k_{dr}	rate coefficient for dissociative recombination, cm^3/sec
k_{en}	electron-neutral collision rate coefficient, cm^3/sec
K	ratio, outside diameter/inside diameter
Length	length of explosively driven jet, m (Section 5)
L	distance from pipe entrance, m
m	mass of air, kg
m	electron mass, 9.11×10^{-31} kg
μ	viscosity, Pa-s
μ_w	viscosity at the wall, Pa-s
M	Mach number

M	heavy particle mass, kg
N	total number density, cm^{-3}
n_e	electron number density, cm^{-3}
n_{e0}	electron number density in the absence of attachment effects: $n_{e0} = \sqrt{\frac{j_b Y \rho}{e W_i k_{dr}}}$
n_+	positive ion number density, cm^{-3}
n_-	negative ion number density, cm^{-3}
Nu	Nusselt number
P or p	static pressure, Pa
Pr	Prandtl number
q	e-beam energy deposition rate, MW/cm^3
Q	rate of energy addition per unit volume, watt/cm^3
r	radius, m
R	gas constant, $\text{kcal}/\text{mol}\cdot\text{K}$
Re	Reynolds number
S	entropy, $\text{kJ}/\text{kg}\cdot\text{K}$
S	specific entropy, $\text{Joule}/(\text{K cm}^3)$
t	flow time, sec
t	time to reach equilibrium, sec (Section 5.3.3.3)
T	temperature, K
u,U	flow velocity, m/sec
W_i	mean energy to create an ion-electron pair, eV
w	parameters in energy deposition rate equation, g/cm^2 (Equations 7-1 and 8-30)
x	streamwise coordinate, cm
$Y(E_b)$	mass stopping power for high energy (nonthermal) electrons, $\text{MeV cm}^2/\text{g}$
z	axial position along the nozzle, downstream from throat, mm (Section 6.3.2)

Greek Symbols

α	Dimensionless oxygen attachment parameter (Sec. 8.3.3), $\alpha = k_a[\text{O}_2]^2/(k_{dr}n_{e0})$
α	Townsend coefficient, (Sec. 8.2.2.1)
α	Fourier number
ΔG	Gibbs free energy, kcal/mol

ΔH	heat of reaction, kcal/mol
η	fraction of Joule heating deposited as vibrational excitation
γ	fugacity coefficient
ϑ	Particle flux (cm ² ·sec) ⁻¹
μ	electron mobility, m ² /(volt·sec)
ν_c	electron–neutral collision frequency, sec ⁻¹
ω_0	frequency corresponding to the lowest vibrational quantum state, rad/s
Σ	electron Hall parameter (dimensionless), $\Sigma = n_e$
Δ	Mass density, kg/meter ³ (g/cm ³ in Equations 7-1 and 8-30)
Φ	Scalar electrical conductivity, mho/meter
σ_m	cross section for momentum transfer, cm ²
τ	shear stress
τ_{VT}	vibration-translation relaxation time, sec ⁻¹
Π	dimensionless electron number density: $\Pi = n_e/n_{e0}$

Subscripts

e	Electrons
e	external
F	final
i	internal
I	intermediate
v	vibrational
1	forward (+z) direction
2	backward (-z) direction
+	Positive ions
–	Negative ions

ACRONYMS

3-D	three-dimensional
AEDC	Arnold Engineering Development Center
AFRL	Air Force Research Laboratory
AGARD	Advisory Group for Aerospace Research and Development

Al	aluminum
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
Be	beryllium
C	carbon
CCD	charge coupled device
CFD	computational fluid dynamics
Co	cobalt
COS	carbonyl sulfide
Cr	chromium
Cu	copper
DAS	data acquisition system
DoD	Department of Defense
e-beam	electron beam
EOS	equation of state
ES&H	environmental, safety, and health
Fe	iron
FEA	finite element analysis
FY	fiscal year
GW	gigawatt
HAWK	electron beam accelerator at Sandia National Laboratories
He	helium
HELSTF	High Energy Laser System Test Facility at White Sands
ID	inner diameter
ITS	Integrated Tiger Series
LHMEL	Laser Hardened Material Evaluation Laboratory
LITA	laser induced thermal acoustics
LLNL	Lawrence Livermore National Laboratory
MAP	mission area plans
MARIAH II	Magnetohydrodynamic Accelerator Research Into Advanced Hypersonics
MAWP	maximum allowable working pressure

MHD	magnetohydrodynamics
Mn	manganese
MNS	mission need statements
Mo	molybdenum
MOP	maximum operating pressure
MSE	MSE Technology Applications, Inc.
MSHWT	Medium Scale Hypersonic Wind Tunnel
N	nitrogen
NASA	National Aeronautics and Space Administration
NASA-LaRC	NASA Langley Research Center
NASA-AMES	NASA Ames Research Center
Nb	niobium
Ni	nickel
NIST	National Institute of Standards and Testing
NO _x	nitrogen oxide
O ₂	oxygen
OD	outer diameter
POP	proof of principal
R&D	research and development
RDHWT	radiatively driven hypersonic wind tunnel
Re	rhodium
Si	silicon
SNL	Sandia National Laboratories
SOW	statement of work
SSTO	single stage to orbit
STP	standard temperature and pressure
Ta	tantalum
TAP	technical area plans
T&E	testing and evaluation
Ti	titanium
TsAGI	Central Aerohydrodynamics Institute, Moscow, Russia

TSTO	two stage to orbit
UHP	ultrahigh pressure
USAF	U.S. Air Force
UTA	University of Texas at Arlington
V	vanadium
WBS	work breakdown structure
WPAFB	Wright Patterson Air Force Base

APPENDIX A – RDHWT/MARIAH II RESEARCH PLAN VERSION 2, 1999

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Acronyms and Abbreviations

1-D	one-dimensional
2-D	two-dimensional
A	amp (ampere)
AEDC	Arnold Engineering Development Center
AFRL	Air Force Research Laboratory
atm	atmosphere
cm (cm ²)	centimeter (square centimeter)
DoD	US Department of Defense
e-beam	electron beam
GHz	gigahertz
GW	gigawatt
K	kelvin
kb	kilobar
kg	kilogram
kW	kilowatt
J	joule
LLNL	Lawrence Livermore National Laboratory
m	meter
MARIAH	Magnetohydrodynamic Accelerator Research into Advanced Hypersonics
MHD	magnetohydrodynamic
ms	Millisecond
MSHWT	medium-scale hypersonic wind tunnel
MW	megawatt
NASA	National Aeronautics and Space Administration
psf	pounds per square foot
psi	pounds per square inch
RDHWT	Radiantly Driven Hypersonic Wind Tunnel
SNL	Sandia National Laboratories
T&E	test and evaluation
UHP	ultrahigh pressure
US	United States
USAF	United States Air Force
WBS	Work Breakdown Structure

1.0 Background and Introduction

There is a need for the United States (US) to develop military flight vehicles which fly at hypersonic speeds in the atmosphere serve as transporters for space access and have capabilities of fast response, global reach (strike and reconnaissance), and missile defense. Currently, the development of these various flight vehicles is constrained by the lack of ground-based test facilities, which are considered necessary to provide affordable development testing (vs. flight testing) and to reduce technical risk to acceptable levels.

In 1992, the US Air Force (USAF) and National Aeronautics and Space Administration (NASA) jointly conducted a study to assess the US test needs and capabilities for development of hypersonic flight systems.¹ The results of this study were confirmed by the joint NASA/Department of Defense (DoD) National Facilities Study in 1994² and again in 1997 by the DoD Aeronautical Test Facilities Assessment study.³ These studies revealed serious gaps in hypersonic test capabilities relative to test needs. An especially important issue is that the US does not have test facilities that can be employed for development testing of air breathing propulsion flight systems at the necessary flight simulation conditions above Mach 4. Technologies are available for building development test facilities to Mach 7, but not beyond where some envisioned air-breathing systems would fly to perhaps as high as Mach 20. It is critical that the environment of hypersonic flight be simulated, and actually duplicated for most cases, in terms of velocity, temperature, pressure, air chemistry, and test time.

Technologies for duplicating hypersonic flight conditions in wind tunnels that will provide the required test environments above Mach 7 have not been satisfactorily developed. There have been three major technical obstacles to the development of these hypersonic wind tunnels: (1) providing sufficient energy into the air while (2) maintaining correct air chemistry, and (3) availability of materials that will contain the high-temperature, high-pressure test gas. Electric arcs and compression heating have been employed to heat the test gas in a stagnation chamber and expand the test gas through a nozzle throat to the desired velocity. These techniques have proven to provide insufficient run time, unacceptable gas chemistry, and/or unacceptably low gas density in the test gas. Materials capable of withstanding the requirements of high stagnation temperatures and the severe nozzle-throat heat-transfer requirements limit practical run times to a few milliseconds or less at enthalpies required for flight duplication above approximately Mach 10.

Adding energy to the test gas downstream of the nozzle throat has been considered a possible solution to the nozzle-throat heat-transfer and chemical-dissociation problems. Two ideas have emerged: (1) adding thermal energy to the supersonic test gas by radiant energy means and expanding to the desired velocity, pressure, density, and temperature, and (2) magnetohydrodynamic (MHD) body force acceleration of the test gas followed by expansion of the test gas. Both ideas, however, have their respective physical constraints. Radiant heating requires an ultra high-pressure (UHP) driver operating to 20,000 atm just to achieve Mach 12 simulation at the correct gas entropy. Higher-Mach number duplication would require even higher pressure, which raises additional questions relative to high-pressure generation, containment, and run time. The MHD approach requires that the test gas be electrically conductive. Seeding the test gas with an alkali metal such as potassium or cesium to achieve the needed conductivity has been demonstrated successfully at relatively low pressures, provided the air and seed static temperature is of the order or 2500 K or greater, but these static temperatures have been shown to be impractical for achieving the required flight duplication conditions.^{4,5} In addition, such seeding materials have unknown effect on the test results and are undesirable from that standpoint. However, if a way can be found to maintain electrical conductivity at low temperature, MHD acceleration may have potential even at low to modest pressures. It has been proposed that seeding the gas with an electron beam (e-beam) or electric arc filaments is a potential concept that should be explored.⁶ A hybrid concept of coupling supersonic thermal energy addition by radiant means with MHD acceleration augmentation may reduce the requirements of the UHP air supply. This combination may provide an optimized solution and also provide a broader range of needed hypersonic test capabilities.

1.1 Radiantly Driven Hypersonic Wind Tunnel

R. Miles and others at Princeton University conceived the Radiantly Driven Hypersonic Wind Tunnel (RDHWT) concept in the early 1990s.⁷ Initial conceptual studies were conducted under sponsorship of the USAF Arnold Engineering Development Center (AEDC). The Air Force Research Laboratory (AFRL) has sponsored additional concept studies and research. Three, potentially viable, supersonic thermal energy addition approaches have been identified: (1) laser, (2) e-beam, and (3) microwave. (Each of these three methods of energy addition has been loosely termed as “radiant energy addition” when in fact the e-beam technique is better termed a “beamed energy” technique). In December 1997, a proof-of-concept laser energy addition experiment was successfully conducted at the AFRL. In August 1998, experiments were conducted at the Sandia National Laboratories (SNL), successfully demonstrating that heating a supersonic stream of air using an e-beam is possible. Both sets of experiments were conducted under AFRL sponsorship. Although both sets of experiments are very encouraging and have revealed no showstoppers, they were a modest beginning toward demonstration at unit power levels and gas densities representative of flight simulation. This research plan describes additional radiant energy experimental demonstrations that are required to provide confidence that the required energy levels can be obtained at reasonable flow quality. This plan also identifies issues that must be resolved in the areas of high-pressure-air storage, nozzle-throat survivability, boundary layers, thermal protection, and systems integration.

1.2 Magnetohydrodynamic Accelerator Research into Advanced Hypersonics

NASA sponsored the Magnetohydrodynamic Accelerator Research into Advanced Hypersonics (MARIAH) concept studies. The stated objective of the studies was to develop MHD accelerator technology for application to hypersonic wind tunnel test and evaluation (T&E) facilities. A target facility sought was to be capable of simulating post-bow-shock conditions for 5-degree deflection angle at free-stream flight conditions of Mach 15 and 2,000 psf dynamic pressure. Both seeded and unseeded plasmas were considered, driven by an electric arc heater. External energy sources such as microwave, laser, and e-beam were considered to initiate gas-stream ionization. The study revealed that it was impractical to achieve the target performance requirements with a Cs-seeded or unseeded accelerator using a conventional electric-arc preheater with equilibrium ionization. The required entropy conditions cannot be achieved because of the relatively low stagnation pressure and nozzle-throat heat transfer limitations. However, the study did suggest that MHD augmentation of the radiantly heated wind tunnel potentially has merit to achieve the target requirements, provided that nonequilibrium air ionization can be sustained.

1.3 The RDHWT/MARIAH II Concept

The RDHWT/MARIAH II concept is an outgrowth of USAF-sponsored RDHWT studies and the NASA-sponsored MARIAH studies. The term “RDHWT/MARIAH II” is used to describe the research program, described herein, leading to enabling technology required to define, design, and build a medium-scale hypersonic wind tunnel (MSHWT). As previously mentioned, the MARIAH study suggested that MHD augmentation of the radiantly heated wind tunnel may have merit provided that nonequilibrium air ionization can be achieved and sustained. Two regimes of MHD channel operation at moderate temperatures were suggested in the MARIAH study to achieve and sustain electrical conductivity: (1) high-pressure operation using guided arcs and (2) low-pressure, moderate-temperature operation using e-beam energy addition.⁷ Additional studies by Macheret, Schneider, Miles, and Nelson have further expanded on the e-beam ionization concept.⁸ As a result of congressional funding beginning in FY98, the USAF is sponsoring research on this concept.

It must be recognized from the start that the key requirement for this facility is achieving high-velocity flow at high pressures and in chemical equilibrium. This is not a new objective; it has been pursued since the early 1960s. This requirement translates into achieving high-speed flow at low entropy. What is new in the

present program is combining high-pressure air supply technology with thermal energy addition in a supersonic flow, and subsequent MHD energy addition to minimize entropy increase due to the energy addition. From a systems point of view, this will no doubt mean operating each of the three subsystems to obtain the desired total system performance (as opposed to trying to maximize each subsystem independently).

1.4 Program Expectations

This research is expected to take approximately eight years and produce design criteria for the MSHWT, which in turn will lead to a large-scale systems T&E facility. An initial, rough estimated cost for this program is \$34.5 million (see Section 4.9). The schedule and cost estimate for the research and concept criteria will be refined and updated as the program continues. In November 1998, the program steering committee recommended that this program be divided into two phases consistent with the expected \$20.5 million congressional funding for FY98–02 and the USAF Program Objective Memorandum (POM) funding of \$14 million approved for FY03–05. This recommendation is reflected in the description of the eight-year research program. Phase 1 describes congressionally funded research and Phase 2 covers USAF POM-funded research.

1.5 Purpose of this Document

This document has two purposes. First, it defines the detailed research required to define concept criteria for the MSHWT based on energy addition by radiant means coupled with magnetohydrodynamic acceleration augmentation to achieve the required test conditions. Second, it presents an estimate of the overall schedule and cost of the research program. The research plan will be updated annually to reflect results of the previous year's work and its impact on future research needs.

2.0 Overall Goals of the RDHWT/MARIAH II Research Program

2.1 General

The overall goal of this research program is to provide sufficient technology to define the concept design criteria for the MSHWT by FY05. This means being positioned to write design criteria for a MSHWT with all major component technologies demonstrated and exit criteria passed. It is estimated that the MSHWT will operate at a power level of 10 to 150 MW and with a targeted cost less than \$100 million.

The envisioned full-/large-scale air-breathing propulsion T&E facility must be kept in mind during this research program. For a test section of the order of 3 m diameter, this facility is expected to require on the order of 1 GW of power added to an air flow with seconds of run time and a flight simulation goal of Mach 8 to 15 with a dynamic pressure in the range of 500 to 2000 psf. The facility must accurately simulate real air in the test section from an aerothermal, thermodynamic, and chemical point of view. In other words, the facility is to duplicate atmospheric flight conditions as near as practical rather than to just simulate them by compromising the test medium.

2.2 Purpose of the MSHWT

The goals of the proposed MSHWT facility are based on the envisioned ultimate need for a large-scale T&E facility that can test full-scale hypersonic air-breathing propulsion systems at flight speeds above Mach 8 to Mach 15 while simulating true air chemistry and entropy conditions. The facility is also envisioned to be capable of performing aerodynamic, aerothermal, and aero-optic testing. The purpose of the MSHWT is two-fold: (1) to serve as a valuable medium-scale research, development, T&E test facility, and (2) to serve as a prototype for a future, larger-scale hypersonic aircraft-like T&E facility.

2.3 Performance Goals for the MSHWT

Except for test section size, the performance goals of the MSHWT are the same as for a large-scale hypersonic T&E facility. This means that the overall goal of the research is to develop technology for concept criteria to be used for the design of the MSHWT based on flight performance goals of Mach 8 to 15 and a dynamic pressure ranging from 500 to 2000 psf at run times of one second or greater. For hypersonic air-breathing propulsion testing, duplication of conditions behind a shock generated by a 5-degree wedge is the minimum goal at Mach 15 with a flight dynamic pressure of 2000 psf. The design of the MSHWT will probably be based on specific Mach number design points, tentatively established as Mach 10, 12, and 15. It is expected that the Mach 10 and 12 design points can be achieved at free stream conditions with supersonic thermal heating alone, if nozzle-throat survivability does not provide a limit, and that Mach 15 can be achieved with supersonic thermal heating and MHD accelerator augmentation. Assuming that the electrical conductivity issue is resolved, the upper Mach number limit will probably be bound by the MHD accelerator heat-transfer limit and entrance enthalpy profile conditions. A lower Mach number is probably bounded by the lower density limits permitted for supersonic thermal energy absorption.

3.0 Research Plan Development

3.1 Participants

A decision was made at the program team meeting on 25–26 June 1998 to conduct a workshop to prepare the major elements of the RDHWT/MARIAH II research plan. This workshop was held on 27–29 July 1998 at SNL. The participants in the workshop were:

Mr. Tom Fetterhoff, AEDC/XP.
Mr. John Jordan, Sverdrup Technology, AEDC Group.
Dr. Marion L. Laster, Consultant to Sverdrup Technology.
Mr. Gordon Nelson, MSE Technology Applications, Inc.
Mr. Gloyd Simmons, MSE Technology Applications, Inc.
Dr. Leon Ring, President, ASE, representing MSE Technology Applications, Inc.
Dr. Richard Miles, Princeton University.
Dr. Garry Brown, Princeton University.
Dr. Marc Costantino, Lawrence Livermore National Laboratory (LLNL).
Dr. Ron Lipinski, SNL.
Dr. Larry Schneider, SNL.

The program team produced Version 1 of the research plan with Dr. Laster serving as the editor and compiler. Version 1 was presented to the program steering committee in November 1998. Subsequently, Version 2 reflects recommendations of the steering committee and incorporates new knowledge from the research to date.

3.2 Research Organization and Criteria

The July 1998 workshop participants organized the RDHWT/MARIAH II research into seven major areas: (1) ultrahigh pressure (UHP) air supply and plenum, (2) nozzle-throat survivability, (3) nozzle boundary layer, (4) nozzle cooling, (5) thermal energy addition, (6) MHD augmentation, and (7) systems integration.

The area of UHP gas properties was initially considered as a major research area, but determined not be required because sufficient gas thermodynamic property data has already been gathered under the RDHWT program. This decision may have been premature; thermal energy addition could indeed be attempted for air storage pressures above 20 kb, the current, extrapolated limit of the thermodynamic and transport property Equation of State (EOS) for air. Experimental data to approximately 30 kb of pressure may be required for this program. Therefore, the need for thermodynamic and transport property data is reinstated as a research need under (1) UHP air supply and plenum.

The research needs for each of these areas are described in terms of (1) requirements, (2) critical technical issues, (3) alternatives, (4) exit criteria, (5) key demonstrations and experiments, (6) analytical tools, (7) major deliverables, (8) estimated cost, and (9) estimated schedule. Each subsection of Chapter 4 addresses needs (1) through (7); needs (8) and (9) are addressed in Section 4.9. This research plan also covers the study necessary to identify potential hypersonic flight systems and test needs. For each of the key research areas, the enumeration for the program work breakdown (WBS) is identified in the title.

4.0 Key Research Areas and Issues

This document provides a detailed summary of the key research needs that were determined by the Program Team in the research planning workshop held at SNL on 27–28 July 1998 and modified as a result of the steering committee review in November 1998.

4.1 Hypersonic Flight Systems Test Requirements Study (WBS 2.1.x)

This section identifies the research that must be performed to define technical criteria for development T&E wind tunnel testing of visionary military systems that are expected to fly in the atmosphere and in the Mach 8 to Mach 15 regime. These technical criteria are needed to establish specific facility performance requirements that must be satisfied in the RDHWT/MARIAH II approach, evaluate other proposed facility concept approaches, and aid in advocacy of new hypersonic facilities. Alternative approaches include, but are not limited to, electric arc-heated and impulse wind tunnels, sled track, light-gas-gun acceleration devices, and flight testing. The alternative approach study will be funded from AEDC institutional funds. This task is expected to span Phases 1 and 2 of the program.

4.1.1 Requirements

Aero-thermodynamic, aero-optic, jet interaction, propulsion, thermal-structure, and shroud separation tests are the total scope under consideration. However, the initial focus in this requirements study is on air-breathing propulsion testing, which drives the most demanding tests and the overall facility requirements. Facility Mach number, enthalpy, pressure, run time, flow path size, flow quality, test productivity, measurement capabilities, facility capitalization cost, and cost of testing are factors that must be considered in this analysis and study. The salient features and advantages of alternative facility approaches are to be identified and assessed.

A key element of the study is a trade study of the weapon system development approach to be used by the weapon system Program Manager, depending on test facility capabilities that might become available. For example, could a weapon system Program Manager utilize a short-duration, full-duplication facility to establish air-breathing propulsion systems performance, including ignition and start up, and use a longer-duration facility with less than full duplication to establish durability and operability of the same air-breathing propulsion system? Such less-than-full duplication might include chemical nonequilibrium, seed in the flow, and reduced total pressure corresponding to the flow behind one or more oblique shocks.

4.1.2 Critical Technical Issues

Critical technical issues for the development of a pure air hypersonic wind tunnel operating in the range Mach 8-15 with a dynamic pressure of 500-2000 psf are:

(a) *Test time.* Test time drives any proposed test facility concept and test technique. Test time is critical in establishing facility air storage, energy storage, thermal management, and exhaust management requirements. Air-breathing propulsion testing objectives are usually classified into three categories: performance, operability, and durability testing. Test time requirements must be assessed for all three categories.

(b) *Article size.* The size of a T&E test facility is driven by test article size. Therefore, an assessment of the size of potential systems and subsystems that would be tested is required. Size and velocity/altitude simulation requirements determine mass flow requirements. This, along with test time, also drives facility air storage, energy storage, thermal management, and exhaust management requirements. This research plan leads to a T&E test facility but is focused on development of criteria for a smaller MSHWT. It is intended

that the MSHWT be sized to accommodate testing of “medium size” air-breathing propulsion systems and possibly subsystems of larger systems.

(c) *Air chemistry and flow quality.* Air chemistry and flow quality needs for facility testing must be assessed. The allowable tolerances on these factors are important to selecting a facility concept and design of components.

4.1.3 Alternatives

The technical analyses of the requirements study is based on various system test requirements. A government/academia/contractor Integrated Product Team defines the scope of the system test requirements. Alternative approaches for the study are as follows:

In-house at AEDC with USAF and Sverdrup Corp. personnel.

Contracting to industry outside AEDC using a new contract. The usual federal contracting procedures must be followed.

Contracting to industry outside AEDC using an existing government contract.

The source must be selected based foremost on capability to perform the work. In particular, the organization selected should have an incentive to developing test approaches that minimize cost, including developing approaches requiring less than full duplication. The work must be performed for timely input to the RDHWT/MARIAH II research program.

4.1.4 Exit Criteria

The requirements study is complete when:

Potentially real and visionary hypersonic flight systems have been identified that will operate above Mach 8.

The performance, operability, and durability test requirements for aerothermodynamic, aero-optic, jet interaction, propulsion, thermal-structure, and shroud separation classes of testing have been addressed.

Facility run-time, size, thermodynamic, chemical, and flow-quality requirements have been identified for testing potentially real and visionary systems.

The advantages and disadvantages of the various test facility approaches have been assessed.

Formal written reporting is completed on the above items.

4.1.5 Key Demonstrations/Experiments-None Required.

4.1.6 Analytical Tools

Analysis of test requirements for hypersonic flight systems requires appropriate analytical tools and experience in the design of hypersonic flight vehicles, including missiles and aircraft-like vehicles. Aerothermal analysis of conceptual vehicles in these classes is required to understand configuration and structural response to the severe environment of hypersonic flight, with and without air-breathing propulsion.

4.1.7 Major Deliverables

- (a) Requirements analysis of representative future hypersonic air-breathing propulsion systems. Complete in FY99.
- (b) Other classes of tests—Deliverables and schedules to be determined in FY99.

4.2 UHP Air Supply and Plenum (WBS 1.1.1.3.x)

4.2.1 Requirements

The ultra-high pressure (UHP) air supply requirements are defined by the facility run time, mass flow rate, and the enthalpy/entropy handoff to the energy addition section. The MSHWT is to have a minimum run time of one second, with a desirable run time of 10 to 100 seconds. Specification of the enthalpy/entropy condition, reflected in the plenum pressure and temperature requirement, results from a trade-off between high pressure – high temperature technology and energy addition physics, chemistry, and technology. With current materials technology and modest risk, an air storage system that will operate to at least 20 kb pressure and 900 K and achieve the minimum run time is believed possible and affordable. Off-design operating pressures up to 30 kb also will be considered. This higher plenum pressure may result in being able to reach the Mach 15 minimum requirement (for a shock behind a 5-degree wedge) with supersonic thermal energy addition alone provided that there are no significant throat survivability constraints. Heating the UHP air to even higher temperatures is thermodynamically desirable and gives some relief to the pressure requirements. However, this exacerbates the nozzle-throat survivability issue. The intent is for the air supply system to exploit capabilities of existing materials without entering into a significant materials technology development effort.

All research related to the MSHWT air supply system and experimental demonstrations will be completed in Phase 1, with the exception of support provided to the Phase 2 research demonstrations.

4.2.2 Critical Technical Issues

The critical technical issues for the UHP air supply system are common to the performance requirements of the MSHWT and the full-scale T&E facility, with supersonic thermal energy addition. They are:

- (a) designing, fabricating, and connecting large volumes (of the order of 10^{-3} m^3) for pressure service at 2000 MPa and above,
- (b) managing the thermal environment to minimize heat transfer from the air to its surroundings and to maximize material strength,
- (c) developing a design and materials to ensure pressure vessel and nozzle survivability under 400 MPa partial pressure of pure oxygen at stagnation temperatures of 900 K and recovery temperatures in excess of 1500 K, and
- (d) developing a design to contain 2000 MPa upstream of the nozzle throat while permitting a toroidal magnetic field of up to 10 T at the throat.

Thermodynamic, transport, and heat transfer properties of air to 30 kb pressure are required for risk reduction.

4.2.3 Alternatives

The following alternatives for the air supply are considered:

- (a) static air storage operated in a blowdown mode,
- (b) dynamic pressure intensifiers, and
- (c) liquid air storage with plenum heating.

Alternatives to obtain the thermodynamic, transport, and heat transfer properties of air-property data and analytical models up to 30 kb pressure are:

- (a) US sources, such as LLNL and the National Institute of Standards and Technology, or
- (b) contract with the Institute of Mechanics, Moscow State University.

4.2.4 Exit Criteria

- (a) An air-supply system concept with module and subcomponent proof tests, which provides 20 kb pressure at 900 K for one second or greater. This includes the air-pressure generation system, plenum, nozzle-throat, thermal-management, control, and operating systems.
- (b) MSHWT air-supply, plenum, and nozzle-throat design concept.
- (c) Design, fabrication, and demonstration of the selected design concept.
- (d) Provision of hardware to support other MSHWT component experimental demonstrations. This device is referred to as A-2.
- (e) Delivery of thermodynamic, transport, and heat transfer properties air-property data up to 30 kb.

4.2.5 Key Demonstrations/Experiments

- (a) Demonstrate a credible A-2/MSHWT design concept of the UHP subsystem and its coupling to the energy addition subsystem.
- (b) Demonstrate material strength and chemical survivability in the design pressure – temperature operating envelope.
- (c) Perform an Environmental, Safety, and Health risk analysis of UHP subsystem. Perform computer simulation of high-risk components (i.e., components with safety factor less than four and stored energy greater than 10^4 J) to determine hazard-mitigation requirements.
- (d) Proof test the A-2 design at 2000 MPa and 900 K.
- (e) Perform experiments and/or analysis to reduce the risk of extrapolation of existing air EOS and heat transfer data to the UHP operating regime.

4.2.6 Analytical Tools

Time-dependant, finite-element codes and material models for the analysis and design of the MSHWT air-supply concepts and design of the A-2 are required and available at LLNL. Transport, heat transfer, and thermodynamic air property data or computer models are needed to 30 kb pressure.

4.2.7 Major Deliverables

- (a) MSHWT conceptual design alternatives—FY99.
- (b) Estimated costs for MSHWT alternatives—FY99.
- (c) MSHWT air-supply design concept selection—FY99.
- (d) MSHWT conceptual design—FY02.
- (e) A-2 design and cost estimate—FY99.
- (f) A-2 fabrication and delivery—FY00.
- (g) Transport, heat transfer, and thermodynamic property data to 30 kb pressure—FY00.

4.3 Nozzle-Throat Survivability (WBS 1.2.1.3.x)

4.3.1 Requirements

Nozzle throats will need to maintain their geometric integrity with air flow at 20 kb stagnation pressure and 900 K stagnation temperature for a run duration of at least one second. Survivability for multiple runs or longer single-run duration is desirable from the standpoint of operational productivity and cost. Should these goals not be achievable, the maximum operational plenum pressure limit will be defined and demonstrated. This task is to be completed in Phase 1 during FY02.

4.3.2 Critical Technical Issues

(a) *Recovery temperature at the throat wall.* In the UHP regime, the recovery temperature at the throat wall may be significantly higher than the temperature in the plenum due to real gas effects. Recent calculations by Princeton University have shown that for a plenum stagnation pressure of 20 kb and temperature of 900 K the throat-wall recovery temperature will be approximately 1700 to 1800 K. Wall temperature is a critical parameter for throat survivability.

(b) *Wall shear stress.* The wall shear stress may be the critical factor for throat survivability in those cases where temperatures are maintained relatively low, but where pressure is exceptionally high, i.e., mechanical erosion of the wall material may be the critical parameter.

(c) *Oxidizing environment.* The test medium will be air for most applications, and the nozzle material must be compatible at very high (400 MPa) oxygen partial pressures and high (900 to 1700 K).

4.3.3 Alternatives

The goal of this research is finding an available high-strength material that will handle the mechanical pressure and shear loads up to the recovery temperature in air for nozzle throats. Alternatively, the high-pressure and -temperature operational limits of available materials in air are to be established. If oxidation and/or heat transfer limits overly constrain the operational goal, i.e., to less than Mach 12 with thermal energy addition, film cooling with an alternative gas such as N₂ or He must be considered. Ceramic coating of the nozzle throat must also be considered to alleviate oxidation, erosion, and heat-transfer problems.

4.3.4 Exit Criteria

The nozzle throat must be capable of surviving multiple runs (of the order of ten) at the stagnation pressures and temperatures specified in air for seconds of run time. The nozzle-throat geometry and size are

not to change for at least one second of run time. Should nozzle-throat survivability be a serious issue below plenum stagnation conditions of 20 kb and 900 K, the limits of acceptable survivability must be determined.

4.3.5 Key Demonstrations/Experiments

Two facilities will be used for these experiments. Initial nozzle-throat material screening tests will be conducted using existing UHP vessels at LLNL in a blow-down experiment. The vessels will be pressurized and heated to obtain conditions as close as possible to the design pressure and temperature for at least millisecond run-time experiments. Following these experiments, the A-2 facility will be used to evaluate nozzle-throat materials at larger size and run times of at least one second.

4.3.6 Analytical Tools

Methods to reasonably estimate survivability characteristics and limits of nozzle throats are desired that can be employed instead of having to totally rely upon experimental data.

4.3.7 Major Deliverables

Limitations of nozzle-throat materials have to be known by mid-Phase 1. This may be the most significant issue that limits the MSHWT performance with supersonic thermal energy addition. The deliverable is to define and demonstrate the performance and survivability capability of alternative materials that can best be used with active or heat-sink cooling techniques in the design of the MSHWT. The task will be complete in FY01.

4.4 Nozzle Boundary Layer (WBS 1.2.1.3.x)

4.4.1 Requirements

Nozzle boundary-layer properties must be quantified at Reynolds number up to 10^{10} for stagnation pressures and temperatures up to 20 kb and 900 K. This task is to be completed in FY02.

4.4.2 Critical Technical Issues

(a) *Boundary layer growth rate.* Knowledge of the boundary-layer growth rate is critical for the design of a nozzle contour and is also important for establishing the minimum length of the high-pressure energy-addition region.

(b) *Recovery temperature.* In the UHP regime, the recovery temperature at the wall may be significantly higher than the stagnation temperature due to real gas effects. This temperature is a critical parameter for wall survivability.

(c) *Wall surface-roughness effects.* The exceptionally high Reynolds numbers associated with this UHP facility leads to nanometer-scale structure. Even a very smooth wall will be rough on this scale and may dominate the near-wall boundary-layer properties. The impact of surface roughness on boundary layer growth, heat transfer, and wall shear stress must be understood.

4.4.3 Alternatives

- (a) Experimental measurements using blow down and the A-2 facilities.
- (b) Analytical estimates using existing computer models.

4.4.4 Exit Criteria

Characterization is complete with code validation. Boundary layer growth rates and recovery temperatures are measured under true Reynolds number conditions and with surface roughness reflecting the expected surface quality of the nozzle.

4.4.5 Key Demonstrations/Experiments

Experiments will be conducted using two facilities. Initially, experiments will be done using a high-pressure, 2.5 kb, room-temperature, blow-down facility that has been transferred from LLNL to Princeton University, where the experiments will be conducted. Key experiments that will be conducted during FY99 include the following:

- (a) Development of diagnostics for velocity-profile measurement and static temperature measurement.
- (b) Measurements of boundary-layer growth rate using pressure taps in the nozzle, as well as exit velocity and/or density profile.
- (c) Measurement of wall shear stress by accurate measurement of velocity gradient at the nozzle exit.
- (d) Measurement of the effects of Reynolds number scaling and roughness on the boundary layer growth rate. At the high Reynolds numbers characteristic of these flows, small-scale structures are much smaller than the wall roughness; consequently, roughness effects may dominate the boundary-layer growth rate.

The second series of experiments will be conducted using the A-2 facility, which is to be constructed at LLNL during the first two years of this program. This facility should have the capability of operating over a wide range of plenum pressures and temperatures, at least 20 kb and up to 900 K. Key experiments to be conducted include the following:

- (a) Measurement of total enthalpy and comparisons with predictions. This measurement will rely on accurate velocity and static temperature measurements at the exit to infer the total enthalpy in the plenum.
- (b) Measurement of gas composition as a function of temperature and pressure. These measurements will rely on absorption spectroscopy to determine whether significant fractions of NO₂, O₃, and other contaminant species are present in the core of the flow and/or in the boundary layer.
- (c) Measurements of boundary-layer structure and boundary-layer density profiles by Rayleigh scattering at the exit of the test nozzle section. These measurements will be used with the ray propagation code to determine laser refraction by the boundary layer and the percent of laser energy striking the wall.
- (d) Code validation. Existing analytical codes will be tested and modified as required to provide a reliable prediction tool for nozzle design at high Reynolds number.

4.4.6 Analytical Tools

Existing analytical codes based on the Baldwin–Lomax turbulence model will be used in the code validation study. Depending upon the success of the validation study, other codes may also be tested.

4.4.7 Major Deliverables

Prediction codes that correctly simulate the properties of the thin, very-high-Reynolds-number boundary layer and that can be reliably used for predicting nozzle performance in the design of the MSHWT facility nozzle. Experiments that validate code predictions are to be completed as follows:

- (a) 2.5-kb-pressure facility—FY00.
- (b) A-2 facility with nozzle—FY02.

The validated code is to be delivered in FY02.

4.5 Nozzle Cooling (WBS 1.2.1.3.x)

4.5.1 Requirements

There are three nozzle sections in the RDHWT/MARIAH II concept that must be thermally protected. These are (1) the section downstream of the nozzle throat, where the thermal energy is added, (2) the section downstream of the thermal energy addition section ahead of the MHD accelerator, and (3) the section between the MHD accelerator and the test section. When the MHD accelerator is not used, the second section expands the flow to the test section. Nozzle-throat integrity and thermal protection research are covered in Section 4.3.

In the thermal-energy addition section, nozzle heat loads must be determined as a function of the radiation-source heat load emanating from the laser, e-beam, or microwave and the initial air-stagnation enthalpy from the plenum so that an assessment of the nozzle cooling requirements can be made. For the transition section ahead of the MHD channel entrance, the heat load is a function of the enthalpy profile emanating from the thermal-energy addition section. For the expansion from the MHD exit to the test section, the heat load is a function of the enthalpy emanating from the MHD accelerator. Once the heat-load assessments are made for each section, criteria for design of a thermal protection system can be established, and demonstrations can be performed. The nozzle walls must be capable of surviving hundreds of test runs at the various facility design points.

4.5.2 Critical Technical Issues

For each nozzle section, the heat loads must be determined and nozzle-cooling/protection strategies developed.

4.5.3 Alternatives

Approaches for nozzle-wall thermal protection are passive cooling, backside fluid cooling, transpiration cooling, and film cooling. Nozzle coatings that offer a measure of thermal protection may be useful as well.

4.5.4 Exit Criteria

Validation of the heat-load prediction models with experimental data is required. Cooling strategies must be defined. Scalable demonstrations of the nozzle cooling strategy must be accomplished.

4.5.5 Key Demonstrations/Experiments

The nozzle-wall heat loads will be measured during the thermal-energy addition demonstration experiments. The heat-load experiments will be conducted at all radiation levels defined in the energy

addition experiments. The capability of analytical codes to assess nozzle heat loads will be assessed. Both blow-down and A-2 pressure intensifier experiments coupled with radiation energy addition will serve as the basis for heat-transfer measurements on the nozzle wall. If these experiments reveal that an active thermal protection system is required, appropriate experiments will be designed and conducted to demonstrate the thermal-protection system approach. The thermal protection downstream of the MHD channel must also be demonstrated. This is envisioned to be done along with the thermal protection demonstrations for the MHD channel.

4.5.6 Analytical Tools

Heat-load prediction tools are needed. AEDC has a series of codes suitable for conventional nozzle analysis. At least one of these, VIPER, appears to be suitable for the incorporation of high-pressure thermodynamic properties. The code includes chemistry and, with minimal modification, could be used for evaluation of wall shear stress, heat flux, and prediction of available chemical species at the wall.

4.5.7 Major Deliverables

This task is done in concert with the nozzle boundary-layer research. The deliverables for this task are nozzle heat-load prediction capabilities and the demonstration of cooling strategies, which can be used in the MSHWT facility nozzle design. This task is to be completed in FY02.

4.6 Supersonic Thermal Energy Addition (WBS 1.3.1.3.x)

Based on prior studies of the RDHWT concept, three forms of supersonic thermal energy addition have been assessed to be potentially viable candidates for adding thermal energy in the supersonic nozzle downstream of the nozzle throat. These candidates are laser-beam, e-beam, and microwave energy deposition. Chemical combustion cannot provide the necessary total enthalpy to meet the goals of this research. Research is planned on the laser and e-beam to determine which one can provide the best flow quality and the least capital and operating cost. Down-selection to the “best” candidate is desired as soon as practical in the interest of minimizing the research program cost. No research is planned on the microwave energy concept because of the perceived technical complexity and high capital cost, but it is addressed in this section for completeness. The preponderance of the supersonic energy addition research is to be completed in Phase 1 of this program. Some carryover of megawatt-level demonstration experiments into Phase 2 can be expected.

4.6.1 Requirements

The performance limits of energy addition are to be determined in terms of minimum and maximum flight simulation of Mach number (enthalpy) and altitude (entropy). The limits of the performance envelope will also be determined by the maximum achievable air-plenum stagnation pressure and temperature and nozzle-throat survivability limits. The performance goals to be achieved are defined in Chapter II of this document. As a practical matter, a lower-Mach-number simulation limit is expected to occur for the laser and e-beam energy concepts as a result of the inability of air at low densities to absorb sufficient beam energy. A lower density limit may not exist for microwave energy for practical purposes. Based on successful results of the initial e-beam supersonic thermal-energy-addition experiments in FY98 and guidance from the steering committee, the program will focus on the e-beam thermal-energy approach through CY1999, then down-select to either the e-beam or laser-energy addition approach in early CY2000. The key selection criteria will be e-beam performance, including effects on gas chemistry, and relative capital and operating cost of the e-beam system vs. the laser system.

4.6.2 Critical Technical Issues

4.6.2.1 Laser

(a) *Molecular absorption constants.* In order to achieve Mach numbers in excess of eight, laser absorption must occur at gas temperatures near 1000 K and at high pressures. Energy deposition is a function of the molecule absorption constant, and the absorption spectrum of CO₂ has been measured experimentally to near 1000 K at moderate pressures. The laser will excite specific levels of the CO₂ molecule, and the absorption coefficients of high-lying states are presently obtained only by calculation based on extrapolation from the measurements. The importance of the high-lying states to the laser absorption must be addressed as well as the absorption line broadening or narrowing effects of the very high pressures encountered in this work.

(b) *Thermal blooming and aerothermal beam steering.* Preliminary models have shown that the high-temperature boundary layer will steer the laser beam away from the wall. This is important because it (1) assures that the laser beam is fully absorbed by the gas and (2) prevents or reduces energy deposition on the wall, decreasing the heat transfer. Additionally, the laser beam is expected to be deviated by thermal nonuniformities in the flow itself. Experimental demonstration of laser beam “capture” and boundary layer guiding is critical for successful energy deposition and wall survival.

(c) *Thermal equilibration.* The laser beam will excite specific vibrational and rotational states of the CO₂ molecule. Transfer of this energy deposition into the translational modes of the air requires that the vibrational modes of CO₂, N₂, and O₂ rapidly reach thermal equilibrium. At high pressures, this is not expected to be a problem, but it may limit the low-Mach-number or low-dynamic-pressure operation of the wind tunnel. The state-specific absorption of the CO₂ molecules may lead to optical bleaching (in which specific states may be substantially depleted) and saturation phenomena (in which specific states may be very highly populated). Additionally, the selectivity of the higher states may open up new channels for absorption, with subsequent different thermal equilibration mechanisms. Code validation, and perhaps more detailed modeling to explore this phenomena, is needed and may result in a need to determine more accurately the rate coefficients describing the thermalization process.

(d) *Flow stability and chemistry.* The effect of the laser beam and energy addition process on the flow stability and chemistry are unknown. It is anticipated that the energy can be added with little effect on the chemistry, but this has not been confirmed at the energy densities that will be necessary in the full-scale device. The energy addition and thermalization process in air must not be oscillatory or erratic for a useful test medium. Also, the gas chemistry should be near that of true air after the energy addition and thermalization process. These issues, as with thermalization, can be examined with better modeling and computer codes, which will need validation.

(e) *Scaling.* Measurements conducted at power levels up to 1 MW must be scaled by a factor of 10 to 100 for a credible T&E facility. This scaling will rely heavily on the aerodynamic and energy-addition models that are developed as part of this program. Critical scaling parameters must be identified and tested.

4.6.2.2 Electron Beam

(a) *Magnetic confinement and focusing of e-beam.* The e-beam profile must be controlled so that wall heating is manageable and the primary energy deposition occurs in the core of the high-pressure flow field. This is envisioned to be accomplished using a solenoidal magnetic field. The ability to achieve and properly control the desired beam profile is a critical technology. The field strengths and dimensions of the full-scale facility represent an extension of the magnetic steering technology and, although thought to be of modest extent, need to be demonstrated. Of particular concern are the effects of collisions with the high pressure gas on the primary and secondary electron trajectories.

(b) *Dynamic mechanisms in e-beam heating.* While the trajectories of the high-energy electrons will be largely controlled by the magnetic field, the integrated gas density will determine the penetration. The fact that the e-beam does not have uniform intensity will lead to a nonuniform heat deposition and, consequently, a nonuniform fluid density across the nozzle. This means deeper penetration of the e-beam through the hotter portion of the flow and further nonuniform energy deposition. This “hole burning” could lead to instabilities and may also be an important mechanism to minimize wall heating. This can be examined by appropriate modeling with experimental validation.

(c) *Flow chemistry and thermalization.* The interaction of the e-beam with the individual gas molecules leads to ionization and chemical dissociation. While the ionization fraction is expected to be small, there may still be significant chemical alterations leading to contamination of the flow with such species as NO_2 and O_3 . Significant nonabsorption of the e-beam energy is not acceptable. The air density and temperature envelope for acceptable thermalization is unknown and must be understood and explored with appropriate, validated codes.

(d) *Run-time considerations.* For T&E purposes, it is important to have run times in excess of seconds and potentially as long as tens to hundreds of seconds. Robust e-beam windows must be developed that can maintain this continuous power loading, and the e-beam source itself must be capable of operating without significant fluctuations or degradation during this time interval.

(e) *Scaling.* A large-scale facility will either have a single very-high-power (hundreds of megawatts) e-beam source or multiple sources that enter at different locations around the perimeter of the wind tunnel and are combined together to deliver energy into the high-pressure nozzle region. Issues associated with scaling from single beams to multiple beams, magnetic confinement of multiple beams, and the uniformity that can be achieved must be established before moving to a T&E-scale facility.

4.6.2.3 *Microwave*

(a) *Microwave absorption mechanism.* The controlled absorption of microwave energy into air can occur either through microwave coupling to molecular transitions or through microwave coupling to a weakly ionized plasma. At present, no credible molecular transitions have been identified that effectively couple with available or near-term projected high-power microwave sources. Coupling via weakly ionized plasma is credible, but is known to be unstable at high pressure with highly localized filamentary arc formation. If these arcs can be controlled or this instability suppressed, then microwave-energy addition into high-pressure supersonic air may be viable.

(b) *Creation and sustainment of conductivity.* The air must be weakly ionized for microwaves to be absorbed. This can be achieved by external ionization through e-beams or by the microwaves themselves. Generally speaking, e-beam-stabilized conductivity is desirable because it avoids instabilities associated with microwave heating. The amount of energy required, however, may be on the same order of magnitude as the energy deposited by the microwave. Alternative methods for stabilizing microwave-energy addition and generating conductivity need to be developed.

(c) *Microwave injection.* Due to the fact that microwaves will break down low-pressure air, a microwave beam cannot be injected from the downstream, low-pressure region of the flow, but must either pass through the walls directly into the high-pressure section or through the throat into the high-pressure section. If the beam is passed through the walls, there is a great likelihood that breakdown will occur in the boundary layers, where the high temperature enhances conductivity and reduces the breakdown threshold. The possibility of injecting microwaves through the throat is worth exploring, but leads to significant engineering complexity in the plenum. If feasible, however, then the wind tunnel can act as a wave-guide for the microwaves, and resonator technology may be used to enhance the field strength at a particular location in the nozzle where the energy addition is desired.

(d) *Flow chemistry.* If the energy deposition occurs through a weakly ionized plasma process, then the presence of ions may lead to chemical reactions producing contaminant species such as NO₂ and O₃. The levels of contamination must be ascertained in order to determine the utility of a microwave-driven T&E facility.

(e) *Scaling.* Megawatt-scale microwave facilities are currently available, but must be scaled to higher power if they are to be used for this application. In particular, if the microwaves must be passed through the nozzle throat and into the test section, a single coherent microwave beam with a full energy may be required. This may be generated by coherently coupling a set of microwave amplifiers, but nonetheless represents new technology.

4.6.3 Alternatives

The potentially viable alternatives known for energy addition are laser energy absorption, e-beam energy absorption, and microwave energy deposition. The laser frequency must couple to the CO₂ molecule absorption spectrum if no seeding is used. Should seeding be acceptable, such as by using the SF₆ molecule for absorption, this could be an alternative. The laser energy source alternatives are determined to be CO₂, HF, and CO lasers. The e-beam alternatives are low- or high-voltage beams. It is yet to be determined what the appropriate coupling mechanism is for microwaves, but it is believed that the required frequency range of the microwave source is 110 to 250 GHz.

4.6.4 Exit Criteria

Overall, the energy addition research is to demonstrate and validate predictive capability for fully coupled energy addition at representative densities and temperatures of the MSHWT. Specific exit criteria for each of the three radiant energy approaches are outlined below.

4.6.4.1 Laser

The laser addition approach will be considered viable if the following factors can be determined:

- (a) A laser with an energy density on the order of 100 MW/cm² can be passed through low-pressure air containing an absorbing molecular species, CO₂, and focused into and captured by the flow in a wind-tunnel nozzle.
- (b) A laser can be shown to add energy (4 to 6 times the kinetic energy), producing a uniform, stable flow with total enthalpy significantly higher than the plenum total enthalpy and at conditions equivalent to a dynamic pressure up to 2000 psf.
- (c) It can be demonstrated that an intensity on the order of 100 MW/cm² can pass into an appropriately contoured nozzle without unacceptable damage to the walls, where the walls are protected by either optical refraction from the low-density boundary layer, high-reflectivity optical coatings, or a combination of the two.
- (d) It can be shown that existing lasers in the megawatt range can be scaled to the appropriate power for credible testing and evaluation facilities.
- (e) Codes modeling the energy addition and flow processes—including coupling of the energy to the flow, thermalization and flow chemistry, boundary-layer flow physics and interaction with the laser beam, and onset of an instability or flow breakdown—have been validated for the conditions of the MSHWT.

4.6.4.2 *E-Beam*

The e-beam approach will be considered viable if the following factors can be determined:

- (a) Electron energy can be deposited in a controllable fashion into a supersonic airflow, leading to uniform and stable energy addition (4 to 6 times the kinetic energy).
- (b) The dynamic coupling of an e-beam to a high-density flow can be shown to be stable and controllable so uniform time-invariant flow, with a total enthalpy significantly higher than the plenum total enthalpy, and conditions equivalent to a dynamic pressure up to 2000 psf can be achieved.
- (c) It can be demonstrated that e-beam power levels commensurate with a full-scale facility can be passed into the nozzle without creating unacceptable wall heating or wall damage.
- (d) It can be shown that e-beam power, control mechanisms, and beam insertion techniques can be scaled to the appropriate power for a credible-scale T&E facility.

4.6.4.3 *Microwave*

The microwave approach may be considered viable if the following factors can be determined:

- (a) Microwave energy can be deposited into a supersonic air flow in a controllable fashion, generating uniform flow and significant total enthalpy increase.
- (b) A credible approach can be devised for coupling high-power microwave energy into the high-pressure nozzle region without producing parasitic breakdown and absorption in the boundary layers or in the low-pressure portion of the flow.
- (c) It can be shown that microwave sources can be scaled and coupled to generate sufficient power and sufficient coherence for a large-scale T&E facility.
- (d) It can be shown that the flow is stable, reasonably uniform, and that gas chemistry is near that of true air.

4.6.5 **Key Demonstrations/Experiments**

For any thermal energy approach to be viable, there must be experimental demonstrations of stable energy addition. Also, it must be demonstrated that at least 75% of the total enthalpy of the MSHWT is simulated with air.

4.6.5.1 *Laser*

A 10-kW laser experiment was successfully accomplished in December 1997 that demonstrated that laser-beam energy could be transmitted to a supersonic gas stream resulting in a net increase in total enthalpy. The following sets of demonstration experiments are proposed.

(a) *10- to 30-kW HF laser experiment.* This experiment is to demonstrate the viability of the HF laser as a source and to couple to CO₂ molecules in the working gas for energy addition. Experiments will test the CO₂ thermalization models, CO₂ saturation, and the HF laser performance.

(b) *Laser-energy addition, 130-kW CO₂.* The higher power will allow a higher-pressure front end and will move into the region where the aerothermal effects become important. This experiment will be conducted with SF₆ added into the air to an appropriated concentration to fully absorb the incident laser energy downstream of the throat and will be a critical step in moving into the fully coupled regime.

(c) *High-power laser-energy addition.* A high-power (350–800-kW) experiment will be conducted as a stepping stone to the final megawatt-class experiments. This experiment will use a working gas and laser of convenience, with the emphasis being on the laser power and energy added to the flow as intermediate between the 10-kW experiment and the Megawatt experiment. The experiment will demonstrate the beam steering in the boundary layer, energy addition at the higher pressures, thermalization and chemistry issues, and continued viability of the approach in a graduated fashion.

(d) *Megawatt, HF laser-energy addition.* This experiment will demonstrate full aerothermal interaction between the laser and the flow field, energy deposition through the CO₂ molecule, and wall survivability. It will be designed to closely model the performance goals of the MSHWT and satisfy all exit criteria.

(e) *Model validation.* A key step at each of the experimental demonstrations is the validation of analytic, physical, and numerical models and codes making *a priori* predictions of the experimental results. No experimental demonstration will be considered complete until a viable model has been validated that allows credible calculations of other conditions.

4.6.5.2 *E-Beam*

(a) *30-kW e-beam experiments.* The first demonstration of e-beam heating was concluded at SNL using the HAWK accelerator coupled with a low-pressure (1200-psi), Mach 3.6-flow facility. Run time was on the order of 5 ms. These experiments were successfully completed in 1998.

(b) *100–200-kW e-beam experiments.* This series of experiments will be similar to the 30-kW experiments, but will be done at higher beam energy. Flow quality, including gas chemistry measurements, will be made to understand beam effects and gas chemistry issues.

(c) *1-10-MW experiments.* A 10-MW experiment is currently under design. Such an experiment would initially be conducted using the A-2 high-pressure front end capable of operating at up to 20 kb pressure or higher. The objective would be to establish the viability of e-beam coupling to high-pressure air in the regime where 2-D heating effects are important, and to establish the flow chemistry effects as in the 100-200-kW experiments. These experiments would be designed to closely model the performance goals of the MSHWT and satisfy all exit criteria.

(d) *Model validation.* A key step at each of the experimental demonstrations is the validation of analytic, physical, and numerical models and codes making *a priori* predictions of the experimental results. No experimental demonstration will be considered complete until a viable model has been validated that allows credible calculations of other conditions.

4.6.5.3 *Microwave*

No experiments are planned as part of this program because of the relative complexity of the approach. However, an experiment in which 50-kW microwave energy will be beamed into subatmospheric density Mach 3 airflow is planned as part of a USAF Office of Scientific Research New World Vistas effort. In this experiment, a 5-ms, high-power microwave generator will beam microwave energy through the throat of a Mach 3, 2-D rectangular nozzle to low-pressure air, where either a self-initiated or an externally sustained microwave discharge will generate a weakly ionized plasma. This plasma will be stabilized by a solenoid magnetic field and used for the study of plasma drag phenomena in supersonic flow.

4.6.6 *Analytical Tools*

Analytical tools are needed to spatially and temporally model each of the energy deposition processes in the supersonic nozzle flow. The energy deposition is to be coupled into the fluid-dynamic equations of motion accounting for any nonequilibrium chemistry effects.

4.6.7 Major Deliverables

- (a) Conduct and assess 100–200-kW e-beam experiments—FY99.
- (b) For (a), measure and assess flow quality and gas chemistry—Apr 2000.
- (c) Estimate cost of laser and e-beam MSHWT subsystem hardware and operating cost—Apr 2000.
- (d) Down-select thermal-energy approach, e-beam vs. laser, based on results of (b) and (c)—Apr 2000.
- (e) Conduct and assess thermal-energy experiments with thermal-energy addition enthalpy demonstrated for at least 75% of MSHWT designed enthalpy conditions—FY00–01.
- (f) Assess thermal-energy-addition hardware scaling issues—Jul 2000.

4.7 MHD Energy Augmentation (WBS 1.4.1.3)

The purpose of the MHD energy addition is to augment the test Mach number capability of the air stream by electromotive body forces ($\mathbf{J} \times \mathbf{B}$) above that which can be provided by the supersonic thermal-energy addition techniques. For the MSHWT, the goal is to achieve an equivalent flight Mach number of 15 and dynamic pressure of 2000 psf in the flow behind the bow shock wave for the equivalent of a 5-degree inlet wedge. An optimum supersonic thermal-energy-addition front end coupled to the MHD accelerator is needed. This portion of the research program will span Phases 1 and 2. In Phase 1, analytical performance tools, electrical conductivity experiments, and design of the MHD channel for the Phase 2 demonstration experiments will be conducted. In Phase 2, the MHD accelerator demonstration experiments will be performed. Two alternatives for MHD acceleration, Options A and B, are discussed in Section 4.7.3 below.

4.7.1 Requirements

The flight Mach number, dynamic pressure, and altitude define the total enthalpy and entropy goals to be achieved in the test section of the MSHWT. This means that a velocity augmentation by a factor of at least 1.25 or more is needed to achieve the Mach 15 test condition goal. The MHD augmentation will be constrained by the channel inlet flow enthalpy and entropy (the entropy, S/R , is expected to be approximately 25), gas conductivity, wall heat-transfer limitations, and the thermodynamic-energy addition process used. The inlet enthalpy and entropy conditions are defined by the upstream thermal-energy addition exit conditions. This research is to define the “best” envelope of MHD augmentation within these constraints, thus the best tradeoff, and to perform demonstration experiments to validate the concept guided by the performance objectives.

Additionally, the MHD accelerator must provide an air stream that has minimal and known levels of dissociated species and contaminants, and must also provide reasonable flow uniformity in the test section as defined by USAF requirements.

4.7.2 Critical Technical Issues

(a) *Operating regime of MHD accelerators.* MHD accelerators have been operated successfully at static pressure of 1 to 4 atm and at static temperatures above 2500 K. However, the exit entropy levels were much too high to achieve the performance goals needed for hypersonic air-breathing propulsion testing. To overcome this problem, the channel inlet entropy must be much lower, which means that the static pressure must be much higher, the static temperature must be much lower, and/or some adequate combination of lower temperature and higher pressure are used.

The constraint on entropy ($S/R \approx 25$, see above) precludes operation at high temperatures and moderate pressures, as has been done in MHD channels with electric arc preheating at stagnation pressures up to

approximately 100 atm. Operation of seeded MHD accelerators at very high static pressures and high temperatures has been suggested but never demonstrated, nor believed possible because of materials limitations and chemistry issues. Low-static-temperature (below 500 K), low-static-pressure (below 1 atm) operation of MHD accelerators is a potentially attractive option provided that sufficient electrical conductivity can be achieved, but this likewise has not been demonstrated. For any given inlet entropy, a higher pressure and temperature would provide a higher thermodynamic efficiency toward achieving the desired test conditions. Two MHD options, A and B, are considered, both at a nominal inlet entropy (S/R) of about 25. Option A is for low static pressure and temperature, where it is believed feasible to achieve sufficient conductivity with opposing e-beams perpendicular to the flow. To achieve the low static temperature and pressure, a rather high channel-inlet supersonic Mach number is expected. Option B is for a higher inlet static pressure and temperature. For Option B, other means than e-beams probably will be required to establish flow conductivity (to be discussed later). Option B has the potential of being more thermodynamically efficient and also offers a potentially lower channel-inlet Mach number, but there is some risk of creating unwanted species such as NO, dependent on the ionization method used as well as increased channel wall heating.

(b) *Electrical conductivity issues.* Electrical conductivity must be sustained in the gas flow through the accelerator at a level sufficient to ensure electromotive force acceleration. External means of establishing and maintaining conductivity, to achieve values of conductivity of 50 to 100 mho/m, are expected to be required.

(c) *Channel boundary-layer issues.* Overheating of the channel walls is a major issue. Wall recovery temperature, heat loads, and thermal boundary-layer management must be addressed. The degree to which the boundary layer is an issue depends on channel inlet conditions, the boundary-layer electrical conductivity, and the mode of operation in the MHD accelerator. Both velocity and thermal overshoots in the boundary layer are to be avoided. Thermal overshoots can result in high electrical conductivity near the electrode walls and sidewalls. This may in turn cause interelectrode shorting axially along the electrode walls as well as transverse shorting in the sidewall boundary layers. The latter effect (sidewall shorting), if sufficiently pronounced, can produce relatively high accelerating MHD forces in the boundary layer compared to that in the core flow, clearly an undesirable situation. Tailoring the flow conductivity to prevent over acceleration of the boundary layer on the electrode walls will probably be required.

(d) *Flow quality.* An important issue and requirement for a T&E facility is that the gas delivered to the test section must be near true air, implying minimal dissociation and contamination. A spatially and temporally uniform core flow in the test section is also required.

(e) *E-beam issues.* Establishing electrical conductivity with e-beams is the approach identified in Option A. E-beams have been demonstrated as ionizers in MHD generators, but in a different working gas (Ar, seeded with Cs). Major issues with respect to e-beams are described below.

<i>Sustained conductivity</i>	Conductivity must be determined as a function of the gas static pressure and temperature expected in the channel. The conductivity must be sustained volumetrically, not just locally. To meet this requirement, multiple beams will be necessary. The number of beams required must be determined as a part of the testing program.
<i>Beam-injection methods</i>	The beam must be introduced across the sidewall, and must either pass through the magnet poles or originate inside the magnet, at the inner sidewall.
<i>Foil-window integrity</i>	E-beams are generated in a near vacuum. Consequently, foil windows are used to isolate the vacuum region from the working region. These foils are

necessarily thin and heat up extremely rapidly from the high beam flux. To maintain foil integrity, the electron pulses must be of short duration, typically a few milliseconds to a few tens of milliseconds. Advanced window designs, such as cooled foils, or aerodynamic windows offer the possibility of extending the pulse duration. A pulse duration of one second or more must be demonstrated as a part of the technology development program.

(f) *Guided-arc issues.* Guided arcs have been proposed as a potential means of establishing and maintaining electrical conductivity for Option B. Sustaining electrical conductivity, generation of unwanted species, flow uniformity, and arc injection methods are the primary issues.

4.7.3 Alternatives

(a) *Option A-MHD acceleration with e-beam-enhanced conductivity.* In this mode, it will be necessary to operate the MHD accelerator at low static pressure, moderate static temperatures, and high supersonic velocities. Mach numbers in the MHD channel are anticipated to be high, of the order of five or greater, with static pressures below 1 atm. At the present time, this is regarded as the most promising option for MHD acceleration.

(b) *Option B-other accelerator options.* Other methods for MHD acceleration have been proposed, including guided arcs and a hybrid MHD-electrodynamic accelerator. A preliminary evaluation of these alternatives will be conducted to assess their potential validity. This concept must be evaluated through bench-scale experiments before it can be recommended as a means of achieving MHD interaction. Small-scale experiments directed toward this end will be conducted early in the program. If early results are promising, a large-scale MHD test program will be defined.

4.7.4 Exit Criteria

- (a) The required electrical conductivity in the gas must be experimentally demonstrated and shown to be sustainable for a duration of one second or more.
- (b) The energy added by MHD means must be experimentally demonstrated to validate analytical predictions of MSHWT performance. A velocity augmentation of at least 1.25 is to be demonstrated at static enthalpy and entropy conditions that can be confidently used to predict and design the MSHWT accelerator.
- (c) The performance limits of the MHD augmentation must be defined, including that caused by wall heating and electrical conductivity limitations.
- (d) The channel wall integrity must be maintained after multiple runs.
- (e) It must be demonstrated that windows for e-beams can be designed and fabricated so as to maintain their integrity over a number of runs. Window integrity must also be demonstrated in separate experiments of nominally one second duration (or longer).

4.7.5 Key Demonstrations and Experiments

Experiments predicated on Option A (e-beams) will be pursued first because sustaining electrical conductivity by an e-beam is judged to be more practical. A two-phase set of experiments is proposed. To convincingly demonstrate this option, it will be necessary to demonstrate the use of e-beams to induce

nonequilibrium conductivity, to develop designs for long-duration windows and e-beams, and to demonstrate nonequilibrium MHD interaction at an adequate scale. These experiments are further described below.

Phase I(a): e-beam conductivity experiments in static air. The objective is to demonstrate that sufficient electrical conductivity can be created and sustained in low-pressure, low-temperature air. These experiments will be conducted in a static test cell using available e-beam generators at SNL. The ranges of key experimental parameters are shown below.

Temperature range:	250 to 350 K.
Pressure:	0.1 to 1 atm.
Beam current density:	0.1 to 0.5 A/cm ² or greater.
E-beam pulse duration:	0.3 ms.
Test-channel cross section:	1 to 2 cm ² .

The beam energy will be selected based on optimum energy absorption into a 1-atm test channel.

Phase I(b): e-beam experiments in static air with an applied magnetic field. These experiments have the same objective as Phase I(a) and will essentially duplicate the measurements of Phase I(a), but will have the purpose of determining the effects of a magnetic field on the conductivity. Additionally, the average Hall parameter across the cell will be experimentally determined.

Phase I(c): design and demonstration of an MHD sidewall section with e-beam injection. The technology demonstration will simulate a section of an MHD sidewall. The sidewall section will incorporate multiple ports for e-beam injection. Various beam-injection designs, including hollow cathodes, will be considered. The Phase I(c) tests will demonstrate (a) that window integrity can be maintained over a number of runs of nominally one second duration (or longer), and (b) that elevated conductivity, induced by multiple e-beams, can be sustained throughout the volume of the test cell for a duration of at least one second.

Testing of the system in a low-speed flow environment without a magnetic field will be conducted to verify design parameters. The experiments are planned to be conducted using available blow-down or high-pressure driver facilities.

Phase II: experimental demonstration of air acceleration by conductivity enhancement with e-beam injection in an operational MHD duct with an applied magnetic field. The objectives are as follows:

- (1) Demonstrate that required conductivity levels can be sustained throughout the MHD channel by the use of multiple e-beams.
- (2) Demonstrate stable, uniform velocity augmentation of 1.25 or greater by MHD electromotive force acceleration through the MHD channel at enthalpy and entropy conditions, which can be used confidently to predict MSHWT performance.
- (3) This phase of the program will require a MHD duct, a magnet, an e-beam source, and a driver facility. Present plans call for conducting this testing in an impulse tunnel at a site to be determined. The experiments will be conducted at a sufficiently large scale to provide confidence that the nonequilibrium e-beam concept and the MHD will work at the MSHWT scale. Three major subtasks for this phase are related to hardware:

- Acquisition of a suitable magnet.
- Acquisition/fabrication of a suitable front end high-pressure driver for the experiments. Because long duration is not essential to proving nonequilibrium MHD interaction, an impulse facility may serve as a driver.
- Acquisition/location of a suitable e-beam source.

4.7.6 Required Analytical Tools

Both 1-D and multi-dimensional codes incorporating $\mathbf{J} \times \mathbf{B}$ force, induced electrical conductivity, and wall heat losses are required to analyze the flow through the channel and calculate channel performance. The multi-dimensional code must also account for viscous effects.

The existing MSE 1-D computer codes will be used to analyze the flow through the channel. This code will be modified to incorporate a simple model for the e-beam-induced conductivity. Parametric studies will be done to characterize the MHD acceleration as a function of applied magnetic field and transverse injected current.

A multi-dimensional MHD analysis code, possibly utilizing the Princeton 2-D code as a starting point, will be developed/adapted. Parametric studies similar to those described above will be run to more precisely quantify the MHD interaction and the e-beam-induced conductivity.

4.7.7 Major Deliverables

- (a) Estimate performance envelopes of the MSHWT facility with and without MHD augmentation—FY99.
- (b) Determine functionality of the e-beam electrical conductivity approach—FY99.
- (c) Prepare and deliver 1-D and 2-D MHD performance prediction codes—FY00.
- (d) Design MHD accelerator demonstrator experiment—FY02.
- (e) Fabricate and conduct MHD accelerator demonstration—Phase 2.

4.8 Systems Integration (WBS 1.7.1.x)

Systems integration includes all of the tasks and activities necessary to ensure that major components of the MSHWT (the UHP supply system, nozzle subsystems, thermal-energy addition subsystem, MHD subsystem, etc.) are compatible with each other in terms of scale, operating regime, and stability of operation. Most importantly, systems integration ensures that the total system meets its performance requirements. The system integration studies span Phases 1 and 2 of the program.

4.8.1 Requirements

The requirements of the systems integration phase of the development program are determined by the performance requirements specified for the MSHWT. These are summarized below.

- Dynamic pressure up to 2000 psf.

- Run times of seconds.
- Test-section flight-simulation Mach numbers in the range 8 to 12 and conditions behind a 5-degree wedge at Mach 15.
- Test section dimensions of ~0.5 to 1.0 m across.
- Total power input (including beamed energy and MHD) expected to be in the range of 10 to 150 MW.
- Air chemistry in the test section close to true air.

To ensure that the systems integration phase of the MSHWT development program is successful, several activities must be undertaken:

- (1) Develop performance predictions for the overall system and for the interaction of major subsystems. Characterize the design and off-design performance of candidate or baseline wind tunnel systems. Do subsystems design concept, performance, and cost trades to establish subsystem and total system concept, performance, and cost.
- (2) Demonstrate the effects of scale on the interaction of system components through a program of subscale testing and computer simulation. Because testing will be limited to power levels of a few megawatts or less, scaling issues will be a significant challenge in the Phase 1-2 research and development program (see Section 4.8.2). The subscale testing may take the form of tests on partially integrated subsystems (energy addition/nozzle/high-pressure driver, for example) at power levels and mass flow rates below that of the MSHWT.
- (3) Ensure operational reliability of the total system through analytical studies and experimental demonstrations at the system level (see Section 4.8.5).

4.8.2 Critical Technical Issues

The critical systems technical issues presented below are framed as a set of questions, which must be addressed within the context of the Phase 1-2 program.

- (a) *Performance issues.* What are the performance limits of a MSHWT scale system? What is the range of operation that such a system can sustain in terms of test section Mach number, pressures, and dynamic pressures?
- (b) *Interface issues.* The main interfaces and some of the associated interface issues are described below.
 - (i) High-pressure driver/nozzle.
 - How do variations in the reservoir pressure affect nozzle performance?
 - For a given driver design, what is the range of mass flow rates and test times which can be delivered to the nozzle by the high pressure driver?
 - (ii) Nozzle/energy addition unit.

- How does nozzle design vary for different energy addition schemes?
- Can the required amounts of energy be added in the supersonic region of the nozzle without seriously damaging the nozzle?
- For a given type of energy addition, what are the parameter limits (total power added to the flow, increase in entropy, mass flow limits) across which the nozzle flow will be stable?
- How will the e-beam, laser beam, or microwave energy be introduced into the nozzle?

(iii) Nozzle/MHD accelerator.

- For either the e-beam-seeded concept or the guided-arc concept, what are the ranges of static pressures, static temperatures, and inlet Mach numbers to be delivered to the MHD accelerator? (This will depend to a great extent on the type of energy addition scheme to be used.)
- How does the low-pressure requirement for the e-beam-seeding concept affect the design of the MHD accelerator? (This is fundamentally a size issue, because expansion to a low pressure will generally dictate larger inlet areas and higher Mach numbers than expansion to higher pressures.)

(iv) MHD accelerator/secondary nozzle/test section

- To what degree will operation of the MHD accelerator affect the air chemistry?
- What part of the test section envelope can be reached by varying the MHD parameters (magnetic field, applied electric fields)?
- Thermodynamic limits: Can the entropy level in the MHD accelerator be maintained at or below the limiting test-section entropy?

(c) *Scale issues.* Achieving the Mach 15 condition in the MSHWT will require total power addition in the range 130 to 150 MW for a 1 m test section. Near-term projections of laser technology indicate that to achieve laser power levels of 10 MW or more would require a very large research and development program. E-beam technology appears to be more attractive for this reason. E-beam power levels of 25 MW for one second may be achievable in the five- to ten-year time frame. MHD systems, in the form of power generators, have been demonstrated at the 10- to 12 MW level. Scale-up factors of 4 to 5 will therefore be necessary for the MSHWT, assuming that e-beams are the technology selected for energy addition. On the other hand, testing will probably be limited to power levels below a few megawatts for both the MHD and the energy-addition systems. Thus, scaling of the energy-addition and MHD systems based upon test results will be a significant issue.

Scaling of the high-pressure driver also presents a serious challenge. Here the critical parameters are mass flow rate and run time. The MSHWT will require mass flow rates up to 40 kg/s for one second. This compares to projected flow rates in the A-2 facility of up to 10 kg/s for up to one second.

Resolution of scale issues must be accomplished through a program that combines testing and the use of well validated computer simulation codes.

4.8.3 Alternatives

Several possible configurations of the MSHWT system have been suggested. These include the use of e-beams, microwaves, or lasers for the thermal energy addition section; the possible use of storage or hydraulic drivers for the UHP subsystem; the use of e-beams or guided arcs to sustain the MHD interaction; and a number of other options. It is recommended that these options be sorted into a number of baseline system configurations that can be studied at a systems level. Performance projections for each baseline system across a range of the control parameters should be developed and compared against each other. Scaling issues will also be studied analytically. Such projections must make use of the best available test data from the testing of subsystems and the best available systems simulation computer codes. Two fundamental alternatives for the MSHWT are to be considered, namely, thermal energy addition and thermal energy addition plus MHD augmentation.

Six possible baseline configurations using thermal energy addition plus MHD augmentation are suggested below. Other configurations may be developed if warranted. These baseline configurations can also serve as a basis for planning of the key demonstrations (Section 4.8.5). Note that for each of these alternatives, there may be several options relating to the design and interfacing of the high-pressure air-supply system.

- (a) Laser energy addition followed by an MHD accelerator seeded by e-beams.
- (b) Laser energy addition followed by an MHD accelerator that relies on guided-arc technology.
- (c) Microwave energy addition followed by an MHD accelerator seeded by e-beams.
- (d) Microwave energy addition followed by an MHD accelerator that relies on guided-arc technology.
- (e) E-beam energy addition followed by an MHD accelerator seeded by e-beams.
- (f) E-beam energy addition followed by an MHD accelerator that relies on guided-arc technology.

4.8.4 Exit Criteria

Prior to design of the MSHWT, the systems integration issues described in Section 4.8.2 must be resolved through a program of analysis and testing. Systems integration issues for the MSHWT will be considered resolved if the following exit criteria are met:

(a) *Performance limits of the MSHWT.* Credible performance predictions for each of the baseline configurations must be developed based on analysis, test data, and known scaling laws. It must be demonstrated that these predictions cover a substantial subset of the performance envelope specified by the USAF for the MSHWT.

(b) *Interface issues.* Resolution of interface issues (Section 4.8.2b) will require that the range of operating conditions (pressures, temperatures, Mach numbers, energy added) at each of the system interfaces has been established with confidence. This implies a successful series of demonstration experiments (Section 4.8.5, below), as well as the validation of systems codes and analysis codes used for prediction.

(c) *Down-selection of a specific configuration.* At several points in the development program, down-selections of configuration alternatives must be made. Prior to the end of the Phase 1 program, a single configuration must be identified.

(d) *Experimental demonstrations.* Key demonstrations involving two or more subsystems must be successfully carried out to ensure operational integrity and reliability of the total system and to partially resolve scaling issues. These are described in Section 4.8.5.

(e) *Development of system performance requirements.* The phrase “system performance requirements” is used here to denote a set of requirements that defines the operating envelope for the MSHWT as well as the operating envelope for each major component. These system performance requirements will be based on experimental data, scale requirements, known limits and constraints on the performance of each subsystem, and the overall wind-tunnel performance requirements to be developed by the USAF. These requirements cannot be developed until a substantial amount of research and development has been conducted on the major subsystems.

(f) *Development and validation of computational tools.* Because testing will be done at a greatly reduced scale, the systems issues described above cannot be resolved by testing alone. Final resolution of scale issues must be accomplished through reliance on predictions of well validated computational tools.

4.8.5 Key Systems Demonstrations

Certain experimental demonstrations at the system level must be carried out prior to design of the pilot facility. This testing will be done at a scale below that of the pilot-scale facility and will have the two objectives of (1) establishing the credibility of the analytical simulations and (2) partially resolving scaling and performance issues.

Two key series of demonstrations are planned:

- (a) Demonstration of a specific configuration consisting of a high-pressure driver, a nozzle, and an energy addition unit.
- (b) Demonstration of an MHD accelerator driven by a high-pressure driver. This may take the form of testing an MHD accelerator in an impulse facility.

4.8.6 Analytical Tools

Several analysis tools must be employed to provide predictions of systems performance. Simulation tools, which address the various energy addition options, are currently under development at Princeton University. Simplified (1-D) MHD codes are presently available, although these may require modification to simulate the nonequilibrium modes of MHD interaction being considered in the MARIAH II Program. These codes must undergo rigorous validation before they can be used to predict performance and scale effects with confidence.

Additionally, there is a need for a simplified (i.e., 1-D/algebraic) model of the facility system. The code should be designed to perform sensitivity and trade studies. For example, one should be able to simulate the effect of adding laser power vs. the effect of adding the same amount of power in the MHD accelerator on the final test-section conditions. Another example would be simulating the effect of MHD energy addition on the required reservoir pressures. Such a code will be useful for predicting overall system performance to first-order approximation. Development of this code should draw freely upon experimental data from subsystem/component testing as well as algorithms and models developed for simulation codes that model individual subsystems.

Based upon recent discussions between MSE and LLNL, a more sophisticated computational model for characterizing the performance of UHP drivers may be necessary. A preliminary design for the A-2 facility

can probably be developed using existing analysis tools. However, for a hydraulically driven system, the effects of compression waves interacting with the main piston and the end walls may create uncertainties in the performance and run times. This issue must be studied analytically before constructing the A-2 facility. This may require the development of an additional simulation tool.

4.8.7 Major Deliverables

- (a) Initial estimates of MSHWT performance envelope—FY98.
- (b) Wind-tunnel performance model. Usable by FY00.
- (c) Wind-tunnel system and subsystem cost trade models. Usable by FY01.
- (d) Wind-tunnel cost trade—FY02.
- (e) MSHWT conceptual definition. Prepared to the highest detail possible with any major needed research and risk mitigation needs identified and suggested risk mitigation plans. This is a continuous process that must be addressed yearly and in the annual report.
- (f) MSHWT conceptual design—delivered at end of Phase 1 and updated at end of Phase 2.

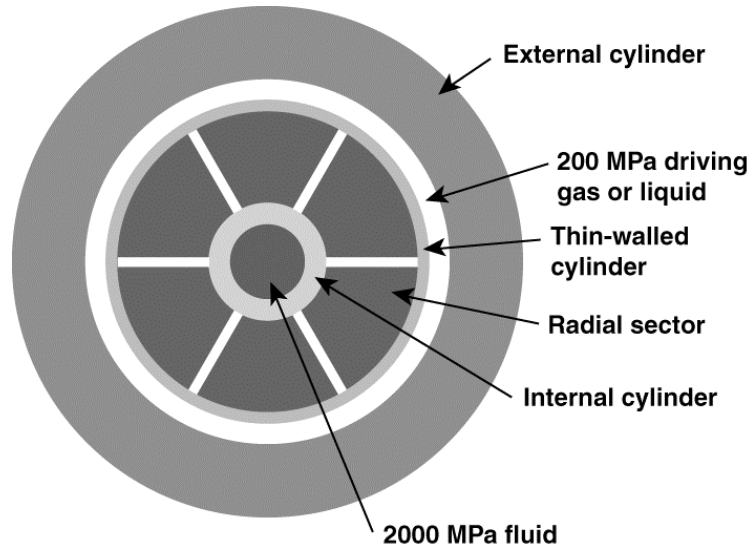
4.9 Costs and Schedule

In the July 98 workshop, the Program Team developed rough costs of the research. Subsequently, these costs were refined assuming either a five-year schedule or an eight-year schedule for the execution of the research. Subsequent to the steering committee review in November 1998, this Phase 1 and 2 research plan was developed. FY98 is used as the starting year, with application of \$1.89 million congressional funding actually received and the expected receipt of \$2.8 million in FY99. As can be observed, the complete research project is estimated to cost approximately \$34.5 million without contingency. Approximately \$20.5 million in funding is expected from congressional sources in FY98–02 and \$14 million from the USAF POM.

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APPENDIX B—SCOPING CALCULATION FOR THE DIMENSIONS OF THE VARIABLE RADIAL SUPPORT VESSEL



r_1 = inner radius of inner cylinder
 r_2 = outer radius of inner cylinder = inner radius of sector
 r_3 = outer radius of sector
 r_4 = inner radius of external cylinder
 r_5 = outer radius of external cylinder
 p_1 = pressure in inner cylinder at r_1
 p_2 = pressure (radial stress) at r_2
 p_3 = pressure (radial stress) at r_3 and at r_4
 p_5 = pressure at r_5
 L = axial length in cylindrical symmetry
 E = Young's Modulus
 ν = Poisson's ratio
 u = radial deformation

Figure B-1. Cross section of a variable radial support UHP vessel. The internal cylinder contains the pressure fluid and provides a sealing surface for the UHP piston. The sectors provide a stress multiplication between the driving gas/liquid and the internal liner. The thin-walled cylinder and the external cylinder contain the driving gas/liquid.

The variable radial support design provides a variable radial inward-directed stress that is added to the radial outward-directed stress owing to the pressurized fluid. Managing the sum of these stresses results in a net radial stress and a resulting hoop stress that can be tailored to provide a desired radial displacement. Management of the Poisson longitudinal stress requires a separate, external longitudinal load. For the ultra-high pressure (UHP) intensifier, the variable radial

support scheme has two major advantages: 1) the radial deformation of the internal cylinder can be managed so that a controlled clearance, packing-free pressure seal is effected between the UHP piston and the internal liner and 2) the loss of material strength of the internal liner due to the high temperature is mitigated by operating the liner in an elastic range. However, these benefits come at the significant disadvantage of complexity and cost of the variable radial support vessel, compared to the fixed radial support of a compound vessel with interference fits between the vessel layers. This appendix provides a summary of the design equations. Table B-1 contains results of “scoping” calculations, which are meant to give a general idea of the size of the UHP intensifier required for various UHP driver configurations and a sense of the trade-offs available for various operating points.

Summary of Design Equations

From Harvey (Ref. 1), the radial deformation of an elastic cylinder at any radius r is:

$$u = \frac{(1-\nu)}{E} \frac{r_1^2 P_1 - r_2^2 P_2}{r_2^2 - r_1^2} r + \frac{(1+\nu)}{E} \frac{r_1^2 r_2^2 (P_1 - P_2)}{(r_2^2 - r_1^2)} \frac{1}{r} \quad (\text{B-1})$$

Since the operating temperature of the inner cylinder and high pressure air is approximately 600°C, organics cannot be used as packing material for a moving seal between the piston and the inner cylinder. One way to deal with this is to make a controlled clearance seal so there is minimal clearance (that is, approximately 2–3 μm). This is done in the variable radial support scheme by coupling P_2 and P_1 so that $u = 0$:

$$P_2 = \frac{r_1^2(1-\nu) + r_2^2(1+\nu)}{2r_2^2} P_1 \quad (\text{B-2})$$

The pressure P_3 required to react P_2 depends on the radii of the sector.

$$\begin{aligned} F_2 &= P_2 A_2 = P_2 (2\pi r_2 L) = F_3 = P_3 A_3 = P_3 (2\pi r_3 L) \\ P_2 &= \frac{r_3}{r_2} P_3 \end{aligned} \quad (\text{B-3})$$

It is convenient to make P_3 the same as the low pressure source for the intensifier (this not only eliminates a separate pressure generating system, but also couples the variable radial support to the high pressure side of the intensifier directly). The intensifier low pressure is related to the intensifier high pressure through the force balance on the intensifier piston:

$$\begin{aligned}
 F_{high} &= P_2 A_{high} = P_2 (\pi r_2^2) = F_3 = P_3 A_{low} = P_3 (\pi r_{low}^2) \\
 P_2 &= \frac{r_{low}^2}{r_2^2} P_3 = \alpha P_3
 \end{aligned}
 \tag{B-4}$$

The area ratio $\alpha = A_{low}/A_{high}$ is variable, but generally around 10. Finally, we can find the outside radius of the sector, r_3 :

$$r_3 = \frac{r_1^2(1-\nu) + r_2^2(1+\nu)}{2r_2^2} (\alpha r_2) \tag{B-5}$$

where we remember that this is an elastic solution for a hollow, thick-walled cylinder with zero radial deformation at the inner wall, as well as for the particular case in which the radial stress acting on the outside radius of the sector is equal to the pressure driving the low pressure side of the intensifier. Note that this solution for the r_i primarily is geometric and depends only weakly on material properties through Poisson's ratio of the inner cylinder. For sectors having a constant length, this means that r_3 can be changed only by varying r_1 and r_2 . One way to decrease r_3 is to make the length of the outside (at r_3) of the sectors longer than the length of the inside (at r_2). Then $F_2 = P_2 r_2 L_2 = P_3 r_3 L_3 = F_3$ and $r_3 = (P_2/P_3)(L_2/L_3)r_2$. However, this results in extending the axial length of the support vessel beyond the high pressure section. Conversely, it also results in a smaller requirement for OD and the total volume of the outer vessel.

We now find the nominal size for the external pressure vessel that must contain the pressure P_3 . (Note that this external vessel only has to generate a radial stress, which could be done nonhydraulically by inserting a conical sector into a conical vessel.) The external vessel is a simple cylindrical thick-walled vessel that is operated in the elastic range with a small safety factor. To get a nominal size, the von Mises criterion is used to find the pressure at which the inner surface of the vessel reaches its elastic limit:

$$\begin{aligned}
 P_3 &= \frac{\sigma_y (K^2 - 1)}{(s\eta)(\sqrt{3}K^2)} \\
 K &= \frac{r_5}{r_4}
 \end{aligned}
 \tag{B-6}$$

and σ_y is the 0.2 percent elastic limit from a standard tensile test.

Summary of Scoping Calculations

The size of the UHP intensifiers is important when considering fabricability, in terms of both materials and machining; performance; and systems integration. The size (that is, the volume of the 2,000 MPa gas) of the intensifier is driven by the total mass requirement, which depends on

the plenum gas density, the flow rate, and the run time. The absolute volume is related to the mass through the density at the starting and final plenum operating points. For these calculations, $P_i = 300$ MPa, $T_i = 517$ K, and $\rho_i = 716$ kg/m³; $P_f = 2,000$ MPa, $T_f = 900$ K, and $\rho_f = 1,151$ kg/m³. In this conceptual design, the UHP intensifiers are deployed in n pairs, so that the total mass is contained in $2n$ intensifiers. In addition to this, two geometry “rules” have an effect on the intensifier size. The length/diameter (L/D) ratio of the cylindrical volume containing the gas must be such that the L/D ratio of the UHP piston can sustain reasonable bending moments. In this scoping calculation, the L/D ratio of the UHP piston is set at seven. The second geometry rule follows from the area ratio of the high pressure to low pressure sides of the UHP piston. This “intensification ratio” generally is in the range of 8–20, and is set to 10 for these calculations. Thus, the 2,000 MPa pressure acting on the high pressure end of the UHP piston requires a pressure of 200 MPa to act on the low pressure end. The force balance on the UHP piston provides that the diameter of the low pressure side of the piston assembly is $\sqrt{10}$ times the diameter of the high pressure side.

The dimensions of the remaining components of the variable support vessel (refer to Figure 5-8) follow from the volume of the high pressure gas, with the addition of a few more “rules”. The wall thickness of the inner liner should be large enough so that it provides a close clearance pressure seal with the moving UHP piston, but small enough so that it can be heated conveniently (if required), to control the heat loss from the gas. It can vary from a few millimeters to a few centimeters and is set to 1 cm. The inner radius of the sector is fixed by the outer radius of the inner liner. The outer radius of the sector is defined by the desired radial stress at the inner liner and the force balance on the sector. The outward radial force on the sector is equal to the product of its contact area with the inner liner and the stress, $\sigma_{s,l}$, between the sector and the inner liner. This radial stress is set to provide the desired radial deformation at the inner surface of the inner liner. Once this stress is specified, the outer radius of the sector is $r_{s,o} = (\sigma_s/P_L)r_{s,i}$, where P_L is the hydraulic pressure acting on the outer surface of the sector. The hydraulic pressure is connected to the same source as the pressure on the low pressure end of the UHP piston. The sector membrane is simply a thin cylinder that prevents the hydraulic pressure from leaking into the gaps between the sectors, and is set to 1.5 mm. The annular hydraulic pressure region should be as narrow as possible to minimize the overall radial dimension of the intensifier, but wide enough so that there are no significant pressure gradients. The thickness of the annular region is set to 5 mm. Finally, the wall thickness of the external pressure vessel should be adequate to provide elastic operation with an acceptable safety factor. For these calculations, the safety factor is set to 1.5 on the elastic limit.

Using these inputs and rules, a simple FORTRAN code provides estimates of the dimensions for the structural components of the UHP intensifier. They are shown in Table B-1 for some representative flow rates and flow times. The nozzle throat effective diameter is found from the desired mass flow rate and the density and sound speed for a Mach 2 expansion from a plenum condition of 2,000 MPa and 900 K. The density is 867 kg/m³ and the sound speed is 1,658 m/s.* The piston stroke includes the pressurization from 300 MPa at 716 kg/m³ to 2,000 MPa at 1,151 kg/m³.

* Robert Anderson, Private Communication, 1999.

Using large caliber (for example, 16 inch) cannons as a metric for established materials availability and fabrication technology, run times and mass flow rates requiring a total mass of the order of 1,000 kg appear to be feasible.

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Table B-1. Scoping calculations for the dimensions of the UHP intensifiers for various flow rates, run times, and number of intensifiers. The plenum conditions are P=2,000 MPa, T=900 K. The density of the fluid in the throat is 867 kg/m³ and the speed of sound in the throat is 1658 m/s. Other dimensional rules are discussed in the text.

Run Time (s)	Total Flow Rate (kg/s)	Number of Intensifiers	Throat Diameter (mm)	Piston Diameter (mm)	Piston Stroke (mm)	Piston Speed (m/s)	Plenum Vessel Length (m)	Sector			External vessel		
								ID (mm)	OD (mm)	Thickness (mm)	ID (mm)	OD (mm)	Thickness (mm)
1	4	8	1.88	54.5	311	0.186	492	74.5	622.0	273.7	635.0	955.4	160.2
1	4	16	1.88	43.2	247	0.148	391	63.3	512.9	224.9	525.9	791.3	132.7
1	10	4	2.98	93.2	531	0.318	841	113.2	1002.3	444.6	1015.3	1527.6	256.2
1	10	8	2.98	74.0	422	0.253	668	94.0	812.7	359.4	825.7	1242.3	208.3
1	10	16	2.98	58.7	335	0.201	530	78.7	663.0	292.2	676.0	1017.1	170.6
10	10	4	2.98	200.7	1144	0.069	1813	220.7	2071.9	925.6	2084.9	3136.8	526.0
10	10	8	2.98	159.3	908	0.054	1439	179.3	1659.2	739.9	1672.2	2516.0	421.9
10	10	16	2.98	126.5	721	0.043	1142	146.5	1332.3	592.2	1345.3	2024.1	339.4
10	100	16	9.41	272.5	1553	0.093	2460	292.5	2787.4	1247.5	2800.4	4213.3	706.5
10	100	32	9.41	216.2	1233	0.074	1953	236.2	2226.5	995.1	2239.5	3369.4	565.0

APPENDIX C—FRICTION HEATING OF A MOVING BRIDGMAN SEAL

The intensifier piston has high-pressure seals on both the low pressure (approximately 200 MPa) manifold and the high pressure manifold (approximately 2,000 MPa). The low-pressure seal is straightforward and seldom gives rise to difficulty. However, the high-pressure seal presents great difficulty due to the high stresses and the deformation of the cylinder bore. Three design approaches for the high-pressure seal include 1) a static seal at the entrance of the UHP piston into the high pressure cylinder, 2) a moving Bridgman unsupported area seal at the top of the UHP piston, and 3) controlled clearance seal at the top of the UHP piston.

In the static seal configuration, the entire length of the high-pressure cylinder carries the radial stress due to the pressure, and the advantage of “massive support” is lost. This is a significant disadvantage, since, at the highest pressures, the shear stress is constant along the entire bore of the vessel. If the seal were at the top of the piston, the shear stress is high only along the inner length of the bore exposed to the high-pressure gas. The remaining metal mass below the piston has a zero radial stress boundary condition, resulting in a radial stress gradient into the high stress region. Its major advantage is that the seal moves with respect to the piston so that it is that the piston is subject to abrasion and scouring instead of the bore of the UHP pressure vessel. Since pistons may be made of very hard (and brittle) material, can be plated, and are easy to remove and service, the static seal offers significant advantages for apparatus with high numbers of operational cycles, such as pumps.

The moving Bridgman unsupported area seal may be of the classic “mushroom” or the “inverted” types, shown in Figure C-1. Both seals are designed to improve with increasing pressure. The seal packing and supporting, hard, anti-extrusion rings move with the piston along the pressure vessel cylinder, thus giving rise to frictional heat and to abrasion/scouring of the cylinder wall. In the nominal design for the UHP driver, the cylinder bore expands by a few tenths of a percent, thereby causing a gap between the piston and cylinder wall, which must be bridged by the anti-extrusion rings. This gap can be reduced to zero using the variable radial support design. Additionally, the mean stress in the packing typically is 10–20 percent higher than the pressure, which the cylinder must support over the length of the packing.

In the controlled clearance seal, the nominal 20 μm clearance between the piston and the cylinder wall is kept approximately constant through application of a variable external radial stress that balances the internal pressure. A section of the piston exterior surface is coated with a weak metal, such as indium, to provide a viscous pressure seal and a lubrication layer between the piston and cylinder wall. Selection of the seal type depends on the details of the design and application. It is typically most successful when the viscosity of the pressure fluid is high enough to result in an acceptably slow leak rate. Its major disadvantage is the requirement to establish and maintain a very tightly controlled clearance between the piston and the bore of the vessel.

The Bridgman “mushroom” seal is the most reliable and is selected where possible. In the UHP driver, the limiting factor is the operating temperature of the seal packing, which is exposed to an initial steady temperature of approximately 500 K and a transient temperature to 900 K due to the compressed air, as well as to a heat load resulting from the friction between the packing and the cylinder wall.

The Bridgman seal between the moving high-pressure piston and the UHP intensifier bore will heat due to friction. The first choice for a seal packing is an organic material. Other inorganic materials, such as lead, indium, or other soft alloys are avoided because of their higher shear strengths and, in some cases, embrittlement of the pressure vessel steel. Since organic materials have relatively low service temperatures, an estimate of the temperature increase of the seal packing resulting from kinetic friction is useful.

The seal can have one of two configurations: 1) a “mushroom” design, where the seal is at the top of the moving high pressure piston and moves with it; or 2) a stationary design where the seal is stationary at the entrance to the high pressure bore and the piston moves past it. Both designs have nominally the same friction heating characteristics (that is, the same contact area, normal force, and coefficient of friction). The mushroom design has a relative displacement between the bore of the vessel and the seal, while the stationary design has a relative motion between the piston and the seal. Since it is easier to repair/replace the piston, the inverted design is preferable; however, it is a slightly more difficult design to make work.

Figure C-1 is a schematic of the Bridgman mushroom design (Ref. 1). The force F_1 on the top of the mushroom, $P_1 A_1$, is reacted by the force $F_2 = \sigma_2 A_2$, where σ_2 is the normal component of the (non-hydrostatic) stress in the packing material of the seal. Here, A_1 is the cross-sectional area of the bore of the pressure vessel at the seal position and A_2 is the annular area of packing. If the shear strength of the seal material is small with respect to the average stress, one can approximate (overestimate) this normal stress by setting it equal to a “pressure” in the seal material $P_2 \approx \sigma_{ave}$, therefore:

$$\begin{aligned}
 P_1 A_1 &= P_2 A_2 \\
 A_1 &= \pi r_2^2 \\
 A_2 &= \pi(r_2^2 - r_1^2) \\
 P_2 &= P_1 \left(\frac{r_2^2}{r_2^2 - r_1^2} \right)
 \end{aligned} \tag{C-1}$$

The friction heating is:

$$W = \vec{F} \cdot \vec{d} = \mu_k P_2 A_s d \tag{C-2}$$

where μ_k is the coefficient of kinetic friction between the seal material and the steel of the piston bore, A_s is the area of the seal material-steel interface, and d is the relative seal-steel displacement. The temperature rise of the seal material is a function of time as the high-pressure piston moves and then stops at the end of its stroke. The final temperature is calculated, assuming the heat generated at the seal material steel interface is partitioned into the seal material and steel by a fraction, α , and the thermal conductivity time constant is small compared to the displacement time. This latter assumption is not particularly good. One can improve on this rough

estimate by doing the time-dependent heat transfer into a cylinder assuming a heat flux, equal to the partitioned friction energy, into the seal and steel. For the present, however, it is assumed that the partitioned heat flux is distributed uniformly in the packing, thereby resulting in an underestimate of the maximum temperature in the packing.

The temperature rise in the seal material is:

$$\begin{aligned}
 \Delta T &= \frac{Q}{m_s c_p} = \alpha \frac{W}{m_s c_p} = \frac{\alpha \mu_k P_2 A_s d}{m_s c_p} = \frac{\alpha \mu_k A_s d}{m_s c_p} P_1 \left(\frac{r_2^2}{r_2^2 - r_1^2} \right) \\
 m_s &= \rho_s V_s = \rho_s \pi (r_2^2 - r_1^2) h_s \\
 A_s &= 2\pi r_2 h \\
 \Delta T &= \frac{\alpha \mu_k 2\pi r_2 h d}{\rho_s \pi (r_2^2 - r_1^2) h c_p} P_1 \left(\frac{r_2^2}{r_2^2 - r_1^2} \right) \\
 \beta &= \frac{r_2^2}{r_2^2 - r_1^2} \\
 \Delta T &= 2 \frac{\alpha \beta^2 \mu_k}{\rho_s c_p r_2} P_1 d
 \end{aligned} \tag{C-3}$$

Setting:

$$\begin{aligned}
 P_1 &= 2(10^9) Pa \\
 d &= 0.8m \\
 r_2 &= 0.05m \\
 \mu_k &= 0.05 \text{ (for Teflon/steel)} \\
 c_p &= 1kJ/kg - K \\
 \rho_s &= 2100kg/m \\
 \beta &= 1.1 \\
 \alpha &= \frac{\kappa_{Teflon}}{\kappa_{steel}} = \frac{0.25W/m - K}{140W/m - K} = 1.8(10^{-3}) \\
 \text{so} \\
 \Delta T &\approx 3K
 \end{aligned} \tag{C-4}$$

One of the thermodynamic paths under consideration is an isothermal heating to approximately $T = 530$ K, then an adiabatic compression to 2,000 MPa and 900 K. This puts the seal material at approximately 250°C (Ref. 2) at the end of the isothermal path and allows no further heating

since the Teflon™ is heated not only by friction but also by conduction from the steel wall. This means that using Teflon as a packing material is problematic. The assertion that the maximum operating temperature for Teflon™ is 250°C should be tested, or a derivative material designed for a higher operating temperature with similar thermal properties should be identified.

The operational advantage of using a Bridgman seal is adequately attractive that a component test of the moving seal at high temperature is advisable. The PY00 funding profile does not include these tests.

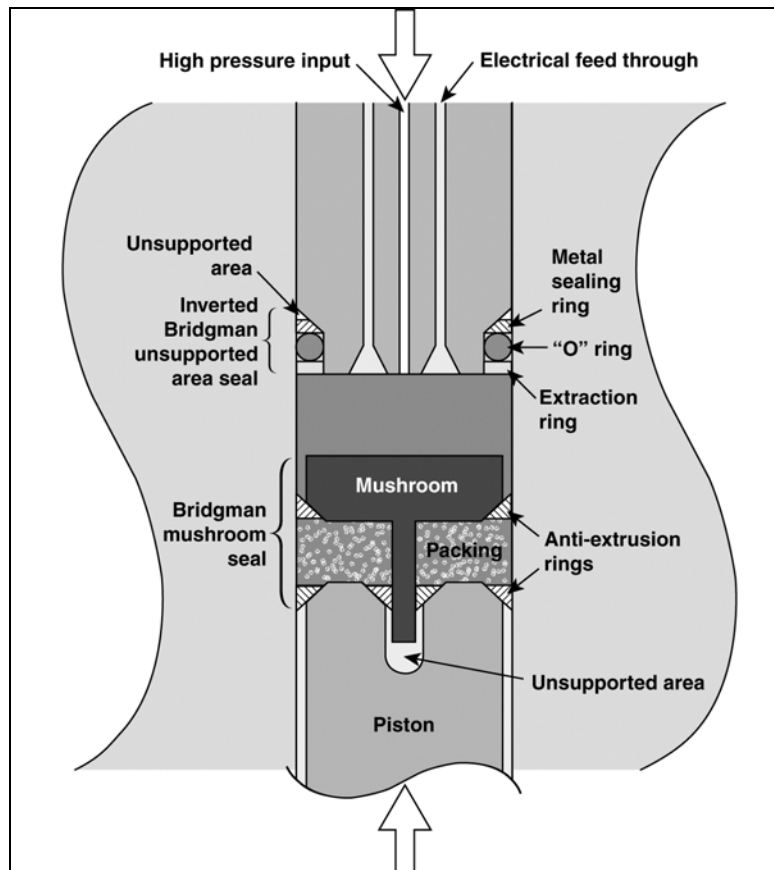


Figure C-2. Two typical Bridgman unsupported area seals.

The “inverted” Bridgman seal usually is a static seal and provides space for electrical and mechanical feedthroughs into the high pressure volume. The “O”-ring provides an initial seal and the metal sealing ring provides the high pressure seal. The “mushroom” Bridgman seal is used both in static and moving applications. The packing provides both the initial and high-pressure seals. The anti-extrusion rings prevent extrusion of the weak packing material, which is at a higher mean stress than the pressure fluid. Both seals, in principle, get better as the pressure increases.

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APPENDIX D—AIR AND NITROGEN EQUATION OF STATE

Air is a real gas at the pressures and temperatures of interest in the ultrahigh-pressure (UHP) subsystem. Figure D-1 shows that the compressibility factor, $Z = Pv/RT$, diverges strongly from its ideal gas value of 1 for densities above approximately 500 kg/m^3 . Approximating thermodynamic variables at high densities using the ideal gas equation of state (EOS) results in significant error. In this research, all thermodynamic variables are found using a real gas EOS. High pressure experimental data for air exist over only a limited region. Sychev et al., (Ref. 1) and Haynes et al. (Ref. 2) review sources of experimental data. The highest pressure data are from Kiyama (Ref. 3) at 455 MPa at a single temperature of 303 K. Michels (Ref. 4) provides accurate data over the range 273–348 K at pressures to approximately 220 MPa.

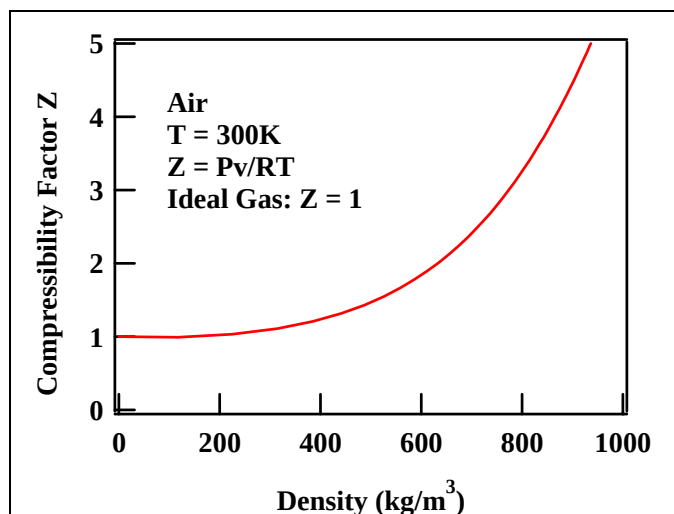


Figure D-1. Air compressibility factor vs. density. Densities in the UHP subsystem are greater than 800 kg/m^3 . Data are from the NIST extended air EOS, calculated using the ALLPROPS code from the University of Idaho Center for Applied Thermodynamics Studies.

The air EOS used for this research is found using extended corresponding states and experimental data for nitrogen for temperatures and pressures to 1,800 K and 2,220 MPa (Ref. 5). The estimated uncertainty of the corresponding states and mixtures approach is about 1 percent in the density. The reader is referred to Ref. 5 for details. Unless otherwise noted, the air and nitrogen EOS used throughout are from the Center for Applied Thermodynamic Studies (CATS) at the University of Idaho Department of Mechanical Engineering (Ref. 5). In some instances, such as in calculation of the viscosity of air, newer, unofficial versions of the algorithm and the input data are used.* The essential differences between the various air EOS data files and algorithms lie in the interface (DOS and Microsoft® Windows 95) and in the EOS data file. There are three separate air EOS data files: 1) the “official” CATS file, which ends at $P = 70 \text{ MPa}$; 2) an extended version to $P = 2,000 \text{ MPa}$, $T = 2,000 \text{ K}$ provided by Eric Lemmon that works with the CATS Windows 95 algorithm (this version is called air EOS V2 in this report); and 3) an extended version to $P = 3,000 \text{ MPa}$, $T = 2,000 \text{ K}$ provided by Eric Lemmon that works with a

* Eric W. Lemmon, Private Communication, 1999.

DOS version of the EOS algorithm, also provided by Lemmon (this version is called air EOS V3 in this report). Aside from the extended pressure range, the significant differences between V2 and V3 are 1) V3 permits calculation of transport coefficients such as viscosity and thermal conductivity and 2) the reference point of the enthalpy of V3 agrees with the NIST reference point. In V2, the enthalpy reference point at $P_0 = 0.101325$ MPa, $T_0 = 298.15$ K is 956.5 kJ/kg. The reference enthalpies for both the original NIST air data file (limited to 70 MPa) and V3 are both 298.4 kJ/kg.

John Felderman at the Arnold Engineering Development Center (AEDC) has performed a comparison of four air EOS:*

- AEDC tabular data used in the 1960s;
- CATS ALLPROPS using air EOS V2 data file;
- DOS ALLPROPS and air EOS V3, both from Eric Lemmon, June 1999; and
- EOS data used by Anderson in his fluid dynamics codes and based on the NIST air EOS.

Felderman's findings are:

- There are only minor differences in the density at a given (P, T) between the four EOSs.
- The enthalpies for EOS 1, 3, and 4 agree. EOS 2 has an offset of about 658 kJ/kg at (P_0 , T_0).
- EOSs 1, 2, and 3 agree in entropy. EOS 4 has a different reference entropy by approximately 3.0 kJ/kg.

Felderman recommends that the MARIAH II/RDHWT Program team members use EOS 3. EOS calculations done at LLNL since June 1999 have used EOS V3. Calculations done using EOS V2 and involving the enthalpy will be converted to the EOS V3 enthalpies.

Table D-1. Air Constants (Ref. 5)

Property	Value	Units
Molecular weight	28.96	kg/mole
Gas constant	287.1	J/(kg-K); (m ³ -MPa)/(kg-K)
Temperature at the normal boiling point	78.67 ± 0.10	K
Temperature at the critical contact point	132.5 ± 0.1	K
Pressure at the critical contact point	3.766 ± 0.020	MPa
Density at the critical contact point	316.5 ± 0.6.0	kg/m ³
Heat of sublimation at 0 K	253.4	kJ/kg

* John Felderman, Private Communication, July 1999.

Table D-2. Air at the Target Flight Condition (Ref. 6)

Property	Value	Units
Temperature	200	K
Density	0.00174	kg/m ³
Pressure	9.9917(10 ⁻⁵)	MPa
Enthalpy	858.32	kJ/kg
Entropy	8.4478	kJ/kg-K
C _p	1.0025	kJ/kg-K
C _v	0.71542	kJ/kg-K
Sound Speed	283.67	m/s

Figure D-2 shows the melting curves for air, nitrogen, and oxygen. Every reasonable thermodynamic path in the UHP subsystem will remain in the supercritical, dense fluid region.

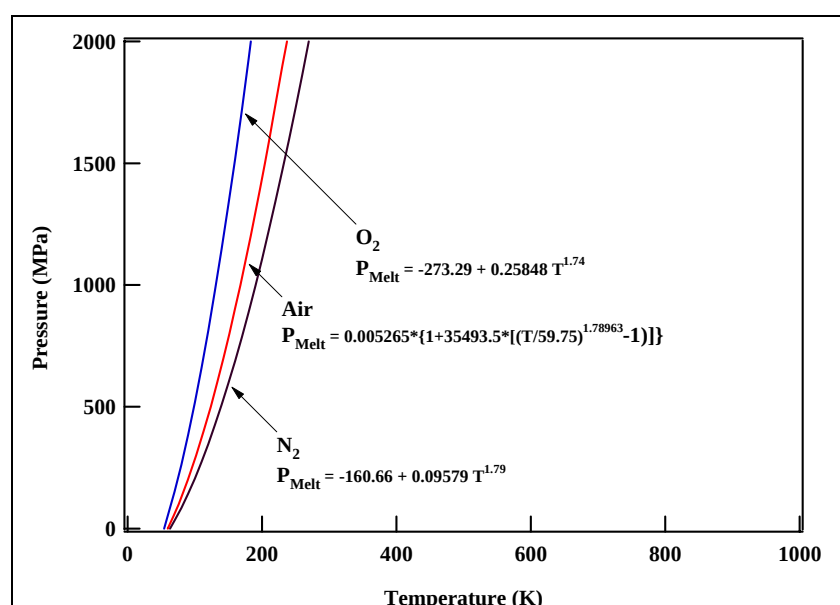


Figure D-2. Melting curves for air (Ref. 5), nitrogen (Ref. 7), and oxygen (Ref. 7).

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7. Center for Applied Thermodynamic Studies, Department of Mechanical Engineering, University of Idaho. The EOS may be downloaded from the web site <http://hobbs.me.uidaho.edu/~cats/cats.html>.

APPENDIX E—CROSSBORE STRESS CONCENTRATION

A fundamental feature of the ultrahigh-pressure (UHP) subsystem approach is connecting an arbitrary number of UHP volumes to meet the mass flow rate/flow time specification. Commercial tubing and fittings are available for connecting volumes up to 1,400 MPa. Only research is performed above the 2,000 MPa range; therefore, the high pressure volumes are singular, small, and require no connections.

Figure E-1 is a schematic showing one method for connecting high-pressure volumes in the static storage approach. The inverted Bridgman unsupported area seals are used to seal the closures between the pressure vessels. The total volume requirement is met by adding pressure vessels in a line, with the vessel at one end providing diagnostics access and the vessel at the other end providing nozzle access. There is no means provided for introduction of a gas upstream of the nozzle throat for film cooling. This scheme, while avoiding the necessity of introducing crossbores (holes in a hollow cylinder connecting the outside to the axial bore of the cylinder), requires a linear geometry (that is, typical configurations to supply a 10 kg/s flow for 1 s have $O(100)$ pressure vessels, each approximately 1-m long). It also suffers from poor accessibility to inspection or maintenance of an interior vessel.

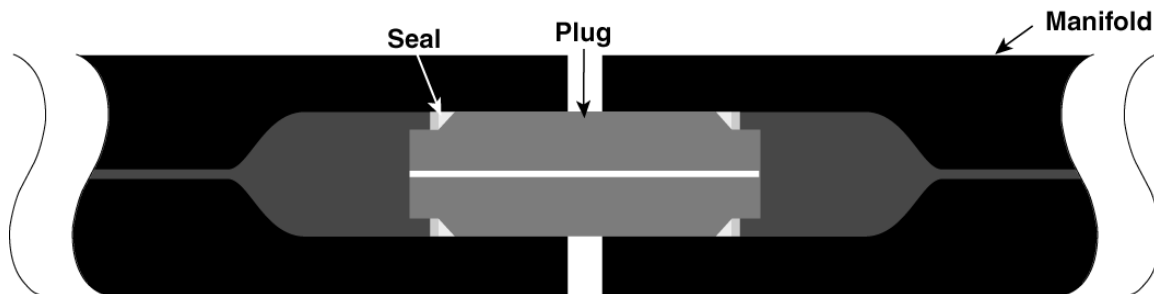


Figure E-1. Schematic showing one method for connecting high-pressure volumes in the static storage approach.

Figure E-2 is a schematic of the radial arrangement for joining multiple UHP volumes. This scheme provides relatively compact geometry and easy accessibility, but at the expense of connecting the radial vessels to an axial manifold by means of a crossbore in the manifold. This configuration offers four challenges: 1) sealing the connection between the end closure and the manifold; 2) managing the stress concentration due to the crossbores; 3) managing the uniaxial compressive load on the end closure; and 4) managing the force balance on the axial manifold.

The high-pressure seal between the end closure and the axial manifold is “self-sealing.” The force balance on the end closure is $P_I A_I = \sigma_r A_M$, where P_I is the pressure in the UHP intensifier; A_I is the annular cross sectional area of the end closure; and σ_r is the contact stress between the end closure and the outside surface of the manifold over area A_M . Making the ratio $A_I/A_M > 1$ (for example, 1.05) results in a contact stress greater than the pressure.

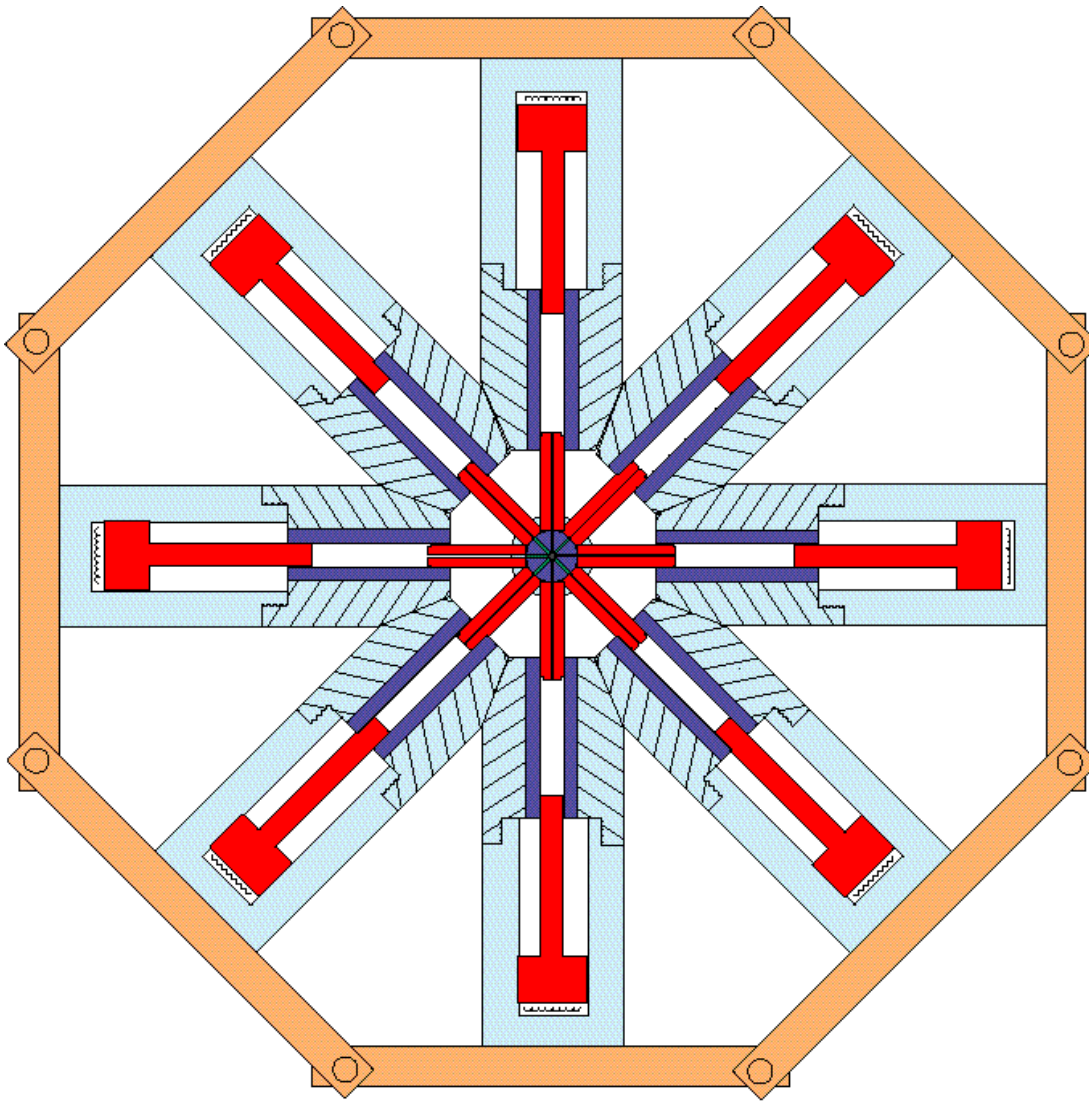


Figure E-2. Schematic of the radial arrangement for joining multiple UHP volumes.

A significant amount of research on crossbores in thick-walled pressure vessels has been reported. The stress concentration resulting from the $2n$ -fold symmetry radial crossbores is of the order of 3–4 times the pressure. Some of the more interesting findings are:

- The stress concentration is minimized if the crossbore and axial bore radii are the same (Ref. 1).
- Making a radius the edge at the intersection between the crossbore and the axial bore does not seem to make much difference in the stress concentration factor and fatigue lifetime (Ref. 2).
- Applying an external radial stress at the crossbore decreases the stress concentration (Ref. 3).

- Autofrettaging the region at the intersection of the crossbore and the axial bore (that is, plastically deforming it) provides a longer fatigue life, as long as the rebound tensile stress is not too large. The net stress concentration factor can be decreased to approximately 1 (Ref. 4).

Elastic Finite Element Analysis Calculations of Crossbore Stress

Elastic Finite Element Analysis (FEA) calculations were made on crossbore configurations to test the hypothesis that an external radial stress field could reduce the stress at the crossbore to a manageable level. Since there is no work hardening or plastic flow, the calculations only provide an indication of where the stress concentrations occur. The absolute value of the stresses are not realistic past the elastic yield point of the material. The elastic calculations were made using the commercial application Mechanica.* The internal pressure for the calculations presented in Figs. F-1 through F-3 (summarized in Table E-1) was 250,000 psi and the radial stress boundary condition at the cross bore was 250,000 psi. Results are summarized in Table E-1 and in Figs. F-1 through F-8.

Table E-1. Summary of elastic FEA calculations on crossbore stresses. The von Mises stresses are unrealistic but give an indication of stress concentration.

Fig	σ_z (psi)	Symmetry	Manifold OD (in)	Manifold ID (in)	Crossbore ID (in)	End closure OD (in)	Maximum von Mises Stress (psi)	Stress Concentration
F-1	0	2	8	1.6	1	8	1,559,000	6.24
F-2	0	4	8	1.6	1	8	942,320	3.77
F-3	250,000	4	8	1.6	1	8	557,860	2.23

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* Mechanica, Release 18, Parametric Technology, Inc., 128 Technology Drive Waltham, MA 02453.

APPENDIX F—SUMMARY OF FINITE ELEMENT ANALYSIS CALCULATIONS

Elastic and elastic-plastic Finite Element Analysis (FEA) calculations provide guidance on design geometry and credible results for stress and thermal fields in their appropriate regions of validity. Elastic calculations are useful for components that must be designed, either through geometry and materials or through stress superposition, to operate in an elastic regime. Due to operating pressures very near, or even greater than, the elastic yield of high performance structural materials and to the presence of stress concentrators in even simple cylindrical symmetry, the stresses in the UHP intensifier components generally result in plastic flow. Thus, designing to a safety factor on the ultimate strength (that is, bursting strength), rather than the elastic strength, of a material is a common practice in ultra-high pressure physics. In some cases, economics drives a decision to operate a component in the plastic, rather than the elastic, regime. Elastic operation generally implies a thicker wall section, so that the cost of a cylindrical device increase with the square of the diameter. Alternatively, smaller wall sections using more expensive, higher performance materials, might be specified. Plastic operation introduces fatigue failure issues, which must be addressed by costly quality assurance, inspection, and replacement requirements. Generally, for research devices such as the A-2, elastic operation is selected unless it simply is not possible owing to the magnitude of the contained pressure or results in prohibitive costs. In the proposed UHP subsystem, major components operating elastically are the inner liner of the UHP intensifier, the low pressure driver of the UHP intensifier, the intermediate intensifiers, and the low pressure gas storage vessel. Key components operating plastically are the various end closures, the axial manifold, the radial sectors, and (possibly) the UHP intensifier external vessel.

As an example of how elastic FEA calculations can provide guidance on stress management, we consider the cross bore in the axial manifold. Marcus Libkind at LLNL made these calculations using the commercial application Pro/Mechanica, Release 18 (Parametric Technology Corporation). While the stresses above the elastic limit of a material that are generated in the calculations are physically meaningless, they indicate the locations of stress concentrations. Ideas about how to reduce these high stresses through geometry or stress superposition can be examined quickly.

In the proposed UHP concept, an arbitrarily large system volume is achieved by adding the volumes of n UHP intensifiers arrayed radially around an axial manifold. The connection between these intensifiers and the manifold requires crossbore holes that intersect the axial hole in the manifold. The stress concentration at this intersection ranges from about 3 to about 7, depending on design details and calculational assumptions. The intensifier end closure (the “piston” in Table F-1) connects the 2000 MPa volume in the intensifier to the axial manifold. The end closure is in static equilibrium, with the pressure force on the end in the intensifier balanced by the contact stress with the external boundary of the axial manifold. This contact stress provides a radial boundary condition compressive stress for the cylindrical manifold, which adds to the oppositely directly radial stress owing to the internal pressure in the manifold. The value of this stress can be changed simply by changing the contact area. Figure F-1 shows Case 1 (see Table F-1), the stresses around a two-fold symmetric crossbore. The stress concentration with respect to the internal pressure is about 6.2. Case 3, shown in Fig. F-2, is for the same condition, except that the superposed radial stress provided by the external end closures from the UHP intensifiers now has a four-fold symmetry, resulting in a stress concentration of about 3.77. Finally, Fig. F-3 shows

Case 5, in which an axial (z) stress is added, reducing the stress concentration to 2.2. Future calculations will explore the ratio of the crossbore diameter to the axial bore diameter, the offset of the axes of the crossbores and the axial bore, and the intersection angle between the crossbore and axial bore.

It is clear from these scoping calculations that the crossbore stress concentrations can be managed by applying superposed external stresses using other, necessary, components of the UHP subsystem. The UHP intensifier end closures are necessary to extract the 2000 MPa air from the intensifier volume, and the axial load frame is necessary to react the force on the nozzle, as well as to anchor the remaining portion of the wind tunnel. The elastic FEA tool will continue to be used to explore design geometries and stress superposition as the UHP concept evolves into specific design calculations.

Once the geometry and approximate sizing of the UHP components is explored using elastic calculations, more realistic results for the stress and thermal fields are found using coupled elastic-plastic-thermal calculations. Scott Perfect at LLNL performed examples of these calculations using “DYNA3D,” an elastic-plastic FEA code, and “TOPAZ,” a transient heat transfer code. These calculations use material-dependent strength and thermal property curves and enjoy a long history of validated results, even at large deformations. They are particularly important in this problem, in which the material mechanical properties depend strongly on the temperature. Figure F-4 shows the general arrangement for the calculational mesh. The geometry is a four fold symmetric section of one layer of four radial intensifier end plugs contacting the axial manifold. The axial manifold shows four crossbores and the axial bore. The radial end closures from the intensifiers provide an external radial stress at their intersection with the axial bore.

The material selected for these initial calculations is an 18% nickel maraging steel because of its generally good strength and oxidation properties. However, its use in the final design is problematical, since it is age-hardened at about 750 K. The material properties for an 18Ni1700 maraging steel (similar to VascoMax 250) are (Ref. 5):

Table F-1. Mechanical properties of VascoMax 250.

Density 8.0 Mg/m ³
Modulus elasticity = 181 GPa
Poisson's ratio = 0.3
Yield strength = 1,650-1,830 MPa
Ultimate strength = 1,690-1,860 MPa
Elongation = 6-10%
Reduction in area = 35-60%
Hardness = Rc 48-50

Table F-2. Thermal conductivity for 18Ni1400.

T (°C)	k (W/m-K)
20	21
100	23
200	26
300	27
400	28
480	28

Table F-3. Mean coefficient of thermal expansion for 18Ni1400.

T (°C)	k (W/m-K)(10 ⁻⁶)
20-100	9.9
20-200	10.2
20-300	10.6
20-400	11.0
20-480	11.3

The specific heat is 0.46 kJ/kg-K.

The work hardening rule is:*

$$\bar{\sigma} = K \left(\varepsilon_0 + \bar{\varepsilon}^p \right)^n$$

$$\varepsilon_0 = \left(\frac{E}{K} \right)^{\frac{1}{n-1}}$$

$$\bar{\sigma}_y = \text{effective yield stress}$$

$$\varepsilon_0 = \text{initial yield strain}$$

$$\bar{\varepsilon}^p = \text{effective plastic strain}$$

For Vascomax 250 :

$$E = 30(10^6) \text{ Psi}$$

$$K = 3.28(10^5) \text{ Psi}$$

$$n = 0.0424659$$

* Scott Perfect, Private Communication

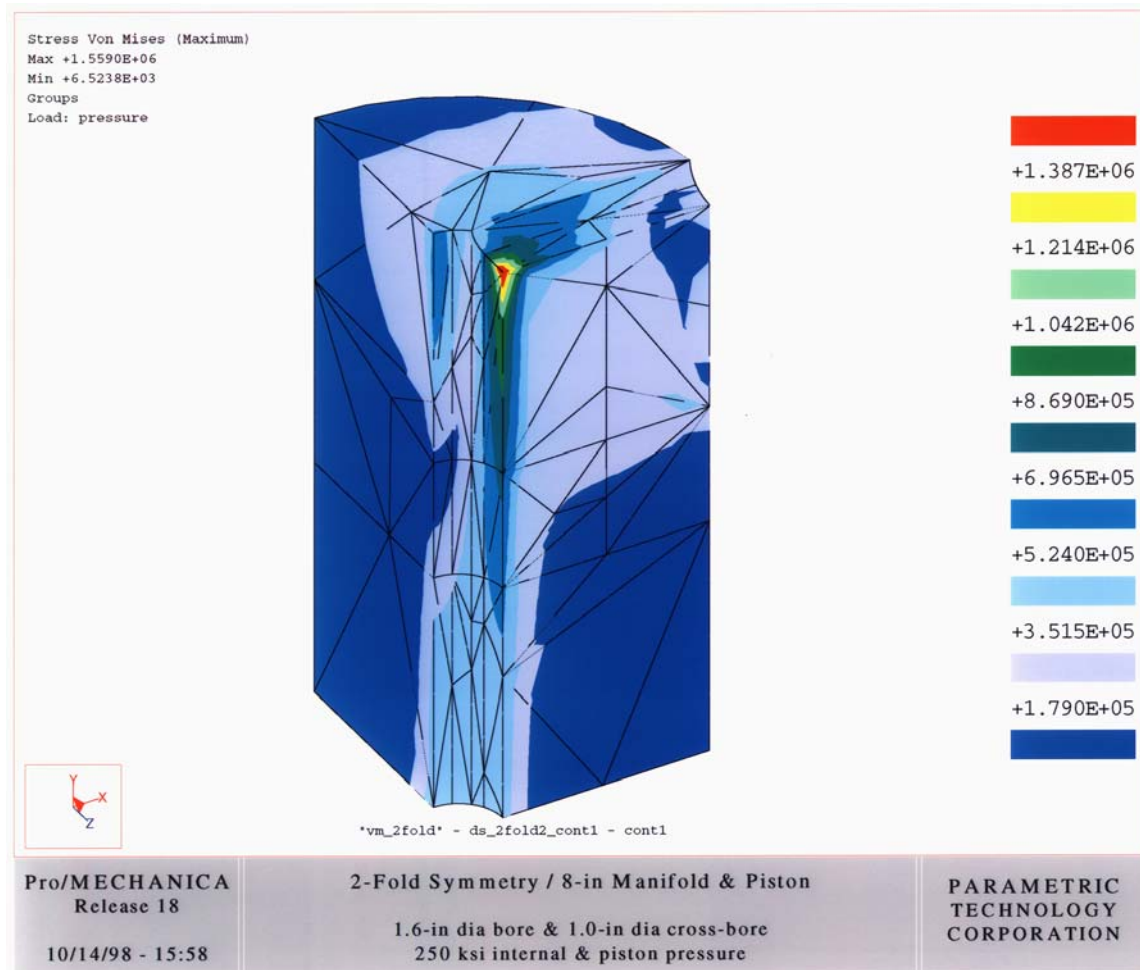


Figure F-1. Elastic FEA calculation of the stress concentration around a cross bore with two-fold symmetry. The externally applied axial stress is zero. The outside diameters of the axial manifold and the intensifier end closure are 8 inches, the inside diameter of the axial bore is 1.6 inches, and the inside diameter of the end closure is 1 inches. The internal pressure in the crossbore and axial bore is 250,000 Psi, and the external contact stress between the intensifier end closure and the axial bore is 250,000 Psi. The stress concentration at the crossbore is 6.2. In a real material, the high stress regions yield, spreading out the concentration and reducing the maximum stress.*

* Marcus Libkind, Private Communication.

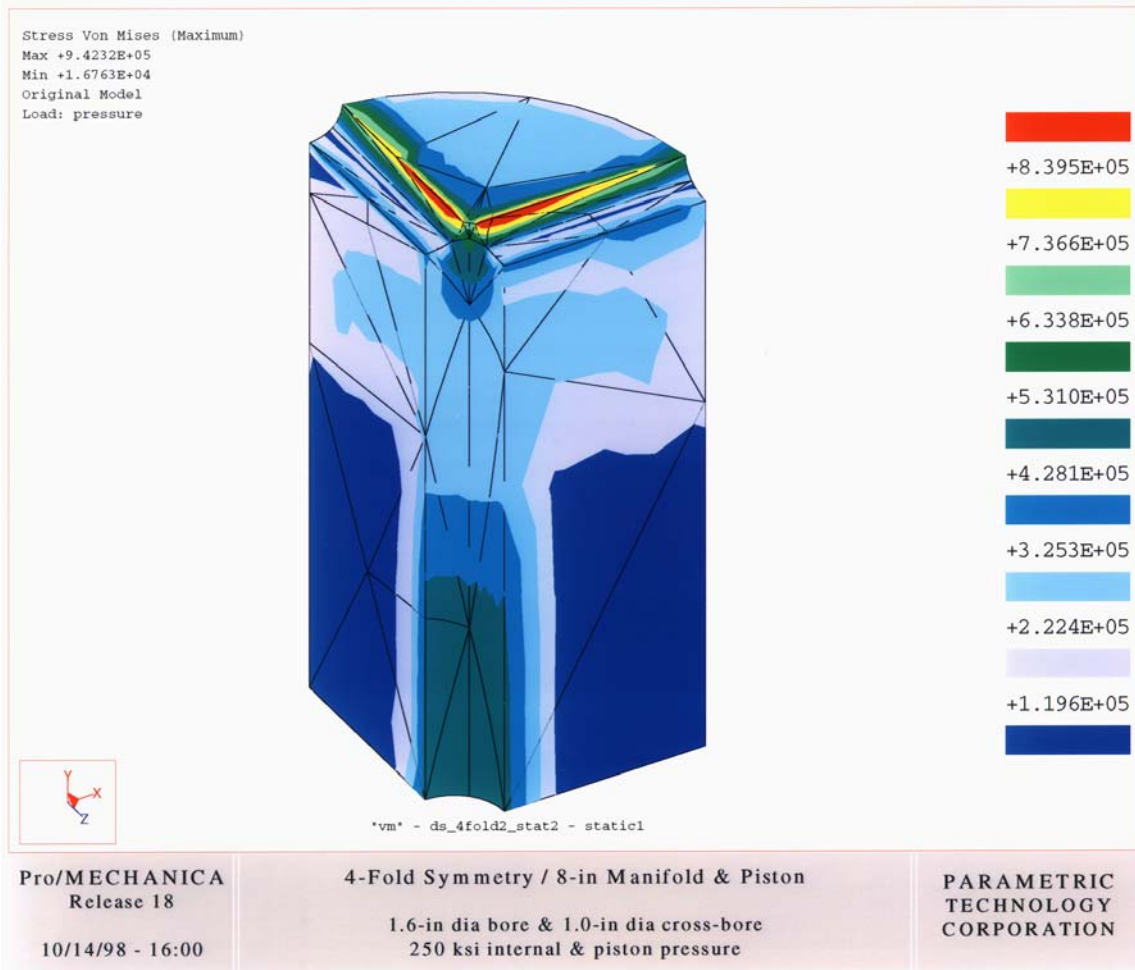


Figure F-2. Elastic FEA calculation of the stress concentration around a cross bore with four-fold symmetry. The conditions are the same as for Fig. F-1. The stress concentration at the crossbore now is 3.7.*

* Marcus Libkind, Private Communication

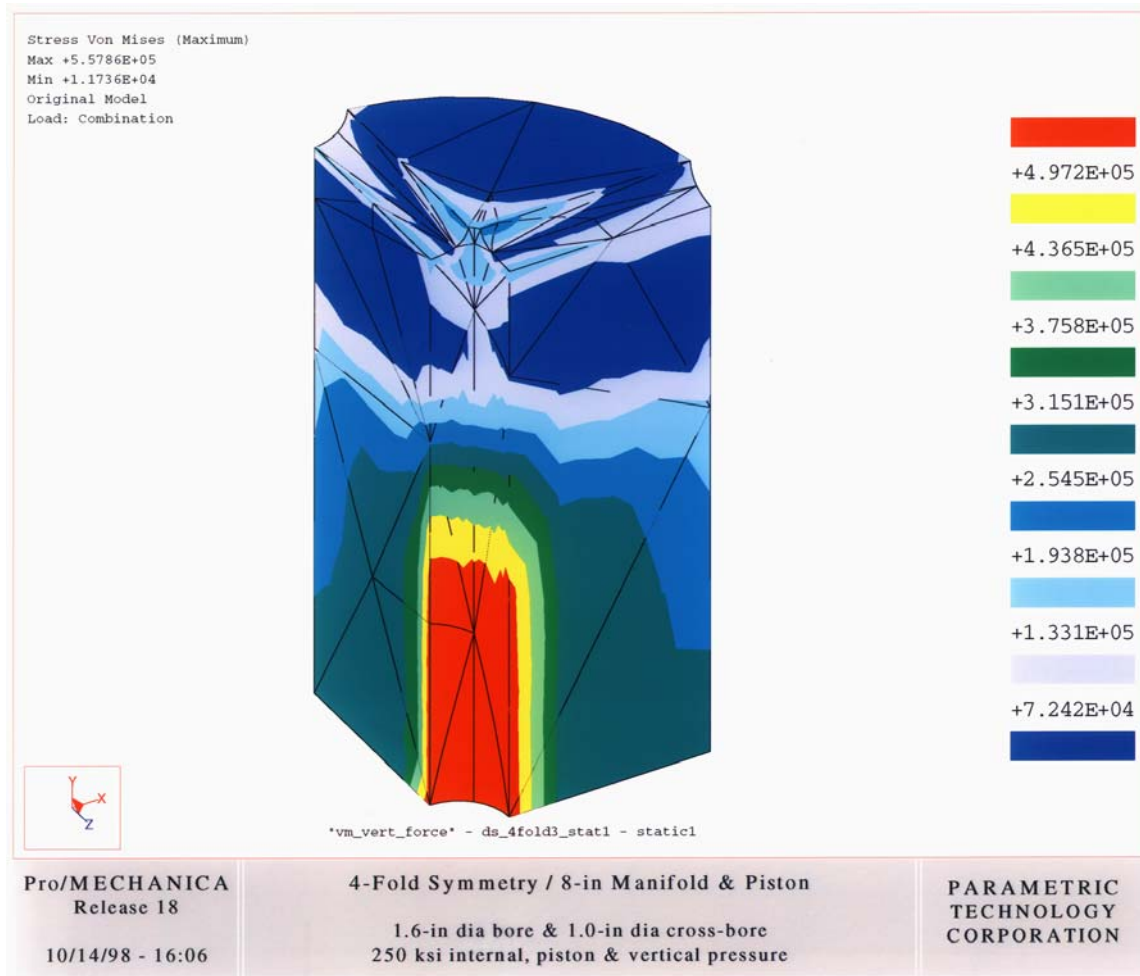


Figure F-3. Elastic FEA calculation of the stress concentration around a cross bore with four-fold symmetry. The conditions are the same as for Fig. F-1, with the addition of a compressive axial stress of 250,000 Psi. The stress concentration at the crossbore now is 2.2.*

* Marcus Libkind, Private Communication.

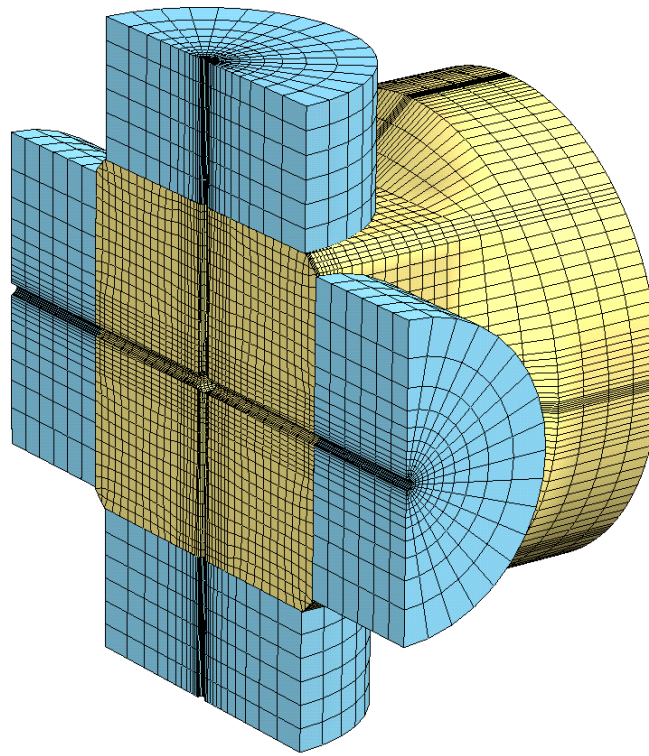


Figure F-4. Solid rendering of the DYN3D model of the axial bore and the four-fold symmetric end closures from the radially arrayed intensifiers. The end closures provide a compressive radial stress equal to the UHP intensifier pressure times the ratio of the cross-sectional area of the intensifier end closure in the intensifier to the contact area with the axial manifold.*

Figure F-5 shows the von Mises stress at a material temperature of 300 K and an internal pressure boundary condition of 2,000 MPa. The intensifier end closures provide a 2,000 MPa external radial stress boundary condition. Figure F-6 shows the crossbore region for the same calculation, with the deformation magnified by a factor of 10. As in the elastic calculations, the absence of an axial stress results in maximum deformation of the crossbore hole along the z axis. Further, essentially all of the material in the crossbore region has a von Mises stress in excess of the yield stress, but the work hardening rule limits the plastic strain (Figure F-7) to below 1% everywhere except for a limited region at the crossbore. Calculations similar to these will be used to tailor the precise shapes and geometrical arrangements of the intensifier end closures to minimize the plastic strain at the crossbores.

* Scott Perfect, Private Communication.

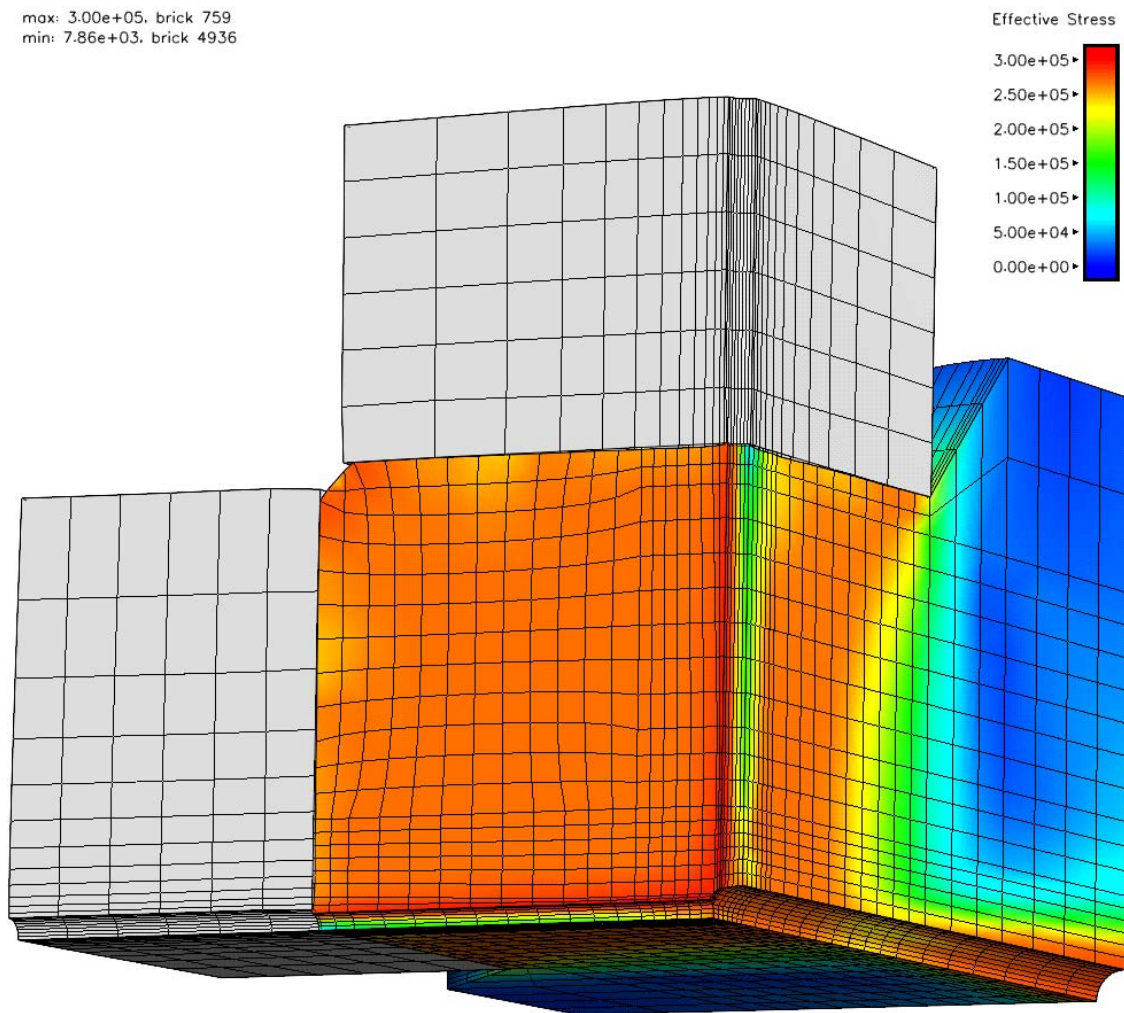


Figure F-5. Elastic-plastic calculation using the model shown in Fig. F-4 and the material properties for VascoMax 250. The pressure in the crossbores and axial bore is 300,000 Psi, as if the external radial compressive stress provided by the intensifier end closures. The stress does not exceed 300,000 Psi because of the plastic flow.*

* Scott Perfect, Private Communication.

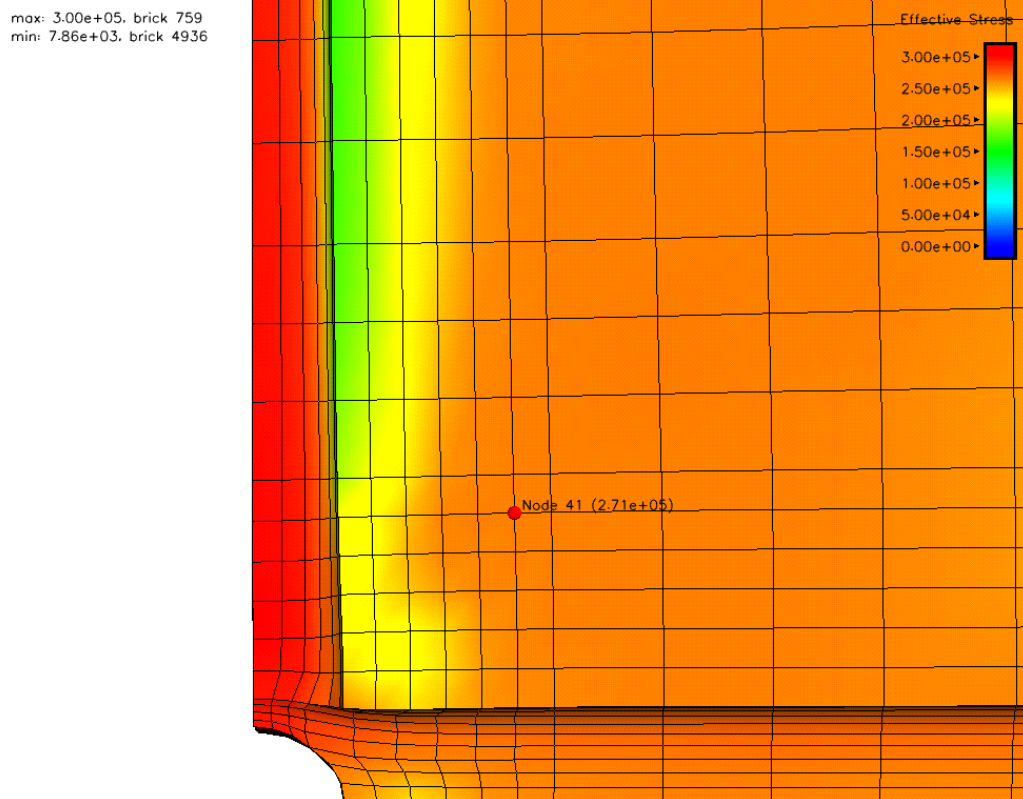


Figure F-6. The same results as for Fig. 5-5, magnified x10. The circular crossbores deform into ovals, with the major axis along the axial bore axis, showing the importance of adding an axial compressive stress.*

* Scott Perfect, Private Communication.

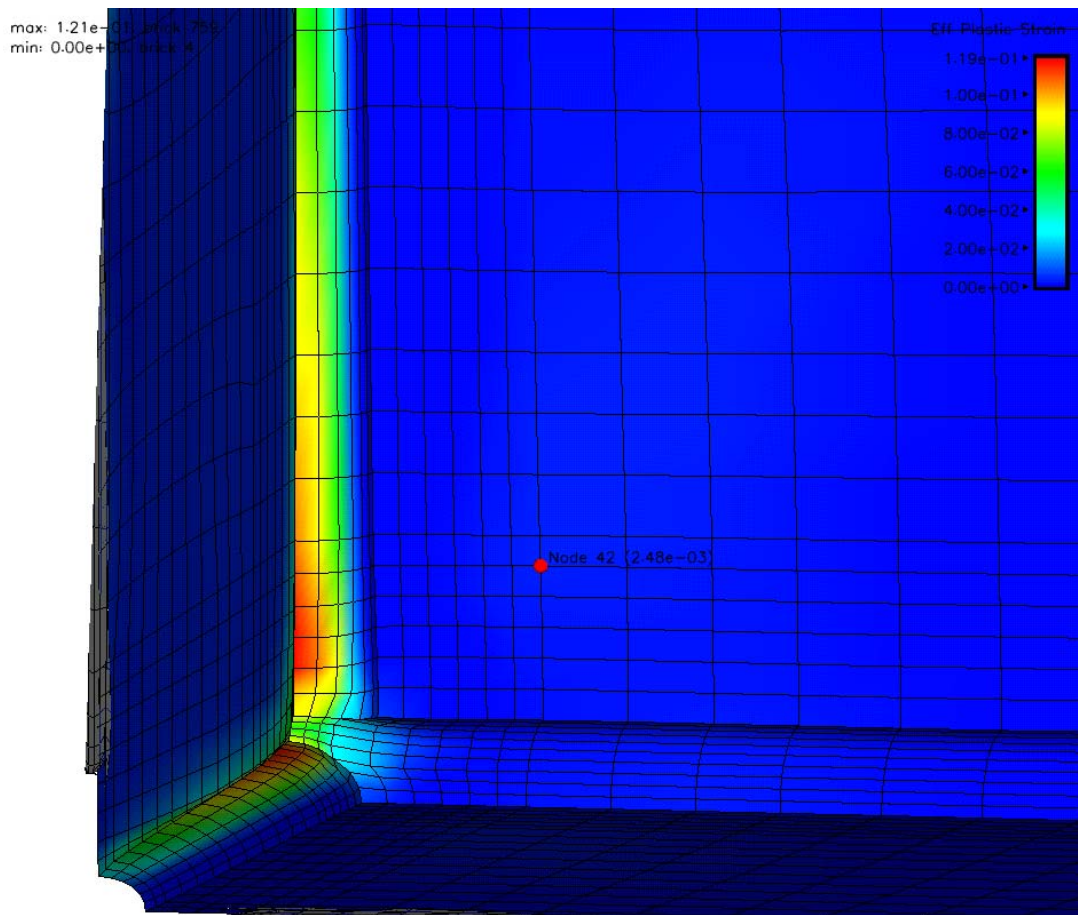


Figure F-7. The plastic strain for the calculation described in Fig. F-5. The maximum plastic strain is 12%, indicating significant local flow and vulnerability to fatigue failure.*

Figure F-8 shows the results of a TOPAZ calculation for the transient heat flow. The calculation is for VascoMax 250, with an initial uniform temperature of 530 K, a constant external boundary condition of 530 K, and a constant internal (in the crossbores and the axial bore) boundary condition of 900 K. The constant temperature boundary condition implies there is no thermal impedance between the 900 K gas and the vessel wall. The time of the snapshot in Fig. F-8 is 100 s. It is clear that significant portions ($> \text{hole diameter}/10$) of the material next to the holes are at temperatures greater than about 750 K which, for VascoMax 250, results in a degradation of 0.2% offset yield strength of 30%. These transient heat flow calculations are coupled with the elastic-plastic calculations both to provide the thermal stresses owing to the thermal gradients and to adjust the mechanical properties to their temperature-dependent values.

* Scott Perfect, Private Communication.

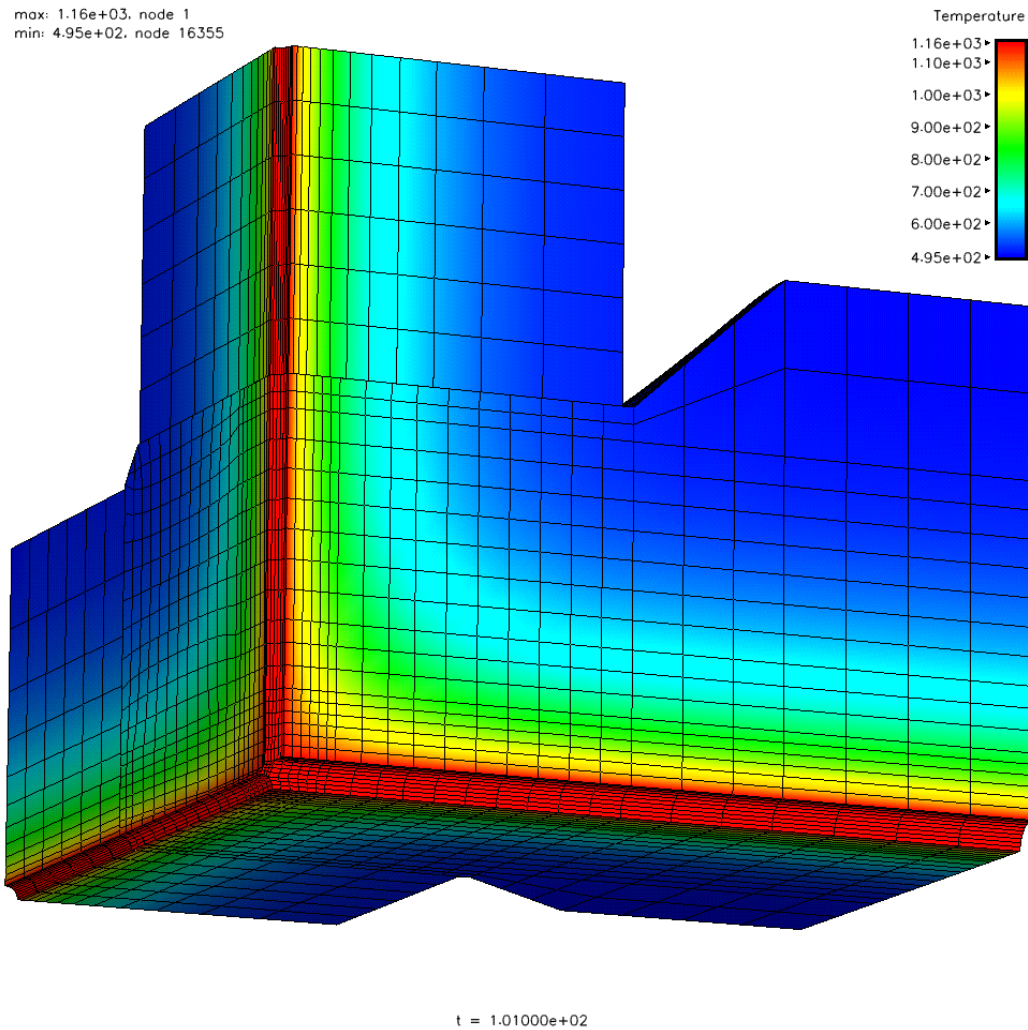


Figure F-8. TOPAZ calculations of the transient heat flow in VascoMax 250 at 100 seconds. Initially, the uniform temperature is 530 K. At $t = 0$, a 900 K boundary condition is placed on the inner surfaces of the crossbores and the axial bore. Significant ($>$ bore radius/10) regions of the material are at $T > 750\text{K}$, where the material strength is 70% of its room temperature value.*

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5. INCO Databook 1976, in *Source Book on Maraging Steels*, American Society for Metals, 1979.

Table F-1. Elastic FEA Calculation

Case	Pressure (Psi)	Piston Load (Psi)	End Load (Psi)	Number of pistons	Manifold OD (inches)	Manifold ID (inches)	Crossbore ID (inches)	Piston OD (inches)	Max von Mises stress (Psi)	Stress concentration	Location of max von Mises stress
1	250,000	250,000	0	2	8	1.6	1	8	1,559,000	6.24	Corner of intersection between crossbore and axial bore
2	250,000	250,000	0	4	8	1.6	0.708	8	933,570	3.73	Crossbore surface theta=0 plane
3	250,000	250,000	0	4	8	1.6	1	8	942,320	3.77	Crossbore surface theta=0 plane
4	250,000	250,000	0	4	16	1.6	1	8	709,680	2.84	Crossbore surface theta=0 plane
5	250,000	250,000	250,000	4	8	1.6	1	8	557,860	2.23	Manifold bore surface at end of manifold