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JANNAF ROCKET ENGINE PERFORMANCE PREDICTION AND EVALUATION MANUAL



CHEMICAL PROPULSION INFORMATION AGENCY

Operating under Contract N00017-72-C-4401

THE JOHNS HOPKINS UNIVERSITY • APPLIED PHYSICS LABORATORY • SILVER SPRING, MD.

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PREFACE

In 1965, the Interagency Chemical Rocket Propulsion (ICRPG) Performance Standardization Working Group was formed for the purpose of improving and recommending methodology suited to eventual adoption as national standards for the analytical and experimental evaluation of the performance of liquid propellant rocket engines. By 1968, the Working Group (made up of members from government, industry, and academia) had:

- Developed a physical model of rocket engine thrust chamber performance
- Selected computer programs to perform the mathematical calculations required by the physical model
- Developed recommended practices for test measurements
- Developed a model for uncertainty in measurements
- Documented the effort in three procedures manuals (CPIA No. 178, 179, and 180) and several computer program manuals.

In 1968, the ICRPG was reincorporated as part of the Joint Army-Navy-NASA-Air Force (JANNAF) Interagency Propulsion Committee. The ICRPG Performance Standardization Working Group became the JANNAF Performance Standardization Working Group. Other JANNAF Working Groups cover such areas as Combustion Instability, and Airbreathing Propulsion and Environmental Effects. Each Working Group has a four-person steering committee (each Government agency being represented), a Working Group chairman or program manager to coordinate the Group's efforts, members from Government agencies, and participants from outside the Government.

Since the reinstitution of the Performance Standardization Working Group in 1968, this Working Group has:

- Extended the methodology from the thrust chamber to the entire engine
- Developed a detailed injector analysis procedure to replace the earlier ICRPG method
- Developed a rigorous step-by-step analysis procedure and a simplified procedure using efficiency definitions
- Replaced the approximate boundary layer model with a more rigorous model
- Established new overall procedures documentation consisting of this manual and the Rocket Engine Performance Test Data Acquisition and Interpretation Manual
- Continued to update and improve all methods and procedures.

This manual was prepared by Capt. W. Pritz and Dr. D. George of the Air Force Rocket Propulsion Laboratory and Mr. S. A. Evans of the Rocketdyne Division of Rockwell International (under Contract F04611-72-C-0092, managed for Rocketdyne by Mr. L. P. Combs and Mr. J. Friedman). Future additions and revision will be issued as appropriate. Recommendations for such additions and revisions are welcomed and should be sent to:

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Most of the attendees at the JANNAF Working Group meetings have contributed in some manner, either directly or through helpful suggestions and discussions, to the preparation of the Manual. Specific acknowledgement for this aid cannot be given other than in the following listing of attendees (those names marked with an asterisk made direct contributions in addition to those made during the meetings). Special thanks go to W. B. Powell who served as Program Manager from 1968 to May 1973 and to R. C. Kahl, the current Program Manager.

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TRW Systems
Ultrasystems, Inc.
United Aircraft Corporation/Research Laboratories, Pratt & Whitney Aircraft and United Technology Center

PUBLICATIONS

Publications of the ICRPG and JANNAF Performance Standardization Working Groups and Other Related Publications:

Rocket Propulsion Nomenclature, CPIA Publication No. 131, ICRPG Performance Standardization Working Group, January 1967, ed. M. R. Beltran, T. C. Kozvic, Dynamic Science.

Performance Evaluation Methods for Liquid Propellant Rocket Thrust Chambers, CPIA Publication No. 132, Prepared for the ICRPG Performance, Standardization Working Group, November 1966, Prepared by J. L. Pieper, Aerojet-General.

Comparison and Evaluation of Computer Program Results for Rocket Engine Performance Prediction, April 1968, I. E. Alber, Dynamic Science Report, Contract NAS7-443 SN-82.

The Effect of Nozzle Flow Striations on Engine Performance, Final Report to the ICRPG Performance Standardization Working Group, August 1967, A. Ratliff, Lockheed Missiles and Space Company Report LMSC/HREC A784646, AD No. 836131.

The Effect of Nozzle Combustion on Engine Performance, Final Report to the ICRPG Performance Standardization Working Group, August 1967, R. C. Mitchell, Rocketdyne Report No. R-7103, AD No. 828742.

Screening of Reaction Rates, Phase II Final Report to ICRPG Performance Standardization Working Group, December 1967, S. S. Cherry, TRW Systems Report No. 08832-6002-T000, AD No. 828795.

Turbine Flowmeter Performance Model, Final Report to U.S. Army Missile Command Redstone Arsenal, October 1967, R. Thompson, and J. Grey, Greyrad Corporation Report AMC-3, AD No. 925354.

One-Dimensional Kinetic Nozzle Analysis Computer Program-ODK, Prepared for the ICRPG Performance Standardization Working Group, July 1968. H. M. Frey, J. R. Kliegel, G. R. Nickerson, T. J. Tyson, AD 841201.

Two-Dimensional Equilibrium Nozzle Analysis Computer Program-TDE, Prepared for the ICRPG Performance Standardization Working Group, July 1968, L. Aceto, T. F. Zupnik, AD 842700.

Two-Dimensional Kinetic Reference Computer Program-TDK, G. R. Nickerson, D. E. Coats, J. L. Bartz, Contract NAS9-12652, December 1973.

Turbulent Boundary Layer Nozzle Analysis Computer Program-TBL, Prepared for the ICRPG Performance Standardization Working Group, July 1968, H. D. Weigold, T. F. Zupnik, AD 841202.

ICRPG Liquid Propellant Thrust Chamber Performance Evaluation Manual, CPIA Publication No. 178, Prepared for the ICRPG Performance Standardization Working Group, 30 September 1968, prepared by J. L. Pieper, Aerojet-General, AD No. 842701.

Addendum No. 1 to CPIA 178, JANNAF Interim Performance Calculational Methodology for Use in SSME Proposal Response, Performance Standardization Working Group, Manual Revision Subcommittee, Dec 1970.

Handbook of Recommended Practices for Measurement of Liquid Propellant Rocket Engine Parameters, CPIA Publication No. 179, ICRPG Performance Standardization Working Group, January 1969.

ICRPG Handbook for Estimating the Uncertainty in Measurements Made with Liquid Propellant Rocket Engine Systems, CPIA Publication No. 180, ICRPG Performance Standardization Working Group, 30 April 1969.

Supplement to the ICRPG Turbulent Boundary Layer Nozzle Analysis Computer Program, NASA TM X 64663, S. Omori, K. W. Gross, A. Krebsback, 17 May 1972.

Catalog of Injector Spray Correlations, L. P. Combs, Rocketdyne, Jet Propulsion Laboratory Contract NAS7-746, 22 June 1972.

User's Guide for the Three-Dimensional Spray Combustion Program, 3D-COMBUST, K. Fertig, W. S. Hines, Rocketdyne, 19 July 1971.

Pulse Mode Performance Model Computer Program and User's Guide, W. D. Chadwick, Rocketdyne, AFRPL Contract F04611-70-C-0074, November 1972.

Plume Contamination Effects Prediction, R. J. Hoffman, et. al, AFRPL-TR-71-109, December 1971.

Liquid Rocket Combustion Computer Model With Distributed Energy Release, L. P. Combs, Rocketdyne JPL Contract NAS7-746, December 1971.

Interim User's Manual for Boundary Layer Integral Matrix Procedure, Version J, M. Evans and H. Morse, Aerotherm Report 6282.

Preliminary User's Manual for Mass Addition Boundary Layer Program, R. Gloss and J. Levine, Dynamic Science, March 1971.

JANNAF Rocket Engine Performance Test Data Acquisition and Interpretation Manual, S. A. Evans and K. W. Gross, CPIA Publication 245, December 1973.

JANNAF Rocket Engine Performance Methodology User's Guide (to be published).

Special Considerations for Combustion Instability Instrumentation and Data Representation, CPIA Publication Number 170, June 1968.

Selection of Instrumentation for Analyzing Combustion Instability in Liquid Propellant Rocket Engines, CPIA Publication Number 148, July 1967.

JANNAF Thermochemical Data, Dow Chemical Company, Thermal Laboratory, Midland, Michigan.

Liquid Propellant Rocket Combustion Instability, NASA SP-194, 1972.

Simplified Procedures for Correlation of Experimentally Measured and Predicted Thrust Chamber Performance, W. B. Powell, Jet Propulsion Laboratory, TM 33-548, April 1973.

Handbook Uncertainty in Gas Turbine Measurements, R. B. Abernethy, J. W. Thompson Jr., et al., AEDC-TR-73-5, May 1972.

Chemical Rocket/Propellant Hazards, CPIA Publication 194, JANNAF Hazards Working Group, May 1970.

Operating Manual for Coaxial Injection Combustion Model, R. D. Sutton, M. D. Schuman, and W. D. Chadwick, NASA CR-129031, Rocketdyne, April 1974.

Computer Program for Calculation of Complex Chemical Equilibrium Conditions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouget Detonations, Gordon and McBride, NASA SP-273, 1971.

Thermodynamic Properties to 6000 R for 210 Substances Involving the First 18 Elements, MacBride, Heimerl, Ehlers, Gordon, NASA SP-3001, 1963.

JANNAF Rocket Engine Performance Prediction and Evaluation Manual, CPIA 246, S. A. Evans, D. George, W. Pritz, November 1974.

Supplement to CPIA 245 and 246, Sample Cases, S. A. Evans, K. W. Gross, D. George.

One-Dimensional, Two-Phase Reacting Gas Nonequilibrium Performance Program, TRW, 15 August 1967, 02875-6005-R00 (Contract NAS9-4358).

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ABSTRACT

Procedures recommended by the JANNAF Performance Standardization Working Group for liquid rocket engine performance prediction are presented.

Rigorous, simplified, and optional procedures are discussed. The methods for using the JANNAF reference computer programs are described and the conceptual bases underlying the methods are detailed. Recommended reporting formats are given. Standard physical properties such as enthalpies and reaction rates for propellants of interest are included. Three sample cases using the recommended procedures are presented as a supplement under separate cover.

INTRODUCTION

The JANNAF Rocket Engine Performance Working Group was originally formed as the Interagency Chemical Rocket Propulsion Group (ICRPG) Performance Standardization Working Group of the Chemical Propulsion Information Agency. This working group was reincorporated as part of the joint Army, Navy, NASA, Air Force (JANNAF) Interagency Propulsion Committee in 1968. The goal of the Working Group is the development of a methodology that includes all aspects of rocket engine performance from analytical calculation to test measurements, that is physically accurate and consistent, and that serves as an industry and government reference.

The approach to performance standardization taken by the Performance Working Group is:

- Development of an accurate, consistent physical model of a rocket engine system
- Identification and development of reference computer programs and associated documentation for modeling the engine system
- Specification of procedures for the analysis and interpretation of rocket engine test data including measurement practices and measurement uncertainties.
- Development of standard definitions of parameters, nomenclature, symbols, and units
- Publication of working manuals describing the approved procedures

The overall JANNAF Rocket Engine Performance Methodology is illustrated in Fig. 1 . The three primary manuals are:

- The User's Manual--will provide Agency Project Managers with a quick introduction to the methodology and instructions for RFP and contract specification of JANNAF Methodology. The manual is currently in the planning stages.
- The Data Acquisition and Interpretation Manual (CPIA 245)--provides the procedures for analysis and interpretation of test data, measurement practices, assessment of uncertainties, and correlation with predicted parameters.
- This manual, the Performance Prediction and Evaluation Manual--defines the calculation procedures including the rigorous, simplified, and optional techniques, and references the computer program manuals.

The interrelationship of these Manuals and other related publications is shown in Fig. 1. The methodology can be separated into: (1) performance prediction and (2) performance data acquisition and interpretation.

The major purpose of this Performance Prediction and Evaluation Manual is to document explicitly the physical and mathematical models used in the prediction of rocket engine performance, to aid in the selection of the proper procedure, to describe how to use the selected procedure, and to provide a guide for evaluating the accuracy of the predictions.

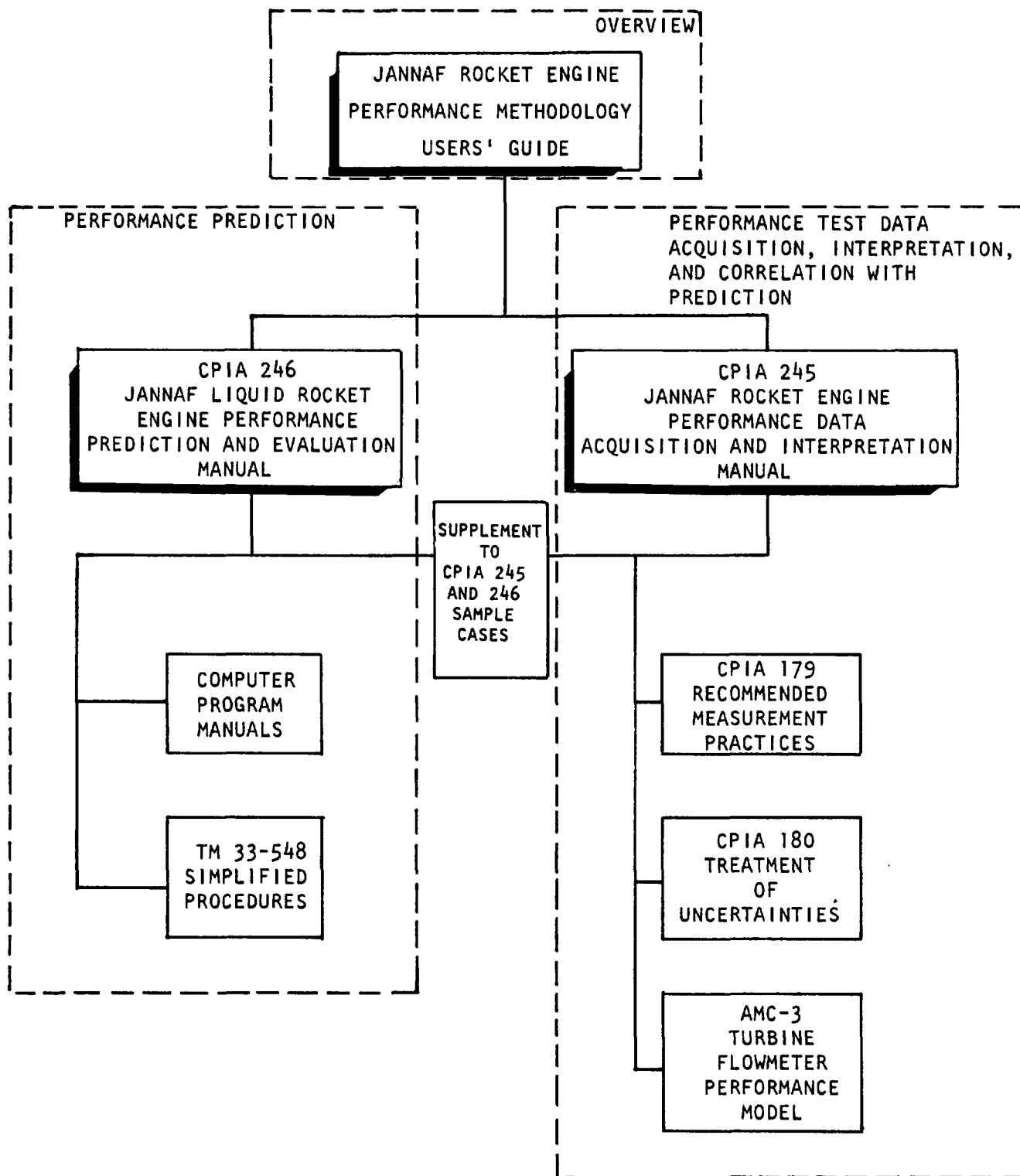


Figure 1. JANNAF Rocket Engine Performance Methodology Documentation

FORMAT OF THE MANUAL

The Manual is divided into six sections. The first section provides an overview and the conceptual physical model. The second section describes the step-by-step application of the rigorous analytical procedure, the required reporting for this procedure, and the detailed methods for executing the calculational steps. The conceptual basis underlying each calculation is explained. The cost (time and effort) of applying the procedure is discussed and methods for determining the uncertainty of the answers are given.

In Section 3, the simplified procedure is derived from the defining relationships for the rigorous procedure. A set of efficiency factors is defined and related to the major physical processes occurring in the thrust chamber. The methods of determining these efficiencies and applying the procedure are presented.

In Section 4, various optional calculational methods for each of the rigorous steps are presented. Section 5 contains an overview of the recommended application of the various procedures, and Section 6 documents standard data required in the analysis. Nomenclature and definitions are given in a final, separate section.

To illustrate the application of the procedures, a series of sample cases are contained in a separate, supplementary volume (CPIA 245/246).

The Manual has been designed to be continuously updated to follow the changes in the state of the art and to add additional concepts as needed. This approach allows an ongoing interaction between the reference procedures and the application of these procedures. The specific concepts that have been adopted to ease the task of continuous revision of the manual are:

- Loose-Leaf Notebook
- Dated Pages
- Two-Page Topic Modules

The loose-leaf format was selected by the JANNAF Working Group to allow replacement of specific pages on either a semiannual or as-needed basis. This concept has been used quite successfully with the JANNAF Thermochemical Data tables which have been continuously updated since 1961. The new pages will be distributed through CPIA to all holders of the Manual. Revisions may be made by the Working Group or by appropriate contract, if extensive enough to warrant outside contracting. Suggestions for revisions are welcomed by the Working Group and should be forwarded to the address shown on page v.

To simplify the task of maintaining a current Manual, each of the topic subsections is dated. A new table of contents for each section that has been revised is provided with the revision. The date of the most recent revision is listed in the table of contents for each topic subsection.

SECTION 1

SECTION 1. JANNAF ROCKET ENGINE PERFORMANCE METHODOLOGY

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SECTION 1. JANNAF ROCKET ENGINE PERFORMANCE METHODOLOGY

SUMMARY

The purpose of this section is to provide a brief introduction to the basic concepts and procedures used in the JANNAF Performance Methodology and, in particular, the Performance Prediction Techniques. The JANNAF Engine System Performance Methodology is based on an analytical model of a rocket engine in which the major sections (reservoir, feed system, and thrust chamber) are defined in terms of control volumes and interfaces between these volumes.

In the JANNAF Methodology, the basic measure of rocket engine performance is the directed impulse per unit mass of propellant expended--the specific impulse. The characteristic velocity (C^*) is also used as a secondary measure of the basic impulse of the engine prior to expansion beyond choked conditions and to aid in predicting overall specific impulse losses by calibration of calculational procedures. (The direct use of C^* in calculating specific impulse is inconsistent with the current procedures since no consistent C_F definition has been developed.) The JANNAF Thrust Chamber Performance Evaluation Procedures are based on a physical model that identifies major processes occurring in the thrust chamber, losses associated with these processes, and interactions between the processes.

The procedures for engine system and thrust chamber range from the rigorous (intended to be the most accurate widely available method) through various optional procedures to the simplified procedure (intended to be the easiest method having acceptable accuracy). The rigorous procedure treats each of the control volumes and each of the physical processes occurring in a fashion that includes the interactions with the other volumes and processes. A number of reference computer programs is used in making the calculations for the rigorous procedure. The simplified method is based on a series of efficiency definitions and the use of simpler computer program options.

This section includes guidelines for selecting an appropriate procedure for a given application in context of accuracy, time, and effort. The use of the predictions for correlating and extrapolating test data is presented and uncertainty of extrapolation discussed.

The location of specific discussions of calculational steps in subsequent sections is introduced. Use of this roadmap to achieve familiarity with the manual is recommended.

Section 1 JANNAF Rocket Engine Performance Methodology
1.1 Reference Frame
1.1.1 PROPULSION SYSTEM

Date: 11/15/74

The JANNAF Rocket Engine Performance Methodology is based on an analytical model of a rocket engine in which the major sections are defined in terms of control volumes and interfaces between these volumes.

The instantaneous impulse (change in momentum) imparted to a rocket vehicle by an engine is given by:

$$dI = F dt \text{ [MLt}^{-1}\text{]} \quad (F \text{ is thrust and } = F_{\text{engine}} + \int P_{\text{ambient}} dA)$$

The impulse per unit mass of propellant expended or specific impulse is:

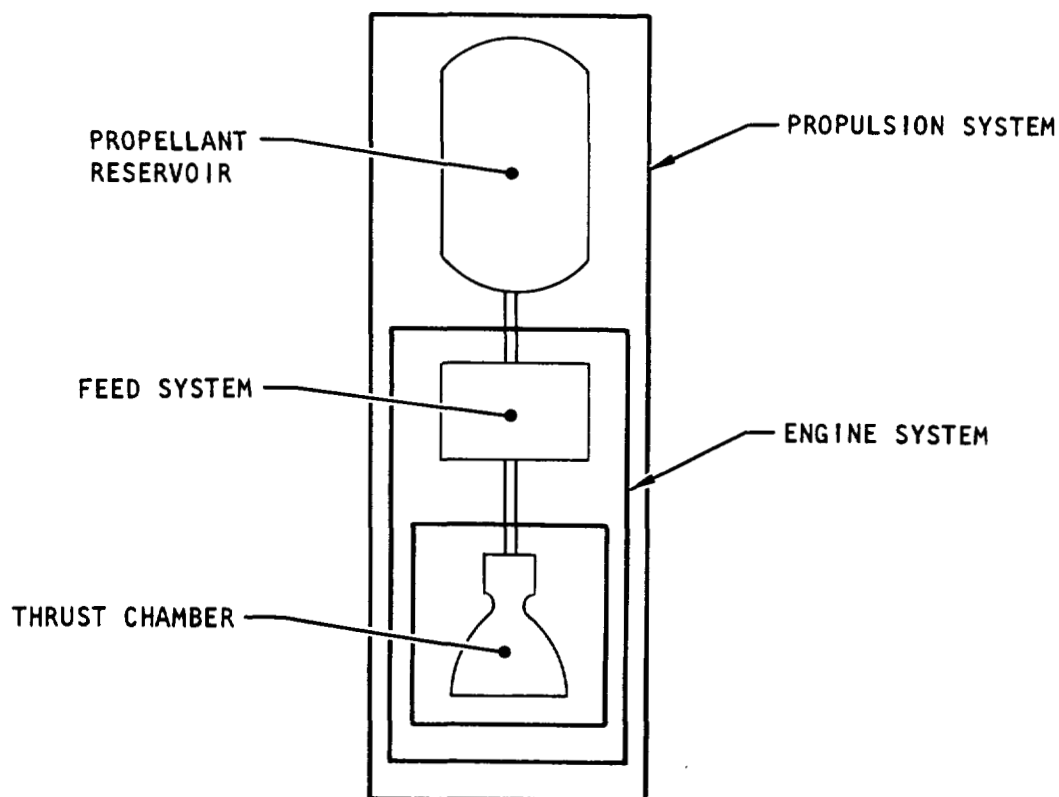
$$ISP = \frac{dI}{dM} = F \frac{dt}{dM} = \frac{F}{\dot{M}} \text{ [Lt}^{-1}\text{]} \quad (\dot{M} \text{ is mass flowrate)}$$

The vacuum (0 ambient pressure) thrust engine specific impulse is the basic measure of excellence of a rocket engine since, for a given propellant loading, ISP is directly related to the change in velocity the rocket vehicle can achieve.

The JANNAF Rocket Engine Performance Prediction Procedure for vacuum specific impulse is based on the treatment of the entire propulsion system as a set of interconnected control volumes, as shown in the illustration on page 1.1.1B. The propulsion system can be divided into the propellant reservoir and the engine system. The engine system is, in turn, divided into the feed system and the thrust chamber. In a pump-fed liquid rocket, the propellant reservoir can generally be analyzed independently from the engine system. For pressure-fed and solid rocket engines, the reservoir and engine system are intimately connected. For the purpose of performance determination in the steady state, the effects of the processes occurring in any of the control volumes can be completely specified by the energy and mass flows, and pressures at the control surface of the control volume. In this way, the calculations within each volume can be performed independently of the calculations in the other volumes, coupled only by interface conditions and the required matching of these conditions.

The thrust chamber produces the bulk of the thrust from the engine and exhausts most of the mass flow. The JANNAF effort has been concentrated upon accurately predicting the thrust and flowrate of the thrust chamber. Physical, analytical, and computer models for combustion, flow, and boundary layer have been developed.

To accurately predict performance, the energy and mass flows into the thrust chamber must be accurate and consistent. The use of control volumes with consistency and accuracy checks at the control surface is intended to provide the required accurate information to the thrust chamber analysis with control upon consistency.



ROCKET PROPULSION SYSTEM REFERENCE FRAME

Section 1 JANNAF Rocket Engine Performance Methodology
1.1 Reference Frame
1.1.2 PROPELLANT RESERVOIR

Date: 11/15/74

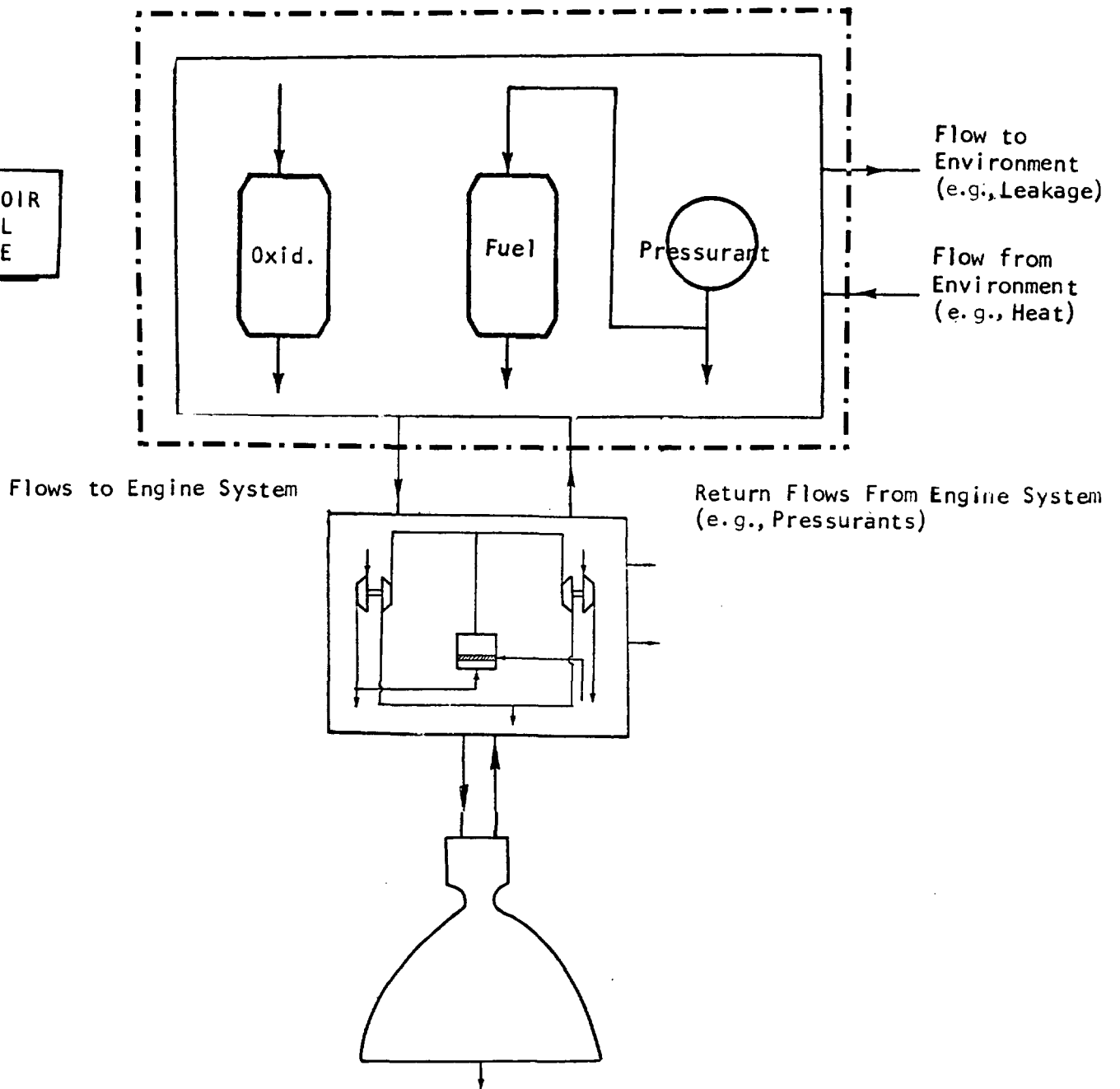
The key items for the reservoir are the composition, enthalpy, and head at the engine interface. These conditions can vary with time and must be specified either by the vehicle contractor or by the propulsion contractor.

The propellant reservoir control volume, shown conceptually on page 1.1.2B, includes all propellant used by the rocket engine, associated pressurants, and components. In a liquid rocket engine having pumps to raise the pressure of the propellants, a specification of the interface between the reservoir and the feed system is generally all that is required. The reservoir calculations can be (and usually are) performed completely independently of the engine system calculations.

In a pressure-fed liquid engine or a solid-propellant engine, conditions in the reservoir directly impact the engine performance. In a solid-propellant engine, in particular, such factors as propellant burning rate are of major importance to the performance of the engine. For these types of engines, the propellant reservoir calculations take on the same importance that the feed system calculations have for the pump-fed engine.

As with the feed system, the concept of the reservoir control volume reduces the complexity of setting up standard procedures and nomenclature for all of the possible combinations and permutations of propellant supply components and fluids. A specification of the interface conditions, a balance of mass, energy, and pressure at the interface (see illustration), and a summary of internal component and process balances are currently acceptable to fulfill the JANNAF requirements. A more detailed specification of reference procedures in internal reservoir calculations may be developed eventually; however, the use of the control volume concept tends to minimize the effect on performance of minor inaccuracies in the reservoir calculations. Unlike the feed system and thrust chamber, reservoir calculations are never steady state, so a time or times must be specified if any of the control surface conditions vary with the changes in the control surface (for example, gravity head varies with height of liquid).

RESERVOIR
CONTROL
SURFACE



Reservoir Control Surface

Section 1 JANNAF Rocket Engine Performance Methodology
1.1 Reference Frame
1.1.3 FEED SYSTEM

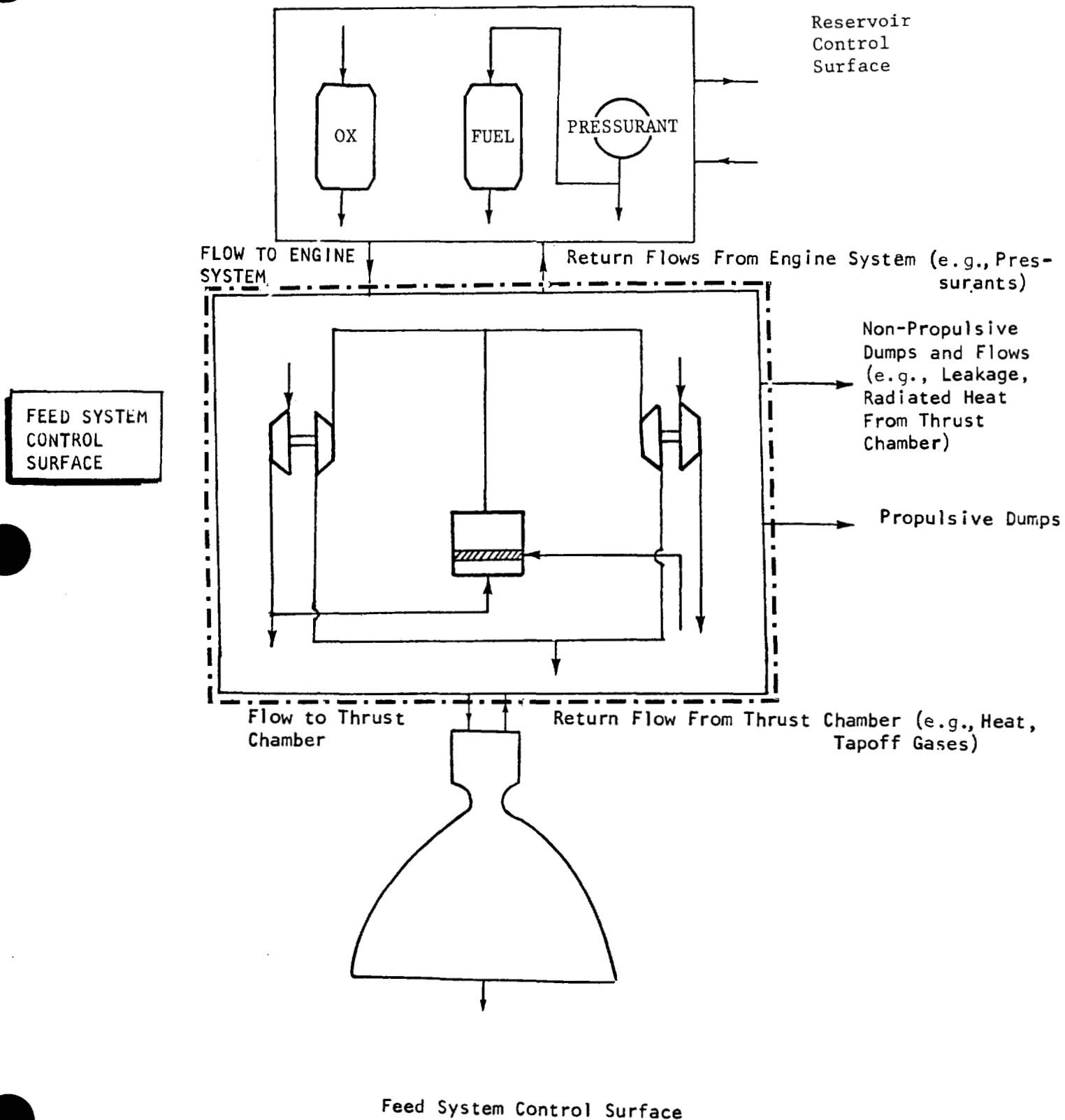
Date: 11/15/74

The feed system control volume surface surrounds all engine system components other than the thrust chamber. The surface ends at the inner thrust chamber wall surface, the inlets from the propellant reservoir, and any overboard dump ports.

The feed system control volume, shown conceptually on page 1.1.3B, is defined to decouple the thrust chamber calculations (which are primarily high-temperature, reacting, gas dynamic in nature) from the calculations in the other engine system components which are primarily fluid dynamic and thermodynamic in character. The predominant thrust of the engine is produced by the thrust chamber and this component has been treated in detail by the JANNAF Working Group. The types and arrangements of components and processes in a complex feed system such as a regeneratively cooled pump-fed engine, are currently beyond the Working Group's standardization effort.

To avoid the need for standardizing the calculation procedure for each individual component at the current time, the feed system concept is used to ensure the accuracy of the feed system calculations. In this concept, the flows crossing the feed system surface (see illustration) must be in total mass and energy balance.

In addition, pressure, mass, and energy must also balance across key components such as pumps, turbines, heat exchangers, and gas generators. The reporting of the data at key positions and the corresponding balances is considered to fulfill the JANNAF requirements with no specifications currently made as to calculational technique.



Section 1 JANNAF Rocket Engine Performance Methodology
1.1 Reference Frame
1.1.4 THRUST CHAMBER

Date: 11/15/74

The thrust chamber control volume is bounded by the inner surface of the physical thrust chamber.

The control surface delineating the thrust chamber is defined to be the inner surface of the physical thrust chamber wall and a surface bounded by the physical exits across which all the exhaust flow passes. All flows into and out of the thrust chamber cross the thrust chamber control surface. Heat from the boundary layer crosses the control surface into the feed system (note that regenerative coolant, radiated heat, or ablative wall outgassing are treated as part of the feed system). Mass in the form of transpiration coolant or outgassing of the wall may cross the control surface in addition to the main injection of propellants.

In the area of the injector, the division between feed system and thrust chamber may become vague and care must be taken to be explicit about the location. The control surface shall generally be at the injector face unless clearly defined otherwise. Some of the computer programs (CICM, LISP) begin calculations in the manifolds so that use of manifold conditions as interface may be convenient if done in a consistent manner. The exit control surface can be drawn for convenience as long as the surface includes the exhaust flow. The shape, if curved or irregular, may have to be taken into account in calculations.

If multiple thrust chambers fed by the same feed system are employed, each thrust chamber must be treated in the same manner. Angles of the thrust chambers with the overall engine system axis must be included in calculating engine system thrust and engine system specific impulse. An example of this system is a multi-chamber plug nozzle type.

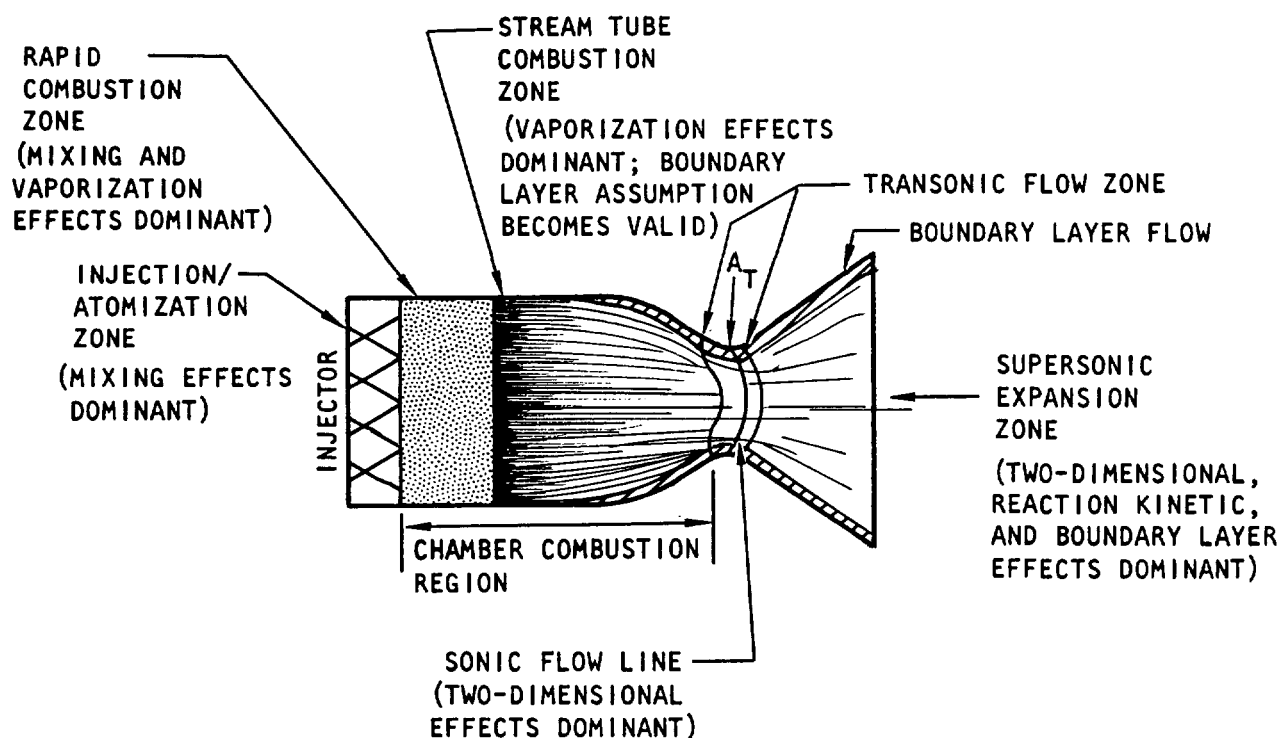
The basic JANNAF thrust chamber characterization is shown in the illustration on page 1.1.4B. Propellants enter the thrust chamber through an injector, are mixed, vaporized, and combusted. Any deviations from complete homogeneous mixing and combustion to equilibrium are referred to as energy release losses. The reaction products are expanded through a subsonic/supersonic nozzle. In the expansion process, chemical reactions continue. Deviations from local equilibrium are referred to as reaction kinetic losses. In the physical expansion process, velocity components normal to the desired direction of thrust may develop. The loss in available momentum and attendant nonuniform expansion is referred to as two-dimensional loss. In the region of the wall, heat transfer and momentum transfer to the wall become important. In addition, in some thrust chambers, there may be significant mass addition at the wall (for example, the turbine exhaust dump of the J-2S sample case in the supplement to CPIA 245/246).

For calculation purposes, the region of the flow that has been significantly affected (other than directionally) by the presence of the wall is called the boundary layer. In the boundary layer, viscous effects become dominant while, in the region unaffected by the wall (the inviscid or core flow), viscous terms can be neglected in the mathematical formulations. Losses in available thrust caused by transfer of momentum and heat to the wall are termed boundary layer losses.

Two parameters are of particular interest for the thrust chamber, the thrust chamber specific impulse defined as thrust chamber thrust divided by thrust chamber mass flowrate and characteristic velocity, defined as:

$$C^* = \frac{P_C A_T}{\dot{M}_T} \quad (LT^{-1}) \quad (P_C \text{ is effective thrust chamber stagnation pressure; } A_T \text{ is geometric throat area})$$

This parameter is a measure of the maximum flowrate possible for a given system pressure (since the expansion nozzle is choked) and is also proportional to both the specific impulse and sonic velocity. In addition, efficiencies for C^* and ISP associated with the physical processes are defined as discussed in Section 3.2.1.



Internal Process in the Real Rocket Thrust Chamber

Section 1 JANNAF Rocket Engine Performance Methodology
1.2 JANNAF Reference Procedures
1.2.1 THE RIGOROUS PROCEDURE

Date: 11/15/74

The JANNAF Rigorous Procedure, consisting of 17 steps, is intended to provide an accurate physical and analytical model giving the most exact answers of any widely available performance calculation procedure.

The JANNAF rigorous performance prediction procedure consists of the 17 steps shown in the accompanying table (page 1.2.1B). The result of carrying out these steps is the most accurate specific impulse/C* prediction widely available and a full reporting of all assumptions used so that the procedure could be reproduced independently with the same result. This universal reproducibility is a prime goal of the procedure.

The procedural steps are discussed in detail in Section 2 of this Manual, as indicated in the table. The subrequirements of each step are presented in Section 2.1. Reporting requirements are outlined in Section 2.2. The details of executing the steps using the reference computer programs (Section 1.2.4) or other calculational method are given in Sections 2.4 through 2.12.

The rigorous procedure, while assuming the use of particular reference computer programs, is general and can be used conceptually for all cases. A particular physical concept is central to each step. The method of analyzing this physical process is specified by JANNAF. The computer programs are the preferred analytical tool, but not to the exclusion of other methods (e.g., direct measurement in tests).

The reference procedure results in a specific impulse prediction that is based on a very specialized type of test data (reaction rates, correlation coefficients). As such, the prediction is further removed from direct testing than data from an engine. However, uncertainty in the prediction must be assessed as for actual engine data. The reporting of this uncertainty is discussed in Section 2.2.11. Calculation of uncertainties is presented in Section 2.13.

The cases in which the rigorous procedure should be employed are discussed in Section 1.3. Currently, because of inadequacies in the injection analysis, the rigorous procedure is not reliably accurate for *a priori* calculations. When calibrated with a test data point, the rigorous procedure is very accurate and serves as a highly useful design and analysis tool.

RIGOROUS ANALYTICAL PROCEDURE

Calculational Step	Relevant Manual Sections			Computer Programs Used*
	Expanded Discussion	Reporting Requirements	Details of Execution	
1. Specify Reservoir Conditions	2.1.1	2.2.1, 2.2.2	2.4.1	--
2. Specify Feed System Conditions	2.1.1	2.2.1, 2.2.2	2.4.2	--
3. Specify Thrust Chamber Geometry	2.1.1	2.2.5, 2.2.6	2.4.3	--
4. Specify Injector Flow Distribution	2.1.2	2.2.5	2.5	--
5. Analyze Injection Process	2.1.2	2.2.7, 2.2.8	2.6	LISP, CICM
6. Analyze Turbulent Combustion	2.1.2	2.2.7, 2.2.8	2.7	LISP, CICM, 3DC
7. Analyze Streamtube Combustion Process	2.1.2	2.2.7, 2.2.8	2.8	STC, DHSTC
8. Specify Boundary Layer Edge Conditions	2.1.3	2.2.7, 2.2.8	2.9	TDK
9. Analyze Boundary Layer Process	2.1.3	2.2.7, 2.2.8	2.9	BLIMP
10. Analyze Wall Response	2.1.3	2.2.7, 2.2.8	2.10	--
11. Check Consistency of Total Heat Load with Feed System Specification	2.1.3	2.2.2	2.10.2	--
12. Check Consistency of Non-boundary Layer Heat Load	2.1.3	2.2.2	2.10.2	--
13. Check Consistency of Wall Boundary Conditions	2.1.3	2.2.2	2.10.2	--
14. Analyze Inviscid Flow	2.1.3	2.2.7, 2.2.8	2.11	TDK
15. Adjust Thrust for Droplets Remaining at Throat (optional)	2.1.4	2.2.1	2.12	--
16. Calculate Propulsive Dump Thrust	2.1.4	2.2.9, 2.2.10	2.12	--
17. Calculate Specific Impulse and Characteristic Velocity	2.1.4	2.2.9, 2.2.10, 2.2.11	2.12	--

*See Section 1.2.4 for description

Section 1 JANNAF Rocket Engine Performance Methodology
1.2 JANNAF Reference Procedures
1.2.2 THE SIMPLIFIED PROCEDURE

Date: 11/15/74

The JANNAF Simplified Performance Prediction Procedure is intended to be a rapid, reasonably accurate method for calculating performance, extrapolating test data, identifying major losses, and generating parametric data.

The JANNAF Simplified Procedure consists of the six steps shown in the accompanying table (page 1.2.2B) derived from the rigorous procedure but requiring less detail. The first three steps are identical to the rigorous procedure but demand less detailed reporting and less rigorous calculations. The fourth step replaces all of the steps in the rigorous procedure concerned with thrust chamber performance and is described in detail in Section 2 of this Manual. The last two steps again match the rigorous procedure.

The simplified procedure is based on expanding the rigorous thrust chamber specific impulse definition into a series of efficiencies, as shown in Section 2.1.1. These efficiencies can be derived from the rigorous calculations in which case an identical answer is produced with no time saving (the only advantage being a relative importance of losses indication). Alternatively, less complex calculational methods can be employed, as discussed in Section 3.2. These alternatives can include the use of results from previous rigorous analysis, empirical data, or simplifying assumptions about loss interactions allowing the use of less rigorous computer analysis.

As discussed in Section 1.3, the simplified procedure is most useful for scaling a single-point rigorous calculation or single conditions test data point to other operating conditions, providing parametric data for test comparison, system trade studies, and preliminary design optimization. When matched to a known point, the trends given by the simplified procedure are reasonably accurate for most work.

SIMPLIFIED ANALYTICAL PROCEDURE

Calculational Step	RELEVANT MANUAL SECTIONS		
	Expanded Discussion	Reporting Requirements	Details of Execution
1. Specify Reservoir Conditions	3.1.1	3.1.2	3.2
2. Specify Feed System Conditions	3.1.1	3.1.2	3.2
3. Specify Thrust Chamber Geometry	3.1.1	3.1.2	3.2
4. Determine Thrust Chamber Efficiencies	3.1.1	3.1.2	3.2
5. Determine Propulsive Dump Thrust	3.1.1	3.1.2	3.2
6. Calculate Specific Impulse	3.1.1	3.1.2	3.2

Section 1 JANNAF Rocket Engine Performance Methodology
1.2 JANNAF Reference Procedures
1.2.3 OPTIONAL PROCEDURES

Date: 11/15/74

The JANNAF Optional Procedures are intended as a backup position when a given design cannot be analyzed using the rigorous computer programs because of mathematical or time constraints.

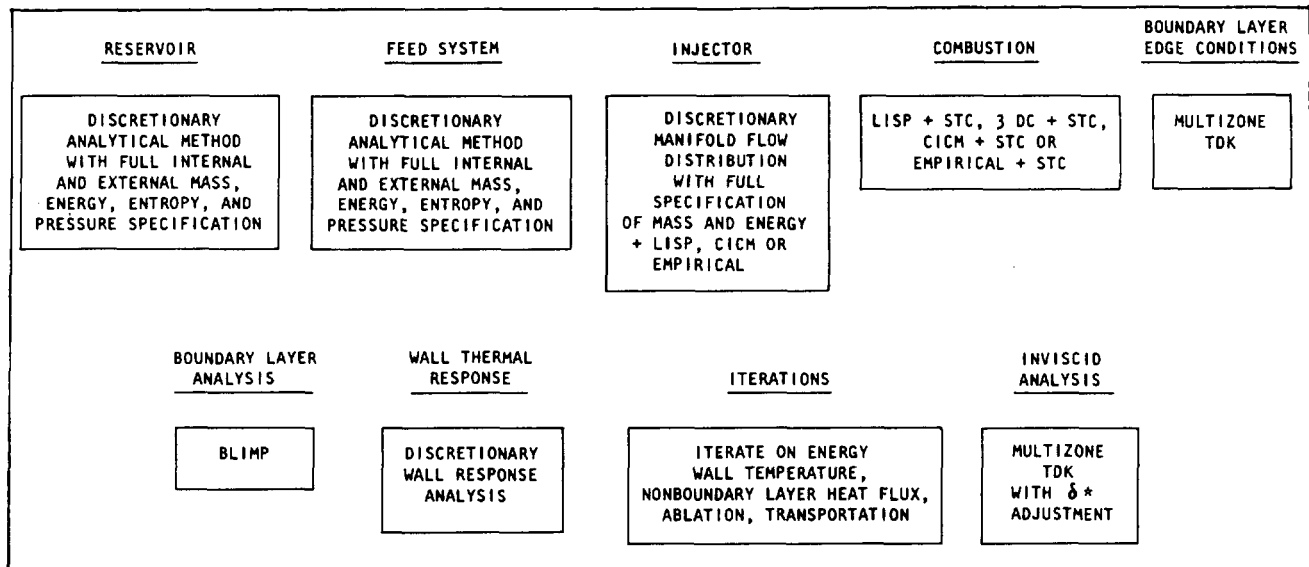
The JANNAF Optional Procedures are provided to yield an analysis as close to rigorous as possible when, for some reason of design or time, the full rigorous cannot be employed. As shown in the accompanying figure, page 1.2.3B, options are provided to each of the steps of the rigorous procedure. At any step, a rigorous calculation can be replaced with any optional step that is consistent in input and output with the prior steps and planned subsequent steps. The replacement cannot be arbitrary, however, and must be explicitly described as well as negotiated with the contracting agency if the procedure is contractually required.

A variety of calculation step combinations are possible with the optional procedures. A general guideline for selection of procedures is to maintain the highest possible accuracy for major losses and loss interactions and to relax the requirements in less important areas. An example of an optional procedure that does not have strong impact on the ultimate answer is the use of the TDE option of TDK instead of TDK to generate boundary layer edge conditions.

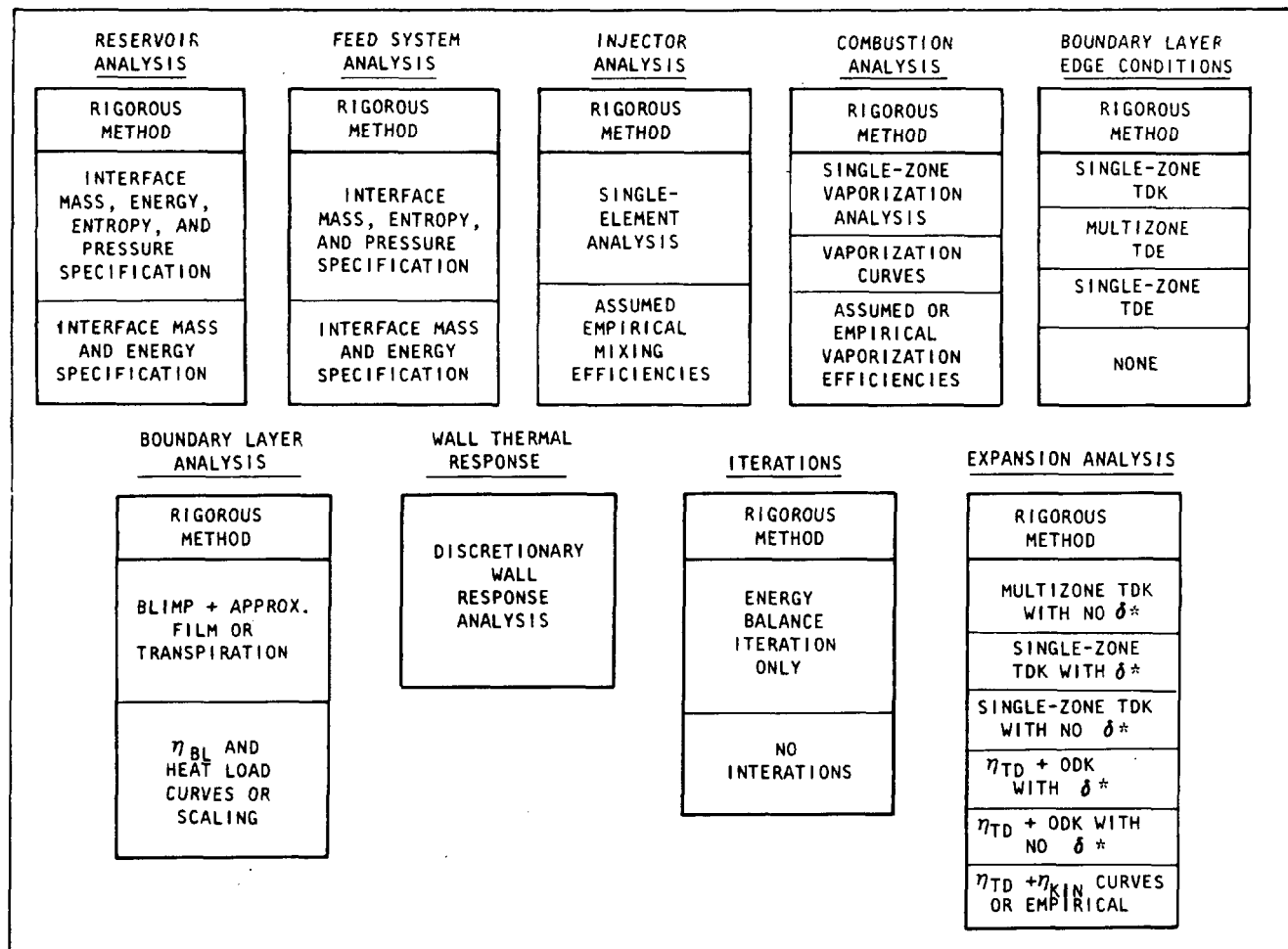
As an example, a possible set of steps could be:

<u>Step</u>	<u>Method of Implementation</u>
Reservoir Analysis	————> Interface Specification Only
Feed System Analysis	————> Interface Specification Only
Injector Analysis	————> Rigorous Method (e.g., LISP or CICM)
Combustion Analysis	————> Single Zone Analysis
Boundary Layer Edge	————> Single Zone TDE
Boundary Layer Analysis	————> Rigorous Method (e.g., BLIMP)
Wall Thermal Response	————> Discretionary
Iterations	————> Energy Balance Only
Expansion Analysis	————> Rigorous Method

The results of this set of steps will closely approximate the rigorous method with some cost savings.



REQUIRED ANALYTICAL COMPONENTS OF THE RIGOROUS PROCEDURE



ANALYTICAL COMPONENTS OF ALTERNATE AND SIMPLIFIED PROCEDURES

*LISP, CICM, 3DC, STC, BLIMP, TDK, TDE, T_{DY} , ODK, ODE ARE ABBREVIATIONS FOR COMPUTER PROGRAM NAMES, AS DESCRIBED IN SECTION 1.2.4

Section 1 JANNAF Rocket Engine Performance Methodology Date: 11/15/74
1.2 JANNAF Reference Procedures
1.2.4 REFERENCE COMPUTER PROGRAMS

JANNAF supports the set of reference computer programs used in applying the JANNAF performance procedures. Each program is available upon request and has an instruction manual (Section 5).

The JANNAF Working Group has supported the development of computer programs in various areas for use in the prediction procedures. The programs, listed in the table on page 1.2.4B, are intended to be the most accurate physical and mathematical models widely available.

The computer programs address the calculation of the major physical processes described in Section 1.1.4 and follow the model shown in the figures of that section for defining regions of dominant effects. In general, a separate program is used for each region in which a different effect dominates.

Each computer program is described in detail in a separate user's manual. The discussion in this manual is limited to a brief review of the theory, key inputs and outputs, special problems, and assumptions. For more detailed discussion, the user's manuals must be consulted. The programmer, supporting agency, and source are listed in Section 5.

SUMMARY OF COMPUTER PROGRAMS

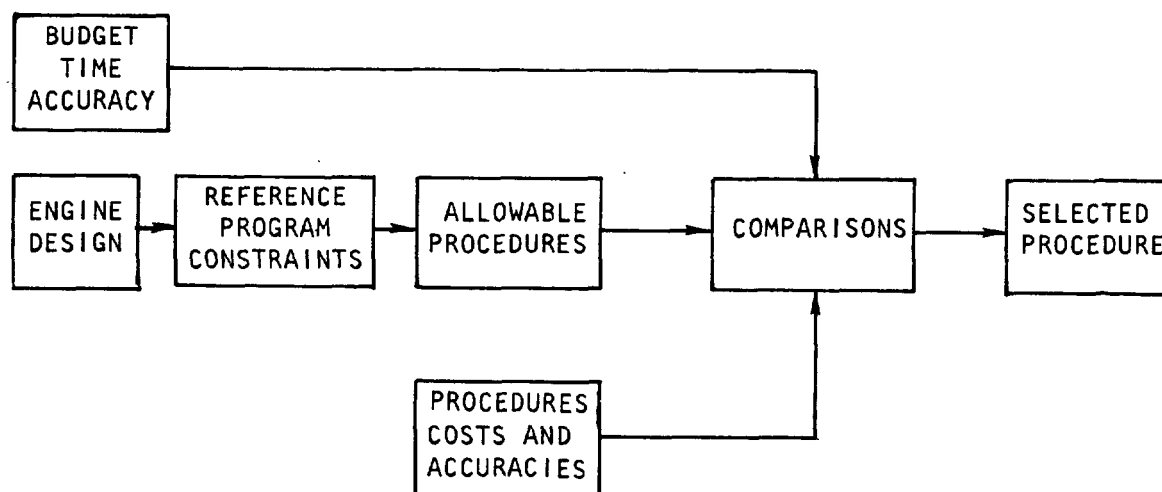
Name	Description	Discussion Section
<u>Programs Used in Rigorous Procedure</u>		
LISP (DER)	Liquid Injector Spray Pattern subprogram (of the Distributed Energy Release model)--calculates droplet spray patterns for liquid/liquid and gas/liquid injectors	2.6.2
3DC	Three-Dimensional Combustion program--calculates simultaneous burning, dispersion, and collisions of sprays following initialization by LISP	2.7.2
CICM	Coaxial element model--replaces LISP for coaxial elements having concentric gas and liquid streams	2.6.6
STC (DER)	Streamtube Combustion subprogram of the Distributed Energy Release Model--calculates combustion after initiation of streamtube-type flow	2.8.2
TDK	Two-Dimensional Kinetic program--calculates simultaneously expanding and reacting gas flow in the throat and nozzle without viscous effects	2.11.2
BLIMP	Boundary Layer Integral Matrix Procedure program--calculates viscous effects at the wall including heat transfer, momentum transfer, and mass transfer	2.9.2
<u>Additional Programs Used in Optional or Simplified Procedures</u>		
ODE (TDK)	One-Dimensional Equilibrium subprogram--calculates ideal flow performance based on isentropic thermochemical relationships	3.2.1
ODK (TDK)	One-Dimensional Kinetic subprogram--calculates kinetics effects for plane uniform flow	3.2.4
TDE (TDK)	Two-Dimensional Equilibrium subprogram--calculates nonuniform expansion effects using isentropic equilibrium relationships	3.2.3
TDy (TDK)	Two-Dimensional Perfect Gas subprogram--uses perfect gas relationships to obtain properties for analyzing nonuniform expansion	3.2.3

Section 1 JANNAF Rocket Engine Performance Methodology
1.3 Selection of Proper Procedures
1.3.1 PROCEDURE SELECTION

Date: 11/15/74

The factors that must be considered are the design/computer program constraints, budget, time, and accuracy.

The selection of procedures starts with a comparison of the engine design with the capabilities of the reference computer programs. The budget, time, and accuracy requirements must then be compared to the capabilities of the various procedures to establish the proper choice. The selection logic is shown below:



Those procedures requiring computer programs having limitations for the particular engine of interest must be eliminated from consideration. For example, a gas-gas injector must be treated with an optional or simplified procedure rather than the rigorous.

The procedures are applied to two general classes of problems. The first class is those for which no experimental information is available. These cases are called *a priori* predictions. For *a priori* predictions, generally at least one operating point will have to be analyzed using the most rigorous procedure possible within computer program and budget limitations. The second class of problems is those for which test data are available. For these cases, the test data may be used to calibrate the selected procedures or may be used to bypass some of the procedure steps (i.e., spray distribution analysis). When a procedure has been calibrated, it can be used with high confidence to predict the performance of the same engine for other operating conditions or to predict the performance of a similar engine design (e.g., modified injector, higher area ratio). A calibrated optional or simplified procedure can usually be used in place of the rigorous procedure for extrapolating test data to new operating points or modified design conditions.

A summary of ROM costs and time requirements for the procedures is given in the following tables:

	COST		TIME	UNCERTAINTY
	MAN	COMPUTER		
RIGOROUS PROCEDURE	2 TO 4 WEEKS	\$ 500*	4 TO 6 WEEKS	0.1 TO 1 PERCENT**
SIMPLIFIED PROCEDURE	8 TO 40 HOURS	0 TO \$500	8 TO 40 HOURS	0.2 TO 2 PERCENT

*CDC Western Computing Center (See section 2.3.1 for detailed breakdown)

OPTIONAL PROCEDURE		
OPTION	ACCURACY	SAVING
SINGLE-ZONE VAPORIZATION	HIGH (WITHIN 0.5 PERCENT OF RIGOROUS	50 TO 90 PERCENT OF STC COST
SIMPLIFIED EDGE CONDITIONS (TDE)	HIGH	ONE TDK RUN
SINGLE-ELEMENT SPRAY	MODERATE TO HIGH (WITHIN 1 PERCENT OF RIGOROUS	50 TO 90 PERCENT OF LISP COST
REAL WALL VS POTENTIAL WALL FOR INVISCID FLOW	MODERATE TO HIGH	8 MAN-HOURS (ONE TDK RUN IF EARLIER EDGE OPTION NOT USED)
SIMPLIFIED ITERATION	MODERATE TO HIGH	POTENTIALLY SEVERAL BLIMP RUNS
ALTERNATE INVISCID	LOW TO MODERATE (WITHIN 2 PERCENT OF RIGOROUS)	MULTIZONE TDK RUN

**Current droplet size correlations in LISP may cause much higher error if used without test data point to establish need for adjustment.

The usual uses for the procedures are:

- Rigorous:
 - Identifying effects of subtle design differences
 - Establishing a basepoint for parametric data
 - Establishing a basepoint for flight performance specifications
- Simplified:
 - Parametric data
 - Quick extrapolation of test data
 - Comparison of widely different operating conditions
 - Most conceptual and preliminary design effects
- Optional:
 - When rigorous cannot work
 - When maximum rigorousness is desired in some parts of analysis but not needed throughout

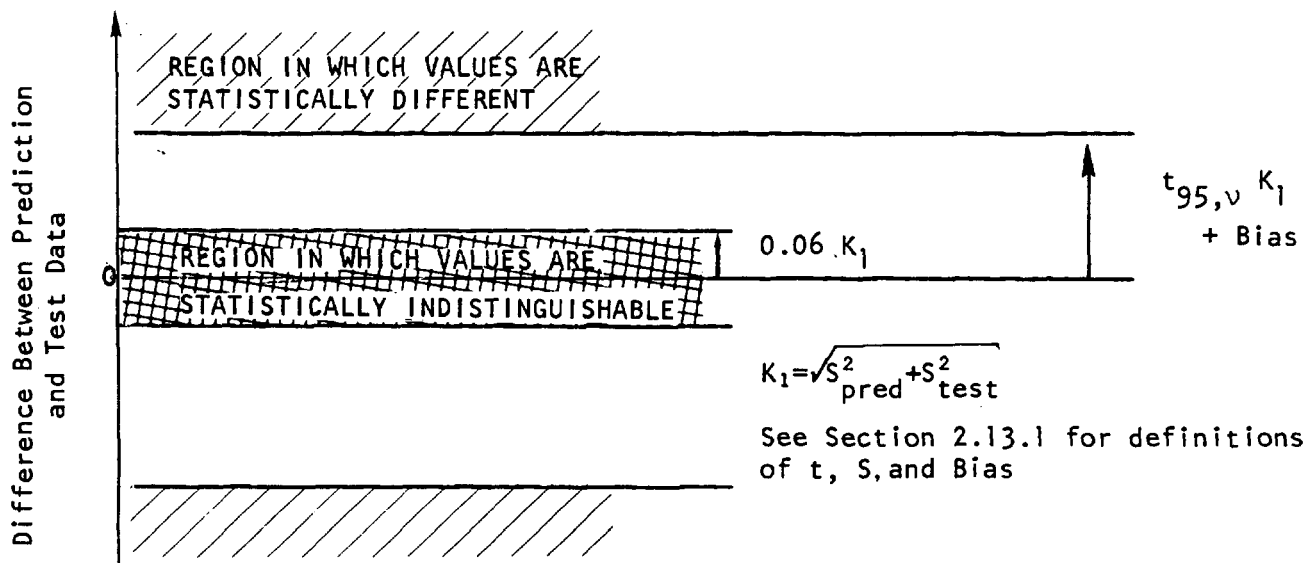
Section 1 JANNAF Rocket Engine Performance Methodology
 1.3 Selection of Proper Procedures
 1.3.2 CORRELATION AND ANALYSIS OF TEST DATA

Date: 11/15/74

The analytical procedures form the reference frame for the correlation and analysis of test data.

The correlation of test data using the analytical procedures is discussed in detail in Ref.*. As shown in the figure below, two statistical correlations can be performed. First, the prediction and test are compared to determine whether the prediction and test data are so far apart as to be statistically different. If this degree of correlation is exceeded, a major error may exist in either prediction or data. This region is beyond the distance given by the Student's t applied to the combined precision and bias in the figure below.

If the prediction procedures are to be used for extrapolation of the test data to new conditions (e.g., higher area ratio), the prediction must be forced into agreement with the test data by performing adjustments to the prediction, as shown in the table on page 1.3.2B, until the prediction and test are statistically indistinguishable. The test for statistical agreement is shown in the figure below. The predictions must be adjusted until the difference between prediction and test is less than 0.06 times the combined precisions.



*CPIA 245, JANNAF Rocket Engine Performance Data Acquisition and Interpretation Manual.

OBSERVED DISCREPANCY	PROBABLE CAUSES	ADJUSTABLE PARAMETERS
C* AND ISP OFF BY SAME AMOUNT	● VAPORIZATION CALCULATION	● DROPSIZES, ZSTART*
C* IN ERROR, ISP ACCURATE	● THROAT AREA ● CHAMBER PRESSURE ● MIXING	● THROAT AREA ● CHAMBER PRESSURE ● MIXTURE RATIO ZONES, ZOM*
ISP IN ERROR, C* ACCURACY	● BOUNDARY LAYER ANALYSIS ● REACTION KINETICS ● MIXING	● WALL TEMPERATURE, STARTING POINT EDGE MR ● REACTION RATES, STEP SIZES ● MIXTURE RATIO ZONES, ZOM*
WALL PRESSURES IN ERROR	● REACTION KINETICS ● WALL CONTOUR	● REACTION RATES, STEP SIZES ● WALL CONTOUR, FIT METHOD
EXIT COMPOSITION IN ERROR	● REACTION KINETICS ● MIXING	● REACTION RATES ● MIXTURE RATIO ZONES, ZOM*
WALL HEAT FLUX IN ERROR	● BOUNDARY LAYER ANALYSIS	● WALL TEMPERATURE, EDGE MIXTURE RATIO
WALL TEMPERATURE IN ERROR	● BOUNDARY LAYER ANALYSIS	● EDGE MIXTURE RATIO

*See Sections 2.8.3 and 2.8.4

Section 1. Application of Procedures
 1.3 Selection of Proper Procedures
 1.3.3 EXTRAPOLATION TO NEW DESIGN CONDITIONS

Date: 11/15/74

The prediction procedures, when matched to test data, can be used to extrapolate with very little increase in uncertainty.

The procedure used in extrapolating from a tested condition to a new design condition is:

- Match prediction to test within correlation given in Section 1.3.2 by adjusting appropriate parameters
- Using adjusted parameters, calculate new conditions
- Estimate uncertainty

Since the performance evaluation procedures have an uncertainty associated with the predicted values, use of these procedures to extrapolate to new conditions from existing data results in a broadening of the uncertainty band around the data, as indicated in the illustration on page 1.3.3B. The uncertainty band around the data is derived as discussed in Section 2.13. However, the use of the Evaluation Procedures to extrapolate data results in less additional uncertainty than any other procedure since the trends with the key parameters are based on the physical system behavior.

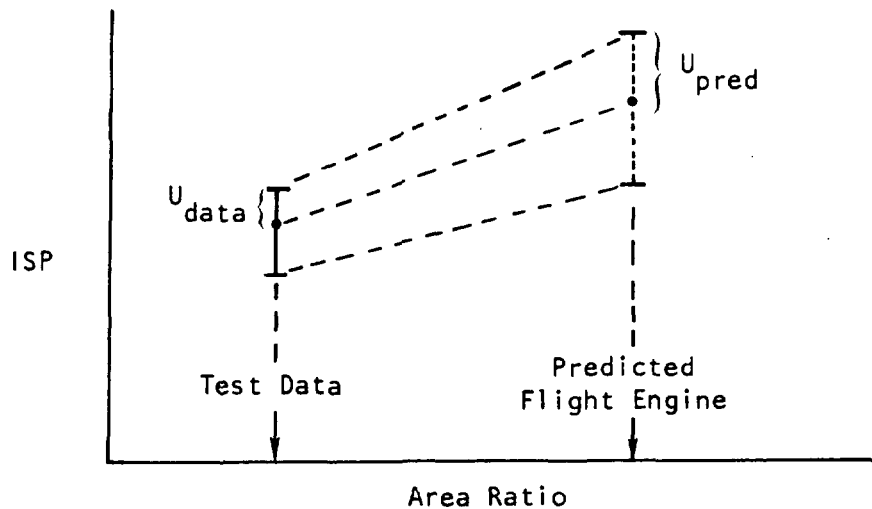
The accuracy of the extrapolation will vary with the parameters that change between the base point and the extrapolated point. Variations in ISP or C* with chamber pressure, area ratio, and thrust are generally more regular than variations with mixture ratio. The broadening of the uncertainty band when using one of the Evaluation Procedures to extrapolate is given by the expression:

$$U_{ISP_{PRED}} = t_{95, \nu} \sqrt{S_{ISP_{TEST}}^2 + S_{ISP_{TEST}}^2 \left(1 - \frac{ISP_{TEST}}{ISP_{PRED}}\right)^2} + B_{ISP_{TEST}}$$

with a similar expression for C*.

$$U_{C^*_{PRED}} = t_{95, \nu} \sqrt{S_{C^*_{TEST}}^2 + S_{C^*_{TEST}}^2 \left(1 - \frac{C^*_{TEST}}{C^*_{PRED}}\right)^2} + B_{C^*_{TEST}}$$

The definitions of U, t, S, and B are given in Section 2.13.1.



If the uncertainty associated with the original data can be determined, the uncertainty of the extrapolation can be estimated.

As seen from the equation, the prediction uncertainty can become as great with existing data as for an *a priori* calculation. At this point, the use of existing data as a base point becomes unproductive.

The selection of procedure to use for extrapolating depends on the accuracy and time constraints. For routine use, the simplified procedure or an optional procedure should prove adequate. The use of the rigorous should be considered for key decisions such as competitive situations or flight commitment.

Section 1 JANNAF Rocket Engine Performance Methodology
1.3 Selection of Proper Procedures
1.3.4 LIMITATIONS OF PROCEDURES

Date: 11/15/74

The basic JANNAF Performance Evaluation Procedures have very few inherent limitations. The primary limitations are traceable to limitations in the reference computer programs or the absence of reference techniques.

Limitations that are inherent in the basic procedures are:

Steady-State Operation. The procedures have been established specifically for steady-state or quasi-steady-state operation. In setting up the energy and mass balance relationships and procedures for calculating thrust, all time-variant terms have been neglected. In transient operation, certain time-varying terms, particularly those having to do with the filling of propellant-carrying passages having significant volumes, become important. By neglect of these terms, the JANNAF procedures are incorrect for transient operation and would have to be rewritten to apply to such operation.

Cylindrical Internal Flow Nozzles. While the standard definitions, mass and energy relationships, and defining equations are correct for any thrust chamber configuration, no reference procedures have been developed for other than DeLaval-type nozzles. The required relationships for thrust chambers having major thrust contributions from pressure acting on other than the walls controlling the primary flow (e.g., base areas of thrust chambers such as annular bells) have not been standardized. The treatment of performance calculations for such thrust chambers should be carried out within the general framework, guidelines, and definitions of the procedures outlined in this manual. However, as for any nonreference technique, a full explanation of the analytical methods and assumptions used must also be supplied.

Relatively Small-Scale Viscous Effects. The procedures are set up assuming separable calculations for the inviscid and viscous regions of the flow. Flows in which viscous effects dominate in more than a relatively small portion of the flow (10 percent) cannot be treated using the procedures. A new formulation and new computer programs would be required for highly viscous flows. The basic definitions of performance factors would still be valid. However, the analytical expressions derived from the basic definitions would be altered.

Vacuum Performance. The procedures are specifically limited to vacuum performance. No terms are included and no analytical techniques are recommended for the effects of ambient pressure acting on the external surfaces of the engine. In testing or in flight, the pressure on the external surfaces results from the air around the engine. The air can be moving, giving a varying pressure on the engine surface. For test or flight performance, a thrust correction must be applied because of these ambient-pressure effects. There are no reference methods for calculating this correction, so the correction must be made using the best techniques possible, with full reporting of technique.

Acceleration Effects. The effects of an acceleration field are not explicitly included in the performance procedures. The major impact of such accelerations are in the reservoir and feed system calculations, which are discretionary anyway. The effect upon thrust chamber flow is not included in any of the procedures, but should be small.

Computational Methods. Many of the limitations upon the JANNAF Performance Evaluation Procedures stem from limitations in the reference computer programs, which were developed to be as general as possible within the constraints of time and funding. However, the computer programs were initially designed to analyze the most typical-type injectors and thrust chambers in existence.

The existing capabilities of the computer programs are outlined in the table below. As indicated, many injector types must be analyzed using non-reference procedures or test data from cold-flow tests. The use of test data can be as accurate as, or more accurate than, the computer programs, since these also depend on correlations from existing tests.

The flow analysis programs are limited to gaseous exhaust products. Condensation of liquid or solid species is not modeled and the basic relationships and data for condensation are not well developed. This limitation affects analysis of a number of propellant combinations such as F_2-O_2/CH_4 and OF_2/B_2H_6 . Even such well-characterized propellants as O_2/H_2 have conditions in which condensation (H_2O) can limit the applicability of the computer programs. Further limitations of the specific programs are discussed in Section 2.

CAPABILITIES OF DISTRIBUTED ENERGY RELEASE SERIES
OF COMPUTER PROGRAMS (LISP, 3DC, STC, CICM)

	Liquid-Liquid	Liquid-Gas	Gas-Gas
Subcritical Pressure	Like Doublet Unlike Doublet Triplet Pentad	Triplet Coaxial	
Supercritical Pressure		Coaxial	

CAPABILITIES OF TWO-DIMENSIONAL KINETIC FLOW
ANALYSIS COMPUTER PROGRAMS

- Axisymmetric Reacting Gas Flow (TDK)
- Axisymmetric Equilibrium Gas Flow (TDE)
- Axisymmetric Perfect Gas Flow (TDY)
- One-Dimensional Reacting Gas Flow (ODK)
- One-Dimensional Equilibrium Gas Flow (ODE)
- One-Dimensional Constant-Composition
(Frozen) Gas Flow (ODF)

CAPABILITIES OF BOUNDARY LAYER ANALYSIS COMPUTER PROGRAMS

- Equilibrium Gas Reactions
- Cooled Walls
- Ablative Walls
- Transpiration-Cooled Walls
- Film-Cooled Walls

SECTION 2

SECTION 2. RIGOROUS ANALYTICAL PROCEDURE

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2.11 Execution of Inviscid Flow Analysis Step	11/15/74
2.11.1 Conceptual Basis	
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2.12 Performance Calculation	11/15/74
2.12.1 Specific Impulse	
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2.13 Uncertainty of Procedure	11/15/74
2.13.1 Uncertainty Parameters	
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SECTION 2. RIGOROUS ANALYTICAL PROCEDURE

SUMMARY

As discussed in Section 1.2.1, the rigorous analytical procedure consists of 17 steps that are to be carried out in calculating a specific impulse/ C^* using the JANNAF Reference Procedure. For purposes of discussion in this chapter, the 17 steps are grouped as follows:

- Specification Steps (2.1.1)
 1. Specify Reservoir Conditions
 2. Specify Feed System Conditions
 3. Specify Thrust Chamber Geometry
- Injector and Combustion Analysis (2.1.2)
 4. Specify Injector Flow Distribution
 5. Analyze Injection Process
 6. Analyze Turbulent Combustion
 7. Analyze Streamtube Combustion
- Thrust Chamber Flow Analysis (2.1.3)
 8. Specify Boundary Layer Edge Conditions
 9. Analyze Boundary Layer Process
 10. Analyze Wall Response
 11. Check Total Heat Load
 12. Check Nonboundary Layer Heat
 13. Check Wall Conditions
 14. Analyze Inviscid Flow
- Specific Impulse Calculation (2.1.4)
 15. Adjust Thrust for Droplets
 16. Calculate Propulsive Dump Thrust
 17. Calculate Specific Impulse and C^*

The recommended reporting formats for the information generated in the 17 steps are detailed in Section 2.2 in the same order as the steps. Reporting of flight-predicted performance with uncertainty and contingency is last (2.2.11).

Following the reporting details, time and cost estimates are given in Section 2.3. Sections 2.4 through 2.12 give the recommended methods for executing the procedural steps, including (1) theoretical basis, (2) use of reference programs, (3) setup of programs, (4) use of empirical data, and (5) other pertinent information.

Definition of uncertainty parameters and the calculation of uncertainty are given in Section 2.13.

Section 2. Rigorous Analytical Procedure
2.1 Calculational Procedure
2.1.1 SPECIFICATION STEPS 1 THROUGH 3

Date: 11/15/74

The rigorous analytical procedure begins with three specification requirement steps, one each for the reservoir, feed system, and thrust chamber.

Following the reference frame definitions of Section 1.1, the initial set of steps for the prediction procedures is a specification of the reservoir, feed system, and thrust chamber in a manner that eliminates ambiguity and allows for reproduction of the analysis by independent agencies. The specifications for the reservoir and feed system include a detailing of calculational procedures and data to check the accuracy of those procedures, since no JANNAF-recommended calculation methods are available, and differences between organizations will probably exist in both method and input data. The three specification step requirements are detailed on page 2.1.1B.

The first step is the reservoir conditions specification and is of critical importance since these conditions determine the rest of the analysis. Often these conditions will be specified by the contracting agency or the vehicle contractor. In this case, care must be taken to ensure that all critical parameters are mutually agreed upon. Enthalpy and composition are the key parameters to be specified. For flight systems, pressure and momentum are also important since the acceleration head can significantly affect thrust and flowrate (with second-order influence on specific impulse).

For the feed system, the analyst is free to use any acceptable analytical procedure. The philosophy is to provide sufficient data that the accuracy of the analysis can be checked by a mass and energy balance around the control volume, and by specific checks for certain components within the feed system. For the feed system, an exact definition of the feed system control surface must be provided, and care must be taken to ensure that the information is at this surface.

For the thrust chamber, data are required in the form needed by the reference computer program.

RIGOROUS PROCEDURE STEPS 1 THROUGH 3

1. RESERVOIR CONDITIONS SPECIFICATION

(This step may be bypassed if interface conditions are specified by agency or may be carried out by vehicle/engine interface coordinator.)

- a. If applicable (e.g., pressure-fed engine system), perform an analysis of the reservoir system using any appropriate procedures. Outline these procedures in sufficient detail to show physical concepts and assumptions.
- b. Specify composition, mass flowrate, enthalpy, pressure, and (optionally) entropy of all flows crossing the reservoir/engine system interface. If applicable, also specify flows (including heat) at reservoir/environment interface. Define interface.
- c. If applicable (e.g., pressure-fed engine system), specify flowrates, compositions, pressures, enthalpies, and (optionally) entropies at key locations within the reservoir system.

2. FEED SYSTEM CONDITIONS SPECIFICATION

- a. Perform an analysis of the feed system using any appropriate procedures. Outline these procedures in sufficient detail to show physical concepts, calculation techniques, and assumptions.
- b. Specify composition, mass flowrate, enthalpy, pressure, and (optionally) entropy at all interfaces of the feed system (reservoir, environment, thrust chamber). Note that heat flow at the thrust chamber interface must be included. Define interfaces.
- c. Specify composition, mass flowrate, enthalpy, pressure, and (optionally) entropy at key locations throughout feed system such as: (1) before and after active components such as pumps and turbines, (2) before and after heat transfer elements, (3) before and after mixing or combustion elements, (4) before and after major pressure drops, and (5) before and after flowrate splits.
- d. Perform an energy and species mass flow balance around the feed system interface. Note that internal energy sources such as nuclear reactors must be included as a time rate of change of energy within the feed system.
- e. Show power balances across active components, heat transfer elements, mixing devices, and combustion elements.

3. THRUST CHAMBER GEOMETRY SPECIFICATION

- a. Specify injector manifold and element design, pattern, flow passage sizes, and all other parameters necessary for the analytical procedure used for the injection process and all other flow ports in injectors, such as film-cooling ports.
- b. Specify wall chamber contour coordinates along wall and all other parameters required by the combustion and expansion analysis programs.
- c. Specify design of all flow ports in walls of thrust chamber, including transpiration-cooling ports, film-cooling ports, barrier-cooling ports, and internal-flow dumps.

Section 2 Rigorous Analytical Procedure Date:
2.1 Computational Procedure
2.1.2 INJECTOR AND COMBUSTION ANALYSIS STEPS 4 THROUGH 7

The injector and combustion analysis is to be carried out using the reference computer programs when applicable. Otherwise, discretionary analysis or empirical data may be used.

The injector and combustion analysis is carried out in the four distinct steps given on page 2.1.2B. The first step requires establishment of the flowrates and energy levels for each injector element. These values should result from detailed hydraulic analyses or from empirical data. Element-to-element manufacturing tolerance variations should be included in a statistical manner. The simplifying assumption of uniform distribution is unacceptable without full justification by analysis.

Injection analysis includes the flow through the orifices, initial spray formation, and start of combustion. In the region covered by this analysis, two reference computer programs are available: LISP for liquid-liquid or gas-liquid injector elements, and CICM for coaxial-element injectors. For injector types not included in CICM or LISP, either empirical data or a discretionary analytical procedure must be used. In either nonstandard case, full reporting of concepts and assumptions must be made.

For injectors having widely spaced impinging elements, the 3DC computer program may be necessary to continue the spray combustion analysis through the turbulent region to the streamtube region. For other injectors, LISP may be continued to the interface with the streamtube region. The streamtube combustion, in which the flow is essentially axial and mixes only by turbulent diffusion rather than by transverse flow, is analyzed for all cases by means of the STC computer program.

The required data tables for various propellant properties and other input data are discussed in Sections 2.6 through 2.8. The proper manner of using LISP, 3DC, CICM, and STC are also described in those sections.

RIGOROUS PROCEDURE STEPS 4 THROUGH 7

4. INJECTOR FLOW DISTRIBUTION

- a. Using procedures (analytical and/or empirical) deemed appropriate, specify flows of mass and energy to each injector element. Outline method of analysis and any assumptions.
- b. Adjust total enthalpy for nonboundary layer heat loss (i.e., radiation, recirculation, injector face, and all other modes not included in boundary layer analysis).

5. INJECTION ANALYSIS

- a. For liquid-liquid injectors of the following types, use the LISP computer program of the DER series using the discharge coefficients to adjust the mass flowrates to match those determined in step 4. Injector types are as follows:
 - Like Doublet
 - Unlike Doublet
 - Triplet
 - Pentad
 - Like-Doublet Pair
- b. For liquid-gas coaxial injectors, use CICM computer program to determine spray droplet size distribution and empirical relationships to determine mass flux distributions across injector elements. (For other than O_2/H_2 , new data tables are required.)
- c. For other element types, use analytic and/or empirical relationships to set up input for option 8 in LISP or for direct input to step 7.
- d. Report fully, source and selection of droplet sizes, element types (if used to approximate actual elements), spray coefficients, injector sector, etc.

6. TURBULENT COMBUSTION ANALYSIS

- a. For certain special cases (few widely spaced elements) analyzed using LISP, run the 3DC program using the punched card (or scratch tape when available) output from LISP.
- b. For cases analyzed using CICM, continue analysis until identifiable liquid jet disappears.
- c. For other cases, specify point at which flow is assumed to enter streamtube-type combustion flow regime. Specify flow in format of LISP output.

7. STREAMTUBE COMBUSTION ANALYSIS

- a. Use output (punch card or, if available, scratch tape) from LISP, 3DC, or from CICM or information derived from other analysis and/or empiricism to run STC computer program in DER series. Select K-prime version for propellants in which a constant wet-bulb temperature with no droplet heating is appropriate, droplet heating version for supercritical or subcritical cases in which droplet heating is of importance (as discussed in more detail in Section 2.8). Select starting plane (ZOM) as discussed in Section 2.8.3.

Select mixture ratio zones and physical regions following guidelines outlined in Section 2.8.2.

Section 2 Rigorous Analytical Procedure
2.1 Computational Procedure
2.1.3 THRUST CHAMBER FLOW ANALYSIS STEPS 8 THROUGH 14

Date: 11/15/74

The flow of the combustion products through the thrust chamber is predicted using the TDK computer program for the region of negligible viscous effects and the BLIMP computer program for the region near the wall in which viscous effects are dominant.

The steps required in the analysis of the thrust chamber flow are given on page 2.1.3B. The exhaust expansion through the thrust chamber is analyzed in two distinct regions. The region near the wall is numerically evaluated using the BLIMP computer program that includes all heat, mass, and momentum transfer to and from the physical walls. The region outside the boundary layer is assumed to have negligible viscous effects.

This inviscid flow analysis is carried out using the TDK computer program. TDK is initialized using the mixture ratio zones from STC. The program carries out a simultaneous reaction kinetic and two-dimensional method of characteristics analysis resulting in a description of the expanding gas flow throughout the nozzle. Key outputs are the flow conditions at the boundary layer edge, C^* , C_D , and ISP.

Using the TDK edge conditions, the BLIMP computer program is run to predict boundary layer conditions. Using this information, the wall response is analyzed using a discretionary procedure (for example, ablation analysis computer programs are available for use with BLIMP as outlined in Ref. *). The wall response is compared with that originally assumed for input to BLIMP. If the total heat load, nonboundary layer heat load, or wall boundary conditions differ from the initial BLIMP and feed system analysis by enough to cause an error of more than 0.1 percent in specific impulse (based on exchange factors or simplified procedures), the analysis must be iterated until the accuracy is satisfied.

Once the boundary layer/feed system/wall boundary conditions are in agreement as to amount of energy rejected from the exhaust to the feed system, and the wall temperature and mass transfer, the potential edge streamline is defined using the BLIMP displacement thickness (δ^*), and TDK is rerun.

The results (specific impulse, flowrate, velocity, density, and pressure) of this potential wall TDK analysis are used with the momentum and displacement thickness from BLIMP to obtain overall specific impulse, as discussed in the following section.

*Interim Users' Manual for Boundary Layer Integral Matrix Procedure, Version J., M. Evans and H. Morse, UM-74-41, Aerotherm, Accurex Corporation, March 1974.

RIGOROUS PROCEDURE STEPS 8 THROUGH 14

8. BOUNDARY LAYER EDGE CONDITION SPECIFICATION
 - a. Run TDK with the actual wall contour and output of STC.
 - b. Specify wall temperature distribution and calculate all flows at the thrust chamber wall, including ablative material.
9. BOUNDARY LAYER ANALYSIS
 - a. Run the standard BLIMP computer program as specified in Ref. * and discussed in Section 2.9. Report all judgmental inputs such as initial thickness.
 - b. Report momentum thickness, displacement thickness, wall heat transfer coefficient distribution, and total wall heat load.
10. WALL THERMAL RESPONSE ANALYSIS
 - a. Analyze all response to boundary layer heat input using procedures deemed appropriate. Outline analysis procedures, assumptions, wall thermal properties, coolant properties, and any other major factors considered.
 - b. Determine wall temperature profile, ablation rates, etc.
11. TOTAL HEAT LOAD CHECK
 - a. Compare total heat load from step 9 with that used in step 2, and revise feed system analysis if appropriate (following guidelines established in Section 2.10).
 - b. Redo any portion of the analyses to this point affected to the extent that specific impulse is impacted by more than 0.1 percent as discussed in Section 2.13. This impact can be estimated by exchange factors or simplified analysis (see guidelines in Section 2.10).
12. NONBOUNDARY LAYER CHECK HEAT LOAD
 - a. Check nonboundary layer heat load (radiation, heat at injector face and at wall near injector) estimated for consistency with boundary layer analysis.
 - b. Adjust analyses as necessary following 0.1-percent guidelines.
13. WALL BOUNDARY CONDITIONS
 - a. Compare calculated wall temperatures, ablation rates, or transpiration rates to values used in BLIMP.
 - b. Rerun BLIMP analysis if changes impact results above the 0.1 percent of ISP guideline.
14. INVISCID FLOW ANALYSIS
 - a. Adjust the thrust chamber wall for boundary layer δ^* , making sure adjustment is smooth.
 - b. Rerun TDK analysis with STC output.

Section 2 Rigorous Analytical Procedure

Date: 11/15/74

2.1 Computational Procedure

2.1.4 SPECIFIC IMPULSE CALCULATION STEPS 15 THROUGH 17

Overall specific impulse includes the potential flow thrust, the boundary layer thrust correction, an optional correction for condensed materials, and the thrust of any dump flows not exhausted through the thrust chamber.

The final steps of the rigorous procedure are given on page 2.1.4B. The thrust calculated by TDK ignores the effects of any remaining unburned droplets or any condensed species. If these particles make up a significant portion of the flow such that specific impulse could be changed by more than 0.1 percent, an estimate should be made of these two-phase flow effects (for example, using the method of Ref. *). The thrust chamber thrust must be corrected for the two-phase effect.

The potential flow thrust does not match the real thrust made up of both inviscid and viscous regions. A correction must be made to the thrust for this difference. The correction is given by:

$$\Delta F_{BL} = 2\pi R_E \cos \alpha_E \left[\rho_{TDKP} V_{TDKP}^2 \theta_E - P_{TDKP} \delta_E^* \right]$$

where θ_E is the exit momentum thickness from BLIMP, δ_E^* is the exit displacement thickness, ρ is density, V is velocity, P is pressure, R is radius, α is wall angle, TDKP refers to the TDK run with potential wall (i.e., adjusted for δ^*), and subscript E is exit. (Derivation is given in Section 2.9.)

The engine specific impulse is then given by the sum of all the thrust effects divided by the net (total less return flows like pressurants) mass flow used by the engine (step 17a, first equation).

The characteristic velocity is defined by the conditions at the thrust chamber throat calculated in TDK. The C^* is defined in terms of the real throat area and the total mass flow, so these corrections must be made to the value printed out by TDK (step 17a, second equation).

Any other procedure may be used in addition to the recommended procedure. The preference for the results of the alternate method must be fully documented (step 17b).

The uncertainty of the predictions must be assessed (step 17c) as detailed in Section 2.13. Any discretionary contingency may be included for a developmental engine and reported as in Section 2.2.11.

*One Dimensional Two Phase Reacting Gas Nonequilibrium Performance Program, J. R. Kliegel, et al. TRW Systems, NAS9-4358, Aug 1967.

RIGOROUS PROCEDURE STEPS 15 THROUGH 17

15. DROPLET THRUST ADJUSTMENT (optional) (Section 2.12)

- a. Estimate increase or decrease in thrust caused by droplets remaining at the throat, using procedure deemed appropriate.
- b. Report procedure fully.

16. PROPULSIVE DUMP THRUST (Section 2.12)

- a. Calculate thrust of propulsive dumps using either rigorous thrust chamber programs, simplified analysis, or empirical results as deemed appropriate to keep total error due to simplification in sum of dump thrusts less than the 0.1-percent guideline.
- b. Justify and report analytical or empirical procedure used.

17. CALCULATION OF SPECIFIC IMPULSE AND CHARACTERISTIC VELOCITY (Sections 2.12, 2.13)

- a. Calculate overall specific impulse and characteristic velocity using standard equations:

$$ISP_{PRED} = \frac{\dot{M}_{VAP} ISP_{TDKP} + \Delta F_{DROPS} - \Delta F_{BL} + F_{PROP DUMP}}{\dot{M}_{NET TO ENGINE}}$$

$$C^*_{PRED} = \left(\frac{\dot{M}_{VAP}}{\dot{M}_T} \right) \left(\frac{A_{TR}}{A_{TP}} \right) C^*_{TDKP} \left[\begin{array}{l} A_{TR} \text{ is throat area of physical nozzle} \\ A_{TP} \text{ is throat area of analytical con-} \\ \text{tour adjusted for boundary layer} \end{array} \right]$$

- b. Calculate specific impulse and characteristic velocity by any preferred method. Report method as fully as rigorous procedure and present reasons for believing results superior to rigorous procedure.
- c. Calculate bias, precision, and assign contingency. Calculate flight engine performance.

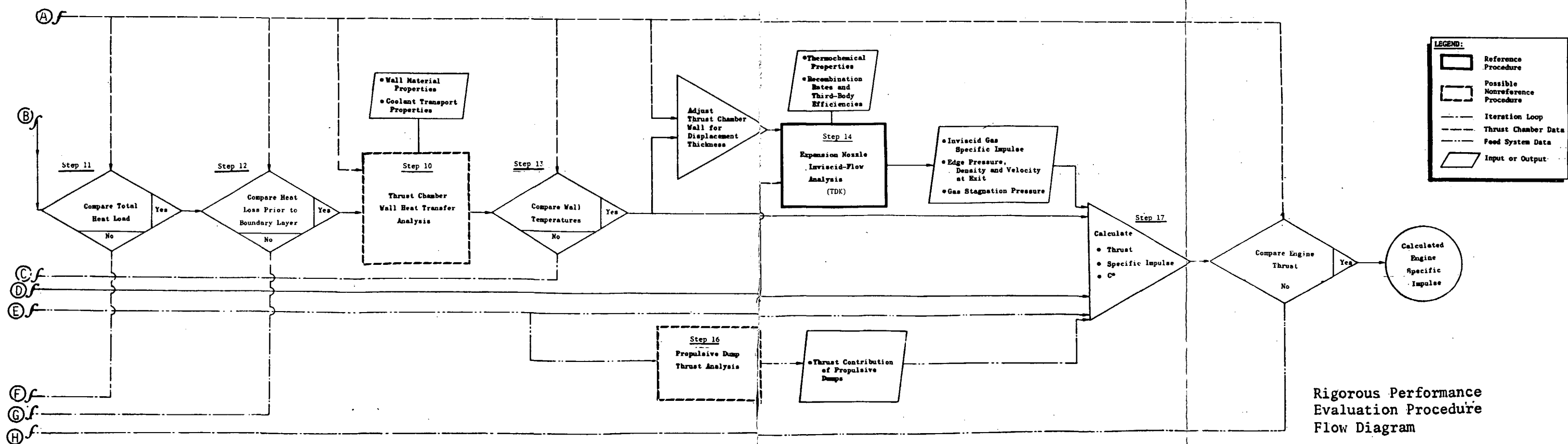
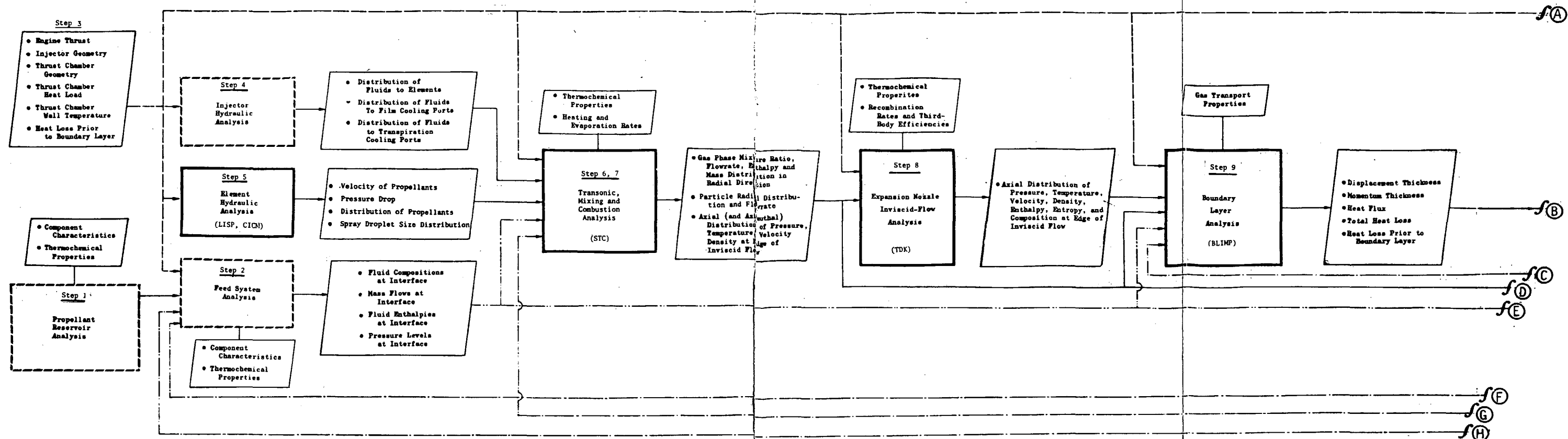
The JANNAF Rigorous Evaluation Procedure treats each of the control volumes and each of the physical processes occurring in a fashion that includes the interactions with the other volumes and processes.

The concept of the Rigorous Evaluation Procedure (and the basis for optional and simplified procedures) is described by the flow chart shown in the illustration on page 2.1.5B. The primary emphasis is on the analysis of the thrust chamber. The results of the analysis of the feed system are used in several places in the thrust chamber analysis and in the overall specific impulse determination. The flow chart can best be understood through a comparison with the steps of the rigorous procedure. The chart is not meant to be used for carrying out the procedures.

The output data of any of the analyses can be checked using test data or, if desirable, the analysis can be bypassed by the use of the proper test data. For example, Step 5 using LISP can be replaced with full element cold-flow data if droplet size and spray mixture ratio information is obtained from the tests. Steps 6 and 7 using STC can be bypassed if data are available on combustion at the throat.

Each of the specified analyses indicated in the flow chart as being a reference is computerized using a computer program or programs accepted by the Working Group. Other optional programs have also been developed in recent years and make use of the same basic data required by the reference computer programs.

The transfer of data from step to step is shown in the chart. Also, the three simultaneous iterations on heat load and wall conditions are shown as diamond-shaped boxes. The overall iteration, matching thrust to the flowrate from the engine system calculations, is shown in the final diamond. This final iteration is usually simple since thrust chamber specific impulse is only weakly a function of flowrate and thrust. All iterations may not be easily satisfied using current computer programs, as discussed in Section 2.10.



Section 2 Rigorous Analytical Procedure
2.2 Reporting Requirements
2.2.1 RESERVOIR AND FEED SYSTEM DESCRIPTION

Date: 11/15/74

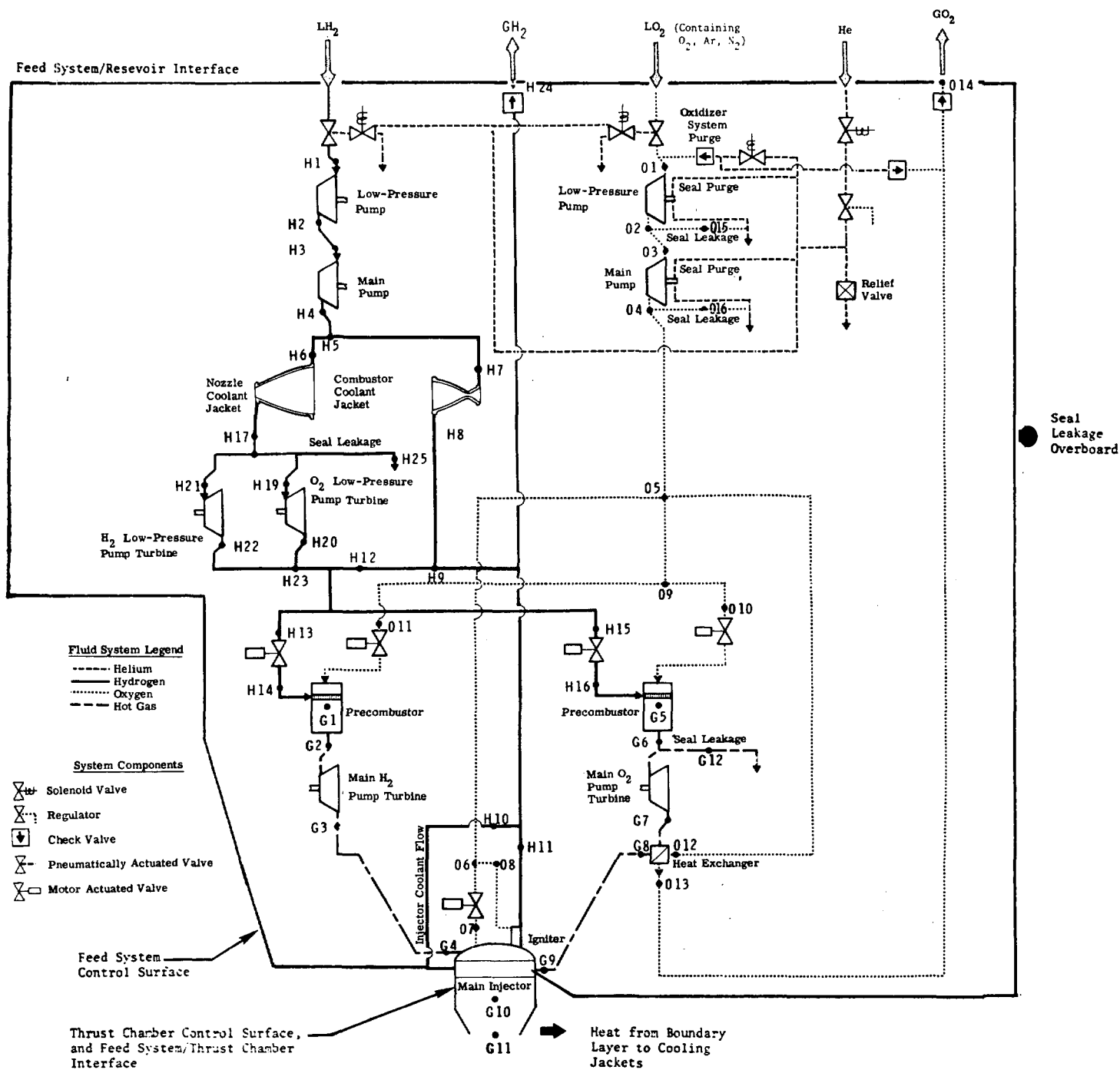
The system description must be in terms of a flow schematic showing interfaces and key points in the system at which conditions are reported. A narrative description is also highly desirable.

An example of a system flow schematic acceptable by the JANNAF standards of reporting is shown on page 2.2.1B. In the sample, locations are identified by type of fluid and numerical position from the inlet. Any distinct identification is acceptable. The sample is a flow-oriented schematic that ignores mechanical relationships (such as the physical connection between pump and turbine). Any other arrangement that provides the same information would be equally acceptable.

In addition to the flow schematic, a narrative description of the feed system is usually advisable. This description should include clarification of any subtleties in the schematic, the specific manner in which flow enters or leaves the thrust chamber, details of leakage flow paths, and any specific assumptions concerning flow paths. The control surface location should be fully described.

In some situations in which a reservoir analysis had to be performed to obtain interface conditions, the reservoir flows should be described in the degree of detail shown here for the feed system.

The numbers shown on the figure are a means of keying tabular data to locations in the feed system (see Sections 2.2.2, 2.2.3, and 2.2.4). The diagram is layed out in a flow series manner rather than functional (i.e., pumps not connected directly to turbines). Note that the nozzle cooling jackets are within the feed system control surface. Heat from the boundary layer crosses the thrust chamber/feed system interface and is deposited in the fluid flowing through the cooling jackets. Seal leakages are collected and dumped across the feed system interface. The collection line is omitted to avoid complication.



EXAMPLE RESERVOIR AND FEED
SYSTEM DESCRIPTION

Section 2 Rigorous Analytical Procedure
2.2 Reporting Requirements
2.2.2 CONTROL SURFACE FLOWS

Date: 11/15/74

The JANNAF-required control surface check is predicated upon two factors: (1) the effort of specifying calculational procedures for all feed systems and components is beyond the current scope of the Working Group, and (2) the engine performance depends only upon the accuracy of the interface flows.

The JANNAF rigorous procedure requires a check on the overall accuracy of the feed system calculations by a power and a mass balance. This check serves as an accuracy indication for the nonstandard calculational procedures used in the feed system, and can be used without detailed calculations to quickly determine the effect of changes in heat flow from the thrust chamber.

In determining the accuracy of the balance, the mass accuracy is found by taking the difference between the sum of all the mass flows entering the system and the sum of all the mass flows leaving the system. This difference should be zero for perfect accuracy. The power accuracy is found by summing all the power (given by mass flow times enthalpy) entering (+) the system with all the power leaving (-) the system. This sum should be zero for perfect accuracy.

The locations shown in the accompanying table (page 2.2.2B) refer to points in the flow diagram shown in Section 2.2.1. The table shows a listing of the control surface mass and energy flows and indicates the accuracy of the analysis used to calculate the flows. The convention adopted is that mass flow into the feed system is positive and flow out is negative. Enthalpy is either positive or negative, depending on temperature, since the JANNAF reference of zero enthalpy for pure elements in their most stable form at 273 K and 1 atmosphere is used throughout.

EXAMPLE POWER AND MASS BALANCE

	TOTAL FLOW, LB/SEC	ENTHALPY, BTU/LB	FUEL	OXIDIZER			POWER, BTU/SEC
			H ₂ , LB/SEC	O ₂ , LB/SEC	N ₂ , LB/SEC	Ar, LB/SEC	
SUPPLY							
H1	194.52	-1922.0	194.52	--	--	--	-373,867
O1	1167.14	-173.29	--	1160.11	0.62	6.41	-202,265
RETURN TO SUPPLY							
H24	-0.49	-63.56	-0.49	--	--	--	31
O14	-2.52	66.56	--	2.50	--	-0.02	-168
LEAKAGES							
O15 & O16	-0.4	-170.73	--	-0.39	--	-0.01	68
G12 & H25	-0.15	-705.65	-0.08	-0.07	--	--	106
PROPULSIVE DUMP NOT SHOWN	-5.36	4851.79	-5.36	--	--	--	-26,006
FLOW TO THRUST HAMBER							
H10	-36.55	-63.87	-36.55	--	--	--	2,334
H11	-2.18	-1184.99	-2.18	--	--	--	2,583
O7	-1022.46	-154.33	--	-1016.30	-0.54	-5.62	157,796
O8	-1.26	-154.33	--	-1.26	--	--	194
G4	-206.09	-962.65	-104.19	-101.30	-0.06	-0.54	198,393
G9	-84.19	-991.36	-45.67	-38.28	-0.02	-0.22	83,463
RETURN FROM THRUST CHAMBER	--	--	--	--	--	--	157,366
BALANCE ACCURACY	100%		100%	100%	100%	100%	99.995%

$$1 - \frac{\sum \dot{M}_{IN} - \sum \dot{M}_{OUT}}{\sum \dot{M}_{IN}}$$

$$1 - \frac{\sum (\dot{M}_{H_2})_{IN} - \sum (\dot{M}_{H_2})_{OUT}}{\sum (\dot{M}_{H_2})_{IN}}$$

$$1 - \frac{\sum \dot{M}_h + \sum \dot{Q}}{\sum |\dot{M}_h|}$$

Section 2 Rigorous Analytical Procedure
2.2 Reporting Requirements
2.2.3 SPECIFICATION OF FLOWS WITHIN CONTROL VOLUME

Date: 11/15/74

The mass flowrate, composition, enthalpy, and pressure must be specified at key points throughout the system. Heat flow by radiation, conduction, or convection not associated with a mass flow must also be detailed.

The flow conditions must be shown at key points in the system. These key points are:

- Interface (control surfaces)
- Before and After Power Transfer Elements (those adding or removing work such as pumps and turbines)
- Before and After Combustors
- Before and After Heat Exchange Elements
- Before and After Mixing or Splitting of the Flow
- Before and After Major Pressure Drops

An example of detailed reporting of system flows is shown on page 2.2.3B. The minimum required information is indicated. Again, the alpha-numeric method of location identification keyed to a flow diagram has been used. A more descriptive location designation is permissible; in either case, a full narrative should be available explaining the exact locations.

A full narrative description of the calculational procedures used in determining the flows should be presented. This description should include any unusual pump calculations, special assumptions (e.g., perfect gas/real gas, isentropic flow/isenthalpic flow/isothermal flow, complete combustion, etc.) and the source of the thermophysical properties used.

The flow information is generally too voluminous and detailed for the body of a report, but must be available to those responsible for evaluation or reproduction of the analysis. At the discretion of the contracting agency, this highly detailed information can be relegated to an Appendix or a limited-distribution supplementary volume.

As shown in the accompanying figure, engineering units were used in the case analyzed. In future work, both engineering and SI units should be provided.

EXAMPLE INTERNAL FLOW SPECIFICATION

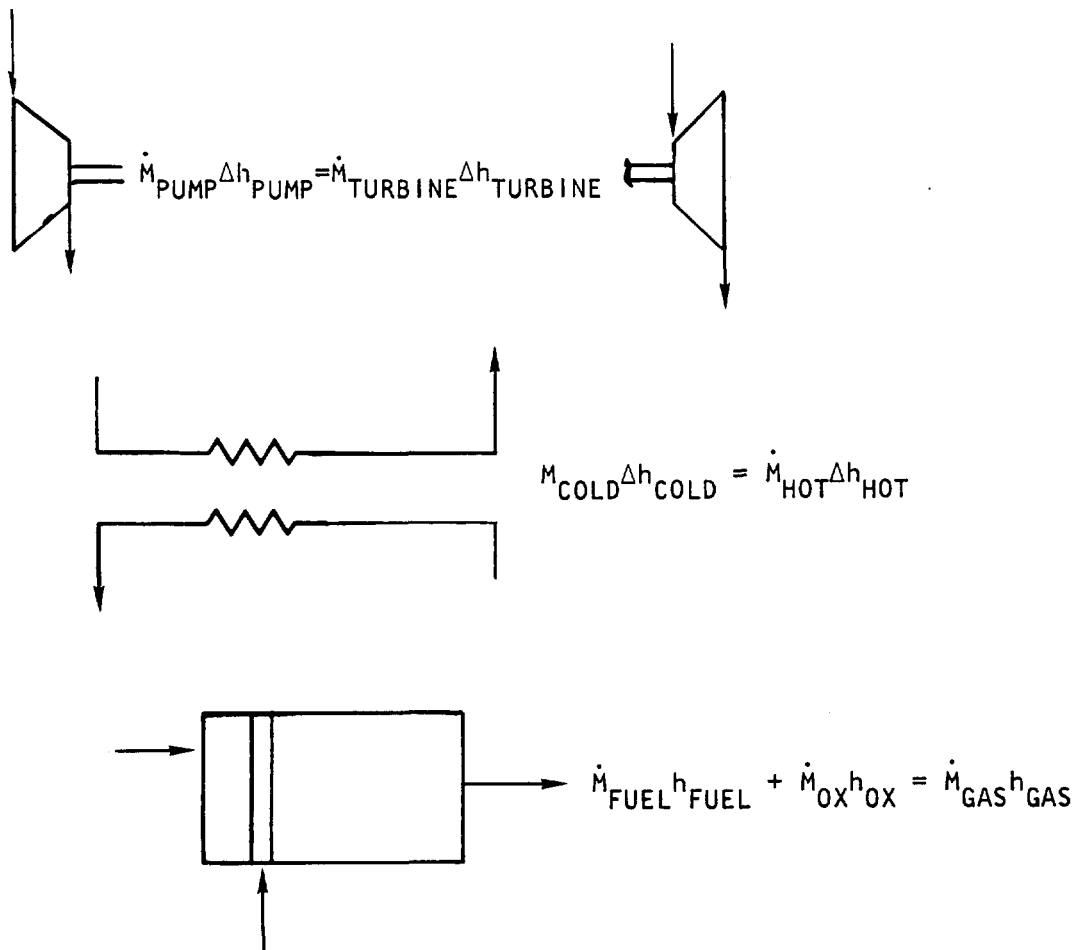
LOCATION	FLOWRATE	PRESSURE	TEMP.	ENTHALPY	ENTROPY	COMPOSITION			
	LBM/SEC	PSIA	R	BTU/LBM	B/LB-R	H2			
H 1									
H 2									
H 3									
H 4									
H 5									
H 6									
H 7									
H 8									
H 11									
H 12									
H 13									
H 14									
H 15									
H 16									
H 17									
H 18									
H 19									
H 20									
H 21									
H 22									
H 23									
H 24									
						O2	N2	AR	
O 1									
O 2									
O 3									
O 4									
O 5									
O 6									
O 7									
O 8									
O 9									
O 10									
O 11									
O 12									
O 13									
O 14									
						H2	H2O	NH3	AR
G 1									
G 2									
G 3									
G 4									
G 5									
G 6									
G 7									
G 8									
G 9									

Section 2 Rigorous Analytical Procedure
 2.2 Reporting Requirements
 2.2.4 SYSTEM COMPONENT POWER BALANCES

Date: 11/15/74

The system component power balances provide a secondary check on feed system analysis accuracy and show possible assumptions or weaknesses in the calculations.

A second check on the accuracy of the feed system (and reservoir if necessary) analysis is the component power balance (an example of which is shown on the opposite page). In this check, a comparison is made between the power extracted from the drive fluid in power transfer, heat exchanger or combustion components and the power added to the working fluid. The two should be equal. As shown, combustion components generally have only working fluid, and the net change should be zero.



The convention that mass or heat flow in is positive and outflow is negative is used throughout. Enthalpy takes on either positive or negative values depending on the temperature level. All enthalpies are referenced to JANNAF base of 0 enthalpy for a pure element in its most stable form at 273 K and 1 atmosphere.

EXAMPLE COMPONENT POWER BALANCES

COMPONENT	LOCATION *	DRIVE FLUID			WORKING FLUID		
		FLOWRATE, LB/SEC	ENTHALPY, BTU/LB	POWER, BTU/SEC	FLOWRATE, LB/SEC	ENTHALPY, BTU/LB	POWER, BTU/SEC
LOW PRESSURE FUEL PUMP	H1	--	--	--	-194.52	-1922.0	373,867
	H2	--	--	--	194.52	-1911.69	371,862
	H21	37.04	-9.71	-360	--	--	--
	H22	-37.04	-63.87	2,365	--	--	--
	NET CHANGE	--	--	2,005	--	--	2,005
HIGH PRESSURE FUEL PUMP	H3	--	--	--	-194.52	-1911.69	371,862
	H4	--	--	--	194.52	-1606.8	-312,555
	G2	203.79	-666.37	-135,800	--	--	--
	G3	-203.79	-957.40	195,109	--	--	--
	NET CHANGE	--	--	59,309	--	--	59,307
LOW PRESSURE OXIDIZER PUMP	O1	--	--	--	-1167.14	-173.29	202,256
	O2	--	--	--	1167.14	-172.03	-200,781
	H19	186.47	-154.33	-28,778	--	--	--
	H20	-186.47	-162.24	30,253	--	--	--
	NET CHANGE	--	--	1,475	--	--	1,475
HIGH PRESSURE OXIDIZER PUMP	O3	--	--	--	-1353.21	-170.73	231,034
	O4	--	--	--	1366.83	-154.33	-210,943
	G6	83.36	-705.65	-58,823	--	--	--
	G7	-83.21	-982.41	81,746	--	--	--
	NET CHANGE	--	--	23,029	--	--	23,032
LOWER COOLING JACKET	Q2	--	--	63,592	--	--	--
	H6	--	--	--	-31.46	-1606.8	50,550
	H17	--	--	--	31.46	414.57	13,042
	NET CHANGE	--	--	63,592	--	--	63,592
UPPER COOLING JACKET	Q3	--	--	59,156	--	--	--
	H7	--	--	--	-37.04	-1606.8	59,516
	H8	--	--	--	37.04	-9.71	-360
	NET CHANGE	--	--	59,156	--	--	59,156
OXIDIZER PRESSURANT HEAT EXCHANGER	O12	--	--	--	-2.52	-154.33	389
	O13	--	--	--	2.52	66.56	168
	G7	83.21	-982.41	-81,746	--	--	--
	G8	-84.19	-991.36	83,463	--	--	--
	NET CHANGE	--	--	557	--	--	557
FUEL PREBURNER	H14	--	--	--	-101.83	-1184.99	120,670
	O11	--	--	--	-101.94	-148.37	15,127
	G1	--	--	--	203.79	-666.37	-135,799
	NET CHANGE	--	--	--	--	--	-2
OXIDIZER PREBURNER	H16	--	--	--	-44.81	-1184.99	53,099
	O10	--	--	--	-38.54	-148.37	5,718
	G5	--	--	--	83.35	-705.65	-58,817
	NET CHANGE	--	--	--	--	--	0

*See figure on page 2.2.1B

Section 2 Rigorous Analytical Procedure
2.2 Reporting Requirements
2.2.5 INJECTOR DESCRIPTION

Date: 11/15/74

The injector must be characterized by both the actual design and the injector section and element types used in the reference computer programs.

The information needed for a complete characterization and analysis of the injector is:

- Physical design and dimensions of injector and elements
- Flow distribution to elements
- Element to element statistical manufacturing tolerance effects
- Element spray pattern (section 2.6.3)
- Injector section and element types used in analysis
- Spray correlation coefficients (section 2.6.3)

Depending upon the exact method of analysis and how heavily empirical data are used, different information must be supplied. If the reference programs are used with built-in correlations, reporting can be held to a minimum. If empirical data are used, extensive descriptions must be used.

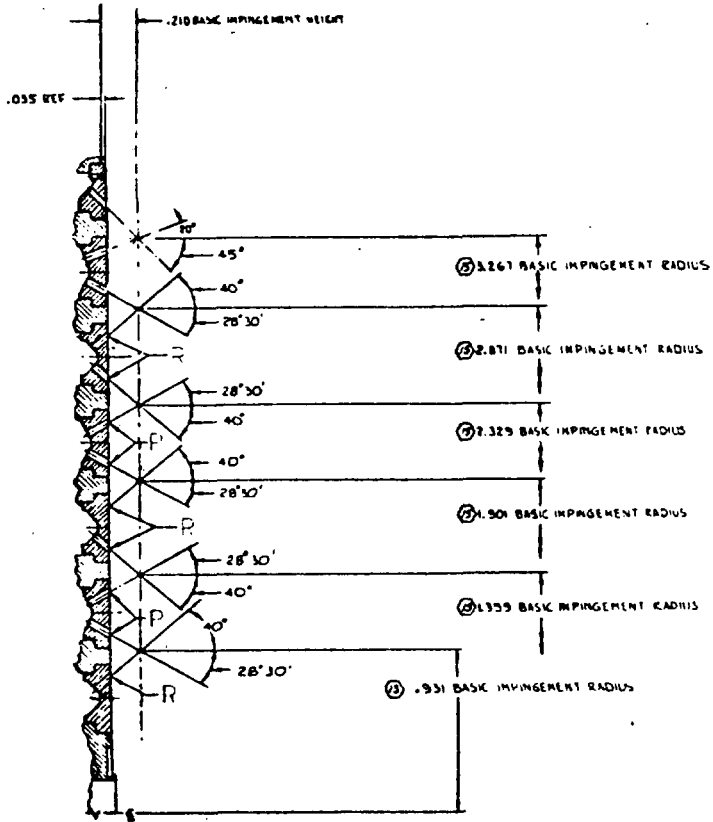
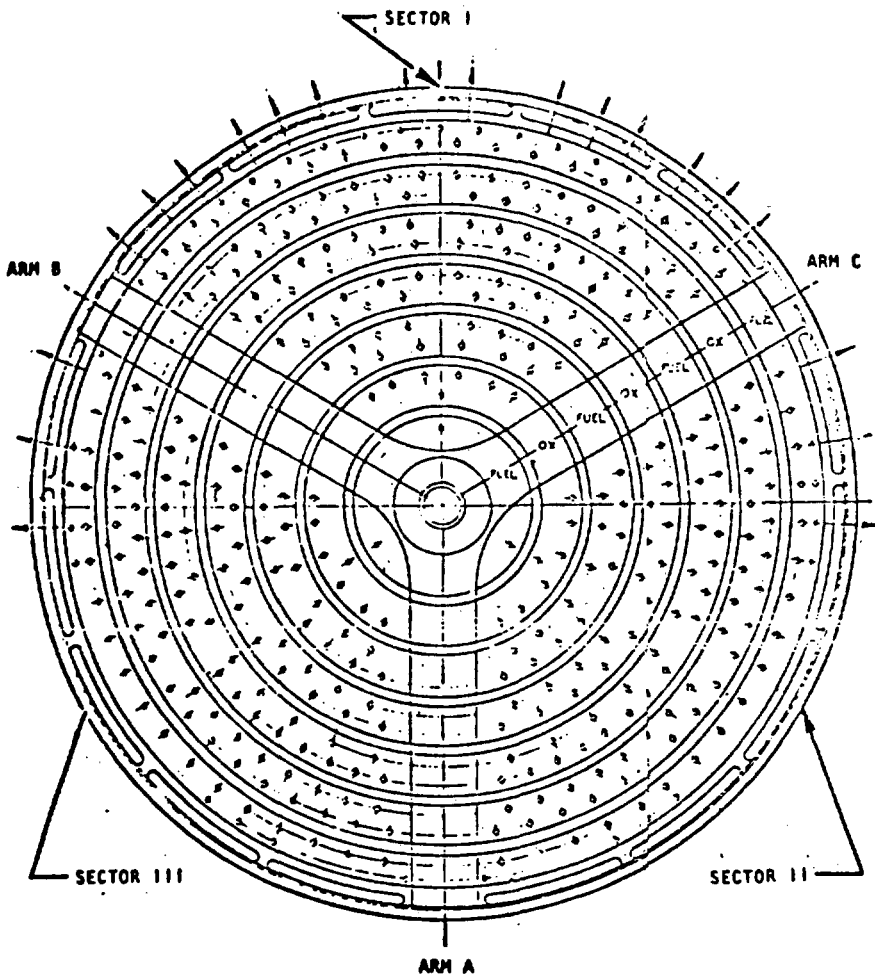
An example of the reporting of the physical design and the analytical analog for the DER reference computer program is shown on the opposite page. A fuller indication of reporting can be found in the supplementary volume (Ref. *) on sample cases. The guiding principle in the reporting of injector information is to present sufficient information that an independent analyst, working only from the reported data, can reproduce the analysis. With the many options and assumptions in the injection analysis, full and clear reporting is particularly crucial.

In addition to drawings and numerical data, a narrative description of the manner in which the analysis was performed is necessary. In particular, assumptions or approximations (e.g. use of like doublets to model showerhead elements, axial position of baffle ends, etc.) must be fully detailed. As with other detailed data, the actual location and distribution of this information in reports is left to the discretion of the contracting agency.

* Supplement to CPIA 245/246

EXAMPLE INJECTOR DESCRIPTION

Design Parameter	Overall	Impingement Row						Film Coolant		Baffle
		1	2	3	4	5	6	Axial	Canted	
Flowrate, lb/sec										
Oxidizer	6.95	0.082	0.489	0.649	0.813	1.278	2.824	DNA	DNA	0.814
Fuel	4.35	0.054	0.319	0.425	0.529	0.846	1.457	0.134	0.065	0.522
Mixture Ratio, o/f	1.598	1.52						DNA	DNA	1.56
Impingement Diameter (D_I), inches	—	1.863	2.718	3.802	4.658	5.742	6.535	DNA	DNA	DNA
Impingement Distance (X), inches	—	0.175						DNA	DNA	0.125
Momentum Angle, degrees	—	3.5°						DNA	DNA	0.5°
		(out)	(in)	(out)	(in)	(out)	6.0° (in)			
Injection Angle, degrees										
Oxidizer	—	28.5°						DNA	DNA	22.5°
Fuel	—	40°						0°	35°	22.5°
Orifice Diameter, inches										
Oxidizer	—	0.0362						DNA	DNA	0.033
Fuel	—	0.0319						0.014/0.0194	0.014	0.0274/0.0194
Number of Orifices										
Oxidizer	225	3	18	24	30	48	54	DNA	DNA	48
Fuel	285	3	18	24	30	48	54	33/4	20	45/6
Film Coolant, percent	2.18	DNA						4.58		DNA
Injector Pressure (ΔP), psid										
Oxidizer	30.1	27.0	27.0	26.9	26.9	25.9	25.9	DNA	DNA	16.7
Fuel	32.3	30.8	30.4	30.9	30.1	30.1	28.9	28.9	28.9	21.2
Injection Velocity, ft/sec										
Oxidizer	—	41.7	41.7	41.6	41.6	40.8	41.3	DNA	DNA	31.7
Fuel	—	57.0	56.6	56.6	56.4	56.4	55.8	54.3	49.9	47.1
Orifice Area, sq in.										
Oxidizer	—	0.001028						DNA	DNA	0.000853
Fuel	—	0.000788						0.000154/0.000288	0.000154	0.00059/0.000288



LMA INJECTOR CONFIGURATION

Section 2 Rigorous Analytical Procedure
2.2 Reporting Requirements
2.2.6 THRUST CHAMBER/NOZZLE DESCRIPTION

Date: 11/15/74

Key items in the thrust chamber/nozzle description are the geometrical design and wall response.

All of the reference computer programs require exact data on the thrust chamber geometry. The recommended format is shown on the opposite page. The TDK reference computer program is particularly sensitive to the smoothness of the expansion nozzle wall contour, so care must be used in the specification of points, particularly if a curve fit has been used to add points to a Rao type contour. The contour should be that during operation, rather than the manufactured contour (if thermal or erosion effects are significant). Wall materials must be specified to thermal analysis.

The wall response in terms of temperature profile, transpiration rate, or ablation rate must also be available. Since the wall response may require one or more iterations, only the final response has to be reported. A narrative discussion of the iterations should be reported as discussed in Section 2.10.

The method of handling special problems should be fully described. Particular problems such as erosion, contour discontinuities, corrugations, and asymmetry should be reviewed with any simplifying assumptions needed for using the computer programs.

A table of wall points (X/RT, Y/RT, and tangent angle) should be supplied with the contour specification. Often, the table printed by TDK will suffice.*

*Supplement to CPIA 245 and 246, sample cases for example



Section 2 Rigorous Analytical Procedure
2.2 Reporting Requirements
2.2.7 COMPUTER PROGRAM INPUT

Date: 11/15/74

The computer program input should be presented both as input listings and as a single list including all programs. A narrative discussion of the source of inputs is necessary.

A listing of the inputs, as printed by the reference computer programs, is necessary to fulfill this reporting requirement. An explanation of the source of the inputs should be provided, particularly for those requiring assumptions, or data not available from the reporting of the previous sections in the combined input table.

The second necessary reporting format, that eliminates duplication and is particularly convenient for comparison with test data, is shown on the opposite page.

Since iterations are required, only the final set of inputs should be reported. This set should be consistent within the specified iteration tolerances and should produce the quoted performance values when used in the reference programs.

EXAMPLE COMPUTER PROGRAM INPUT REPORTING

Parameter	Units	Computer Program (Variable Name)	Value	Assumptions and Remarks
Contraction ratio		LISP(EPS) TDK(ECRAT)		
Static pressure at start	psia	LISP(PCI)		
Throat radius	inches	TDK(RSTAR)		
Upstream wall radius of curvature ratio	--	TDK(RWTU)		
Downstream wall radius of curvature ratio	--	TDK(RWTD)		
Inlet angle	degrees	TDK(THETA1)		
Inlet wall radius of curvature ratio	--	TDK(RI)		
Wall angle at tangent point	degrees	TDK(THETA)		
Wall angle at exit	degrees	TDK(THETA)		
Chamber pressure	psia	TDK(PC)		
Element orientation angle	degrees	LISP(ALFA)		
Element orientation angle	degrees	LISP(BETA)		
Discharge coefficients for elements		LISP(CDDIAI)		
Propellant densities	lb/ft ³	LISP(DENSI)		
Orifice diameter	inches	LISP(DIAI)		
Injector pressure drop	psia	LISP(DPIN51,2)		
Expansion ratio	--	TDK(EPS)		
Nozzle contour		TDK		
Nozzle wall temperature		BLIMP		

Section 2 Rigorous Analytical Procedure
2.2 Reporting Requirements
2.2.8 COMPUTER OUTPUT AND NARRATIVE

Date: 11/15/74

In addition to the performance parameters, a number of other outputs are of interest to determine whether the analysis is correct or has been duplicated.

In reproducing an analysis, the availability of the intermediate results of the reference computer programs is highly valuable. This intermediate data aids in finding input errors, problems in the computer program, and in understanding the effect of assumptions or simplifications.

In addition to reference computer program output, a narrative of the analytical procedures is required to the level of detail necessary for an exact duplication of the calculations, without further consultation. The basic intent of the use of the reference procedures is to trace performance calculations to design details or input assumptions, rather than mathematical procedures. Of particular importance are details of nonreference procedures.

A list of items to be reported and discussed is given on page 2.2.8B. The detail of the discussion will depend on the difficulty and complexity of the particular case.

COMPUTER OUTPUT

- Vaporization efficiency from DER or CICM
- Chamber conditions from TDK
- Throat conditions from TDK
- Momentum, displacement, mass, energy thicknesses from BLIMP
- Heat fluxes and integrated heat loads from BLIMP

CALCULATIONAL DETAILS

- Assumptions, simplifications, or approximations used in reference computer programs
- Exactness of required iterations and number of iterations
- Details and basis of any nonreference procedure (e.g., feed system, wall response)
- Any other narrative description needed for clarity
- Details and basis of any preferred nonreference procedure used in addition to a reference procedure
- Contour option used, selection of wall points and method of adjusting for δ^*
- Number of start line points in TDK, step sizes used in all programs, mesh details from LISP, other details indicating coarseness of mathematical approximation to actual continuum.

Section 2 Rigorous Analytical Procedure
2.2 Reporting Requirements
2.2.9 THRUST CHAMBER/NOZZLE EFFICIENCY SUMMARY

Date: 11/15/74

Thrust chamber/nozzle efficiencies are reported in the rigorous procedure as a convenient indication of relative importance of losses and for use in the simplified procedure for quick estimation of new conditions.

Although efficiency factors are used for calculations only in the simplified and some optional procedures, these factors should also be reported for the rigorous procedure. The recommended reporting format is shown on the opposite page. The definitions of the various efficiencies are given in Section 3.2.1, and in the Nomenclature section.

The efficiencies are separated into those for specific impulse and those for the characteristic velocity. As shown in Ref. *, the effects of the physical loss mechanisms upon specific impulse and C^* can be quite different, giving rise to different efficiencies. Thus, the relationship between ISP and C^* can be found only through knowing all the efficiency factors for both parameters.

The reporting of efficiencies serves two purposes. First, the areas of major loss (and thus potential improvement) can be quickly determined. Second, the efficiencies can be used with the simplified procedure (or an optional procedure) for quick estimates of performance at other operating conditions. The accuracy of these extrapolations is limited by the closeness of the new conditions to those analyzed using the rigorous procedure as indicated in Section 1.3.3.

The efficiencies are also useful in comparing calculations from different sources for similar or identical engines and conditions. Areas of difference can be quickly determined, and the reasons for these differences traced to either design features or assumption used in employing the rigorous procedure.

*Simplified Procedures for Correlation of Experimentally Measured and Predicted Thrust Chamber Performance,
W. B. Powell, Jet Propulsion Laboratory, TM 33-548,
April 1973.

JANNAF PERFORMANCE EFFICIENCY SUMMARY

Parameter	Units	Value	Uncertainty
Specific Impulse Efficiencies			
Heat Loss			
Reaction Kinetic			
Two Dimensional			
Boundary Layer			
Energy Release			
Vaporization			
Mixing			
Thrust Chamber			
Characteristic Velocity Efficiencies			
Heat Loss			
Reaction Kinetic			
Two Dimensional			
Boundary Layer			
Energy Release			
Vaporization			
Mixing			
Thrust Chamber			

Section 2 Rigorous Analytical Procedure
2.2 Reporting Requirements
2.2.10 OVERALL PERFORMANCE SUMMARY

Date: 11/15/74

The summary of engine performance recommended by JANNAF is directly related to the calculational procedure and the reference computer program outputs.

The information reporting recommended in the JANNAF Prediction Methodology consists of several groups of data:

- Performance Summary
- Efficiency Summary
- System Description
- Control Surface Flows
- Internal Control Volume Conditions
- Injector Description
- Thrust Chamber/Nozzle Description
- Computer Program Inputs
- Computer Program Outputs

The formats are set up to be consistent with the reporting of test data (described in CPIA 245) so that the same format can be used for predictions of designs or for comparison of predictions with actual tests.

The recommended prediction summary format is shown on the facing page. The prediction is separated into thrust chamber parameters and overall engine parameters. No droplet thrust effect is shown, but should be included if considered. The thrust chamber ODE reference specific impulse is based on the total flow and energy entering the thrust chamber with expansion to the full physical area ratio (not gas dynamic expansion ratio).

The engine specific impulse is based on the net engine flow (flow that could be used for propulsion) so that deliberate use of propellants for other reasons such as pressurant is not charged against the engine's capability (however, energy taken by the flows is accounted for).

The uncertainty of each value should be estimated as described in Section 2.13. The uncertainty should be reported in the summary and precision and bias terms should be available for further computations.

Note that the effects of mixing are included in the TDK specific impulse for multi-streamtube runs, while the vaporization part of the energy release must be listed explicitly since TDK includes only the gas phase flow.

JANNAF OVERALL PERFORMANCE PREDICTION SUMMARY

Parameter	Units	Value	Uncertainty
Thrust Chamber Performance			
ODE Specific Impulse			
Throat Flowrate			
Exit Flowrate			
Chamber Pressure			
Throat Area			
C*			
TDK Specific Impulse			
Vaporization Efficiency			
Inviscid Specific Impulse			
BLIMP Specific Impulse Decrement			
Net Thrust Chamber Specific Impulse			
Engine Performance			
Net Engine Flowrate			
Propulsive Dump Thrust			
Propulsive Dump Flowrate			
Propulsive Dump Specific Impulse			
Increment			
Engine Thrust			
Engine Specific Impulse			

Section 2 Rigorous Analytical Procedure
2.2 Reporting Requirements
2.2.11 FLIGHT PERFORMANCE PREDICTION

Date: 11/15/74

The use of the JANNAF prediction procedures to calculate flight engine performance must include the uncertainty of the predictions, engine-to-engine and run-to-run statistical variations, and specific flight effects such as acceleration.

The use of a predicted value as the basis for the probable range of flight engine predicted performance must include several very specific differences from the prediction for a test engine, or a design engine. First, the effects of inlet propellant head (pressure and velocity) during flight must be determined. Other specific flight effects such as propellant temperature or composition must also be accounted for.

As discussed in Section 2.13, the predicted value has an associated uncertainty caused by uncertainty in inputs such as reaction rates, viscosities, and enthalpies; and by approximations and tolerances in the mathematical models. The uncertainty (like uncertainty in test data) is made up of two components; a randomly distributed error called precision (S) and a constant error called bias (B). Since the precision is the result of the random errors in a large number of direct and built-in inputs and tolerances, the distribution for S can be assumed to be the Gaussian (or normal) as discussed in Ref. *. The overall precision can be either estimated (since exercising the programs through the random error ranges for all variables would be economically complex) or derived for the effect of the estimated errors in the most critical inputs (those changing performance the most).

The total bias can be either positive (denoted by B^+ and indicating that the predicted value may be low) or negative (B^-). The bias also must be estimated using the procedures described in Section 2.13.2 based upon previous results or knowledge of the effects of the mathematical procedures. In the case of minimum flight performance, the largest likely negative bias is of interest.

Two other effects enter into the prediction, the knowledge that each engine is slightly different because of manufacturing tolerances and that a given engine cannot exactly repeat the same conditions from firing to firing. Both of these effects are random and can be assumed to be normal. Engine-to-engine precision ($S_{\text{ENG-TO-ENG}}$) can either be based upon experience with similar engines or by analyzing the engine with each design input varied independently to the tolerance limit, and then taking the root-mean-square of the performance variations (thus accounting for every tolerance being off simultaneously to some degree). The run-to-run precision ($S_{\text{RUN-TO-RUN}}$) can also be estimated from data or by using the tolerances in control settings, temperature effects, and environmental effects.

*Hays, William L., Statistics, Holt, Rinehart and Winston, N.Y., 1963.

In addition to the known effects that can yield performance different than design, the analyst may include any discretionary contingency (C^+ , C^-) to account for potential (minor) changes from the design analyzed during subsequent development or production.

The predicted performance is then bracketed by the band (Section 2.13.2)

$$\begin{aligned} \text{Prediction} + C^- + B_{\text{pred}}^- - t_{95, \nu} \sqrt{S_{\text{pred}}^2 + S_{\text{ENG-TO-ENG}}^2 + S_{\text{RUN-TO-RUN}}^2} \\ \leq \text{Prediction} \leq \text{Prediction} + C^+ + B_{\text{pred}}^+ \\ + t_{95, \nu} \sqrt{S_{\text{pred}}^2 + S_{\text{ENG TO ENG}}^2 + S_{\text{RUN TO RUN}}^2} \end{aligned}$$

with the minimum probable delivered flight performance given by the lower limit of the band. The prediction should be for the specific nominal flight conditions of interest in terms of acceleration head. Variations from flight to flight are included in the engine-to-engine precision.

The use of such calculated performance as a contractually required value for incentives is entirely at the discretion of the contracting agency. The use of the contingency term usually enables the selection of a mutually agreeable and equitable value.

An acceptable manner of reporting a performance range is shown below:

MAXIMUM PERFORMANCE	
Predicted for (Conditions) Random Variation ($t\sqrt{\sum s^2}$) Prediction Bias (B^+) Contingency (C^+) Maximum Value	
MINIMUM PERFORMANCE	
Predicted for (Conditions) Random Variation ($t\sqrt{\sum s^2}$) Prediction Bias (B^-) Contingency (C^-) Minimum Value	

Section 2 Rigorous Analytical Procedure
2.3 Applicability and Limitations
2.3.1 TIME AND COST CONSIDERATIONS

Date: 11/15/74

The rigorous analytical procedure is meant to be the most accurate, widely available method for predicting rocket engine performance. Since simplifying assumptions are minimized, the cost and time requirements are higher than alternatives.

The rigorous analytical procedure is the most costly in time and schedule of the reference procedures. Before specifying the use of the rigorous procedure, the contracting agency must consider the effort required compared to the benefit derived.

To run a single design point through the entire rigorous procedure requires on the order of 1 month of time and 2 to 3 man-weeks of effort if all input data are available. Multiple points require about half the time per additional point. If some input data must be generated (e.g., spray coefficients for LISP) an additional 1 to 2 weeks is probably necessary.

The computer time costs involved are dependent upon the specific computer and overhead operation. For example, some installations charge directly for printing while others include printing as an overhead in the cost per minute of computing time. The running time also varies with the difficulty of the case. For TDK, the time is proportional to the number of stream tubes; for DER, the time is proportional to stream tubes and droplet groups.

If no iterations on energy or wall temperature are required, only TDK has to be run twice. For most systems, one iteration should be adequate.

As shown in the table on page 2.3.1B, the overall computer cost for a single design point will probably exceed \$500 (on the order of 1/2 hour of CDC 6600 time). Usually, even if costs are allocated differently, the overall will be about the same. If one or more iterations are required, the computer cost goes up almost directly with the number of iterations, but setup cost is much less.

The costs shown on the table were estimated based on the sample cases. Large variations can be expected based on number of mixture ratio zones, area ratio, and step sizes. Setup times assume that all data are immediately available and thermodynamic data are ready. Often, setup times can be much longer if extensive tables have to be developed.

ESTIMATED COSTS FOR RIGOROUS ANALYSIS

	ROM Time (CDC 6600), Minutes	ROM Time (IBM 370), Minutes	ROM Printout Lines	ROM Setup Time, Days (second case)
Feed System Analysis	1	3	500	2 (2 hours)
DER (k' version)	5	15	2000	4 (1)
DER (droplet heating)	10	30	2000	4 (1)
3DC (optional)	5	15	1000	4 (1)
CICM	2	5	2000	2 (2 hours)
TDK	10-20	45-60	5000	2 (2 hours)
BLIMP	2	6-10	500	1 (2 hours)
Wall Response	1	3	500	2 (2 hours)
Reporting				2 (1)

Section 2 Rigorous Analytical Procedure
2.3 Applicability and Limitations
2.3.2 ACCURACY REQUIREMENTS

Date: 11/15/74

The rigorous analytical procedure is intended to be the most accurate, widely available method for calculating performance. For well-characterized conditions, optional or simplified procedures may be close at lower cost (particularly for parametric variation).

As discussed in Section 2.3.1, the rigorous analytical procedure is costly in time and funds. Therefore, this procedure should be used primarily when the most accurate value is needed and alternate procedures cannot provide acceptable accuracy. For parametric variations, one or two points can be analyzed using the rigorous procedure, and the rest of the range filled in using an optional or the simplified procedure.

The accuracy goal of the rigorous procedure is to predict performance within 1 percent *a priori*. For well-characterized systems, the prediction can be even better. For other systems (e.g., highly stratified F_2/H_2 at low pressures), the 1-percent goal is still difficult to achieve. Currently, the built-in droplet sizes for LISP may lead to very poor accuracies for new systems.

The better characterized systems are also more amenable to simplified analysis. As a goal, the simplified procedure has twice the uncertainty for a specific case as the rigorous procedure, with the optional procedures falling between.

An accuracy estimate of an *a priori* calculation is extremely difficult. For example, consider the sample case (Ref. *) for the LMA engine (storable, pressure fed, ablative, Rao contour). The first-try prediction gave a specific impulse within 0.03 percent. For the stratified flow engine (O_2/H_2 , pressure fed, heat sink, cone), the first try was high by 2 percent. If wall heat flux values had not been available to indicate that the film coolant zone mixed with the inner zones, the 2-percent high value would have stood. The problem was caused by the extremely low mixture ratio used in BLIMP. In this case, the simplifying assumption of uniform mixing would actually have yielded a more accurate answer.

Often, analyses performed on similar engines can be used to provide an accuracy estimate for the various procedures. In this case (as discussed in (Ref. **), similarity of propellants and injector type is of major importance.

*Supplement to CPIA 245/246 JANNAF Performance Methodology Sample Cases

**CPIA 245 JANNAF Rocket Engine Performance Data Acquisition and Interpretation Manual

One of the more important uses of the rigorous procedure is as a tool for identifying the effects of relatively minor design differences between competing designs. In this role, even though the absolute magnitude of the performance may be off, the differences will be highly accurate. In particular, fine differences between injector types, cooling methods, or nozzle contours can be discriminated using the rigorous method but not the simplified method.

Summarizing, the rigorous method should be used for identifying subtle design effects, to establish a base point for parametric data, and for flight engine performance specification. More simplified methods should be used for parametric data, quick extrapolation of test data, comparison of widely different operating conditions, and most conceptual and preliminary design efforts.

Section 2 Rigorous Analytical Procedure
2.3 Applicability and Limitations
2.3.3 LIMITATIONS

Date: 11/15/74

The rigorous procedure is based upon specific computer programs and is therefore constrained by the limitations of these computer programs.

The basic physical concepts underlying the rigorous analytical procedure can be applied to any rocket engine system. However, the reference computer programs can be used only for specific types of thrust chambers. If the system being analyzed has a thrust chamber that is beyond the current capabilities of the computer programs, an alternate procedure must be used.

The recommended alternate procedures are discussed in Section 4. The fact that the rigorous procedure cannot be used must be made clear, and the appropriate alternate procedure defined prior to use of the methods in any competition or contract effort.

The major limitations of the reference computer programs are:

- DeLaval type expansion nozzles
- Specific injector element types
- Noncondensing exhaust products
- Small boundary layer effects (less than 10 percent of mass flow in boundary layer)
- No interstream tube mixing

The failure of the reference computer programs to apply in a specific case does not eliminate the applicability of the JANNAF methodology. Even when simplified or nonreference methods are used, adherence to the concepts, definitions, and reporting procedures of the JANNAF methodology makes the analysis of results consistent.

Section 2 Rigorous Analytical Procedure
2.4 Execution of System Specification Steps
2.4.1 RESERVOIR CALCULATIONS

Date: 11/15/74

The data required from the reservoir are the interface conditions with the feed system.

In many cases, the reservoir conditions specification is supplied to the analyst by the vehicle contractor or by the contracting agency. When the conditions are supplied, the critical responsibility of the performance analyst is the explicit definition of the interface. The interface is normally at the point of connection between the engine as shipped and the vehicle; however, exceptions are possible, so a clear definition is necessary. Key items to be specified are listed on page 2.4.1B.

If the performance analyst must also calculate or estimate the reservoir conditions, a number of critical items must be considered. Some analytical tools are available to aid in the effort (for example, Ref. *). The methods of analysis are not specified by JANNAF. However, if the reservoir is analyzed, full reporting is required as discussed in Section 2.2. The methods used should also be presented in narrative form. Items that must be considered are shown in the lower table on page 2.4.1B. For a flight engine, acceleration level (g force) is not negligible and must be included for the time slice of interest.

*R-3985, FORTRAN Program for the Analysis of a Two-Propellant Tank, Single-Gas-Source, Pressurization System, Rocketdyne, a Division of Rockwell International, 27 February 1963.

ITEMS SPECIFIED AT RESERVOIR/FEED SYSTEM INTERFACE

- Propellant Compositions
- Propellant Stagnation Enthalpies
- Static Pressure
- Stagnation Pressure
- Temperature

CRITICAL ITEMS IN RESERVOIR CALCULATIONS

- Propellant Composition and Energy Level
 - Stratification
 - Solubility of pressurants
 - Enthalpy
- External Heat Transfer
 - Temperature stratification
 - Pressure and temperature increase
 - Propellant venting
- Acceleration Effects
 - G load
 - Inlet velocity
- Line Friction Effects
 - Pressure drop
 - Temperature rise
- Pressurant Energy Addition

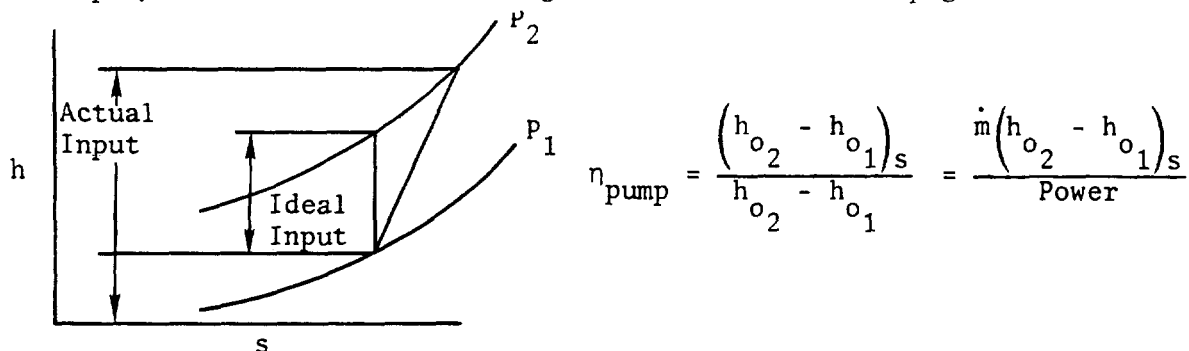
Section 2 Rigorous Analytical Procedure
 2.4 Execution of System Specification Steps
 2.4.2 FEED SYSTEM CALCULATIONS

Date: 11/15/74

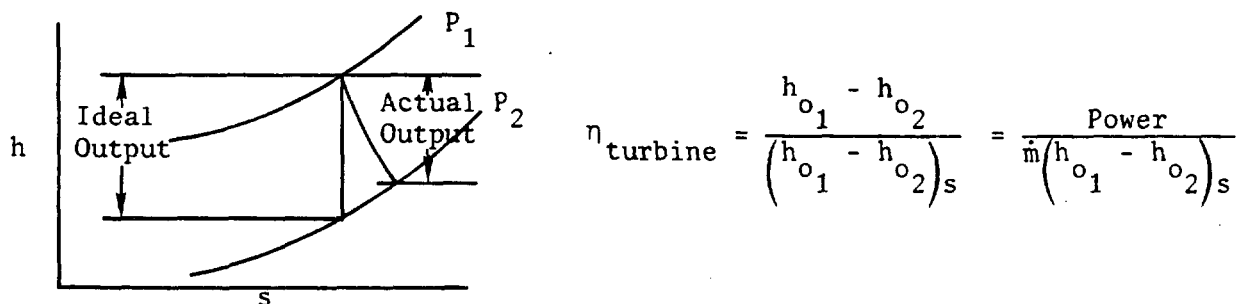
The feed system calculations result in conditions at the thrust chamber interface and throughout the system.

For purposes of analysis, the components within the feed system can be grouped into four types: power transfer components in which work is added to or extracted from the fluids, (2) heat transfer elements in which thermal energy is added to or extracted from the fluids, (3) combustors and mixers in which the composition of the fluids is changed, and (4) flow control components whose major effect is directing, splitting, or combining the flow of the same fluid with only a pressure drop.

Power Transfer Components - The primary power transfer components in a rocket feed system are the pumps and turbines. Analysis of pumps is discussed in detail in Ref. * and Ref. **. The only major JANNAF requirements on the pump analysis are that (1) real fluid (compressibility) effects be included when necessary, and (2) pump efficiency quoted be based on isentropic compression as shown below. Typical pump efficiencies displayed in a useful form are given at the bottom of page 2.4.2B.



Turbine analysis is discussed in Ref. * and Ref. **. As for pumps, real fluid properties should be used except when operating in a region (relatively low pressure - $P/P_{\text{critical}} < 0.1$ or relatively high temperature - $T/T_{\text{critical}} \gg 1$) where compressibility effects are unimportant. Turbine efficiency should also be based on isentropic expansion.



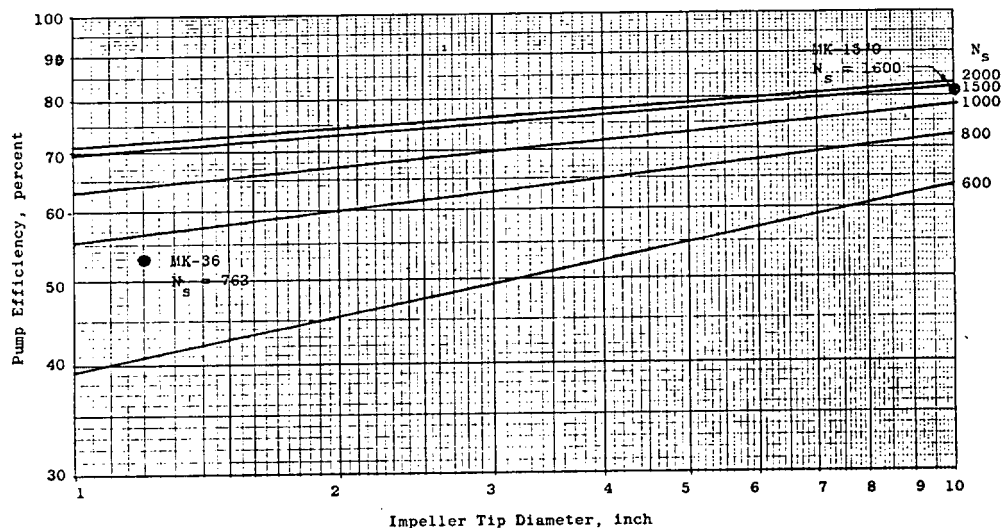
*Stepanoff, A. J., Centrifugal and Axial Flow Pumps, John Wiley & Sons, New York, N. Y., 1948

**Liquid Rocket Engine Centrifugal-Flow Turbopumps, NASA ST8109 prepared by R. Furst, Rocketdyne Division, Rockwell International, Canoga Park, California, December 1973

Heat Transfer Elements - Heat transfer elements in rocket engines include regenerative or dump cooling jackets for gas generators, and thrust chambers and heat exchangers for heating and/or gasifying pressurants. The only requirements established by JANNAF are that there be an energy balance between the hot and cold fluids and that real fluid properties be used when necessary.

Combustors and Mixers - Combustors within the feed system can be treated in a manner similar to a one-dimensional thrust chamber. ODE can be used to determine gas compositions. DER and CICM can be used for more detailed design analysis. If the flow is stratified, the situation is nonequilibrium, and care must be taken in developing the h-s relationship for use in turbine efficiency definition. The major requirements are that stagnation enthalpy be conserved, and that real fluid properties be used rather than ODE properties if the pressures are high ($P/P_{\text{critical}} \gg T/T_{\text{critical}}$).

Flow Control Components - For flow control components such as lines and valves, the major analytical concerns are determining the pressure drops and the types of expansion process. In most instances, an isenthalpic expansion can be assumed. For some types of elements such as smooth orifices or venturis, the process is more nearly isentropic. Some particular pressure drops occur isothermally, indicating heat transfer from one portion of the flow to another. The major JANNAF requirements are that (1) energy be conserved, and (2) real fluid properties be used if necessary rather than ODE or perfect gas properties.



Typical Pump Efficiencies (Ref. **)

Section 2 Rigorous Analytical Procedure
2.4 Execution of System Specification Steps
2.4.3 INJECTOR/THRUST CHAMBER GEOMETRY

Date: 11/15/74

Geometry specifications should include effects of pressure and temperature during engine firing.

The geometry specification for the injector and thrust chamber is illustrated in Sections 2.2.5, 2.2.6, and in Ref. *. The geometry specified must be for the exact conditions and time for which the performance is calculated. This requirement is especially important for heat sink and ablative chambers, but also may impact other types. Both pressure and thermal effects should be included. Simplified procedures for estimating throat growth are given in Ref. **. More complex and accurate methods are given in Ref. ***. The adjustment of the entire contour for changes caused by actual firing must be done judiciously since the contour is also readjusted for the boundary layer flow, and the uncertainty in this adjustment may make the first adjustment less critical except in the region of the throat.

Other wall factors that must be taken into account are corrugations, condensation, discontinuities, and ablation. Usually, corrugations that run parallel to the flow can be ignored unless the area is significantly affected because the boundary layer tends to smooth these corrugations. Other wall irregularities must be specified and the treatment of these irregularities discussed.

*Supplement to CPIA 245/246, JANNAF Performance Methodology Sample Cases

**CPIA 245, JANNAF Rocket Engine Performance Data Acquisition and Interpretation Manual

***Finite Element Stress Analysis, W. Charles Paulsen, Machine Design, September-October, 1971.

Section 2 Rigorous Analytical Procedure
 2.5 Execution of Injector Flow Distribution Step
 2.5.1 ANALYTICAL PROCEDURES

Date: 11/15/74

Injector manifold effects can have a marked effect on flow stratification in the combustion chamber. The manifold flow distribution must be determined and specified in the format acceptable to the computer program being used.

The flow through the orifices in the elements of an injector is controlled by the pressure in the manifold feeding the elements, and by the static pressure at the injector face. For liquids,

$$\dot{M}_e \propto \sqrt{(P_M - P_{\text{FACE}})}_{\text{INJ}}$$

(where P_M is local manifold pressure at the specific orifice of interest) and, for compressible gases

$$\dot{M}_e \propto P_M$$

for each orifice in the injector. In the reference programs, the proportionality constant is a discharge coefficient that must be specified for each class of elements.

The manifold flow distribution can be calculated using a rigorous network flow analysis procedure. The results of this procedure must then be converted to discharge coefficients based on uniform feed pressure, i.e., for the rigorously calculated mass flow,

$$C_{D_e} = \frac{\dot{M}_e}{0.6683 A_{\text{orifice}} \sqrt{\rho (P_{M_{\text{AVG}}} - P_{\text{FACE}})}_{\text{INJ}}}$$

where C_{D_e} is the LISP input analytical discharge coefficient for each element

A second alternative is to use cold-flow data, as discussed in CPIA 245, to establish the relative flowrates for each element.

For two simple cases, constant pressure and constant area manifolds, a simplified method can be used.

Generally, the analyst must deal with manifolds that are designed to maintain approximately constant manifold pressure or those that are designed for constant flow area.

Constant Manifold Pressure - The manifold is generally designed such that $A_M = K \dot{M}_M$, where K is a constant if the density remains constant and the velocity and pressure are essentially constant. The area decreases as flow is extracted from the manifold to go through the elements. For these manifolds, second-order effects such as frictional pressure drop, boundary layer growth, and density changes caused by heat transfer may have to be included as perturbations to the otherwise uniform flow. For liquids, the flowrate is proportional to density for a given ΔP . For gases, the flowrate is proportional to $T_M^{-1/2}$.

Constant Manifold Area - In the constant-area manifold, the velocity (and for gases the density) decreases as flow is removed from the manifold by the injector elements. For a liquid,

$$P_m \propto \dot{M}_m^2$$

while, for a gas,

$$P_m \propto \dot{M}_m$$

As for the constant-pressure manifold, perturbation effects of friction and heat transfer must be assessed.

For both types of manifolds, manufacturing tolerances will affect the areas of the orifices in a random fashion. Since both the oxidizer and fuel orifices have separate random distributions, the modeling of the actual situation is difficult (without resorting to Monte Carlo methods that would require many computer runs). If a large number of elements are used in DER, and large groups of these have the same parameters, these parameters can be statistically varied to match the tolerance distribution. However, if only a few elements are present, the problem of modeling a random distribution becomes difficult and no standard procedure is available.

The reference computer programs assume a uniform manifold pressure, and vary flowrate by use of discharge coefficients. For nonuniform pressure, effective flowrates must be used. If no manifold design is available, the assumption of constant pressure should be used (even though in this case, this is the more optimistic assumption).

Section 2 Rigorous Analytical Procedure
2.5 Execution of Injector Flow Distribution Step
2.5.2 EMPIRICAL PROCEDURE

Date: 11/15/74

Manifold flow distribution can be measured in cold-flow tests. The data from these tests must be corrected for second-order effects such as heat transfer occurring in hot firing.

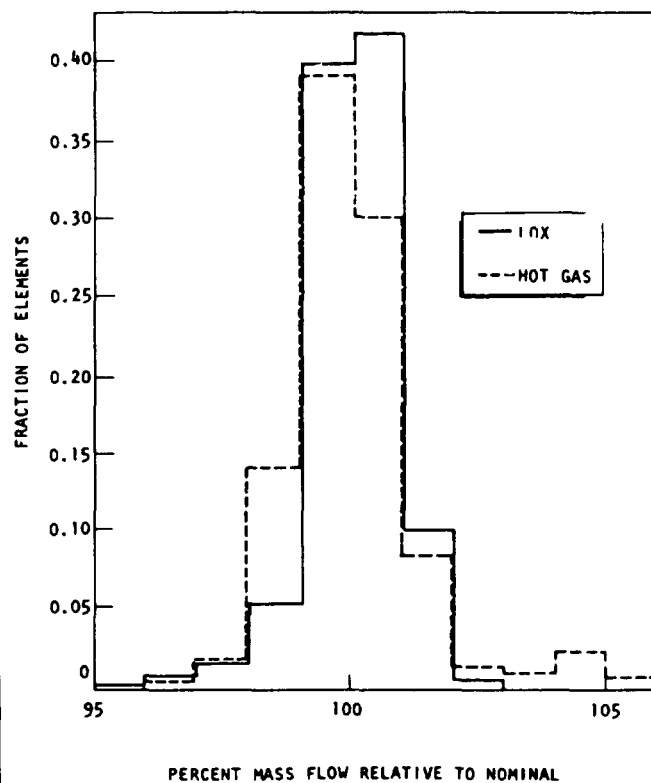
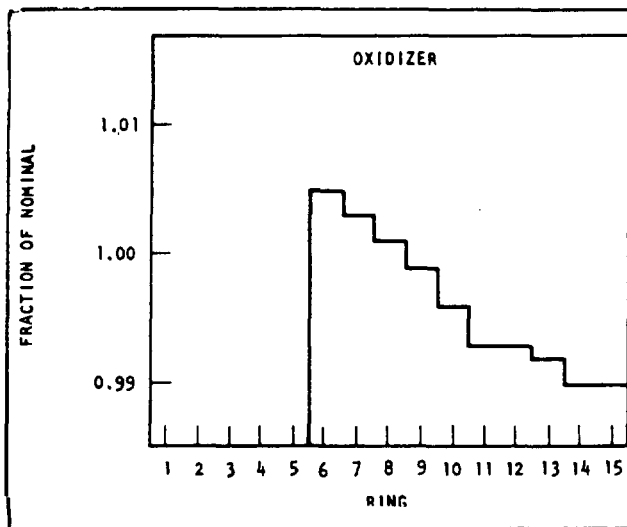
There are a number of methods available (Ref. *) for empirically measuring the relative flow through each element of an injector. The parameter measured is, in effect, a relative discharge coefficient that accounts for most manifold and orifice effects. Second-order corrections must be applied for heat transfer taking place under hot-firing conditions that change the density of the fluids.

Two phenomena are observed in the measurements. First is the large-scale manifold flow distribution from region to region of the injector (in the example, the injector elements are arranged in rings in a transpiration-cooled faceplate with five radial baffles and an annular baffle replacing the sixth ring). Secondly, superimposed upon the large-scale variations are differences in orifice size and shape due to manufacturing. For an injector having a large number of elements, the two effects can be separated mathematically by averaging then taking deviations from the average. In a given element, the oxidizer and fuel random manufacturing variations are essentially independent.

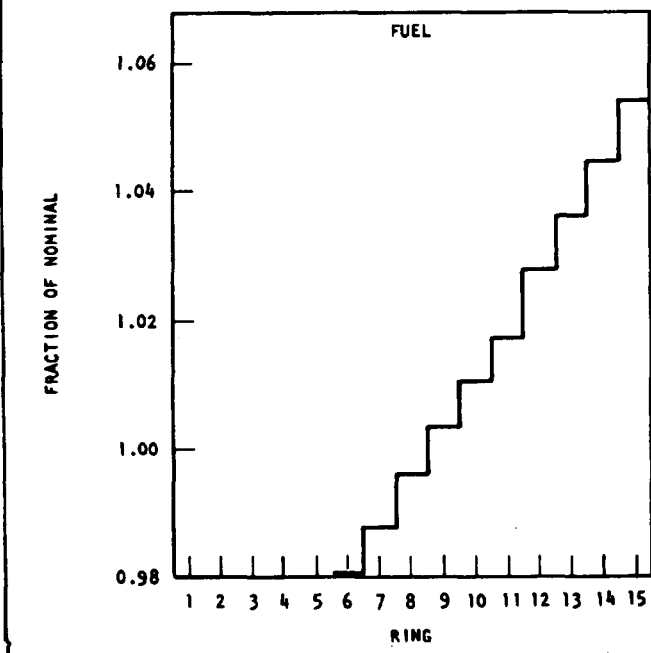
As for calculated variations, the variation in flowrate is modelled in the computer programs, such as LISP and CICM, by a constant manifold pressure with variable discharge coefficients.

An example of injector flow distribution results is shown on page 2.5.2B. The example is for a symmetric injector having elements arranged in annular rings. The rings are numbered outward from the center. The variation in flow from ring to ring is indicated (manifold effects) and the element-to-element variation within rings (manufacturing tolerance) is indicated.

*CP1A 245, JANNAF Rocket Engine Performance Test Data Acquisition and Interpretation Manual, Section 8



EXAMPLE OF FLOW
DISTRIBUTIONS USED
FOR CALCULATING
MANIFOLD DISTRIBUTION



Section 2 Rigorous Analytical Procedure
 2.6 Execution of Injector Analysis Step
 2.6.1 BASIC THEORETICAL CONCEPTS

Date: 11/15/74

The basis of the injector/combustion analysis is the division of flow between an early highly turbulent region in which the injector streams break into drops and a region of relatively smooth (turbulent diffusion) stream tube combustion flow.

The basic concept underlying the JANNAF distributed energy release procedures is that the injection process, in most part, can be treated separately from the combustion process as illustrated in Section 1.1.4. The initial formation of injector spray patterns can then be treated as a statistical correlation problem for impinging elements or a shear flow problem for coaxial elements with only abbreviated combustion effects (note that the simplification is primarily in the later combustion analysis in which flight paths and collisions no longer have to be carried).

Impinging Elements - Many types of impinging elements can be analyzed using the LISP (DER) computer program described in Ref. *. In this program, the distribution of each propellant from an element is assumed to emanate from the impingement point following the correlation

$$\hat{M}(x,y,z) = \frac{\hat{M}_{001}}{z^2} \left\{ \left[1 + C_1 \left(\frac{y}{z}\right) + C_2 \left(\frac{y}{z}\right)^2 \right] + \left[C_3 \left(\frac{x}{z}\right) + C_4 \left(\frac{x}{z}\right)^2 \right] \right. \\ \left. \left[1 + C_5 \left(\frac{y}{z}\right) + C_6 \left(\frac{y}{z}\right)^2 \right] \right\} e^{-a \left(\frac{x}{z}\right)^2 - b \left(\frac{y}{z}\right)^2}$$

where z is the distance downstream from the impingement point and x and y are normal to the z direction. $\hat{M}_{001}$ is the mass flux at the impingement point. The derivation of the empirical coefficients a , b , $\hat{M}_{001}$, $C_1 - C_6$ is described in Section 2.6.3. The spray droplet sizes are carried as a mean droplet diameter that can either be input or calculated internally from correlations. Selection of mean droplet sizes is discussed in Section 2.6.4.

Shear Elements - Elements that achieve mixing and atomization through the shear caused by a difference in velocity between two contacting parallel flowing streams are analyzed using the CICM computer program (currently limited to coaxial geometry and O_2/H_2 propellants) described in Ref. **. The governing relationships used in the model are:

$$\dot{M}_A \sim C_A \left[\frac{M_j (\rho_g U_r)^2}{\sigma_j / \sigma_g} \right]^{1/3} \pi D_j (\Delta Z)$$

*Liquid Rocket Combustion Model With Distributed Energy Release, L. P. Combs, NASA CR-114462, 10 June 1972.

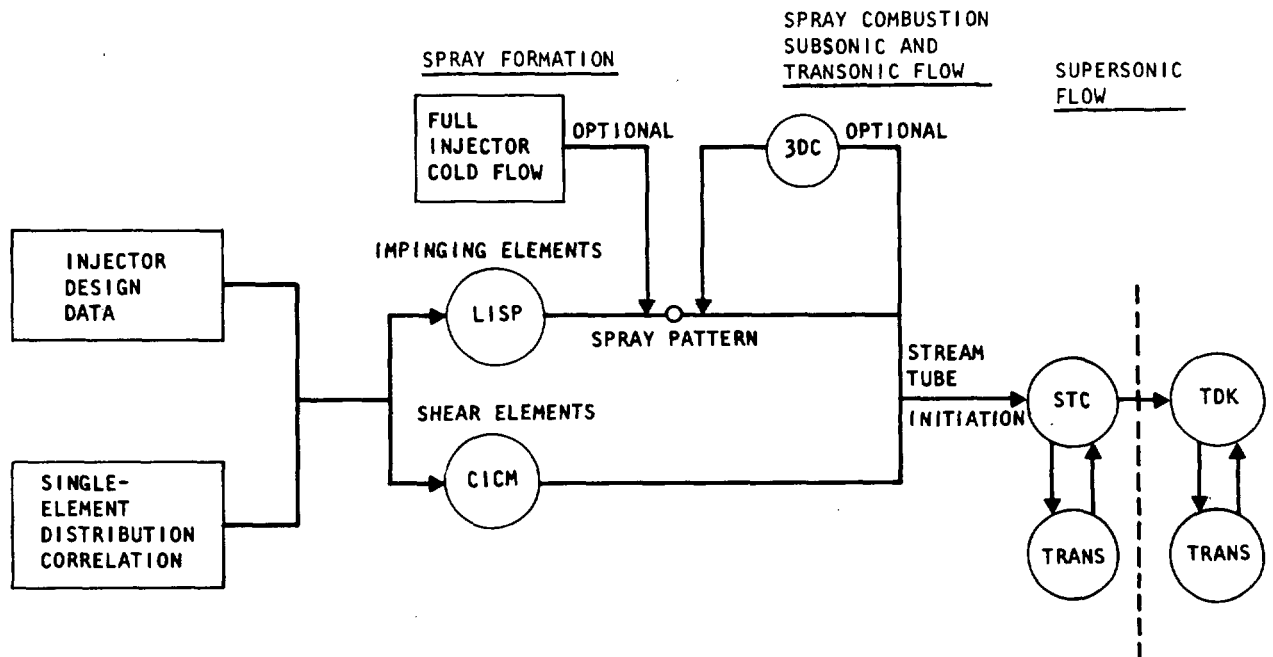
**Operating Manual for Coaxial Injection Combustion Model, R. D. Sutton, M. D. Schuman, W. D. Chadwick, NASA CR-129031, April 1974.

and

$$\bar{D} \sim B_A \left[\frac{\mu_j (\rho_j / \rho_g)^{1/2}}{\rho_g U_r^2} \right]^{2/3}$$

where $\dot{M}_A$ is the mass stripping rate, $\bar{D}$ is mean droplet size at a given station, D_j is jet diameter, U_r is relative velocity between gas and spray, z is axial position, ρ_g is gas density, ρ_j is jet density, μ_j is jet viscosity, and σ_j is jet surface tension. The calculation is carried out stepwise from the exit of the concentric tube whether recessed or flush with injector face. Combustion of the spray is considered from the point at which the flame velocity allows stable combustion. Calculation of the correlation constants B_A and C_A is discussed in Section 2.6.7.

The logical relationships of the injection analysis computer programs are shown in the figure. Note that LISP can be bypassed with empirical data but, currently, CICM cannot.



Injection and Combustion Analysis Procedures Logic Structure

Section 2 Rigorous Analytical Procedure
2.6 Execution of Injector Analysis Step
2.6.2 SETUP OF LISP

Date: 11/15/74

The key concerns in running the LISP computer program are the selection of a representative injector segment, the correct element types, discharge coefficients, spray coefficients, mean droplet diameters, and the stopping distance for the LISP analysis.

The input to the LISP computer program is described in Ref. *. The major inputs illustrated on page 2.6.2B are:

- Injector sector used for analysis in terms of mesh (r, θ)
- Types of elements, number of each type, and location of impingement point of each element
- Discharge coefficient for each orifice of each element (when different) based on uniform pressure drop, and corresponding orifice areas
- Propellant properties (density, heats of vaporization, etc.)
- Spray coefficient (if not using built-in correlations)
- Mean droplet diameter (if not using built-in correlations)
- Transition planes to next step of analysis (ZOM, Section 2.8.3 and 2.8.4)

Sector Selection - The sector should be selected so that the spray pattern from the sector is representative of the entire injector and all elements affecting this sector must be included in the analysis. The maximum number of elements is 60 (10 discrete specifications). A typical mesh with elements is shown in the figure. The mesh used for the sector should be roughly square in the larger sections. The $\Delta\theta$ should be between 2 degrees and 5 degrees, with Δr selected to square the grid. The maximum grid size is 20 x 20.

Types of Elements - In the selection of elements, the resultant spray pattern is actually more important than the actual type. For example, some elements such as showerheads that are not handled by the program can be approximated by a like doublet with a very flat spray pattern.

*DER Computer Program Documentation and User's Guide, Contract NAS7-746, L. P. Combs and W. D. Chadwick, available from R. Kushida at Jet Propulsion Laboratory.

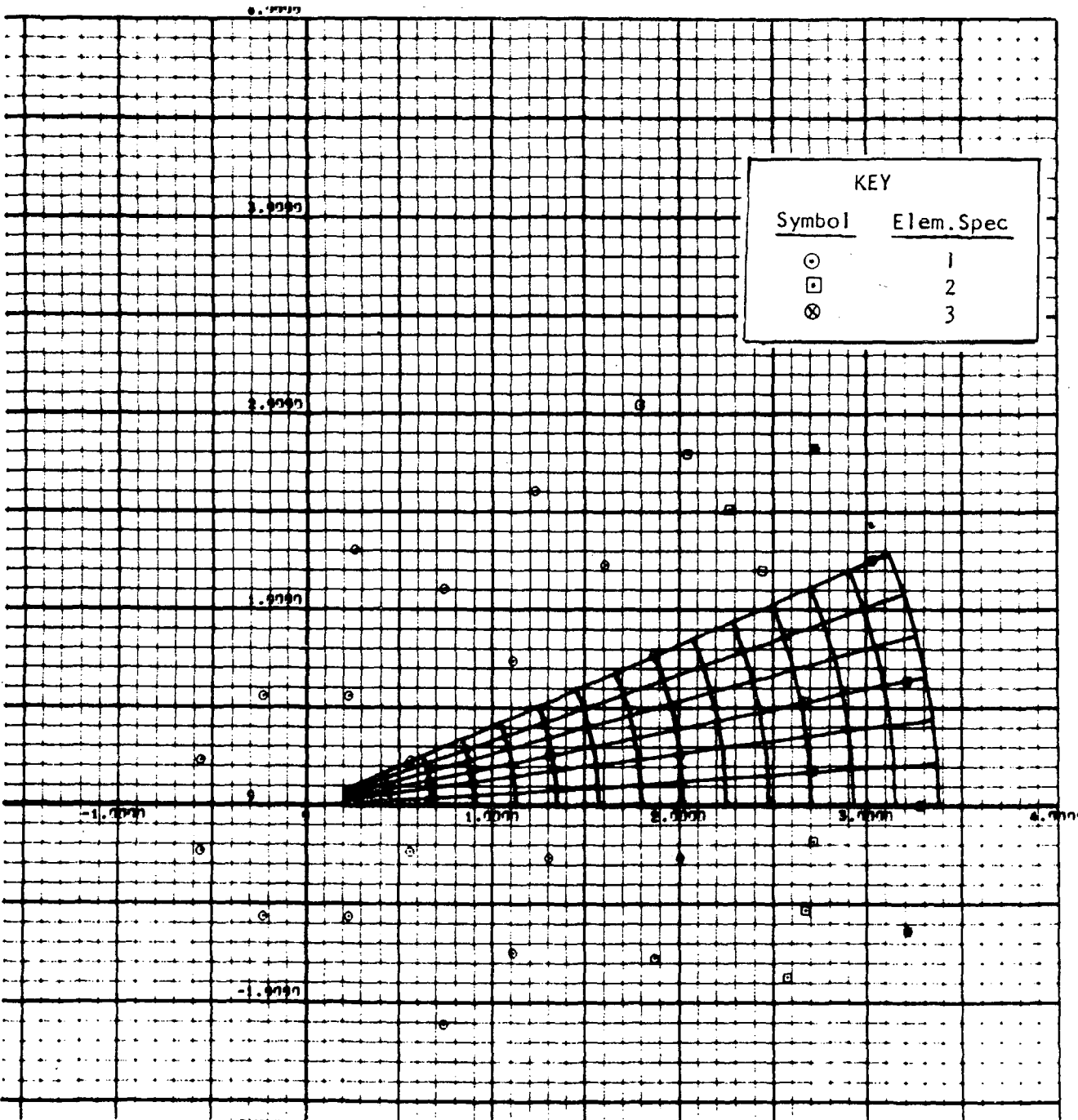
Discharge Coefficient - The discharge coefficient should be adjusted to give the flowrates calculated in step 4. The relationship used in LISP is

M_orifice = 0.6683 C_D A_orifice √ρΔP

with M in lbm/s, A in square inches, ρ in lbm/ft³, and ΔP is psia

Spray Coefficients, Section 2.6.3

Mean Droplet Diameters, Section 2.6.4



LMA INJECTOR ELEMENT SPECIFICATIONS

SPEC	TYPE	NO.	D ₁	D ₂	γ _E	Z _E	β	γ	ZONE
1	ULD(1)	25	.0319	.0362	68.5	.175	0	-5.75	Ring 5
2	ULD(1)	10 (35)	.0397	.0504	65	.175	0	-12.5	Ring 6
3	ULD(1)	15 (50)	.0274	.0330	45	.500 (.125)	0	0	Baffle
4	FLD(2)	3 (53)	.014	.014	45	.500 (.77)	0	0	BLC _{AX}
5	FLD(2)	1 (54)	.01372	.01372	45	.500	0	0	BLC Next to Baffle
6	FLD(2)	2 (56)	.014	.014	45	.500	0	0	BLC _{cant}
7	FLD(2)	1 (57)	.0194	.0194	45	.500	0	0	Baffle BLC
8	BLD(2)	1 (58)	.04042	.04042	45	.500	0	0	Baffle Center

LMA INJECTOR ELEMENT LAYOUT FOR LISP

ELEM	SPEC	R	θ	δ
1	1	0.9315	0	0
2	1	1.359	-7.5	180
3	1		7.5	
4	1		22.5	
5	1		32.5	
6	1	1.901	-10	0
7	1		10	
8	1		20	
9	1		30	
10	1		40	
11	1	2.329	-5	180
12	1		5	
13	1		15	
14	1		25	
15	1		35	
16	1		45	
17	1	2.871	-6	0
18	1		6	
19	1		12	
20	1		18	
21	1		24	
22	1		30	
23	1		36	
24	1		42	
25	1		48	
26	2	3.2675	-3	180
27	2		3	
28	2		9	
29	2		15	
30	2		21	
31	2		27	
32	2		33	
33	2		39	
34	2		45	
35	2		51	
36	3	0.454	60	64
37	3	1.359		
38	3	0.830		
39	3	1.018		
40	3	1.206		
41	3	1.394		
42	3	1.582		
43	3	1.770		
44	3	1.958		-116
45	3	2.146		
46	3	2.334		
47	3	2.522		
48	3	2.710		
49	3	2.898		
50	3	3.086		
51	4	3.62	-3	0
52	4		21	
53	4		45	
54	5		54	
55	6	3.895	9	
56	6	3.895	33	
57	7	3.57	60	
58	8	0	0	120

Section 2 Rigorous Analytical Procedure
2.6 Execution of Injector Analysis Step
2.6.3 CALCULATION OF LISP SPRAY COEFFICIENTS

Date: 11/15/74

The LISP computer-program has built-in coefficients for a number of element types. If a different type or different coefficients for a built-in type are desired, an override option is provided.

The mass flux distribution of droplets of each injected propellant in LISP is given by the relationship

$$\hat{M}(x, y, z) = \hat{M}_{001} \left\{ \left[1 + C_1 \left(\frac{y}{z} \right) + C_2 \left(\frac{y}{z} \right)^2 \right] + \left[C_3 \left(\frac{x}{z} \right) + C_4 \left(\frac{y}{z} \right)^2 \right] \left[1 + C_5 \left(\frac{y}{z} \right) + C_6 \left(\frac{y}{z} \right)^2 \right] \right\} e^{-a \left(\frac{y}{z} \right)^2 - b \left(\frac{y}{z} \right)^2}$$

The coefficients a , b , $\hat{M}_{001}$, and C_1 through C_6 are evaluated empirically from results of cold-flow simulation test data taken by methods such as those described in Ref. *. The correlation procedure consists of the following steps:

- Simplifying the equation for a specific element type by using symmetry and continuity conditions to identify coefficients that either vanish or are functionally related to other coefficients.
- Integrating the simplified equation and appropriate x and y moments along the x and y axes or over the entire x - y plane. The functional form was selected to (1) satisfy continuity, (2) match the observed inverse square variation, and (3) have integrable moments over intervals such as $0 \leq x \leq \infty$, $-\infty \leq y \leq \infty$, etc.
- Performing the equivalent numerical integrations on the cold-flow distribution test data to obtain empirical values of the integrals
- Equating the analytically integrated expressions to the empirically determined values to form a system of algebraic equations, and solving the equations for the coefficients
- Repeating the process for tests run for a range of orifice diameters, impingement angles, momentum ratios, etc., to determine the variation of the coefficients with design parameters of interest.

Section 2 Rigorous Analytical Procedure
2.6 Execution of Injector Analysis Step
2.6.4 LISP DROP-SIZE DETERMINATION

Date: 11/15/74

The current built-in correlation for average drop size is naive and unrealistic for many element types. Care should be used in establishing the $\bar{D}$ to be used and alternatives to the built-in considered.

The calculational procedure currently built into the LISP computer program gives pessimistic results for many element types. Large discrepancies (10 percent) have been observed between test data and performance calculated using the built-in correlation (Ref. *). In general, the built-in correlation should be overridden with an externally determined average diameter ($\bar{D}$).

No analytical methods are available and checked out, although methods developed by Priem and Heidmann (Ref. **) show promise and can be used. The most acceptable procedure is to rely on test data. Droplet size test data can be obtained in several ways:

- Correlation of C* or ISP data
- Liquid wax droplet data
- Holography data
- Liquid cold flow

These methods are described in CPIA 245. The use of C* or ISP data to determine a drop size and then to extrapolate to new conditions is also discussed in Section 1.3.3. As presented by Salmon and Pieper (Ref. *), the use of C* or ISP data is based on the differing effects of vaporization and mixture ratio distribution. If tests have been run for different mixture ratios, LISP can be used to match the slope of energy release efficiency with mixture ratio (mixture ratio distribution). The magnitude of the energy release efficiency is then matched by varying $\bar{D}$.

LISP supplies droplet size groups to either 3DC or STC. The droplet groups are derived by expanding the distribution about the mean size. Several standard distributions are (Ref.***):

Nukiyama-Tanasawa (N-T)

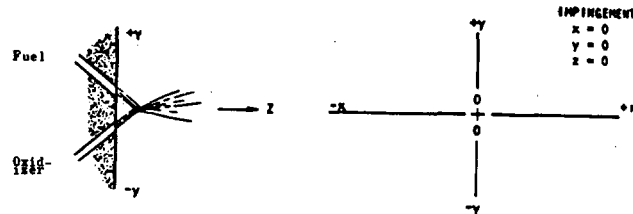
$$\frac{dN}{dD} = aD^2 e^{-bD^n}$$

*Design Analysis Procedures Using the JANNAF Distributed Energy Release Computer Program, J. W. Salmon and J. L. Pieper, JANNAF Combustion Meeting, September 1974.

**Priem, R. J. and Heidmann, N.F., Vaporization of Propellants in Rocket Engines, ARS, J., Vol. 29, 1959, p. 836.

***WADC TR 56-344, Injection and Combustion of Liquid Fuels, Putnam et al., Battelle, March 1957.

The spray correlation with its nine coefficients appears to be an unwieldy expression to employ in even a computerized calculation. The form of the spray correlation becomes much simpler for a given injection element. Consider a single unlike doublet with equal stream momenta and the coordinate system sketched below:



Consideration of fan symmetry requires that coefficient C_3 vanish. Similarly, the requirement that the spray flux must not become negative anywhere downstream of the impingement point leads to the following relations

$$C_2 = \frac{C_1^2}{4}$$

$$C_6 = \frac{C_5^2}{4}$$

Thus, for the unlike doublet the relationship becomes

$$\hat{M}_i(x, y, z) = \frac{\hat{M}_{001}}{z^2} \left\{ \left[1 + C_1 \left(\frac{y}{z} \right) + \frac{C_1^2}{4} \left(\frac{y}{z} \right)^2 \right] + C_4 \left(\frac{x}{z} \right)^2 \left[1 + C_5 \left(\frac{y}{z} \right) + \frac{C_5^2}{4} \left(\frac{y}{z} \right)^2 \right] \right\} e^{-a \left(\frac{x}{z} \right)^2 - b \left(\frac{y}{z} \right)^2}$$

The nine coefficients are reduced to six coefficients. The coefficient M_{001} corresponds to the droplet mass flux at $x = 0, y = 0$, and $z = 1$ inch and can be evaluated directly from experimental cold-flow data from the relationships

$$\hat{M}(x, y, z) = \frac{\hat{M}_{001}}{z^2} \psi$$

$$\hat{M}_e = \frac{\hat{M}_{001}}{z^2} \int_{x,y} \psi da$$

$$\hat{M}_{001} = \frac{\hat{M}_e z^2}{\int_{x,y} \psi da}$$

where $\dot{M}_e$ is the total flow (lbm/sec) of one propellant from an element, and ψ is the experimental distribution function.

Evaluation of the coefficients in the spray flux equation is simplified by the fact that both the spray equation itself and its moments with respect to the x and y axes can be integrated in closed form over the limits $-\infty$ to $+\infty$ or 0 to ∞ . Expressions useful to the evaluation of correlation coefficients from cold-flow data are obtained when the integrations are performed either along the x axis ($y = 0$), along the y axis ($x = 0$), or over the entire x,y plane. Examples of useful expressions include

$$\int_{-\infty}^{\infty} \int_{y=0}^{\infty} \hat{M} dx = \frac{\hat{M}_{001}}{z} \frac{\sqrt{\pi}}{a} \left(1 + \frac{C_4}{2a} \right)$$

$$\int_{-\infty}^{\infty} \int_{x=0}^{\infty} \hat{M} dy = \frac{\hat{M}_{001}}{z} \frac{\sqrt{\pi}}{b} \left(1 + \frac{C_2}{2b} \right)$$

$$\int_0^{\infty} \int_{y=0}^{\infty} x \hat{M} dx = \frac{\hat{M}_{001}}{2a} \left(1 + \frac{C_4}{a} \right)$$

$$\int_{-\infty}^{\infty} \int_{x=0}^{\infty} y \hat{M} dy = \frac{\hat{M}_{001} C_1}{2b} \frac{\sqrt{\pi}}{b}$$

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} y \hat{M} dy dx = \frac{\hat{M}_{001} \pi z}{2b \sqrt{ab}} \left[C_1 + \frac{C_4 C_5}{2a} \right]$$

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} y^3 \hat{M} dy dx = \frac{3 \hat{M}_{001} \pi z^3}{4 b^2 \sqrt{ab}} \left[C_1 + \frac{C_4 C_5}{2a} \right]$$

A variety of other integrals may be defined where convenient for cold-flow data correlation.

With the integrals evaluated empirically the above expressions become algebraic equations in the unknowns. Further examples of the method of correlation may be found in Ref.**.

**Catalog of Injector Spray Correlations, L. P. Combs, NAS7-746, 22 June 1972, Rocketdyne --Available from R. Kushida at Jet Propulsion Laboratory.

Rosin-Rammler Equation

$$\frac{dN}{dD} = \frac{6bn}{\pi} D^{n-4} e^{-bD^n}$$

Logarithmico-Normal

$$\frac{dN}{dD} = \frac{6}{\pi\sqrt{2\pi} \sigma D^4} e^{-1/2\sigma^2 (\ln D/D_{\text{median}})^2}$$

LISP has the N-T distribution built-in, but the distribution can be overridden.

Section 2 Rigorous Analytical Procedure
2.6 Execution of Injector Analysis Step
2.6.5 SPECIAL PROBLEMS OF LISP

Date: 11/15/74

The LISP program cannot yet be considered a full production-type computer program, and any case that does not fall into a standard type may cause difficulties.

The LISP computer program has been checked out for the specific types of injectors and elements used as basic information for the program. All types of injectors and impinging elements can be run, but require special handling. Some special cases are:

Baffles. The current version of the LISP program assumes that all of the elements are in the same plane (although the impingement points can be different). In many baffled injectors, there are elements at the ends of the baffles (for flow continuity). Even without elements, baffles cause flow impingement effects beyond the scope of LISP. Using different element types and forcing spray patterns, the spray from a baffled injector can be approximated (as illustrated in the LMA sample case), but the results are never certain.

Gas. The LISP computer program treats gases as if the gas traveled along straight paths or rays in the manner the spray is treated. As discussed in Section 2.7, the STC program must accept the gas as a uniform flow. LISP cannot handle injectors having one gaseous propellant well. Also, because of the highly simplified combustion model in LISP, the program should not be run beyond a point of minimal (20 percent) gas generation.

Manifold Distribution. Because LISP handles a finite number of elements and element types for any given run, the treatment of propellant distribution may have to be approximate. In particular, the treatment of random vibrations from element to element may be impossible for injectors containing a variety of element types, since each discharge coefficient also requires a separate specification.

Recirculation. Combustion chambers of designs that encourage large-scale recirculation can be approximated in LISP, but are subject to the same problems as gaseous elements.

Secondary Atomization. Secondary atomization is not explicitly considered in LISP so this effect must be included in the initial mean droplet diameter estimate and the droplet distribution function. Since the correct droplet size groups are the primary data passed to STC, this limitation is not important if the experimental data used were taken in a way that included secondary atomization.

Section 2 Rigorous Analytical Procedure
2.6 Execution of Injector Analysis Step
2.6.6 SETUP OF CICM

Date: 11/15/74

The CICM computer program is intended to analyze coaxial shear-type elements. Major inputs include extensive property tables, mixture ratio distributions, and droplet size and stripping rate parameters.

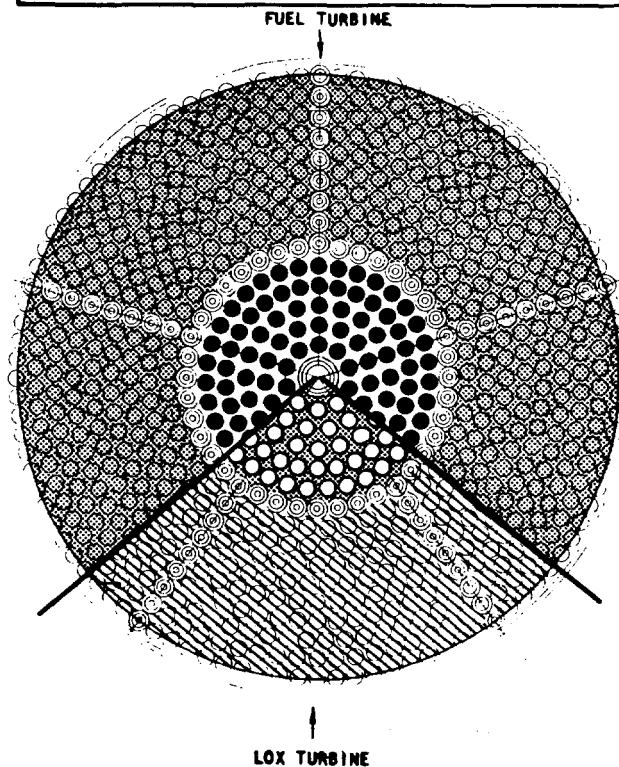
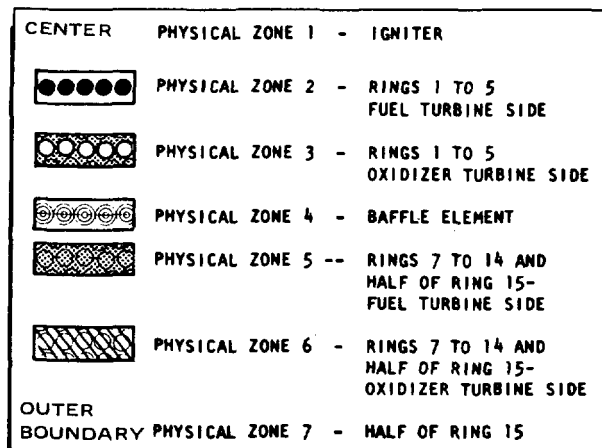
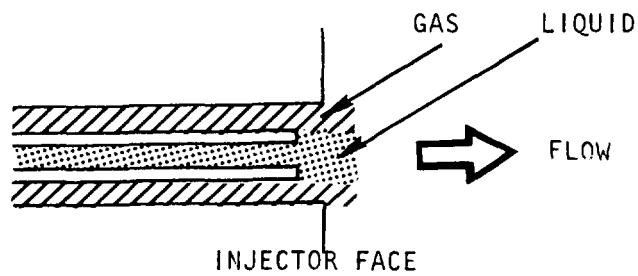
The CICM computer program can analyze a single gas/liquid coaxial injector element of the type shown in the top figure on the opposite page. Three distinct flows are considered--oxidizer, fuel, and transpiration coolant. As the computer program calculation plane advances, droplets are stripped from the central liquid jet and combust in the gas stream (using combustion calculations identical to those in the droplet heating version of STC described in Section 2.8.1). A number of elements are run consecutively to model an injector having distinct zones (middle figure opposite), and the outputs are punched for use in STC, Section 2.8. CICM is described in detail in Ref. *.

Property Tables - Large tables of thermodynamic properties, transport properties, and diffusion coefficients are required, so the setup time for a new propellant combination is significant. These tables are essentially identical to those needed in Droplet Heating STC (DHSTC), as discussed in Section 2.3.1.

Mixture Ratio/Mass Flux Distributions - A coaxial element spray has a mixture ratio and mass flux distribution. These distributions cannot yet be determined *a priori* but must be found empirically for the element and conditions of interest. These empirical distributions are used as input to CICM. The radial distributions are divided into zones and the mass and mixture ratio in each zone are calculated and used as input.

Droplet Size/Stripping Rate Parameters - The two governing parameters are the constants in the equations given in Section 2.6.1 - B_A and C_A . The variable names used in CICM are BSPRC and CSPRC. The derivation of B_A and C_A from test data is discussed in Section 2.6.7.

*Operating Manual for Coaxial Injection Combustion Model, R. D. Sutton, M. D. Schuman, and W. D. Chadwick, NASA CR-129301, April 1974.



2.6.6B

Section 2 Rigorous Analytical Procedure

Date: 11/15/74

2.6 Execution of Injector Analysis Step

2.6.7 DETERMINATION OF CORRELATION PARAMETERS FOR CICM

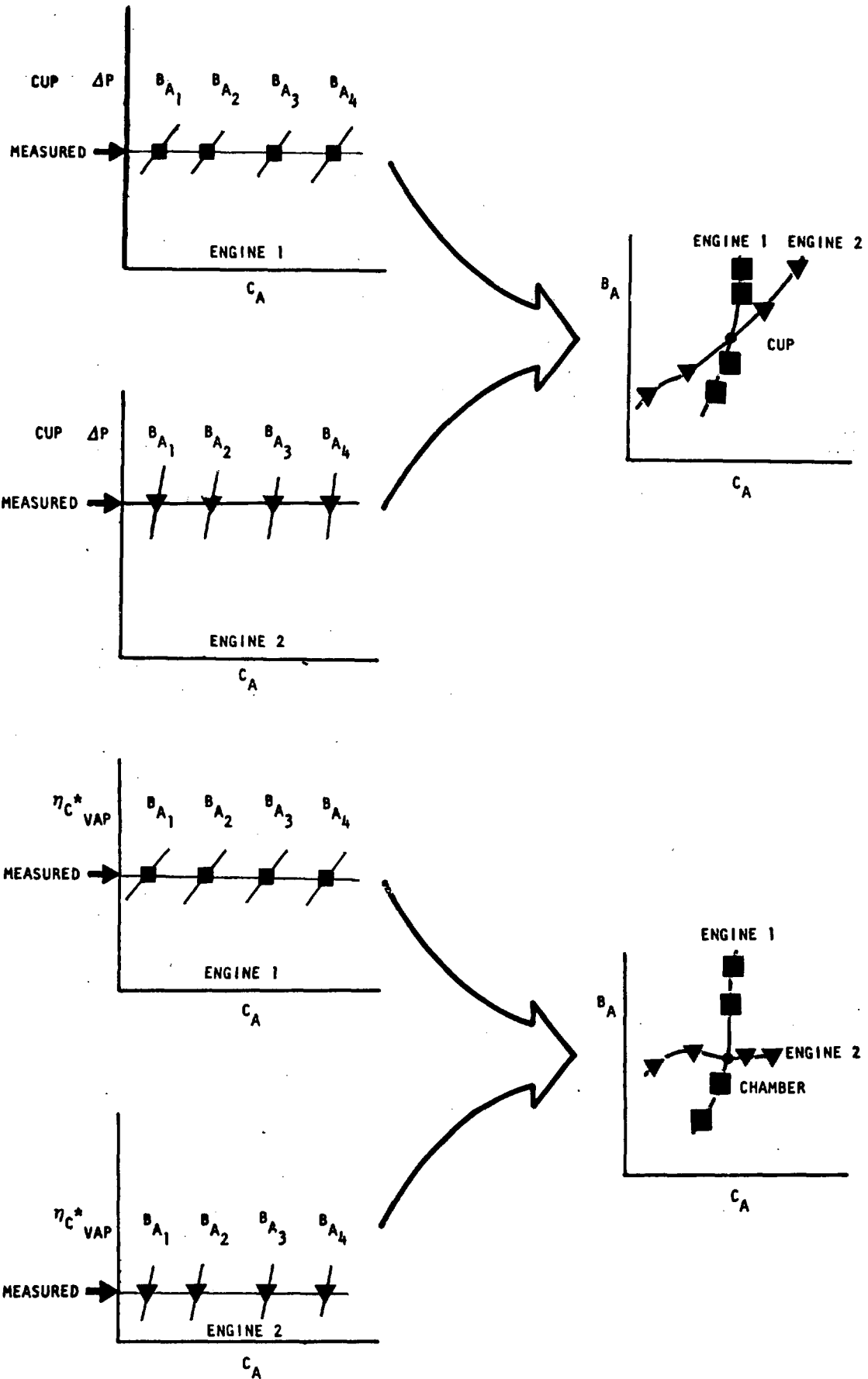
The drop size and stripping rate parameters are based on the assumption that these parameters are essentially constant from engine to engine for a given propellant combination.

Two sets of drop size and stripping rate parameters are required by CICM, one for the recess or cup region, and the other for the unrestrained flow or chamber region. The parameters are currently determined by comparison of data for two different engines. For the cup region, the cup ΔP is used as the empirical measure for cup B_A^* and C_A^* . For the chamber region, η_{c^*} is used to get B_A and C_A for the region beyond the injector face. VAP

As shown on page 2.6.7B, cup ΔP is plotted as a function of C_A for several values of B_A (B_{A1}, B_{A2} , etc.). The values of C_A that match the measured ΔP for each B_A are determined ($\blacksquare, \blacktriangledown$). The sets of points (B_{A1}, C_{A1} ; B_{A2}, C_{A2} ; etc.) are then plotted for the two injectors. The crossing point of the two curves gives the unique combination of B_A and C_A that will reproduce cup ΔP for both engines. The procedure is then applied to η_{c^*VAP} .

The B_A and C_A parameters for the cup and chamber are built into CICM and are intended to correlate all coaxial injectors, both recessed and nonrecessed. The built-in parameters can be modified if future results are unacceptable.

*See Section 2.6.1 for defining relationships for B_A and C_A .



Section 2 Rigorous Analytical Procedure
2.7 Execution of Turbulent Combustion Step
2.7.1 CONCEPTUAL BASIS

Date: 11/15/74

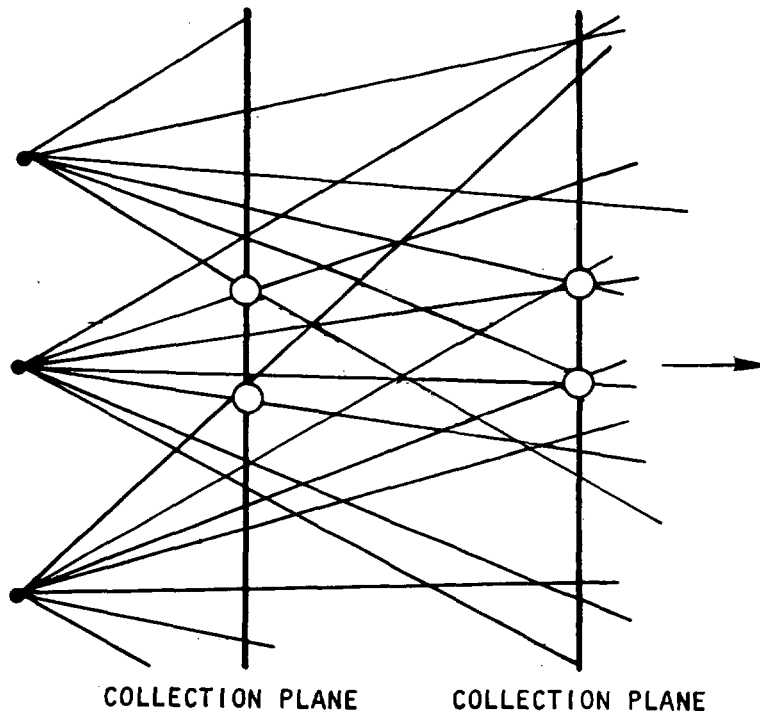
For injectors having relatively widely spaced liquid-liquid impinging elements, the 3DC computer program may have to be employed to extend the spray distribution from LISP prior to initiation of STC.

In the turbulent region, droplet formation is largely complete and full-scale combustion occurs, but flow from region to region is still possible. The LISP program and 3DC program handle this simultaneous continuous mixing and combustion in conceptually different ways, indicated in the figures on page 2.7.1B.

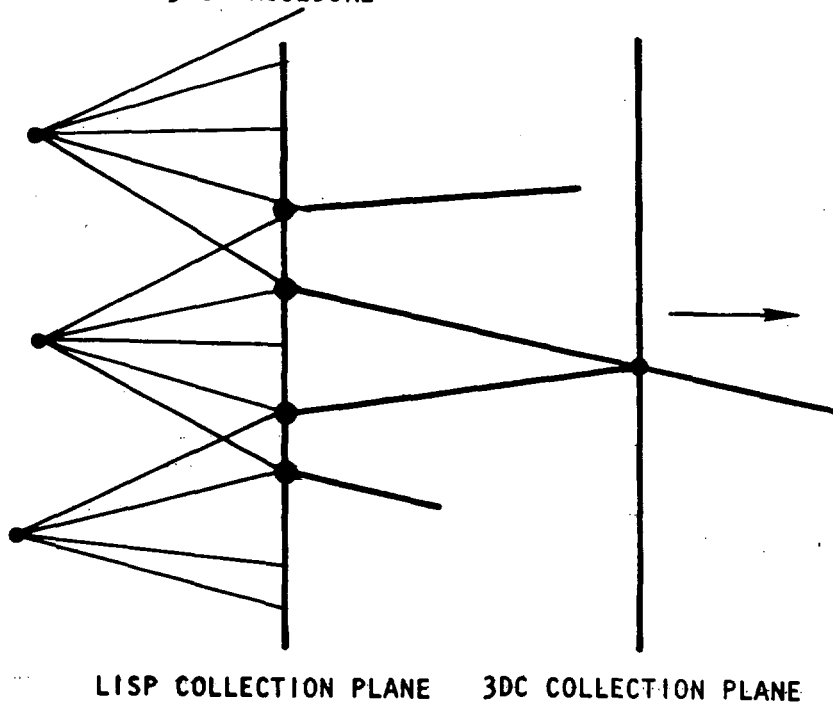
In the LISP program, droplets are assumed to spread outward from the impingement point in rays distributed according to the spray correlation function discussed in Section 2.6.1. At each collection plane, the spray at each mesh point is the sum of the contributions from all elements at that location. At the next plane, the same summation is applied as if each spray pattern expands independently of every other. The further the program is run, the greater the mixing.

In the 3DC computer program, the spray patterns at the last LISP collection plane are summed vectorially (conserving momentum), and a resultant vector from that mesh point propagates to the next mesh point where the vectors are summed into the next set of vectors. By this procedure, the spray is gradually turned until all the flow is axial and no further mixing occurs. Although this procedure is probably more accurate physically, problems in mesh size and interfacing with LISP can cause 3DC to terminate or actually reverse the mixing from LISP, resulting in unrealistically low mixing efficiencies. 3DC uses the k-prime combustion calculations (Section 2.8.1).

LISP PROCEDURE



3DC PROCEDURE



Section 2 Rigorous Analytical Procedure
2.7 Execution of Turbulent Combustion Step
2.7.2 SETUP of 3DC

Date: 11/15/74

The 3DC is initiated at the LISP ZOM plane using the output of drop diameters, distribution, and velocities at that plane.

The 3DC computer program is tailored specifically to match the LISP program outputs. The major inputs are physical property data, geometry, spray conditions at ZOM (Z1 in 3DC), gas conditions at ZOM. 3DC uses a mesh approach similar to LISP, but is currently not capable of as fine a mesh. 3DC should be used primarily for injectors with few widely spaced elements.

Selection of ZOM/Z1 Interface. The interface between LISP and 3DC should occur at the plane where the spray patterns from different elements begin to overlap significantly*. Up to this point, collisional effects can be ignored. Beyond this point, collisional effects can still be ignored but at the loss of physical reality. This plane generally occurs at 0.25 to 1 inch beyond the impingement point.

Gas Conditions. One of the major problem areas encountered in the use of 3DC (and the primary reason the program was left optional rather than required) is the discontinuity in gas conditions at the ZOM/Z1 interface. Gas in LISP is treated in the same manner as droplet spray--radiating outward from the impingement point. At the start of 3DC, all of the gas is averaged into a uniform gas flow (unless a special option is used). With this averaging procedure, mixture ratio continuity cannot be maintained. With the other option, velocity continuity cannot be maintained. For most liquid-liquid cases, very little gas has been formed prior to starting 3DC. The use of 3DC is not recommended currently for gas/liquid injectors.

Mesh Selection. In general, the 3DC mesh should be based on the mesh used in LISP. The mesh is currently limited to 7 x 15 so care must be used if a finer LISP mesh is used. For some cases, the averaging performed in going to a coarser mesh loses so much detail and causes so much artificial mixing that the use of 3DC is not recommended. If LISP and 3DC use the same mesh size, the results for a liquid/liquid-element injector should be accurate.

*Sections 2.8.3 and 2.8.4

Section 2 Rigorous Analytical Procedure
2.8 Execution of Stream Tube Combustion Analysis Step
2.8.1 CONCEPTUAL BASIS

Date: 11/15/74

Two versions of the STC computer program are available. Both assume that radial velocity can be ignored for most of the combustion chamber length and that turbulent diffusion does not affect mixing strongly. The more exact version includes heat transfer within droplets while the quicker assumes constant temperature.

The stream tube combustion model assumes that all radial velocity components become negligible at some point in the flow through the chamber and that diffusion effects are negligible. These assumptions may be in error for large droplets in the turning regions of the throat or for thin boundary coolant layers near the wall where both mass and energy diffusion can have a large impact even when small enough to be negligible in the bulk of the flow. For many cases, however, the model has good physical reality and is recommended for use in all cases even if the starting conditions have to be modified slightly to model additional mixing.

Two combustion models are employed. The more exact of the two--the droplet heating version (Ref. *)--is valid for both subcritical and supercritical pressure. The model is based on the fact that liquid is vaporized from the droplet surface by the heated gas, and this vapor then reacts in the wake of the droplet, obeying the laws of normal gas-phase reaction kinetics.

The program works with conservation of mass, number of droplets, momentum, and energy. The droplets are divided into distinct size groups having the mean diameter from LISP. The gas- and liquid-phase equations are coupled through mass and momentum exchange between phases. Drag forces on droplets are expressed by:

$$F = N_p D C_D (V_g - V_d) | V_g - V_d |$$

with the drag coefficient, $C_D = 24 (Re)^{0.84} (Re < 1)$ or $0.271 (Re)^{0.217} (Re > 1)$.

The droplet heating formulation calculates, for each droplet size group:
(1) the rates of recession (due to vaporization) and expansion (due to

*Documentation for Interim Delivery of the Revised Computer Program With Droplet Heating, NAS7-746, available from R. Kushida, Jet Propulsion Laboratory.

heating) of the surface, (2) the outward diffusion rate of vapor from the surface, (3) the droplet heatup rate, (4) the solubility of the combustion gas in the propellant, (5) the continued vapor diffusion after the droplet passes the critical temperature. Both the burning rate and the heatup rate are proportional to (1) the droplet diameter, (2) the diffusion coefficient, (3) the Nusselt number and (4) terms involving the molecular weights and mass fractions of the vaporized propellant and the combustion gases.

For combustion at pressures substantially (20 percent) below critical pressure in which the droplet heating time to wet bulb temperature is negligible, and solubility of the combustion gas is low, a simplified version of STC can be employed. This combustion model is also used in 3DC and, further simplified, in LISP. In this formulation, the evaporation rate is directly proportional to the diameter, density, Nusselt number, and evaporation coefficient (k') given by

$$k' = \frac{8}{\rho} \int_{T_d}^T \frac{k_g}{\Delta H_v + \frac{T}{T_d} C_{p_v}} dT$$

with the Nusselt number, $Nu = 2.0 + 0.53 (Re)^{1/2}$ and k_g the thermal conductivity of the gas film surrounding the droplet. ΔH_v is the heat of vaporization, C_{p_v} is the vapor specific heat, T_d is droplet temperature, T is vapor temperature, and ρ is vapor density.

Section 2 Rigorous Analytical Procedure
2.8 Execution of Stream Tube Combustion Analysis Step
2.8.2 SETUP OF STC

Date: 11/15/74

The data used in STC are supplied by LISP, 3DC, CICM, or empirically. The data are put in annular form by STC. The concern is the STC start plane.

The data required for STC are the distribution of mass and mixture ratio for gases and droplets at the start plane (ZOM for LISP, ZSTOP for 3DC, DERMIN for CICM), droplet mean diameters, the starting plane for stream tube flow (ZSTART, which may or may not be set equal to ZOM or ZSTOP), and tables of propellant properties, including diffusion coefficients (DHSTC) or k-primes.

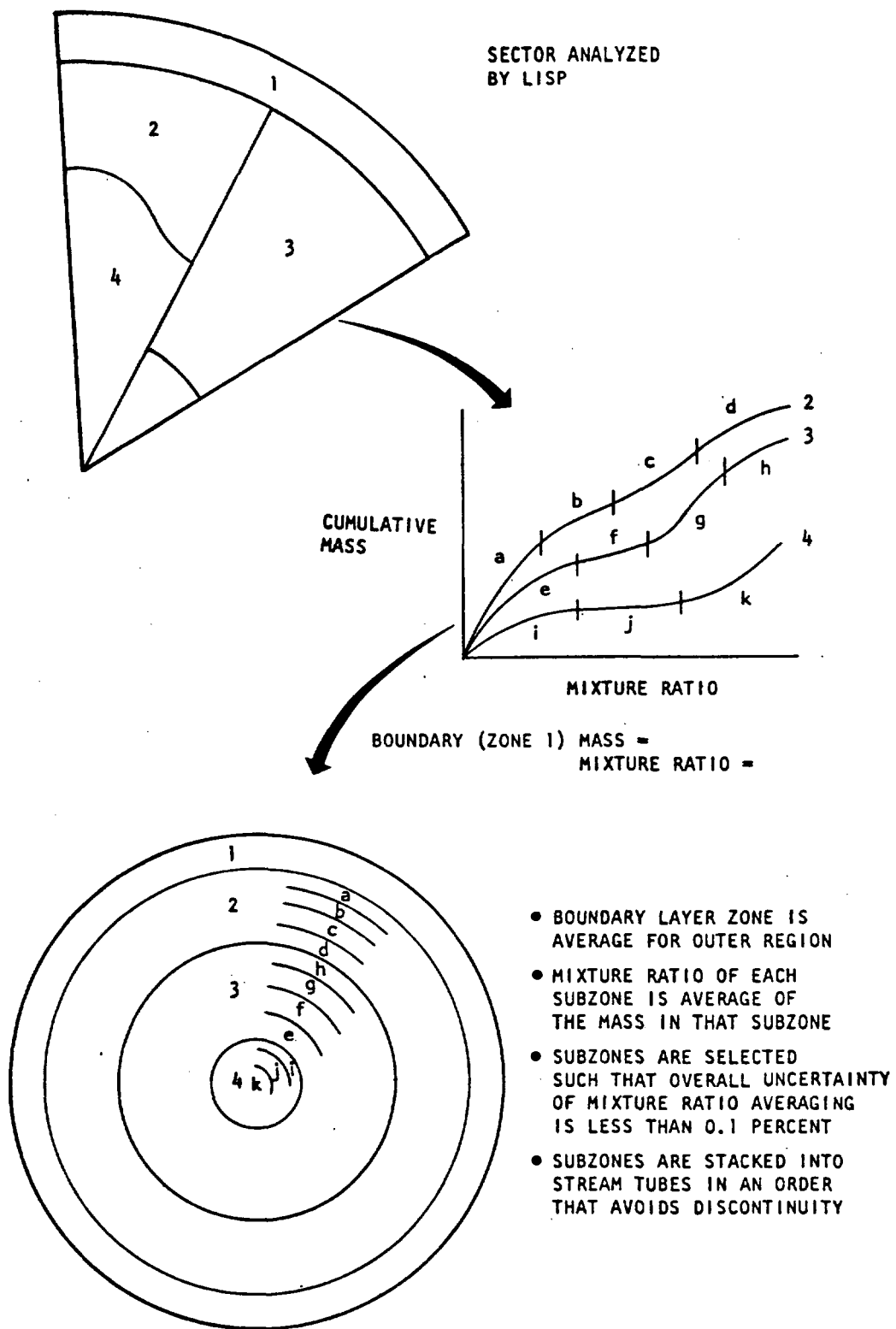
Annularization. The information from LISP, 3DC, or CICM contains a description of the differences in mixture ratio and droplet sizes from different regions of the injector. These regions can have any shape or location up to this point. However, a computer program limitation forces the reordering of the data with partial loss of information. Both the TDK and BLIMP programs assume annular symmetry. Thus, the arbitrarily shaped zones used in injection and turbulent combustion analysis must be converted to annular zones while preserving as much of the effect on performance as possible. The annularization procedure is shown in the illustration and should be followed even when optional procedures bypassing STC are used (Section 4.2.3). As shown, the mass/mixture ratio distribution is determined for each of the injector zones. These distributions are then spread across annular zones. The continuous distributions are divided into intervals preserving mass and mixture ratio continuity.

Propellant Properties. In analyzing a new propellant combination, sufficient time (~2 weeks) should be allowed for the preparation of the required data tables described in Ref. * and **.

Selection of Planes. The selection of ZOM, ZSTOP and ZSTART planes is discussed in the next section.

*DER Computer Program Documentation and User's Guide, L. P. Combs and W. D. Chadwick, available from R. Kushida, Jet Propulsion Laboratory

**Documentation for Interim Delivery of the Revised Computer Program With Droplet Heating, available from R. Kushida, Jet Propulsion Laboratory



Section 2 Rigorous Analytical Procedure Date: 11/15/74
2.8 Execution of Stream Tube Combustion Analysis Step
2.8.3 A *PRIORI* SELECTION OF INTERFACE PLANES (ZOM, ZSTART)

By use of the two planes at the LISP/3DC-STC interface, mixing and vaporization effects can be independently varied and studied.

The three interface planes for combustion analysis are shown at the top of page 2.8.3B. ZOM is the LISP stop plane, ZI is the 3DC start plane, ZSTOP is the 3DC stop plane, and ZSTART is the STC start plane.

As shown on the opposite page, the ZOM and ZSTOP planes affect the mixing efficiencies (C^* and ISP). If 3DC is not used, increasing ZOM always increases mixing. As shown in Section 2.7.1, 3DC turns the flow into stream tubes and cuts off mixing (mixing limited performance). For some pathological cases, 3DC can indicate demixing (probably fallaciously because of the gas interfacing problem). However, LISP should not be run much past the point that either propellant is more than 25-percent vaporized and 3DC should not be run beyond the point of negligible transverse velocities. Usually ZOM or ZSTOP will be between 1 and 2 inches below the impingement point.

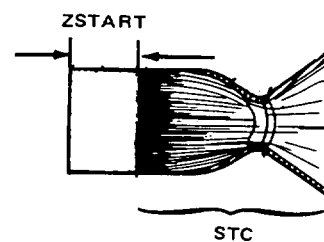
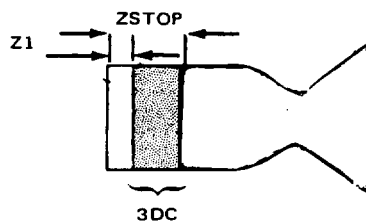
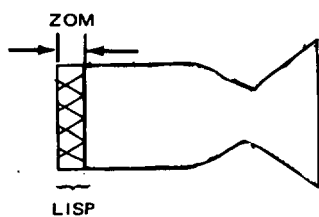
The ZSTART plane in STC sets the vaporization efficiencies (C^* and ISP) for a given $\bar{D}$ as indicated in the bottom figure. Therefore, by independent selection of ZSTART and ZOM, almost any combination of mixing loss and vaporization loss can be selected (if physical reality is ignored). This capability is useful in matching C^* data for later prediction of ISP (Ref.*).

The procedure most closely approximating the physical model is to

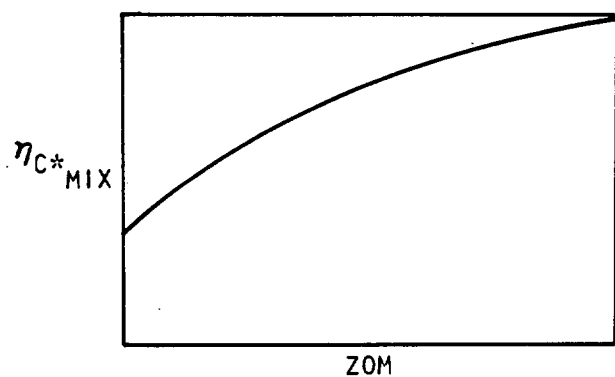
- Run LISP to a ZOM at which the spray patterns from different elements start to overlap. Then initiate 3DC.
- Run 3DC until transverse velocities become negligible. Then initiate STC.
- Run STC with ZSTART = ZSTOP from 3DC

However, because of the program limitations, better agreement with performance data may be achieved through ignoring the physically realistic interfacing and using ZOM and ZSTART as fudge factors. For *a priori* calculations, physical reality should be preserved unless tests or other justification for deviation is available.

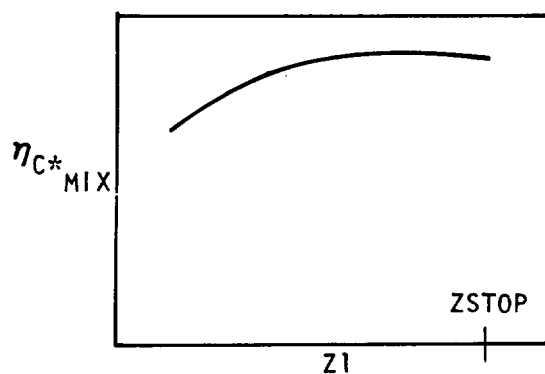
*CPIA 245, JANNAF Rocket Engine Performance Data Acquisition and Interpretation Manual.



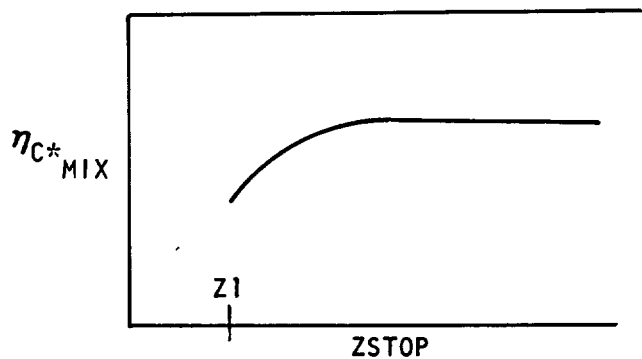
IMPACT OF ZOM PLANE FROM LISP



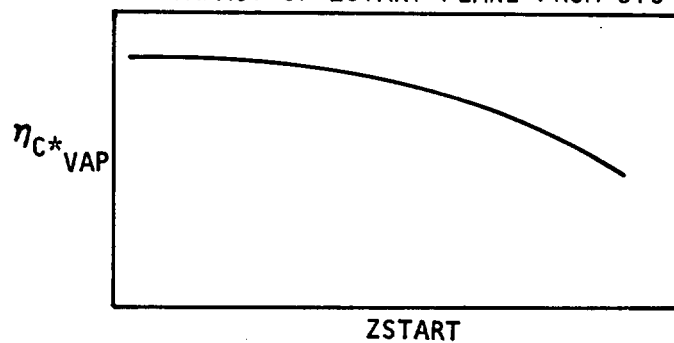
IMPACT OF Z1 PLANE FROM 3DC



IMPACT OF ZSTOP PLANE FROM 3DC



IMPACT OF ZSTART PLANE FROM STC



- Increasing ZOM increases mixing efficiency
- Increasing Z1 increases mixing efficiency
- Increasing ZSTOP increases mixing efficiency
- Increasing ZSTART decreases vaporization efficiency

Section 2 Rigorous Analytical Procedure

Date: 11/15/74

2.8 Execution of Streamtube Combustion Analysis Step

2.8.4 SEMI-EMPIRICAL SELECTION OF STARTING PLANES
(ZOM, ZSTART) AND DROP SIZE

Use of test data to calibrate the selection of the ZOM plane and median dropsize $\bar{D}$, is preferable to an all *a priori* approach.

Because of limitations of built-in correlations for $\bar{D}$ and lack of experience with the selection of ZOM, *a priori* predictions using DER can be highly misleading. If test data are available, these data should be used to calibrate the $\bar{D}$ and ZOM selections. A consistent procedure has been developed and applied by Pieper and Salmon (Ref. *), and is recommended for general use.

The procedure logic is illustrated in Figure 1. The ZOM plane of LISP is varied to develop a relationship between ZOM and the mixing limited performance (complete vaporization) given by η_{MIX} . The median drop size ($\bar{D}$) is varied to develop a relationship between $\bar{D}$ and the vaporization limited performance (complete mixing) given by η_{VAP} . The simplified definitions based on one-dimensional analysis can be used at this stage.

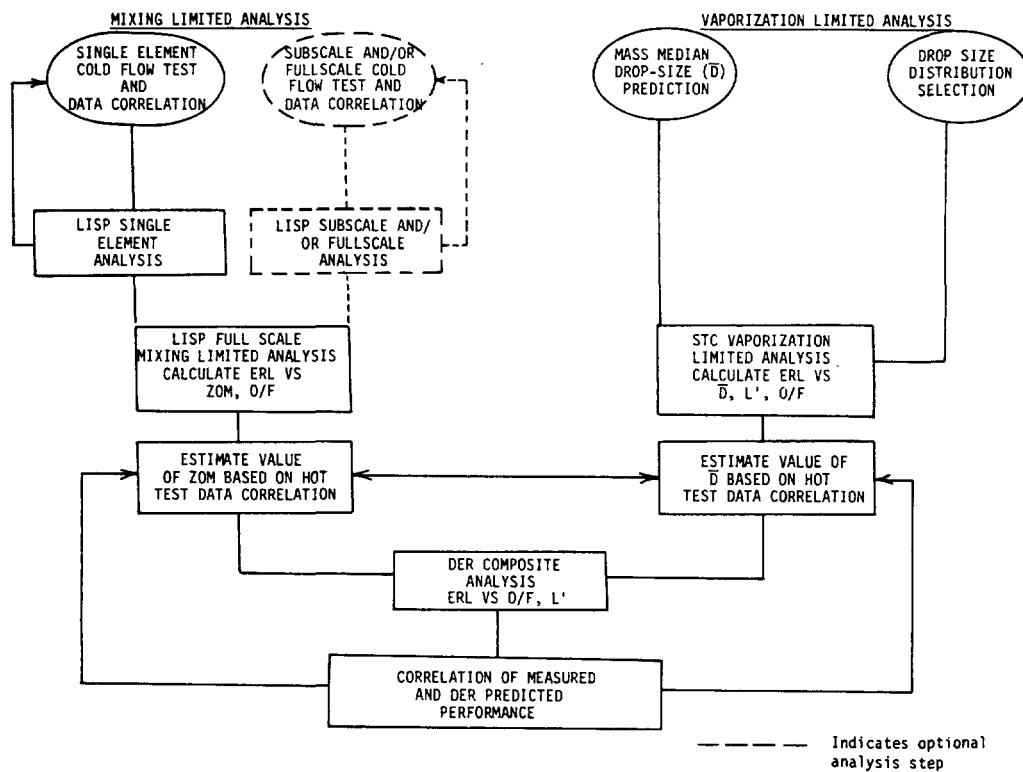


Figure 1. DER Design Analysis Procedure (Ref. *)

*Design Analysis Procedures Using the JANNAF Distributed Energy Release Computer Program, J. W. Salmon and J. L. Pieper, JANNAF Combustion Meeting, September 1974.

As shown in Figure 2, the $\bar{D}$ was determined by comparison of performance for two chamber lengths. With this $\bar{D}$, the value of ZOM that matched the experimental energy release loss of Figure 3 was established. If data at two chamber lengths had not been available, ZOM could have been picked to match the slope of the observed energy release loss with mixture ratio. $\bar{D}$ could then have been used to adjust the magnitude of the energy release loss since $\bar{D}$ has a much smaller effect on the slope. If $\bar{D}$ was fixed by some other data, the vaporization loss could be artificially varied by setting ZSTART in STC to a value other than ZOM.

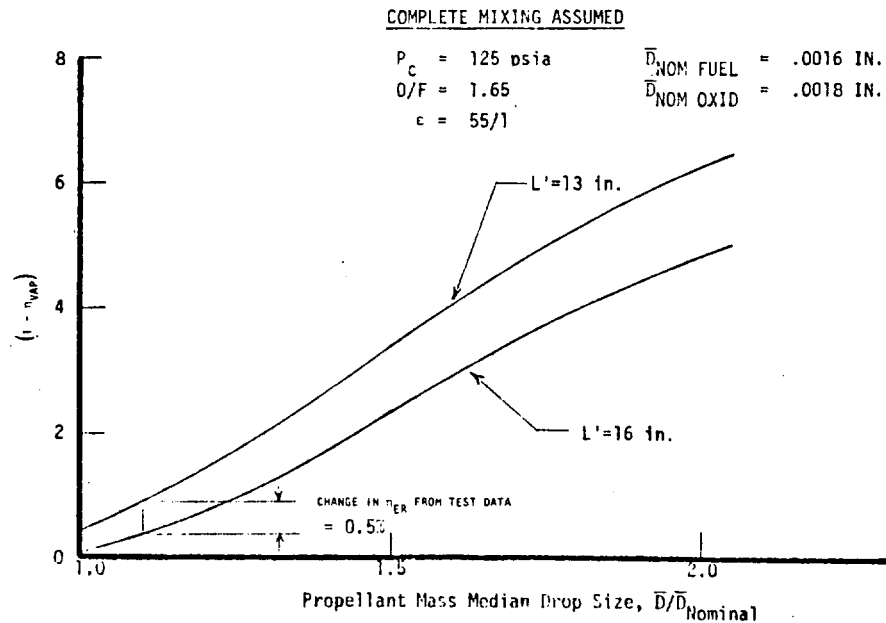


Figure 2. Influence of Drop Size and Chamber Length on STC Vaporization Limited Energy Release Efficiency (Ref. *)

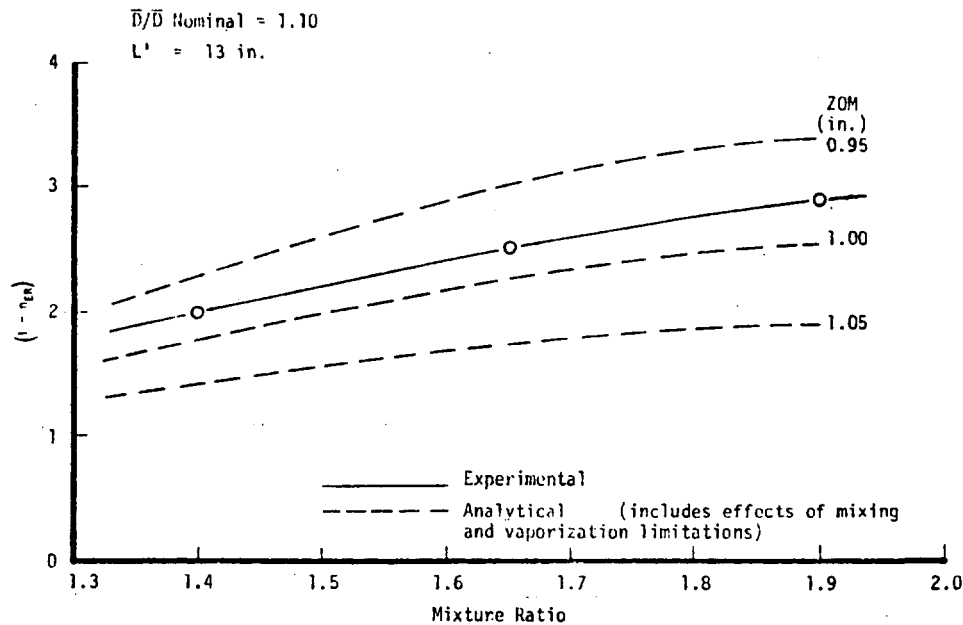


Figure 3. Comparison of the Experimental and Analytical Energy Release Loss (Ref. *)

Section 2 Rigorous Analytical Analysis
 2.9 Execution of Boundary Layer Steps
 2.9.1 CONCEPTUAL BASIS

Date: 11/15/74

Boundary layer theory is based on the observation that flows can be separated into two regimes -- a region that is affected by the presence of a physical wall (other than change of direction) and has significant transport (viscous) phenomena, and a region that is only negligibly influenced by the wall and having negligible transport phenomena (inviscid).

The boundary layer region is defined to include that portion of the flow next to the thrust chamber wall that has been substantially affected by transport interchange with the wall of mass, momentum or energy. By definition, any parameter (enthalpy, momentum, temperature, velocity) that varies more than 1 percent from the value that would exist if there were no transport to the wall causes that part of the mass flow to be included in the boundary layer. The width of the boundary layer from the wall is called the boundary layer thickness and may be different for each parameter used to define the 99 percent of uninfluenced flow point. For the most rigorous calculations, all integrations should extend to the thickest boundary layer (denoted by δ_x).

The mass flow through a real nozzle is given by:

$$\dot{M} = \iint_{\text{exit surface}} \rho \vec{V} \cdot d\vec{A} = \int_0^{\delta_x} 2\pi R \rho V dy + \int_0^{R_E - \delta_x} \frac{\cos \alpha_W}{2\pi R \rho V \cos \alpha_E} dR$$

where the coordinate nomenclature is given in the figure, ρ is density, V is velocity, and α is wall angle. If the nozzle flow was entirely inviscid, the area required to pass the same flow would be

$$\dot{M} = \iint_{\text{potential exit surface}} \rho \vec{V} \cdot d\vec{A} = \int_{\delta_*}^{\delta_x} 2\pi R \rho V dy + \int_0^{R_E - \delta_x} \frac{\cos \alpha_W}{2\pi R \rho V \cos \alpha_E} dR$$

If the pressure is assumed to be constant across the boundary layer and the strip $\delta_x - \delta^*$ is assumed to be thin, $\rho V \sim \rho_{PW} V_{PW}$ in the strip so

$$\begin{aligned} 2\pi R_E \rho_{PW} V_{PW} (\delta_x - \delta^*) + 2\pi \int_0^{R_E - \delta_x} \frac{\cos \alpha_W}{R \rho_{PW} V_{PW} \cos \alpha_E} dR \\ = \int_0^{\delta_x} 2\pi R_E \rho V dR + \int_0^{R_E - \delta_x} \frac{\cos \alpha_W}{2\pi R \rho V \cos \alpha_E} dR \end{aligned}$$

where subscript E is exit, PW is potential wall.

Making a second assumption that the inviscid flow is unaffected out to the streamline at δ_x , the two integrates cancel, giving

$$\delta^* = \int_0^{\delta_x} 1 - \frac{\rho V}{\rho_{PW} V_{PW}} dy$$

The last assumption is quite accurate for flow over a wing in free flight. However, *for internal flow, the upstream potential wall contour is influenced by the presence of the boundary layer.* This upstream wall shape can change the potential flow solution at the exit *if the boundary layer becomes thick, completely invalidating the δ^* concept.* This assumption is in accord with the assumption used that $\delta_x \ll R_E$. However, the assumption that the potential flow is identical to real flow out to $R_E - \delta_x \cos \alpha_w$ also requires the boundary layer to be thin everywhere upstream (particularly at the throat).

The nozzle thrust is given by:

$$\vec{F}_Z = \iint_{\text{exit surface}} \vec{V}_Z \rho \vec{V} \cdot d\vec{A} + \iint_{\text{exit surface}} P \hat{Z} \cdot d\vec{A}$$

and

$$F_Z = \int_0^{\delta_x} 2\pi R (\rho V V_Z + P_E \cos \alpha_w) dy + \int_0^{R_E - \delta_x \cos \alpha_w} 2\pi R (\rho V_Z^2 + P) dR$$

and, in terms of the equivalent mass potential flow,

$$F_Z = \int_0^{R_E - \delta_x \cos \alpha_w} 2\pi R (\rho V_Z^2 + P) p dR + \int_{\delta^*}^{\delta_x} 2\pi R (\rho V V_Z + P \cos \alpha) p dy - \Delta F_{BL}$$

where ΔF_{BL} is not the thrust loss caused by the boundary layer (which is given by the difference between inviscid flow in the actual contour and the real flow including viscous effects = $F_{TDKRW} - F_{TDKPW} + \Delta F_{BL}$) but is a correction that must be applied to the effective potential flow to get the thrust of the real flow. Working through the algebra using the same assumptions as for δ^* gives:

$$\begin{aligned} \Delta F_{BL} = & 2\pi R_E \rho_{PW} V_{PW}^2 \cos \alpha_{WE} \int_0^{\delta_x} \frac{\rho V}{\rho_{PW} V_{PW}} 1 - \left(\frac{V}{V_{PW}} \right) dy \\ & - 2\pi R_E P_{PW} \cos \alpha_{WE} \delta^* \end{aligned}$$

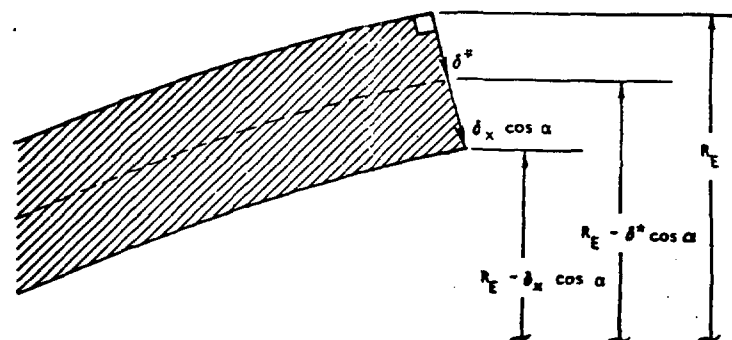
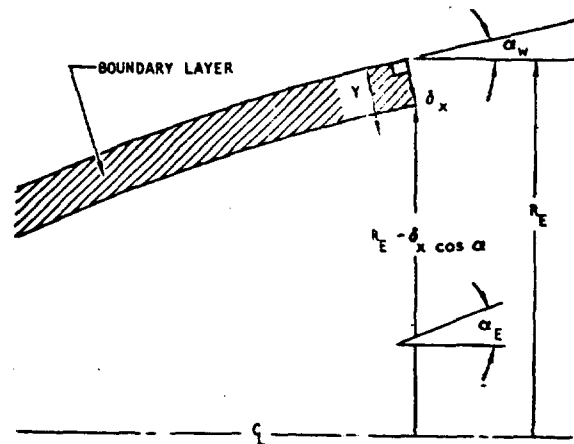
which is used in calculating overall thrust as shown in Section 2.12.1

The integral is identified as the thickness of potential flow that would carry the same momentum as the boundary layer, θ , so

$$\Delta F_{BL} = 2\pi R_E \cos \alpha_{WE} (\rho V^2 \theta - P \delta^*)_{WALL POTENTIAL FLOW}$$

Three results have been accomplished by the definition of boundary layer parameters:

- Viscous calculations have been localized to an essentially one-dimensional region near the wall where the flow parameters are established externally.
- An equivalent constant mass flow potential contour has been defined to avoid an inviscid calculation having varying mass.
- A thrust correction to the equivalent inviscid flow has been found to match the actual, less easily calculated case.



Section 2 Rigorous Analytical Procedure
2.9 Execution of Boundary Layer Steps
2.9.2 SETUP OF BLIMP

Date: 11/15/74

Setup of BLIMP requires the boundary layer edge conditions, coefficients for curve fits of physical properties, wall temperature, and mass addition at the wall.

The BLIMP computer program uses conditions from the δ_x streamline in TDK (assumed to be the same as wall conditions for thin boundary layers). Therefore, TDK must be run once with the real wall contour to initiate BLIMP. Currently, only the wall pressure and mixture ratio are used. The gas composition and thermophysical properties are calculated internally using a method equivalent to ODE. There are two problems inherent in this procedure: (1) the gas mixture ratio cannot vary as it does in the combustion chamber during burning, and (2) the other edge properties such as enthalpy and velocity differ from the actual reaction kinetic conditions calculated by TDK.

The physical property data are the same as that used in ODE and are readily available. The coefficients are curve fits to the C_p , enthalpy and entropy tables presented in Ref. * and Ref. **.

The information required at the wall is wall temperature and mass addition. However, these data are not available (except by test) unless a boundary layer solution has already been performed. Therefore, as discussed in Section 2.10, an iteration may be necessary to match the actual wall response (Section 2.10) to the boundary layer solution.

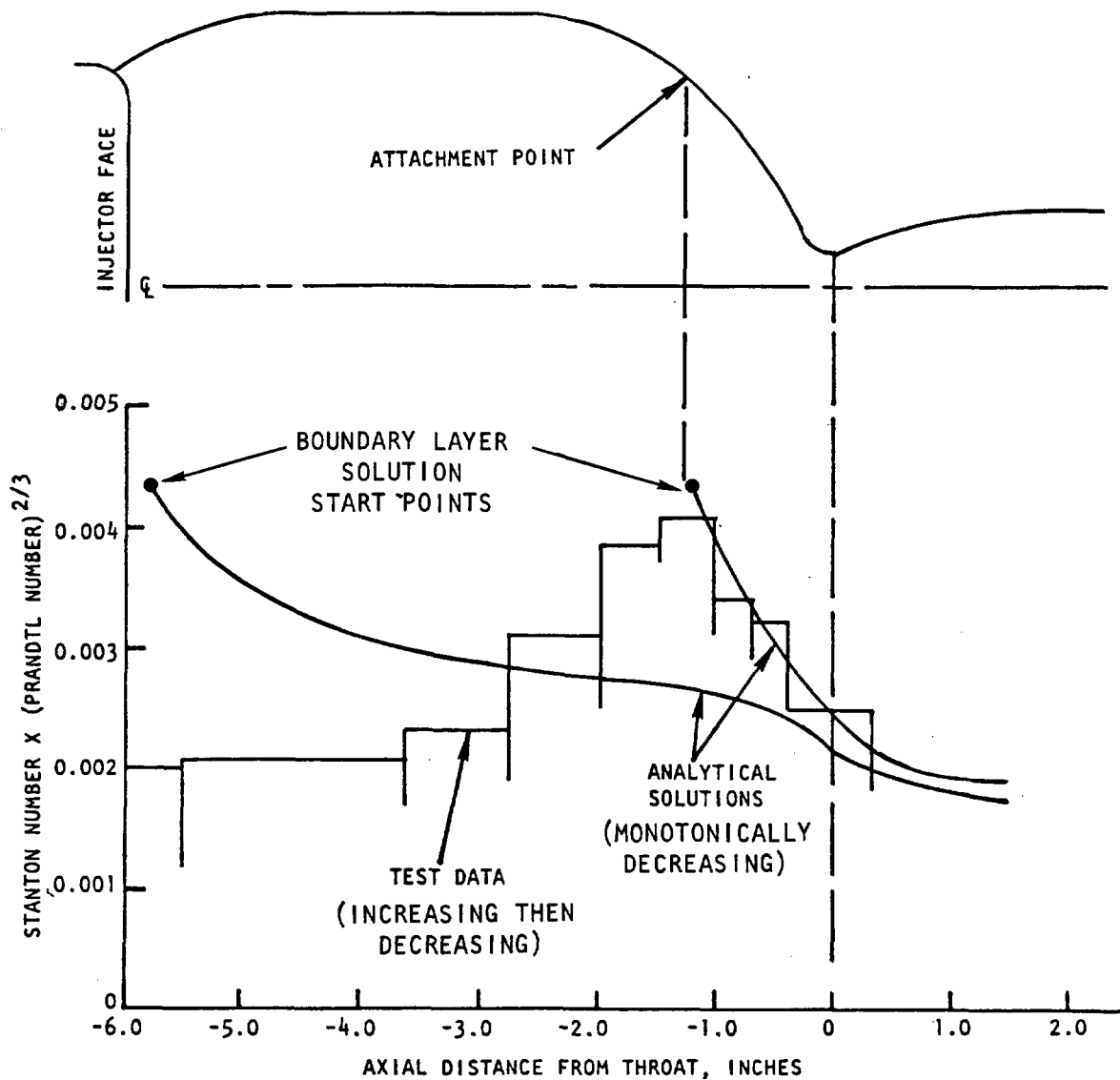
The procedure for the initial TDK run that supplies the BLIMP edge conditions is essentially identical to the procedure for the final potential wall TDK run as described in Section 2.11. For the first run, the real wall is used adjusted to the actual pressure, temperature, and run time for which the analysis is carried out. Wall roughness or small irregularities parallel to the flow can be ignored since the boundary layer will tend to smooth over these effects making the axisymmetric assumption valid. Irregularities across the flow direction have severe effects on the flow and should be smoothed out unless actually present in the contour.

Usually BLIMP will be initiated at the ZOM (or ZSTOP) plane where stream tube-type flow begins. Heat loss prior to this point is assumed to be spread throughout all the flow by turbulence and radiation. Initial values of momentum and energy thickness must be input, and these should

*JANNAF Thermochemical Tables

**NASA SP-3001, Thermodynamic Properties to 6000 R for 210 Substances
Involving the First 18 Elements, MacBride, HeimeI, Ehlers, Gordon, 1963.

be small and consistent with the laminar sublayer losses that are likely to occur up to the starting point. If the ZOM starting point is not used, experience indicates that the boundary layer approximation becomes valid at the point where the term $(St Pr^{2/3})$ measured in tests, begins monotonically decreasing (often at start of contraction), as shown in the figure below.



The blimp results are very sensitive to mixture ratio at the outer edge for injectors having film cooling, as indicated in the stratified flow sample case. Some mixing of outer zone film cooling should be assumed and heat transfer used as a guide.

Section 2 Rigorous Analytical Procedure
2.9 Execution of Boundary Layer Steps
2.9.3 TREATMENT OF MASS ADDITION

Date: 11/15/74

The BLIMP computer program can handle mass addition from ablation, transpiration, or wall injection. Mass and thrust equations must be modified accordingly.

The BLIMP computer program is capable of treating mass addition at the wall, as demonstrated in the J-2S sample case. For ablation or transpiration, mass addition can be input as it occurs along the wall. For point injection like the J-2S, the mass addition must be spread slightly so as not to exceed the program capabilities (see sample case for typical redistribution).

Three procedures are changed by the addition of mass: (1) the wall displacement for the second run of TDK, (2) the mass used for inviscid flow and total flow, and (3) the boundary layer thrust correction.

Wall Displacement

For mass addition, the quantity δ_{BODY} printed out by BLIMP is used in place of δ^* . The body displacement is defined as:

$$\delta_{\text{BODY}} = \delta^* + \delta_{\text{MASS ADDED}}$$

where δ^* is still defined as the area change for the inviscid flow to flow the same mass as the real situation of mass added in the boundary layer.

The term $\delta_{\text{MASS ADDED}}$ is the displacement in area of the inviscid required to accommodate the added mass flow. $\delta_{\text{MASS ADDED}}$ is calculated in the same way as δ^* by integrating across the boundary layer and comparing with the area required if the flow were all potential flow.

The potential flow wall is displaced from the real wall by δ_{BODY} to account for the area available to the primary flow and then the area that would flow the same mass as in the central flow.

Mass Flow

The total mass flow at the nozzle exit is given by:

$$\dot{M}_E = \dot{M}_{\text{INVISCID}} + \dot{M}_{\text{ADDED}}$$

The inviscid thrust is given by:

$$F = \dot{M}_{\text{INVISCID}} \text{ISP}_{\text{TDKP}}$$

and the inviscid contribution to the thrust chamber specific impulse is:

$$\frac{\dot{M}_{\text{INVISCID}}}{\dot{M}_E} \text{ISP}_{\text{TDKP}}$$

If the mass addition is below the throat, $\dot{M}_{\text{INVISCID}} = \dot{M}_T$.

Thrust Correction

The total thrust chamber thrust equation becomes:

$$F = F_{\text{INVISCID}} + \dot{M}_{\text{ADDED}} U_E \cos \alpha_E + 2\pi R_E P_E \delta_{\text{BODY}} \cos \alpha_E - 2\pi R_E \rho_E U_E^2 \theta \cos \alpha_E$$

The term $\dot{M}_{\text{ADDED}} U_E \cos \alpha_E$ is the momentum added by the added mass as if it were all exhausted at the edge velocity. The decrement to this momentum for the actual velocity profile is included in the momentum thickness along with the decrement to the inviscid momentum. The boundary layer thrust correction becomes:

$$\Delta F_{\text{BL}} = 2\pi R_E \cos \alpha_E \left[\rho_E U_E^2 \theta - P_E \delta_{\text{BODY}} \right] - \dot{M}_{\text{ADDED}} U_E \cos \alpha_E$$

If ΔF_{BL} becomes negative, the added mass more than compensates the thrust loss from viscous effects, giving a net thrust increase. For no mass addition, all equations reduce to the no mass addition form. ΔF_{BL} with mass added is used in the usual manner described in Section 2.12.1.

Section 2 Rigorous Analytical Procedure
2.10 Execution of Wall Response and Iteration Steps
2.10.1 WALL RESPONSE CALCULATIONS

Date: 11/15/74

Wall response calculations are currently discretionary. However, recommended concepts are available for various cooling methods.

Some of the common wall cooling methods encountered in the analysis of rocket engine performance are:

- Heat sink
- Fluid cooling jacket
- Transpiration
- Ablative

Each of these cooling types requires a specific analysis. Approximations are required in most of the situations to fit the assumptions in the BLIMP computer program.

Heat Sink and Fluid Cooled. For heat sink and fluid-cooled hardware, no material leaves the walls (hopefully). Therefore, the heat deposited in the wall at any position is a function only of the wall temperature and the corresponding boundary layer solution. This heat deposition rate results in a particular wall temperature distribution (time varying for heat sink hardware) that must be found using three-dimensional fluid conditions. The procedure interdependence is eased slightly by the fact that the boundary layer film coefficient is relatively insensitive to wall temperature so that heat deposition rate is essentially proportional to $(T_{AW} - T_W)$ where T_{AW} is the adiabatic wall temperature and is fixed by the mainstream temperature independent of wall temperature. For heat sink hardware, a specific time slice must be selected.

Transpiration. For transpiration-cooled hardware, the wall temperature is fixed by the transpiration rate and the heat deposition rate (the transpiration rate is fixed by the feed system calculations and a change in this rate requires a complete recalculation).

Ablative. Several methods exist for ablative walls. The simplest (and, for low ablation rates, reasonably accurate) is to assume the wall reaches the ablation temperature everywhere. More sophisticated

techniques exist such as the re-entry ablation computer programs written to interface with BLIMP. The 2-D ABLATE computer program also has been used successfully to correlate test data (Ref. *). The latter program was part of the ICC series from which LISP, 3DC, and STC were taken (Ref. ** and Ref. ***).

Difficulties have been encountered in trying to exactly match boundary conditions and heat loads using BLIMP. Often, an approximation will have to be made or test data ignored to achieve internal consistency of the prediction methods. That is, wall temperature data may have to be ignored to correctly match the heat loads. Since heat load has a direct effect on specific impulse, while wall temperature has only a second-order effect, if both cannot be matched, experimental wall temperature should be ignored. The fact that both experimental heat load and wall temperature cannot be matched in a given instance may be either incompleteness of the model or the difficulty of accurate wall temperature measurement. For *a priori* prediction, a consistent set of values for heat load and wall temperature can be achieved, and the only constraints are time and cost.

*Verification of a Comprehensive Thrust Chamber Compatibility Model for Liquid Rocket Engines, W. L. Pritz and R. J. Schoner

**AFRPL-TR-69-138, Technical Report, Development of Injector Chamber Compatibility Analysis

***AFRPL-TR-72-19, Extension of a Thrust Chamber Compatibility Model

Section 2 Rigorous Analytical Procedure
2.10 Execution of Wall Response and Iteration Steps
2.10.2 CHECKS AND ITERATIONS

Date: 11/15/74

For a full system, a balance must be established between accuracy and the cost of iterating. Simplified procedures can be used to estimate ISP error corresponding to inconsistencies in heat load or wall temperature and to aid in adjusting the calculations.

Three iteration checks are required in the rigorous procedure. The three parameters that must be assumed first in order to perform the calculations and which can then be determined based on the actual results are:

- Total Heat Load (First estimate from simplified film coefficient or test data)
- Nonboundary Layer Heat Load (First estimate from previous data)
- Wall Temperature Profile (First estimate consistent with heat load)

Because all three parameters are interdependent, no single parameter can be adjusted independently of the others. To avoid a large number of iterations, careful pre-estimating of the size of changes caused by adjustments to the computer program inputs must be made. To estimate the ISP error caused by a particular error in one of the parameters, simplified procedures can be used. For example,

$$\frac{\partial \text{ISP}_{\text{ODE}}}{\partial Q}$$

can be used to estimate the error caused by inconsistency in boundary layer heat load or nonboundary layer heat load.

Other simplifications that can be made involve the sensitivity of various parameters. The boundary layer film coefficient is not strongly affected by wall temperature or heat load, so this parameter can be used to re-estimate one from the other. The percentage thrust loss for the boundary layer ($\Delta F_{\text{BL}}/F_{\text{TC}}$) is not very sensitive to injection energy level and can be used in making new estimates.

The feed system sensitivity to heat load can be quickly established using an engine balance routine with several heat load values. In some systems there will be no change, while others may be highly sensitive with parameters like gas generator mixture ratio varying wildly.

Although the iterations are listed in three consecutive steps, they must actually be carried out simultaneously because the input wall temperature affects the calculated heat loads which, in turn, set the wall temperature.

The exact manner of iteration depends upon the specific system design and the additional parameters that are strongly influenced. In all cases, a simplified accuracy check like that shown above is acceptable in determining whether the 0.1-percent level has been reached.

If a given thrust level is desired rather than a given flowrate, an additional iteration is required. In this case, a specific impulse must first be assumed to estimate a total flow requirement. Then the specific impulse is calculated for this flowrate and the thrust calculated. Iteration is performed until desired thrust is obtained aided by the relative insensitivity of ISP to M.

The final calculations should be internally consistent in terms of energy balance. That is, the heat load from the boundary layer calculation must be used in the engine system calculations. When working with test data, there may be no analytical solution that matches both the measured heat load and measured wall conditions (e.g., temperature profile). In this case, the predictions must be made internally consistent independent of the test data. If possible, heat loads and injection temperatures should be matched since these parameters have the stronger influence on performance as discussed in Section 2.10.1.

Section 2 Rigorous Analytical Procedure
2.11 Execution of Inviscid Flow Analysis Step
2.11.1 CONCEPTUAL BASIS

Date: 11/15/74

The inviscid flow analysis is based on a method-of-characteristics/reacting gas flow procedure originating from an average constant properties transonic analysis.

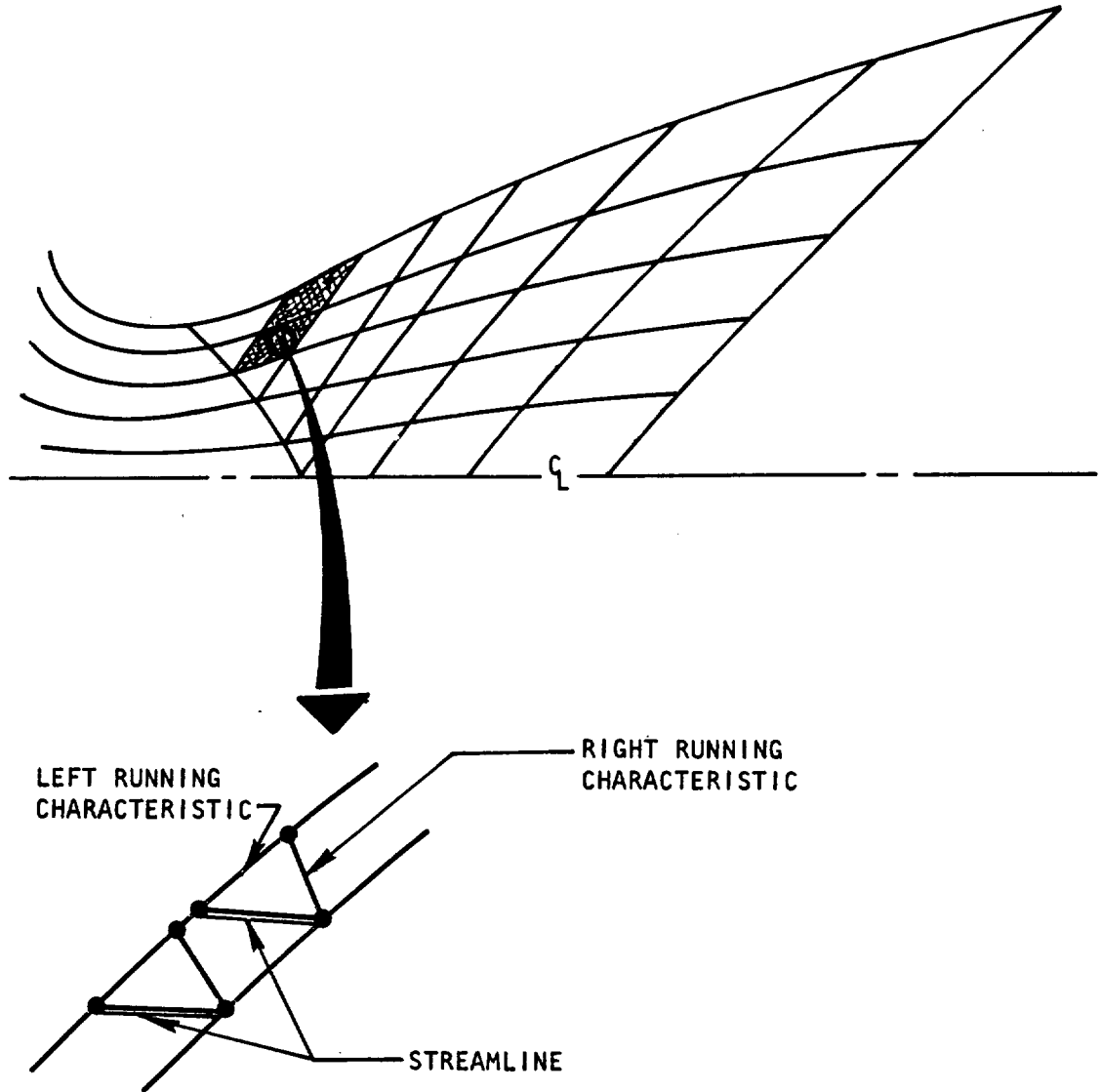
The information on gas-phase mass and mixture ratio distribution from STC is input to TDK at the start of convergence. The subsonic analysis is performed using ODK properties to define average γ values for the gases in each stream tube in the region of the throat. The TRANS sub-program uses these properties to establish the transonic flow field.

Starting at the line in the early supersonic portion of the nozzle, the TDK program performs a simultaneous method of characteristics and chemical reaction kinetics analysis. The program works with right-running characteristic lines and streamlines to generate left-running characteristic lines, as illustrated on page 2.11.1B. Stream lines separating different mixture ratio stream tubes (zones) are preserved throughout the calculation. The reaction kinetic equations are integrated along the stream line segments to obtain the gas composition at the next characteristic line. The composition varies along the line since flow parameters vary along the line.

The mass flowrate is calculated by integrating the ρV product along the initial line. The equation is given in the figure. This integration is also performed along each left-running characteristic to indicate drift. The total enthalpy is also calculated but not used in the program to adjust the calculations. The error in the predicted parameters caused by enthalpy drift can be estimated by dividing the enthalpy drift ($h_{OT} - h_{OE}$) by the kinetic energy ($V^2/2g$) at the exit (h_O is stagnation enthalpy, V is velocity, T is throat, and E is exit).

The force is calculated by integrating the wall pressure over the thrust chamber surface beyond the supersonic start line, and adding this to the thrust at the start line calculated by integrating the pressure and momentum along the start line. This approach is used rather than integrating along the last characteristic to avoid the full accumulation of numerical errors that may cause inaccuracies in the last characteristic.

The equation used is given in the illustration.



$$\dot{M}_{TDK} = 2\pi R_T^2 \int_0^1 \rho'' \left(\frac{\sin(\phi-\alpha)}{\sin \alpha} \right) R dR$$

initial line

$$F_{TDK} = 2\pi R_T^2 \left[\int_0^1 \left\{ P + \rho U^2 \frac{(\sin(\phi-\alpha) \cos)}{\sin \alpha} \right\} R dR + \int_{wall}^{R_E} P R dR \right]$$

initial line

α = streamline angle

ϕ = $\arctan \left(\frac{dR}{dx} \right)$, initial line inclination

Section 2 Rigorous Analytical Procedure
2.11 Execution of Inviscid Flow Analysis Step
2.11.2 SETUP OF TDK

Date: 11/15/74

The basic inputs to TDK are the output from STC, the thrust chamber geometry, reaction rate data, and thermophysical property data.

Four types of data must be furnished to TDK:

- Mass, enthalpy and mixture ratio distribution from STC
- Thrust chamber geometry
- Reaction rate data
- Thermophysical property data

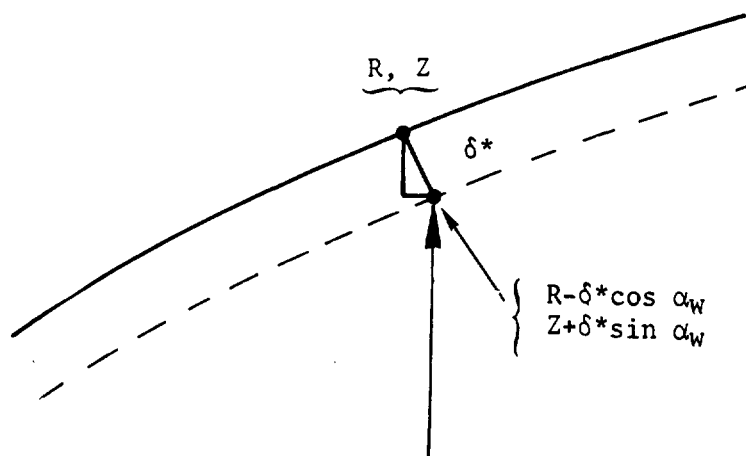
The STC data must be input in the form of mass fraction, mixture ratio, and enthalpy for each stream tube. An effective chamber pressure must also be input to TDK. The mass fractions, mixture ratios, and enthalpies are for gas-phase propellants only.

The thrust chamber geometry requirements are described in Section 2.2.6. The geometry should correspond to the instantaneous geometry for the time of interest. The two wall options in TDK (other than conical) that give the best results are the spline fit with a small (~12) number of wall points or the arbitrary with a large (~300) number of wall points. The use of many points in the spline fit has given problems in the past. The printed contour should be checked for uniformity of wall angle variation prior to accepting the results of a run. Using the perfect gas option first to check the wall contour has proved to be a good practice.

Mass and enthalpy drift should also be checked. For cases close to equilibrium, the A and B parameters*, indicating kinetic calculation accuracy, should be printed and checked. Also, a crosscheck against the simplified procedure is often useful.

For the final TDK run, the wall contour is displaced from the original contour by δ^* . This displacement is normal to the wall. Both the R and Z coordinates are changed as indicated in the figure and accompanying equations. For a positive δ^* , the radius is decreased and the axial position is increased. If TDK is run using normalized parameters ratioed to the throat radius (e.g., RWTU, RWTB, R/R_T , Z/R_T), these ratios must be changed to reflect both the movement of the wall and the change in throat radius. Care must be taken in redefining the radius of curvature terms since the varying boundary layer thickness will cause the potential wall to have varying radius of curvature. In this case, an average or approximate value must be used.

*Two-Dimensional Kinetic Reference Computer Program, Nickerson, Coats, Bartz, NAS9-12652, December 1973.



$$\left(\frac{Z}{R_T}\right)_{PW} = \left[\left(\frac{Z}{R_T}\right)_{RW} + \left(\frac{\delta^* \sin \alpha_w}{R_T}\right) \right] \left(\frac{R_T}{R_T - \delta^*}\right)$$

where:

PW is potential wall

RW is physical wall

$$\left(\frac{R}{R_T}\right)_{PW} = \left[\left(\frac{R}{R_T}\right)_{RW} - \left(\frac{\delta^* \cos \alpha_w}{R_T}\right) \right] \left(\frac{R_T}{R_T - \delta^*}\right)$$

NOTE: For mass addition, δ^* is replaced by δ_{BODY} as discussed in Section 2.9.3

Reaction rate data are supplied in Section 6. The data are in the form of a rate in argon, with efficiency factors for other third bodies.

The thermophysical property data are those supplied in Ref. * and curve fit is described in Ref. **.

The basepoint propellant enthalpies for other than perfect gas conditions are supplied in Section 6, and should be used throughout the analysis as well as for TDK.

*JANNAF Thermochemical Data

**NASA SP-3001, Thermodynamic Properties to 6000 R for 210 Substances

Involving the First 18 Elements, MacBride, HeimeI, Ehlers, Gordon, 1963.

Section 2 Rigorous Analytical Procedure
2.12 Performance Calculation
2.12.1 SPECIFIC IMPULSE

Date: 11/15/74

With the thrust chamber analysis complete and the feed system flows available, specific impulse can be calculated directly when dump thrust is calculated.

The calculated engine specific impulse is given by

$$ISP_{ENG PRED} = \frac{\dot{M}_{VAP} ISP_{TDKP} + \Delta F_{DROPS} - \Delta F_{BL} + F_{PROP DUMP}}{\dot{M}_{NET TO ENGINE}}$$

and the thrust chamber specific impulse is given by

$$ISP_{TC PRED} = \frac{\dot{M}_{VAP} ISP_{TDKP} + \Delta F_{DROPS} - \Delta F_{BL}}{\dot{M}_{TC}}$$

where M_{TC} is the thrust chamber exit flowrate.

Any correction for droplet flow would be nonstandard. There are existing two-phase flow computer programs similar to ODK and TDK (Ref.* and **) that can be used to supply an estimate of the difference in thrust caused by drops or particles.

Only the vaporized mass flow is used for TDK thrust. The mass flow indicated by TDK may be slightly off because TDK ignores the area taken up by droplets and assumes the full throat area is available for gas flow.

The propulsive dump thrust can be calculated by any procedure that impacts overall performance error by less than 0.1 percent. Usually, the simplified procedure will be adequate, or empirical data can be used. An example of propulsive dump is the turbine exhaust of the H-1 which is ducted external to the nozzle to the exit plane and dumped at that point, providing a small axial thrust.

* One Dimensional Two Phase Reacting Gas Non-Equilibrium Performance Program, J. R. Kliegel, et al., Rept. MSC-1178, TRW Systems, Aug 1967, NAS9-4358.

**Axisymmetric Two-Phase Reacting Gas Non-Equilibrium Nozzle Flow Analysis, J. R. Kliegel, et al, Contract NAS9-4358.

In the specific impulse calculation, the vaporization loss portion of the energy release loss is carried in $\dot{M}_{VAP}$; the mixture ratio distribution portion is included in ISP_{TDKP} . The vaporization and mixture ratio distribution are established by the distributed energy release model discussed in Sections 2.5 through 2.8. Reaction kinetics and two-dimensional flow effects are also included in ISP_{TDKP} . The boundary layer effect comes in through ISP_{TDKP} and the boundary layer thrust correction term ΔF_{BL} . Any nonpropulsive propellant losses (leakage, dumping) are taken into account (e.g., radiation-cooled skirt) by $\dot{M}_{NET TO ENGINE}$. Radiative energy losses and mass addition (e.g., ablation, transpiration) are accounted for by the boundary layer and the energy level used for TDK.

Currently, there is no reference or standard of performance against which to measure engine ISP. The level achievable is specific to the type of engine feed system (e.g., regenerative, staged combustion, etc.). Measures used in the past, such as ISP for tank enthalpies, can be misleading since the best efficiency could exceed 1.0. An absolute limit given by tank enthalpy and entropy (extremely high stagnation pressure) may be useful but needs more research.

For the thrust chamber, the standard of specific impulse performance is the one-dimensional isentropic equilibrium expansion specific impulse for injection enthalpy, chamber pressure (as defined in CPIA 245), uniform mixture ratio, and complete vaporization. This reference value indicates the magnitude of all thrust chamber losses.

The standard of performance for the injector is the calculated specific impulse for injection enthalpy, uniform mixture ratio, and complete vaporization. This reference value indicates the magnitude of injector-related losses.

Section 2 Rigorous Analytical Procedure
2.12 Performance Calculation
2.12.2 Characteristic Velocity (C^*)

Date: 11/15/74

The C^* value printed by TDK must be corrected for throat area and total throat mass flowrate to obtain a correct C^* .

The definition of C^* for the JANNAF methodology is

$$C^* \equiv \frac{P_C A_T}{\dot{M}_T}$$

where A_T is the physical throat area at the specific firing time. The C^* value printed out by TDK in the second run uses the mass flow for gas ignoring the droplet blockage area and the throat area corrected for the boundary layer δ^* . Therefore, the mass flow must be corrected to the total mass flow at the throat, including droplets and the throat area must be corrected to the physical throat area. That is:

$$C_{CALC}^* = \left(\frac{\dot{M}_{VAP}}{\dot{M}_T} \right) \left(\frac{A_T}{A_T - 2\pi R_T \delta^*} \right) C_{TDKP}^*$$

As discussed in CP1A 245, C^* data are often more readily available than ISP data for injector technology and development tests. The C^* can be used to calibrate the vaporization and mixture ratio distribution portions of the analysis in the manner described in Section 2.6.4. Vaporization loss tends to raise and lower the C^* level, while mixture ratio distribution tends to change the shape of the C^* variation with overall mixture ratio.

Two reference values are useful for C^* comparisons. The first is the one-dimensional isentropic equilibrium expansion value for injection enthalpy, chamber pressure, uniform mixture ratio and complete vaporization. Comparison with this value indicates overall chamber effects on C^* .

The second reference value, the calculated C^* for injector-enthalpy, chamber pressure, uniform mixture ratio, and complete vaporization can be used to indicate the magnitude of injector-related losses. The relationship of the C^* injector-related losses and ISP injector-related losses can be determined for use in extrapolation.

2.13 Uncertainty of Procedure

2.13.1 UNCERTAINTY PARAMETERS

All measured data and predictions using this data contain errors. The parameter selected by JANNAP for characterization of error is the uncertainty (U) made up of bias (B) and precision (S).

All predictions using data based on measurements may contain errors either known or unknown. For this reason, a band must be placed around prediction, indicating the potential range of actual value for the parameter being predicted. The wider the band, the less information presented, but the more certainty that a new, independent prediction will fall within the band. Conversely, the smaller the band, the greater the information about the parameter, but lower certainty of enclosing future measurements or the true value.

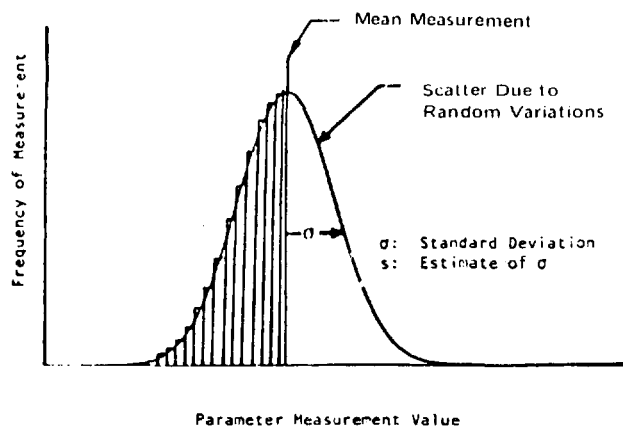
The band is made up of two components, as illustrated on page 2.13.1B, a fixed and repeatable portion known as bias, defined as the error of the average position of all possible predictions with the uncertainty of the data, and the precision given by the standard deviation of random errors about the average position.

Random error is seen in repeated measurements of the data used in the computer program. Measurements do not and are not expected to agree exactly. There are always numerous small effects which cause disagreements. The variation between repeated measurements is called precision error. The second component, bias, is the constant or systematic error. In repeated measurements, each measurement has the same bias. The bias cannot be determined unless the measurements are compared with the true value of the quality measured.

For simplicity of presentation, a single number (some combination of bias and precision) is needed to express a reasonable limit for error. The single number must have a simple interpretation (the largest error reasonably expected) and be useful without complex explanation. It is impossible to define a single rigorous statistic because the bias is an upper limit based on judgment which has unknown characteristics. Any function of these two numbers must be a hybrid combination of an unknown quantity (bias) and a statistic (precision). However, the need for a single number to measure error is so great that the adoption of an arbitrary standard is warranted. The standard most widely used is the uncertainty interval (shown opposite),

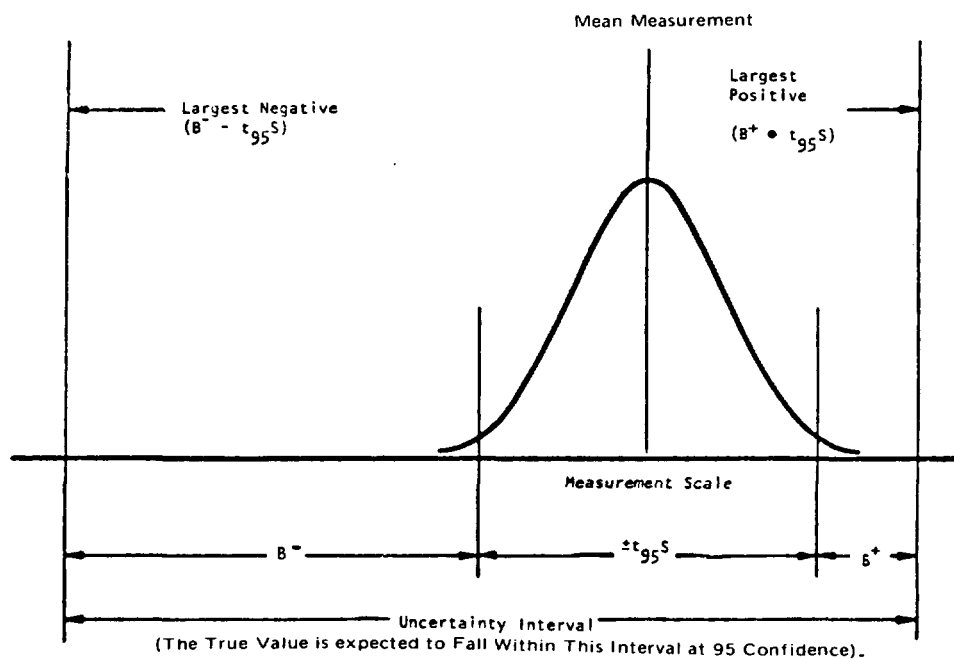
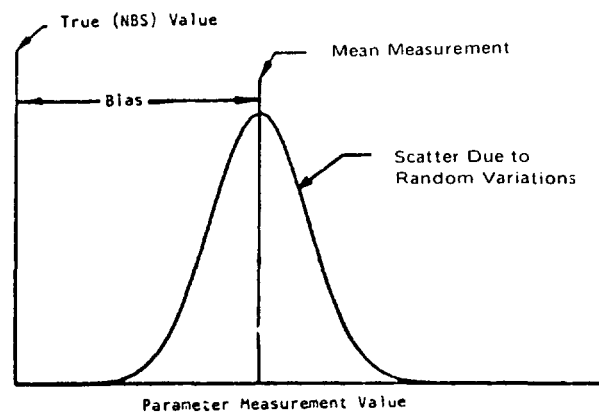
$$U, \text{ given by } U^- = B^- - t_{95}S \text{ to } U^+ = B^+ + t_{95}S$$

where B is the bias limit, S is the precision index, and t_{95} is the 95th percentile point for the two-tailed Students "t" distribution. The t value is a function of the number of degrees of freedom (ν) used in calculating S. For small samples, t will be large, and for larger samples t will be smaller, approaching 1.96 as a lower limit. The use of the t arbitrarily inflates the limit U to reduce the risk of underestimating S when a small sample is used to calculate S. Since 30 degrees of freedom yield a t of 2.04, and infinite degrees of freedom yield a t of 1.96, an arbitrary selection of $t = 2$ for values of ν from 30 to infinity was made, i.e., $U = \pm(|B| + 2S)$, when $\nu > 30$. Because of the large number of factors involved in the prediction, ν can normally be assumed to be greater than 30.



Precision Error

Bias Error



Uncertainty, Nonsymmetrical Bias

Section 2 Rigorous Analytical Procedure
 2.13 Uncertainty of Procedure
 2.13.2 ESTIMATION OF UNCERTAINTY

Date: 11/15/74

The uncertainty in the prediction procedure stems from uncertainty in data (such as reaction rates, thermophysical properties), from assumptions and simplifications in the mathematical formulations, and from iteration tolerances.

The reference computer programs and the analytical procedure can be looked on as an alternate method of measuring performance. In this view, a series of tests is performed (reaction rates, thermophysical data, etc.) and performance values are calculated. This procedure is conceptually the same as measuring thrust and flowrate to calculate specific impulse.

The treatment of uncertainty in test data is discussed fully in Ref.*. The random or precision error in a final value resulting from error in data or procedure is determined by propagating the individual errors as:

$$S_{\text{PRED}} = \sqrt{\sum_i \left(S_i \frac{\partial \text{PRED}}{\partial X_i} \right)^2} = \sqrt{\sum_i \left(S_{\text{PRED}_i} \right)^2}$$

Where the partial derivative indicates the change in the prediction with a unit change in the particular piece of input data.

The bias in the prediction is determined from bias in data or procedures as:

$$B_{\text{PRED}}^{\pm} = \pm \sum B_{\text{KNOWN}}^{\pm} \pm \sqrt{\sum \left(B_{\text{UNKNOWN}}^{\pm} \right)^2 + \sum \left(B_{\text{UNKNOWN}}^{\text{U}} \right)^2}$$

The bias term should usually be small in magnitude since large bias can usually be corrected out. Calculation of bias is shown on the opposite page.

The exact uncertainty could be rigorously calculated by knowing all biases and precisions in data, iteration, and simplification, and by exercising the reference computer programs to find the sensitivity factors for every contributing parameter. However, such a method would be excessively time consuming. In practice, the use of simplified procedures and a consideration of only those parameters that have a major impact on the answer should give a reasonable result.

The uncertainty interval is given by:

$$U^{-} = B^{-} - t_{95, \nu} S_{\text{PRED}} \text{ to } U^{+} = B^{+} + t_{95, \nu} S_{\text{PRED}}$$

*CPIA 245, JANNAF Rocket Engine Test Data Acquisition and Interpretation Manual

Estimation of Bias

1. Biases of known sign and known magnitude are summed (when they are not corrected):

$$B = \sum_{i=1}^m b_i$$

2. Bias limits with unknown sign and unknown magnitude are root sum squared:

$$\pm B = \pm \sqrt{(b_1)^2 + (b_2)^2 + (b_3)^2 + \dots + (b_k)^2}$$

3. Bias limits with known sign and unknown magnitude are squared and combined:

$$B^+ = \sqrt{*(b_1^+)^2 * (b_2^+)^2 * (b_3^+)^2 \dots * (b_n^+)^2}$$

$$B^- = \sqrt{*(b_1^-)^2 * (b_2^-)^2 * (b_3^-)^2 \dots * (b_n^-)^2}$$

4. Bias limits of unknown sign and unknown magnitude ($\pm b$) are combined with bias limits of known sign and unknown magnitude (b^+ , b^-) by root sum squaring the $\pm b$ limits with the combined b^+ limit and by squaring and subtracting the $-b$ limits from the combined b^- limits:

$$B^+ = \sqrt{*(b_1^+)^2 * (b_2^+)^2 \dots * (b_n^+)^2 + b_1^2 + b_2^2 + \dots + b_k^2}$$

$$B^- = \sqrt{*(b_1^-)^2 * (b_2^-)^2 \dots * (b_n^-)^2 - b_1^2 - b_2^2 - \dots - b_k^2}$$

$$B^+ = \sqrt{\sum_{i=1}^n *(b_i^+)^2 + \sum_{j=1}^k b_j^2}$$

$$B^- = \sqrt{\sum_{i=1}^n *(b_i^-)^2 - \sum_{j=1}^k b_j^2}$$

EXAMPLE

Type of Bias	Estimated Bias Limit
b	+5 seconds
$\pm b$	± 2 seconds
$\pm b$	± 3 seconds
b^+ , b^-	+10 seconds, 0 seconds
b^+ , b^-	-1 second, -6 seconds
b^+ , b^-	+7 seconds, -4 seconds

These estimated biases are combined as follows:

$$B^+ = 5 + \sqrt{10^2 - 1^2 + 7^2 + 2^2 + 3^2} = 5 + \sqrt{161} = 5 + 12.7$$

$$B^- = 5 + \sqrt{0^2 - (6)^2 - 4^2 - (2)^2 - (3)^2} = 5 - \sqrt{65} = 5 - 8.06$$

*These signs are the known signs associated with the bias limit.

**The sign is determined by the sign under the radical:

$$\left. \begin{array}{l} B^+ = 17.7 \quad \text{or} \quad B^+ = 12.7 \\ B^- = -3.06 \end{array} \right\} \begin{array}{l} \text{seconds, with a calibration} \\ \text{correction of 5 seconds} \end{array}$$

$$B^- = -8.06$$

Section 2 Rigorous Analytical Procedure
2.13 Uncertainty of Procedure
2.13.3 ALLOCATION OF ALLOWABLE ERROR

Date: 11/15/74

Often, a specific accuracy goal is desired (e.g., 1 percent for *a priori* new conditions using rigorous procedure). In this situation, the question of the necessary accuracy for each of the subcalculations must be answered.

When a specific uncertainty goal must be met, each of the calculational building blocks entering into the final prediction also must meet an uncertainty consistent with the overall goal. If the prediction is assumed to have negligible bias, the uncertainty required by each of the subcalculations is given by:

$$S_{\text{PRED}_n} = \frac{\text{Goal}/2}{\sqrt{N}}$$

where N is the number of subcalculations. For the rigorous analytical procedure, the parts that go into the specific impulse are:

- Vaporized mass flowrate
- TDK specific impulse
- Boundary layer thrust loss
- Dump thrust
- Net mass flowrate to engine

In this case, $N = 5$ and $\sqrt{N} \approx 2.25$. If the overall uncertainty goal is 1 percent and biases are negligible, the maximum precision for each of the above five calculations must be:

$$S_{\text{PRED}_n} = \frac{1}{4.5} \text{ percent} = 0.22 \text{ percent}$$

where the 0.22 percent is of the total performance value. For example, if total ISP is 500 $\text{lb}_f \cdot \text{s}/\text{lb}_m$, the allowable error is 1.1 $\text{lb}_f \cdot \text{s}/\text{lb}_m$. This tolerance is tight for major contributions such as ISP_{TDKP} , but relatively loose for small contributions such as F_{dump} . For a dump contributing only 1 percent of the thrust, the error as a fraction of dump thrust can be 20 percent or more.

If the precision in some areas is known to be less than the allowable, the allowables in other areas can be increased using the same RMS procedure. The extension to situations in which bias is suspected and carried in the uncertainty is also straightforward. A decision may be needed as to the allocation between bias and precision.

Note that the procedure assumed that the five subcalculations are statistically independent (i.e., a change in one does not cause a predictable change in another). This assumption is not strictly true since TDK results are used for the boundary layer calculation and vaporized mass is somewhat related to net mass. When such dependence can be isolated, the allowable tolerance can be allocated to the net change caused by independent effects. Otherwise, only the overall uncertainty is meaningful and tolerances on individual calculation steps cannot be allocated independently, since both the error in the step and the interaction with error in subsequent steps must be considered. For example, if the injector analysis does not influence the boundary layer calculation, then an error in injector analysis does not change the boundary layer analysis. However, if the injector analysis strongly influences the boundary layer analysis, then an error in the injector analysis produces additional error in the boundary layer analysis which must be taken into account when establishing accuracy requirements for both analyses.

SECTION 3

SECTION 3. SIMPLIFIED ANALYTICAL PROCEDURE

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SECTION 3. SIMPLIFIED ANALYTICAL PROCEDURE

SUMMARY

The simplified procedure is intended for rapid, inexpensive estimation of ISP, C^* , and relative importance of losses for parametric data or quick correlation of test data. The simplified analytical expressions are derived directly from the rigorous definitions by isolating physical processes in arbitrary order to form ratio efficiencies identified with these processes shown in the illustration below. As shown, each of the efficiencies applied to the specific impulse from the previous calculation reduces the specific impulse by an amount to account for that particular loss mechanism.

The simplified procedure consists of six steps. The first three steps are specification steps like those of the rigorous procedure, but with abbreviated requirements. The thrust chamber performance steps of the rigorous procedure (4-14) are replaced with a single step for determining the efficiency factors used in calculating thrust chamber performance. The determination of these efficiencies is the topic of Section 3.2. The final two steps of the procedure are similar to the last two steps of the rigorous, in which the separate pieces are put together to obtain a specific impulse and C^* .

The calculational steps and reporting requirements are discussed in Section 3.1. The estimation of uncertainty for the simplified procedure is discussed in Section 3.3.

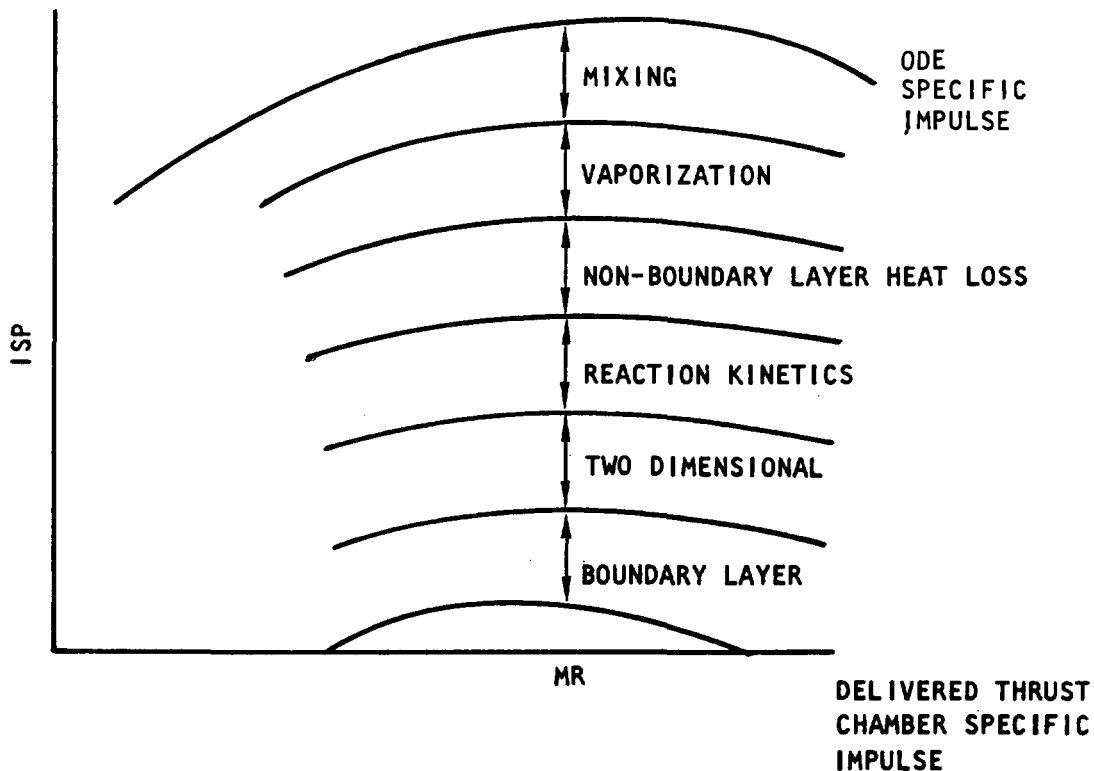


ILLUSTRATION OF THRUST CHAMBER LOSSES FROM IDEAL PERFORMANCE

Section 3 Simplified Analytical Procedure Date: 11/15/74
3.1 Calculational Procedure, Reporting, Applicability
3.1.1 CALCULATIONAL STEPS

The simplified procedure is intended for rapid, inexpensive estimation of performance and relative magnitudes of losses for parametric data or quick correlation of test data. In general, the procedure is not meant to have the accuracy of the rigorous procedure.

As discussed in Ref.*, the JANNAF Simplified Analytical Procedure is based on the defining equations for the rigorous procedures. The terms of the rigorous procedure are expanded in terms of efficiencies related to the major physical processes occurring in the thrust chamber (Section 1.1.4) with the interaction effects arbitrarily but consistently assigned to specific efficiencies. The simplified procedure is much less restrictive in reporting and in the requirements for the use of reference computer programs. The calculational steps are given in the table on page 3.1.1B.

The three specification steps (parallel to the rigorous procedure) require significantly less data. For example, only type of nozzle, area ratio, and percent length (relative to 15-degree conical nozzle having same area ratio) are needed rather than a full contour. Additional information such as throat radius of curvature can be provided if pertinent.

The determination of efficiency factors is discussed in Section 3.2, and is the only major effort required by the simplified procedure. These factors can be computed using simplified options of the reference computer programs, other computer programs that have been calibrated against the reference programs, or empirical data as discussed in Ref*.

The calculation of propulsive dump thrust will usually be made using the simplified thrust chamber procedure. The calculation of specific impulse and C^* is identical to the rigorous steps except that thrust chamber specific impulse and C^* are redefined in terms of efficiencies.

*JPL Technical Memorandum 33-548, Simplified Procedures for Correlation of Experimentally Measured and Predicted Thrust Chamber Performance,
W.B. Powell, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, 1 April 1973.

SIMPLIFIED PROCEDURE CALCULATIONAL STEPS

1. RESERVOIR CONDITIONS SPECIFICATION

Specify composition, mass flowrate (or flowrate ratios) and enthalpy of all flows crossing the reservoir/engine system interface.

2. FEED SYSTEM CONDITIONS SPECIFICATION

Specify composition, mass flowrate (or flowrate ratios) and enthalpy of all flows crossing the feed system interfaces (including heat flow from thrust chamber).

3. THRUST CHAMBER GEOMETRY SPECIFICATION

Specify type of injector, contraction ratio, combustion chamber length, type of nozzle contour, area ratio, and percent length.

4. DETERMINATION OF EFFICIENCY FACTORS

Determine efficiency factors as defined in Section 3.2. Explain sources of efficiencies in sufficient detail that analysis can be reproduced independently.

5. PROPULSIVE DUMP SPECIFIC IMPULSE DETERMINATION

Specify propulsive dump specific impulse using any procedure deemed appropriate. Explain procedure.

6. CALCULATION OF SPECIFIC IMPULSE AND CHARACTERISTIC VELOCITY

- a. Calculate overall specific impulse and characteristic velocity using standard equations:

$$ISP_{CALC} = \left\{ \dot{M}_{TC} \frac{ISP_{ODER}}{AVG \ TC \ MR} \left[\eta_{ISP \ KIN} \eta_{ISP \ TD} \eta_{ISP \ MIX} \eta_{ISP \ VAP} \eta_{ISP \ HL} \right] - \left(1 - \eta_{ISP \ BL} \right) \right\} + \dot{M}_{PROP \ DUMP} ISP_{PROP \ DUMP} \Bigg/ \dot{M}_{NET \ TO \ ENGINE}$$

$$C^*_{CALC} = C^*_{ODE} \frac{AVG \ INJ \ MR}{\left[\eta_{C^* \ TD} \eta_{C^* \ KIN} \eta_{C^* \ BL} \eta_{C^* \ VAP} \eta_{C^* \ MIX} \eta_{C^* \ HL} \right]}$$

where the ODE reference values are based on actual injector/thrust chamber energy levels. Nomenclature is covered in later sections.

- b. Calculate parameters by any preferred method. Report method and specify reasons for believing results superior to specified procedure.

Section 3 Simplified Analytical Procedure Date: 11/15/74
3.1 Calculational Procedure, Reporting, Applicability
3.1.2 REPORTING

The reporting for the simplified procedure is much abbreviated and consists primarily of (1) the data needed to calculate the ODE reference specific impulse, and (2) the thrust chamber efficiency factors.

The reporting requirements for the simplified procedure are:

- Summary of interface flows (or relative flows)
- Thrust chamber and injector types and key parameters
- Specific impulse and efficiency summary (shown on page 3.1.2B)
- Narrative of sources of efficiencies, dump performance, and flows

The method of inclusion and distribution of the data is a discretionary matter for the contracting agency. The major concern is that the standard definitions be used for consistency between presentations and that the selection of parameters be defensible. Flows should be reported in an abbreviated form of that for the rigorous (Section 2.2.1).

Note that the specific impulse summary lists a dump flow ISP increment. This increment is derived from the relationship listed in Step 6 of section 3.1.1, and is given by

$$\Delta \text{ISP}_{\text{DUMP}} \equiv \frac{\dot{M}_{\text{DUMP}}}{\dot{M}_{\text{NET}}} \text{ISP}_{\text{DUMP}} - \left(1 - \frac{\dot{M}_{\text{TC}}}{\dot{M}_{\text{NET}}} \right) \text{ISP}_{\text{TC}}$$

Alternatively, the flows and dump specific impulse can be reported and the specific impulse calculated directly as

$$\text{ISP} = \frac{\dot{M}_{\text{DUMP}} \text{ISP}_{\text{DUMP}} + \dot{M}_{\text{TC}} \text{ISP}_{\text{TC}}}{\dot{M}_{\text{NET TO ENGINE}}}$$

JANNAF SPECIFIC IMPULSE PREDICTION SUMMARY
Simplified Procedure

Parameter	Units	Value	Uncertainty
Thrust Chamber Performance			
ODE Specific Impulse			
Chamber Pressure			
Area Ratio			
C*			
Thrust Chamber Specific Impulse			
Engine Performance			
Propulsive Dump Specific Impulse			
Increment			
Engine Thrust			
Engine Specific Impulse			

JANNAF PERFORMANCE EFFICIENCY SUMMARY
Simplified Procedure

Parameter	Units	Value	Uncertainty
Specific Impulse Efficiencies			
Heat Loss			
Reaction Kinetic			
Divergence			
Boundary Layer			
Energy Release			
Vaporization			
Mixing			
Thrust Chamber			
Characteristic Velocity Efficiencies			
Heat Loss			
Reaction Kinetic			
Divergence			
Boundary Layer			
Energy Release			
Vaporization			
Mixing			
Thrust Chamber			

Using charts, existing base points for scaling, and ODK, the simplified procedure can be completed in less than 1 man-day (and actual day) for the first case. Higher accuracy or sophistication adds time proportionately.

The simplified procedure is intended for the following uses:

- Parametric data generation
- Scaling from test points
- Sensitivity factors for estimation of error in rigorous procedure and in checking iteration tolerance
- Scaling to off-design points from rigorous analysis
- Preliminary design optimization (e.g., area ratio-percent length tradeoff, etc.)

The simplified procedure is not intended to have the full accuracy of the rigorous procedure and, therefore, the uncertainty goal can be up to twice that for the rigorous procedure (i.e., when the rigorous procedure is 1 percent, the maximum goal of the simplified procedure is 2 percent; when the rigorous procedure is 0.2 percent, the simplified procedure is 0.4 percent). When used in scaling from test parts over a small range, the additional inaccuracy introduced by using the simplified rather than rigorous procedure may be completely negligible.

The cost of using the simplified procedure depends entirely on the degree of detail and accuracy desired. Existing data and charts, such as those provided in Section 3.2, can be used to produce an answer with less than 1 man-day of effort. At the other extreme, the rigorous procedure can be used to determine all the efficiencies needed in the simplified procedure (section 3.2.2). Since many efficiencies can be held constant or varied easily using more rapid computer programs, the efficiencies from a single rigorous calculation can be used to calculate specific impulse over a range of parameters.

Section 3 Simplified Analytical Procedure
 3.2 Determination of Efficiency Factors
 3.2.1 CONCEPTUAL BASIS

Date: 11/15/74

The simplified analytical expressions are derived directly from the rigorous definitions by isolating physical processes in arbitrary order to form ratio efficiencies identified with these processes.

The defining relationships given in Section 2.12 form the basis of the simplified expressions shown on the opposite page. The TDK specific impulse and C^* have been expanded in terms of the major physical processes. The order of expansion is arbitrary as is the choice of multiplication efficiencies. Additive efficiencies [i.e., $\Sigma(1-\eta)$] would have had the advantage of a common reference, but would still have required an assigned order of operations, and the vaporized mass term would have remained multiplicative. The vaporized mass correction term is included in the vaporization efficiency for both ISP and C^* , while the throat area correction to C^* is identified as a boundary layer effect. The terms from the rigorous definition are identified by solid arrows.

As shown in the following sections, many of the terms (efficiencies) can be approximated quite closely using more rapid, less costly calculation techniques or empirical data. Also, the variation of the efficiencies with various parameters can be determined in general, and these scaling relationships used to predict new conditions from some base point.

The terms η_{VAP} η_{MIX} are often grouped and identified as an energy release efficiency (η_{ER}) that includes all losses caused by the propellant injection--incomplete atomization, large-scale unmixedness (accidental and deliberate) and small-scale unmixedness. For deliberately stratified thrust chambers, the portion of η_{MIX} caused by this stratification may be further separated as η_{STRAT} , with the remaining element and other manifold effects grouped into an η_{SPRAY} term. Although not explicitly shown, the interaction effects have been implicitly assigned to various efficiencies

If there is mass addition in the boundary layer, the first set of terms in the ISP equation must be multiplied by

$$\left(\frac{\dot{M}_{INVISCID}}{\dot{M}_{INVISCID} + \dot{M}_{ADDED}} \right)_E$$

and the C^* equation must be multiplied by

$$\left(\frac{\dot{M}_{INVISCID}}{\dot{M}_{INVISCID} + \dot{M}_{ADDED}} \right)_T$$

Section 3 Simplified Analytical Procedure
3.2 Determination of Efficiency Factors
3.2.2 SIMPLIFIED EFFICIENCY DEFINITIONS

Date: 11/15/74

The benefit of the simplified procedure is in the use of less expensive computer methods.

The use of the simplified procedure can save time and cost in several ways:

- Use of efficiencies from single-point rigorous analysis
- Use of easier computer programs to calculate efficiencies or trends in efficiencies
- Use of existing efficiencies from charts, previous rigorous analysis, or test data.

The definition of the efficiency factors in terms of the rigorous computer programs was given in the preceding section. As described in the following sections, reasonable approximations can be made that permit the use of easier computer programs to calculate the various efficiencies. The simplifications for the specific impulse efficiencies are shown in the table on page 3.2.2B. Similar simplifications for the C^* efficiencies are given in various subsequent sections.

As shown in the table, the need for TDK is eliminated, saving the major cost item of the rigorous procedure. Other simplifications include the use of the real wall throughout, avoiding the rerun of the potential flow following the boundary layer analysis.

At each step of simplification, some uncertainty is introduced as to actually reproducing the rigorous answer. If any particular process is of major interest or importance, so that the increased uncertainty is unacceptable, an alternate procedure (Section 4) can be used to calculate that efficiency.

Thrust Chamber Specific Impulse

$$\begin{aligned}
 & \text{ISP}_{\text{ODER AVG INJ MR}} \left[\left(\text{ISP}_{\text{TDKP VAP MR MULTIZONE HL}} \right) \times \left(\frac{1}{\text{ISP}_{\text{TDKP VAP MR MULTIZONE}}} \right) \times \left(\frac{\text{ISP}_{\text{TDKP VAP MR MULTIZONE}}}{\text{ISP}_{\text{ODKP VAP MR MULTIZONE}}} \right) \times \left(\frac{\text{ISP}_{\text{ODKP VAP MR MULTIZONE}}}{\text{ISP}_{\text{ODEP VAP MR MULTIZONE}}} \right) \times \left(\frac{\dot{M}_{\text{VAP}}}{\dot{M}_{\text{TC}}} \times \frac{\text{ISP}_{\text{ODEP VAP MR MULTIZONE}}}{\text{ISP}_{\text{ODEP INJ MR MULTIZONE}}} \right) \times \left(\frac{\text{ISP}_{\text{ODEP INJ MR MULTIZONE}}}{\text{ISP}_{\text{ODEP AVG INJ MR}}} \right) \times \left(\frac{\text{ISP}_{\text{ODEP AVG INJ MR}}}{\text{ISP}_{\text{ODER AVG INJ MR}}} \right) - \left(\frac{\Delta F_{\text{BL}}}{\dot{M}_{\text{TC}}} \times \frac{1}{\text{ISP}_{\text{ODER AVG INJ MR}}} \right) \right] \\
 & \downarrow \qquad \qquad \downarrow \qquad \qquad \downarrow \qquad \qquad \downarrow \qquad \qquad \downarrow \qquad \qquad \downarrow \qquad \qquad \downarrow \\
 & \text{ISP}_{\text{ODER AVG INJ MR}} \left[\eta_{\text{ISP}_{\text{HL}}} \times \eta_{\text{ISP}_{\text{TD}}} \times \eta_{\text{ISP}_{\text{KIN}}} \times \eta_{\text{ISP}_{\text{VAP}}} \times \eta_{\text{ISP}_{\text{MIX}}} - (1 - \eta_{\text{BL}}) \right]
 \end{aligned}$$

C*

$$\begin{aligned}
 & \text{C}^*_{\text{ODER AVG INJ MR}} \left[\left(\text{C}^*_{\text{TDKP VAP MR MULTIZONE HL}} \right) \times \left(\frac{1}{\text{C}^*_{\text{TDKP VAP MR MULTIZONE}}} \right) \times \left(\frac{\text{C}^*_{\text{TDKP VAP MR MULTIZONE}}}{\text{C}^*_{\text{ODKP VAP MR MULTIZONE}}} \right) \times \left(\frac{\text{C}^*_{\text{ODKP VAP MR MULTIZONE}}}{\text{C}^*_{\text{ODE VAP MR MULTIZONE}}} \right) \times \left(\frac{\dot{M}_{\text{VAP}}}{\dot{M}_{\text{T}}} \times \frac{\text{C}^*_{\text{ODE VAP MR MULTIZONE}}}{\text{C}^*_{\text{ODE INJ MR MULTIZONE}}} \right) \times \left(\frac{\text{C}^*_{\text{ODE INJ MR MULTIZONE}}}{\text{C}^*_{\text{ODE AVG INJ MR}}} \right) \times \left(\frac{A_{\text{T}}}{A_{\text{T}} - Z \pi R_{\text{T}} \delta_{\text{T}^*}} \right) \right] \\
 & \downarrow \qquad \qquad \downarrow \qquad \qquad \downarrow \qquad \qquad \downarrow \qquad \qquad \downarrow \qquad \qquad \downarrow \\
 & \text{C}^*_{\text{ODER AVG INJ MR}} \left[\eta_{\text{C}^*_{\text{HL}}} \times \eta_{\text{C}^*_{\text{TD}}} \times \eta_{\text{C}^*_{\text{KIN}}} \times \eta_{\text{C}^*_{\text{VAP}}} \times \eta_{\text{C}^*_{\text{MIX}}} \times \eta_{\text{C}^*_{\text{BL}}} \right]
 \end{aligned}$$

Note that the correction from potential wall to real wall is included in the boundary layer term for both C* and ISP.

Subscript nomenclature:

R	= real wall (physical wall contour)	ODK	= calculated by ODK computer program
P	= potential wall (analytical wall adjusted for boundary layer)	TDK	= calculated by TDK computer program
AVG INJ MR	= average injector mixture ratio	HL	= heat loss
VAP MR	= mixture ratio of gases	TD	= two-dimensional
MULTIZONE	= multiple mixture ratio zone analysis	KIN	= kinetic
INJ MR	= mixture ratio as injected	VAP	= vaporization
ODE	= calculated by ODE computer program	MIX	= mixing
		BL	= boundary layer

SIMPLIFIED SPECIFIC IMPULSE EFFICIENCY DEFINITIONS
(See Section 3.2.1 for nomenclature)

Efficiency Term	Rigorous Definition	Simplified Definition	Computer Program
$\eta_{ISP_{HL}}$	$\frac{ISP_{TDP} \cdot VAP \cdot MR \cdot MULTIZONE}{HL}$ $\frac{ISP_{TDP} \cdot VAP \cdot MR \cdot MULTIZONE}{ISP_{TDP} \cdot VAP \cdot MR \cdot MULTIZONE}$	$\frac{ISP_{ODER} \cdot AVG \cdot INJ \cdot MR}{HL}$ $\frac{ISP_{ODER} \cdot AVG \cdot INJ \cdot MR}{ISP_{ODER} \cdot AVG \cdot INJ \cdot MR}$	ODE
$\eta_{ISP_{TD}}$	$\frac{ISP_{TDP} \cdot VAP \cdot MR \cdot MULTIZONE}{ISP_{ODKP} \cdot VAP \cdot MR \cdot MULTIZONE}$	$\frac{ISP_{TDER} \cdot AVG \cdot INJ \cdot MR}{ISP_{ODER} \cdot AVG \cdot INJ \cdot MR}$ or $\frac{ISP_{TDY}}{ISP_{ODY}}$	TDE or TDY
$\eta_{ISP_{KIN}}$	$\frac{ISP_{ODKP} \cdot VAP \cdot MR \cdot MULTIZONE}{ISP_{ODEP} \cdot VAP \cdot MR \cdot MULTIZONE}$	$\frac{ISP_{ODKR} \cdot VAP \cdot MR \cdot MULTIZONE}{ISP_{ODER} \cdot VAP \cdot MR \cdot MULTIZONE}$	ODK
$\eta_{ISP_{VAP}}$	$\frac{\dot{M}_{VAP}}{\dot{M}_{TC}} \cdot \frac{ISP_{ODEP} \cdot VAP \cdot MR \cdot MULTIZONE}{ISP_{ODEP} \cdot INJ \cdot MR \cdot MULTIZONE}$	$\frac{\dot{M}_{VAP}}{\dot{M}_{TC}}$	STC-One Zone
$\eta_{ISP_{MIX}}$	$\frac{ISP_{ODEP} \cdot INJ \cdot MR \cdot MULTIZONE}{ISP_{ODEP} \cdot AVG \cdot INJ \cdot MR}$	$\frac{ISP_{ODER} \cdot INJ \cdot MR \cdot MULTIZONE}{ISP_{ODER} \cdot AVG \cdot INJ \cdot MR}$	ODE
$\eta_{ISP_{BL}}$	$\frac{ISP_{ODEP} \cdot AVG \cdot INJ \cdot MR}{ISP_{ODER} \cdot AVG \cdot INJ \cdot MR}$ and $\frac{\Delta F_{BL}}{\dot{M}_{TL}} \cdot \frac{1}{ISP_{ODER} \cdot AVG \cdot INJ \cdot MR}$	$\frac{1 - 2\pi R_E P_E V_E^2 \cos \alpha_E \theta_E}{\dot{M}_{TC} \cdot ISP_{ODER} \cdot AVG \cdot INJ \cdot MR}$	BLIMP

Section 3 Simplified Analytical Procedure
 3.2 Determination of Efficiency Factors
 3.2.3 HEAT LOSS EFFICIENCY

Date: 11/15/74

The heat loss efficiency can be approximated using ODE with average mixture ratio. Experience indicates that both ISP and C* vary linearly with the energy removed.

The most simplified expressions for the heat loss efficiencies are given by:

$$\eta_{ISP_{HL}} \approx \frac{\frac{ISP_{ODER}}{AVG \text{ INJ MR}}}{\frac{ISP_{ODER}}{AVG \text{ INJ MR}}} \frac{HL}{HL}$$

and

$$\eta_{C^*_{HL}} \approx \frac{\frac{C^*_{ODER}}{AVG \text{ INJ MR}}}{\frac{C^*_{ODER}}{AVG \text{ INJ MR}}} \frac{HL}{HL}$$

In other words, the ODE program can be run with and without heat removed for the average injector mixture ratio (unless some propellants are removed prior to the throat, as in a tapoff system, in which case, a correction to mixture ratio should be made). The task can be made even easier by developing curves of

$$\frac{1}{ISP} \frac{\Delta ISP}{\Delta h} \text{ and } \frac{1}{C^*} \frac{\Delta C^*}{\Delta h}$$

as functions of mixture ratio, chamber pressure, area ratio, etc.

For propellants examined to date, these sensitivity factors are independent of Δh , and depend only on mixture ratio, area ratio, and propellant combination. The same factors can be used to scale the injector ISP and C* for heat added (as in a regenerative thrust chamber). That is

$$\frac{ISP_{ODE}}{AVG \text{ INJ MR}} = \frac{ISP_{ODE}}{AVG \text{ INJ MR}} \left[1 + \left(\frac{1}{ISP} \frac{\Delta ISP}{\Delta h} \right) \times (h_{INJ} - h_{REF}) \right]$$

REF COND

and

$$\frac{ISP_{ODE}}{AVG \text{ INJ MR HL}} = \frac{ISP_{ODE}}{AVG \text{ INJ MR REF COND}} \left[1 - \left(\frac{1}{ISP} \frac{\Delta ISP}{\Delta h} \right) \times \frac{Q_{NON-BL}}{\dot{M}_{INJ}} \right]$$

where Q_{NON-BL} is the heat transferred by turbulence and radiation in the region near the injector.

If the only heat added comes from the thrust chamber, and all the thrust chamber heat is added to propellants that eventually are injected, conservation of energy requires that:

$$\eta_{ISP_{HL}} \frac{ISP_{ODE}}{AVG \text{ INJ MR}} = \frac{ISP_{ODE}}{AVG \text{ INJ MR REF COND}} \left[1 + \left(\frac{1}{ISP} \frac{\Delta ISP}{\Delta h} \right) \times \frac{Q_{BL}}{\dot{M}_{INJ}} \right]$$

Note that the effect of such added heat is nearly cancelled out by the difference in boundary layer efficiency between cooled-wall and adiabatic-wall conditions. That is, there is a gain in overall specific impulse from adding heat in the combustion chamber. However, if the heat is then extracted from the boundary layer, most of the apparent gain is cancelled out, leaving only a small (<1%) net gain for regenerative cooling compared to an adiabatic wall engine.

The simplification shown here adds very little error to the calculations, so no more exact expressions are presented.

Section 3 Simplified Analytical Procedure
 3.2 Determination of Efficiency Factors
 3.2.4 TWO-DIMENSIONAL EFFICIENCY

Date: 11/15/74

The two-dimensional efficiency can be readily calculated using either the TDE or TDY options rather than the full TDK analysis.

The two-dimensional efficiency is given by

$$\eta_{ISP_{TD}} = \frac{ISP_{TDKP} \text{ VAP MR MULTIZONE}}{ISP_{ODKP} \text{ VAP MR MULTIZONE}} \quad \begin{array}{l} \text{(TDKP is TDK with potential wall} \\ \text{ODKP is ODK with potential wall)} \end{array}$$

Of the effects included, the mixture ratio, kinetic and multizone influences are small, so a highly accurate simplification is

$$\eta_{ISP_{TD}} = \frac{ISP_{TDEP} \text{ AVG INJ MR}}{ISP_{ODEP} \text{ AVG INJ MR}} \quad \begin{array}{l} \text{(TDEP is TDE with potential wall} \\ \text{ODEP is ODE with potential wall)} \end{array}$$

where TDE is the two-dimensional equilibrium option of the TDK group of subprograms. Since, for most quick estimates, the generation of a potential wall is a nuisance, a further accurate simplification,

$$\eta_{ISP_{TD}} = \frac{ISP_{TDER} \text{ AVG INJ MR}}{ISP_{ODER} \text{ AVG INJ MR}} \quad \begin{array}{l} \text{(TDER is TDE with real wall} \\ \text{ODER is ODE with real wall)} \end{array}$$

A further simplification for parametric data is the use of perfect gas constant γ) efficiency given by the TDY option. Typical results that can be used for parametric data are shown on the opposite page.

For C^* , the exact expression is

$$\eta_{C^*_{TD}} = \frac{C^*_{TDKP} \text{ VAP MR MULTIZONE}}{C^*_{ODKP} \text{ VAP MR MULTIZONE}}$$

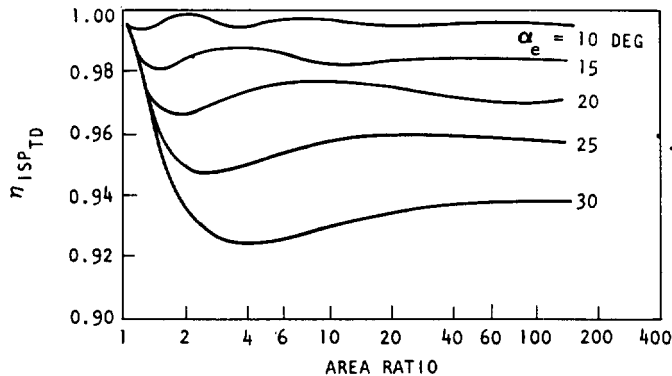
The contour does not affect one-dimensional C* calculations, and making the same simplifications as for the ISP gives

$$\eta_{C^*_{TD}} = \frac{\dot{M}_{ODE}}{\dot{M}_{TDE}}$$

since the pressures and throat areas are the same.

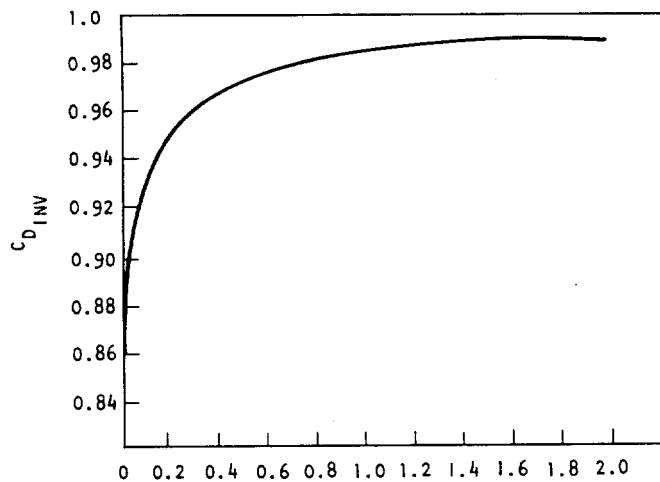
The last expression for $\eta_{C^*_{TD}}$ is just the reciprocal of the inviscid discharge coefficient for the nozzle. Thus,

$$\eta_{C^*_{TD}} = \frac{1}{C_{D_{INV}}}$$

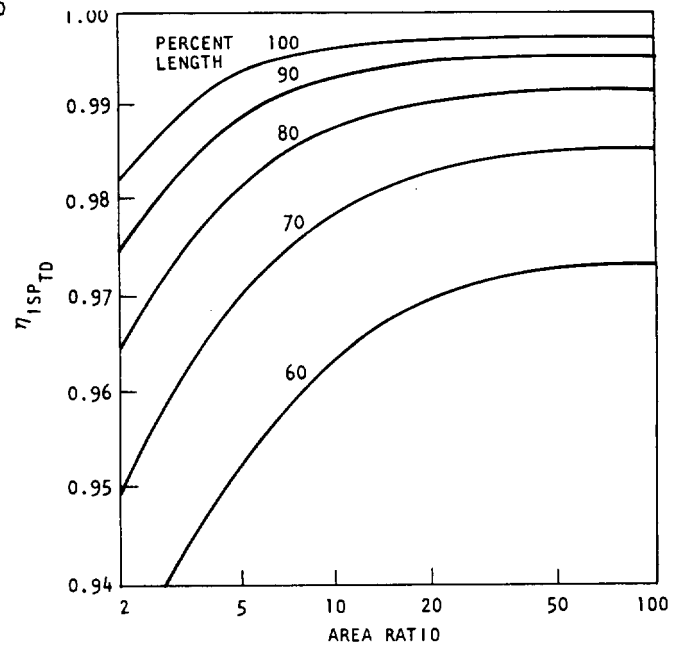


A. TWO-DIMENSIONAL EFFICIENCY ESTIMATE FOR CONICAL NOZZLES

B. TWO-DIMENSIONAL EFFICIENCY ESTIMATE FOR BELL NOZZLES (RAO OPTIMUM, SHIRLEY SMITH PARABOLA)



UPSTREAM WALL RADIUS OF CURVATURE



C. INVISCID DISCHARGE COEFFICIENT (DATA FIT)

Section 3 Simplified Analytical Procedure
 3.2 Determination of Efficiency Factors
 3.2.5 REACTION KINETIC EFFICIENCY

Date: 11/15/74

For highly stratified flows, very little simplification is possible for η_{KIN} . For uniform flows, a highly simplified expression can be developed.

The reaction kinetic efficiency definition is:

$$\eta_{ISP_{KIN}} = \frac{\begin{array}{c} ISP \\ ODK \ P \\ VAP \ MR \\ MULTI-ZONE \end{array}}{\begin{array}{c} ISP \\ ODE \ P \\ VAP \ MR \\ MULTI-ZONE \end{array}}$$

The only generally accurate simplification that can be made is the use of the real rather than potential nozzle contour. All other simplifications must be considered carefully for impact on accuracy since kinetic effects are strongly influenced by mixture ratio.

For highly stratified mixture ratio, some reduction of zones by averaging may be possible. The allowable degree of mixture ratio averaging can be estimated from a curve of kinetic loss with mixture ratio from ODK. In the limit of fully mixed and reacted flow, the expression reduces to a single stream tube model.

The reaction kinetic efficiency is a function of thrust level, chamber pressure, nozzle contour, mixture ratio, and area ratio. Attempts have been made to obtain approximate scaling relationships, but no generally applicable results are yet available. The trends are shown on the next page.

Parameter	Change	Effect on η_{ISP_KIN} of Change
Thrust	Increase	Increase
Chamber Pressure	Increase	Increase
Wall Contour	More Rapid Expansion (especially near throat)	Decrease
Area Ratio	Increase	Decrease
Mixture Ratio	Any	Unpredictable (must go to 1 at MR = 0 and ∞)

The C^* kinetic efficiency unlike the ISP term can be readily simplified for most propellants. In general, in the subsonic region, reaction kinetics effects are negligible except for very low pressure (<10 psia) or low-thrust (<100 pounds) chamber. Thus, to a good approximation,

$$\eta_{C^*_KIN} \approx 1.0$$

For low thrust or low pressure, ODK can be used to estimate the kinetic effect on C^* in a manner analogous to ISP.

Section 3 Simplified Analytical Procedure
 3.2 Determination of Efficiency Factors
 3.2.6 VAPORIZATION EFFICIENCY

Date: 11/15/74

The vaporization efficiency includes the effects of reduced gas mass flow and shifted gas-phase mixture ratio.

Both the ISP and C* vaporization efficiencies are defined in terms of the ratio of vaporized-to-total mass flowrate and the ratio of ODE performance for the vaporized mixture ratio to that for the total mixture ratio (summed over stream tubes). The defining relationships are:

$$\eta_{ISP_VAP} = \frac{\dot{M}_{VAP}}{\dot{M}_{TC}} \frac{ISP_{ODEP} \text{ VAP MR}}{ISP_{ODEP} \text{ INJ MR MULTIZONE}}$$

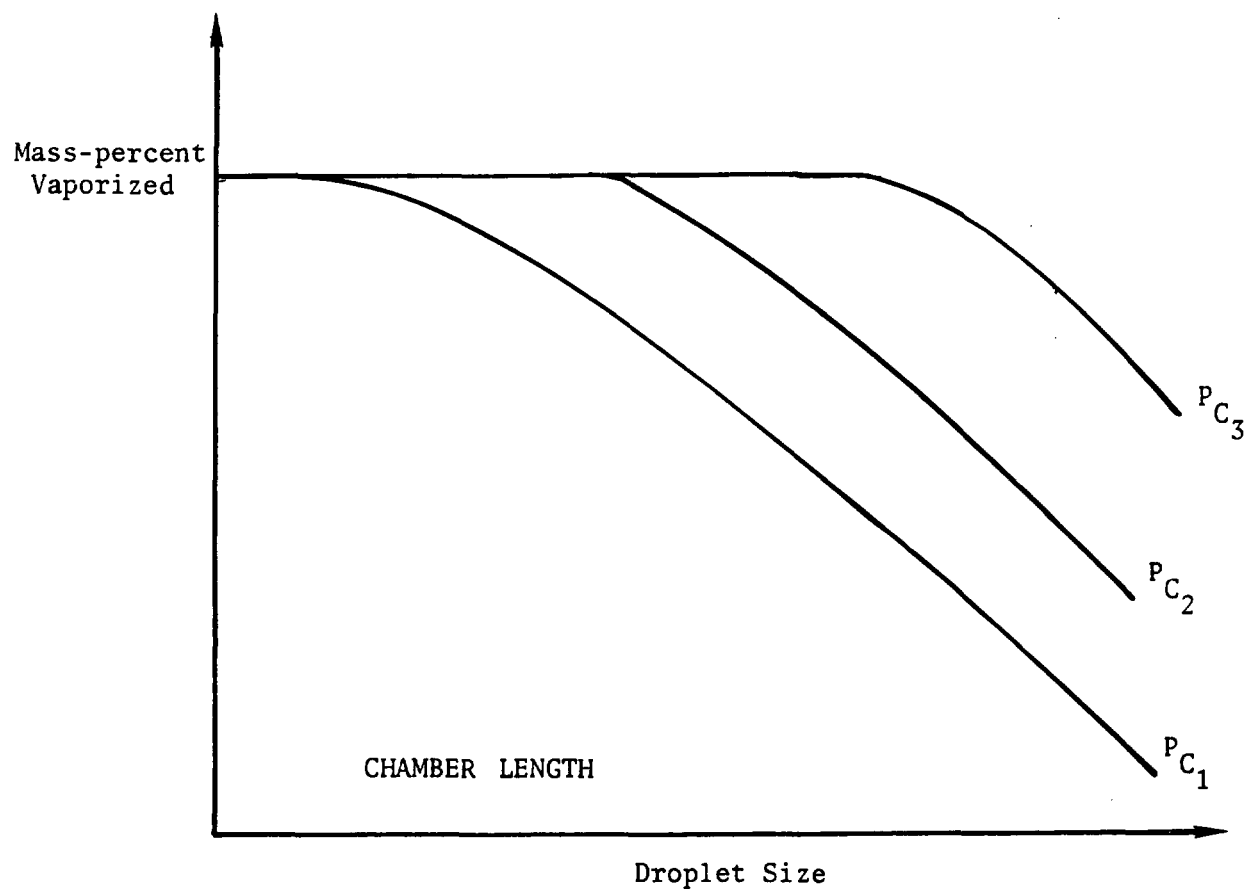
$$\eta_{C^*_VAP} = \frac{\dot{M}_{VAP}}{\dot{M}_T} \frac{C^*_{ODE} \text{ VAP MR}}{C^*_{ODE} \text{ INJ MR MULTIZONE}}$$

The vaporization efficiency can be estimated based on the evaporation efficiency of various size droplets for some average thrust chamber conditions. The only realistic simplification is to ignore the shift in mixture ratio between fully vaporized and partially vaporized. Also, the product of $\eta_{VAP} \eta_{MIX}$ can be inferred from test data and substituted without further discrimination, as discussed in Section 3.2.7.

For calculations, the real nozzle wall can be substituted for the potential wall with no loss in accuracy. A typical vaporization curve is given in the figure on page 3.2.6B. The completely simplified expressions are:

$$\eta_{ISP_VAP} = \frac{\dot{M}_{VAP}}{\dot{M}_{TC}}$$

$$\eta_{C^*_VAP} = \frac{\dot{M}_{VAP}}{\dot{M}_T}$$



Simplified Vaporization Curves

Section 3 Simplified Analytical Procedure
 3.2 Determination of Efficiency Factors
 3.2.7 MIXING EFFICIENCY

Date: 11/15/74

The mixing efficiency accounts for both large-scale and small-scale deviations from complete mixing. Manifold effects (often deliberate, film cooling) cause large-scale maldistribution, while element spray effects cause small-scale maldistribution.

The mixing efficiency includes all mixture ratio distribution effects. η_{MIX} can be determined either analytically using ODE (real wall is acceptable) or by inference from test data as shown on page 3.2.7B. For calculational purposes, a further discrimination into subcomponents may be useful:

$$\eta_{MIX} = \eta_{SPRAY} \eta_{STRAT}$$

In this way, engines tested with deliberate stratification can be scaled to other amounts while holding the basic element mixing constant. Methods of estimating η_{STRAT} are discussed in Section 4.2.4.

When the combined vaporization and mixing efficiency are calculated from test data, the combination may have to be scaled for changes in stratification or changes in vaporization. This scaling can be performed without determining the actual magnitude of either effect.

In the example on the opposite page, the first column shows data obtained in low area ratio testing. The specific impulse based on the test data is shown in the upper dotted box. Using the reference specific impulse and the efficiencies for the other loss mechanisms, the magnitude of the injector-related losses (indicated by $\eta_{ISP_{ER}}$) can be estimated:

$$(\eta_{ISP_{ER}} = \frac{ISP_{MEAS}}{ISP_{ODER} (\eta_{ISP_{HL}} \eta_{ISP_{TD}} \eta_{ISP_{KIN}})} + (1 - \eta_{ISP_{BL}}))$$

For the case shown, $\eta_{ISP_{ER}}$ does not vary with area ratio, so the estimated value can be used with the appropriate efficiencies and reference specific impulse to predict the specific impulse that can be achieved with the tested injector/combustion chamber and a high area ratio nozzle.

Parameters	Test Conditions	Extrapolation
L*, inches	40	40
MR	2.2:1	2.2:1
Area Ratio	2.5:1	20:1
ISP _{ODER} , lbf-sec/lbm (Injection enthalpy)	325	417
ISP, lbf-sec/lbm	295.2	354
$\eta_{ISP_{HL}}$	0.998	0.998
$\eta_{ISP_{TD}}$	0.985	0.985
$\eta_{ISP_{KIN}}$	0.986	0.944
$1 - \eta_{ISP_{BL}}$	0.015	0.035
$\eta_{ISP_{ER}}$	backed out 0.952	0.952

Section 3 Simplified Analytical Procedure
 3.2 Determination of Efficiency Factors
 3.2.8 BOUNDARY LAYER EFFICIENCY

Date: 11/15/74

The ISP boundary layer efficiency accounts for the boundary layer thrust correction and the switch from potential wall to real wall. The C* boundary layer efficiency accounts for the potential-to-real wall conversion.

To avoid the use of a potential wall in the simplified calculation, the ratio of potential-to-real wall ODE ISP is included in the boundary layer efficiency. The basis for this inclusion is that

$$\frac{ISP_{ODEP}}{ISP_{ODER}} = \frac{F_{ODEP}}{F_{ODER}} = \frac{F_{ODER} - 2\pi R_E P_E \cos \alpha_E \delta^*}{F_{ODER}}$$

when the other efficiency terms are close to 1, the efficiency expression becomes

$$\left[(\text{term} \sim 1) \left(1 - \frac{2\pi R_E P_E \cos \alpha_E \delta^*}{M_{TC} ISP_{ODER}} \right) - \frac{\Delta F_{BL}}{M_{TC} ISP_{ODER}} \right] = \left[(\text{term} \sim 1) - (1 - \eta_{BL}) \right]$$

or

$$\eta_{ISP_{BL}} \approx 1 - \frac{\Delta F_{BL} + 2\pi R_E P_E \cos \alpha_E \delta^*}{M_{TC} ISP_{ODER}}$$

or

$$\eta_{ISP_{BL}} \sim 1 - \frac{2\pi R_E \rho_E V_E^2 \cos \alpha_E \theta_E}{M_{TC} ISP_{ODER}}$$

where the difference between $(\rho_E V_E^2)_P$ and $(\rho_E V_E^2)_R$ has been ignored. The loss in accuracy caused by this definition of $\eta_{ISP_{BL}}$ is discussed at length in Ref. *. The error caused by the mathematical manipulations is

$$(1 - \eta_{BL} \eta_{TD} \eta_{MIX} \eta_{VAP} \eta_{KIN}) \frac{2\pi R_E P_E \cos \alpha_E \delta^*}{M_{TC} ISP_{ODER}}$$

*Simplified Procedures for Correlation of Experimentally Measured and Predicted Thrust Chamber Performance, W. B. Powell, Jet Propulsion Laboratory, TM 33-548, April 1973.

which is negligible. The error caused by equating two-dimensional potential flow pressures and velocities to one-dimensional values should also be small.

Experience with large numbers of cases indicates that boundary layer efficiency scales as

$$(1 - \eta_{BL}) = (1 - \eta_{BL})_{REF} \left(\frac{F_{REF}}{F} \right)^A \left(\frac{P_{C_{REF}}}{P_C} \right)^B \left(\frac{\epsilon}{\epsilon_{REF}} \right)^C \left(\frac{\%L}{\%L_{REF}} \right)^D$$

where ϵ is area ratio and $\%L$ is percent length relative to a 15-degree cone, and REF is the base point. The constants A, B, C, and D must be found from design point computer runs for similar propellants and wall cooling. Typically, A, B, C, and D are on the order of 0.05 to 0.2. (For Rao or Shirley Smith Parabolas, $A \sim 0.1$, $B \sim 0.05$, $C \sim 0.2$, and $D \sim 0.1$ for most propellants.)

The boundary layer heat load is also needed for parametric calculations. The observed scaling for heat load is:

$$Q_{BL} = Q_{BL_{REF}} \left(\frac{F_{REF}}{F} \right)^{P_N} \left(\frac{P_C}{P_{C_{REF}}} \right)^{B_N} \left(\frac{\epsilon}{\epsilon_{REF}} \right)^{E_N} \left(\frac{\%L}{\%L_{REF}} \right)^{D_N} +$$

$$Q_{BL_{REF}} \left(\frac{F_{REF}}{F} \right)^{A_{CC}} \left(\frac{P_C}{P_{C_{REF}}} \right)^{B_{CC}} \left(\frac{\epsilon_C}{\epsilon_{C_{REF}}} \right)^{C_{CC}} \left(\frac{L^*}{L^*_{REF}} \right)^{D_{CC}}$$

where the scaling for nozzle and combustion chamber may be different.

Since C^* boundary layer efficiency is a direct function of δ_T^* (the displacement thickness at the throat), no simplifications can be made. Parametric δ_T^* can be developed and scaled as required. Typically,

$$0.997 < \eta_{C^*_{BL}} < 1.003$$

where

$$\eta_{C^*_{BL}} = \frac{A_T}{A_T - 2\pi R_T \delta_T^*} \quad (\text{Note: for mass addition, } \delta_{T_{BODY}} \text{ replaces } \delta_T^*)$$

Section 3 Simplified Analytical Procedure
 3.3 Uncertainty of Procedure
 3.3.1 ESTIMATION OF UNCERTAINTY

Date: 11/15/74

The uncertainty basis for the simplified procedure is the same as for the rigorous, with the uncertainties being the calculational terms with which uncertainties are associated.

The uncertainty for the simplified procedure is estimated using the procedure discussed in Section 2.13. The uncertainty in the simplified procedure will be greater than that in the rigorous and will increase as more simplifying approximations are introduced. The increase in uncertainty enters in two distinct ways that must be considered. First, when a change is introduced in the calculation procedure (for example, replacing a TDK and ODK defined efficiency with TDE and ODE calculations), the precision must be changed to that representative of the new calculation. This new precision may have no relationship at all to the original precision. The second term introduced is a bias between the exact calculation and the simplified approximation. The bias term, therefore, accounts for the inability of the approximation to exactly match the rigorous procedure as well as for any bias between the rigorous and true values.

With estimates for the precision and biases in each of the efficiencies and other factors in the simplified procedure calculation, the uncertainty can be calculated using the same method shown in Section 2.13.

$$S_{\text{PRED}} = \sqrt{\sum_i \left(S_{\text{PRED}_i} \frac{\partial \text{PRED}}{\partial X_i} \right)^2}$$

and

$$B_{\text{PRED}}^{\pm} = \pm \sum B_{\text{KNOWN}_i}^{\pm} \pm \sqrt{\sum \left(B_{\text{UNKNOWN}_i} \right)^2} \pm \sqrt{\sum \left(B_{\text{UNKNOWN}}^U \right)^2}$$

where the summations are over all of the terms in the defining equation, as discussed in Section 2.13.

The uncertainty is given by:

$$U^{\pm} = B_{\text{PRED}}^{\pm} \pm t_{95, \nu} S_{\text{PRED}}$$

Section 3 Simplified Analytical Procedure
3.3 Uncertainty of Procedure
3.3.2 ALLOCATION OF ERROR

Date: 11/15/74

The amount of error acceptable in each calculation depends on the number of factors used in the performance parameter.

The individual factors that are included in the specific impulse definition for a full engine when the simplified procedure is used are:

- ODE specific impulse
- $\eta_{ISP_{HL}}$
- $\eta_{ISP_{TD}}$
- $\eta_{ISP_{KIN}}$
- $\eta_{ISP_{VAP}}$
- $\eta_{ISP_{MIX}}$
- $\eta_{ISP_{BL}}$
- $\Delta_{ISP_{DUMP}}$
- $\dot{M}_{TC}/\dot{M}_{ENG}$

Following the development in Section 2.13, each of these factors will have an allowable precision of:

$$S_n = \frac{\text{Goal}/2}{3} = \frac{\text{Goal}}{6}$$

assuming the bias terms are negligible compared to the precision terms.

If the goal is 2 percent, the precision of each of the efficiencies must be better than 0.33 percent (0.0033). This means that the uncertainty in each efficiency (assuming negligible bias) can be almost 0.7 percent (0.007). This accuracy is well within the current state of the art for most propellant combinations. For a 1-percent goal, the uncertainty is 0.16 percent, again not excessively small compared to the current capabilities, even with simplifying assumptions (for the same goal, the sub-components of the rigorous procedure can have an uncertainty of 0.44 percent).

If one of the factors is known to be more or less precise than the allowable, the allowables for the remaining factors can be calculated by reverting to the defining relationship:

$$\frac{\text{Goal}}{2} = \sqrt{\left(\sum_{i=1}^m S_i^2 \right)_{\text{KNOWN}} + (N - m) S_n^2}$$

where m is the total number of known precisions and N is the total number of independent factors entering into the calculation.

SECTION 4. OPTIONAL PROCEDURES

CONTENTS	DATE
4.1 Calculational Procedures, Reporting and Applicability	11/15/74
4.1.1 Calculational Steps	
4.1.2 Reporting and Applicability	
4.2 Alternative Methods	11/15/74
4.2.1 Specification Steps	
4.2.2 Injector Analysis	
4.2.3 Combustion Analysis	
4.2.4 Boundary Layer Analysis	
4.2.5 Iterations	
4.2.6 Inviscid Flow Analysis	
4.2.7 Typical Examples	

SECTION 4. OPTIONAL PROCEDURES

SUMMARY

The optional procedures are basically simplifications or variations that allow portions of the rigorous procedure to be bypassed. At each step of the rigorous procedure, one or more options is possible. Cases in which an optional procedure may be used in place of the rigorous procedure are:

- Failure of the reference computer programs to handle the specific case
- Insufficient time or funding for rigorous, but more detail needed than full simplified
- Detailed rigorous study of one physical process for which simplification of other processes does not add uncertainty (for example, a study of nozzle contour on performance could require full TDK and BLIMP analysis with the simplifying assumption of full vaporization and mixing to save costs)

Any combination of optional steps can be specified, but some of these possible combinations are inconsistent in that data required by later steps may not be calculated in simplified early steps. The logical consistency of a specified procedure should be verified prior to commitment to that procedure. The options to each step and resulting limitations on later steps are discussed in Section 4.2.

Section 4 Optional Procedures

Date: 11/15/74

4.1 Calculational Procedures, Reporting, and Applicability

4.1.1 CALCULATIONAL STEPS

The optional procedures are basically simplifications or variations that allow portions of the rigorous procedure to be carried out using an alternative calculation method. At each step of the rigorous procedure, one or more options are possible.

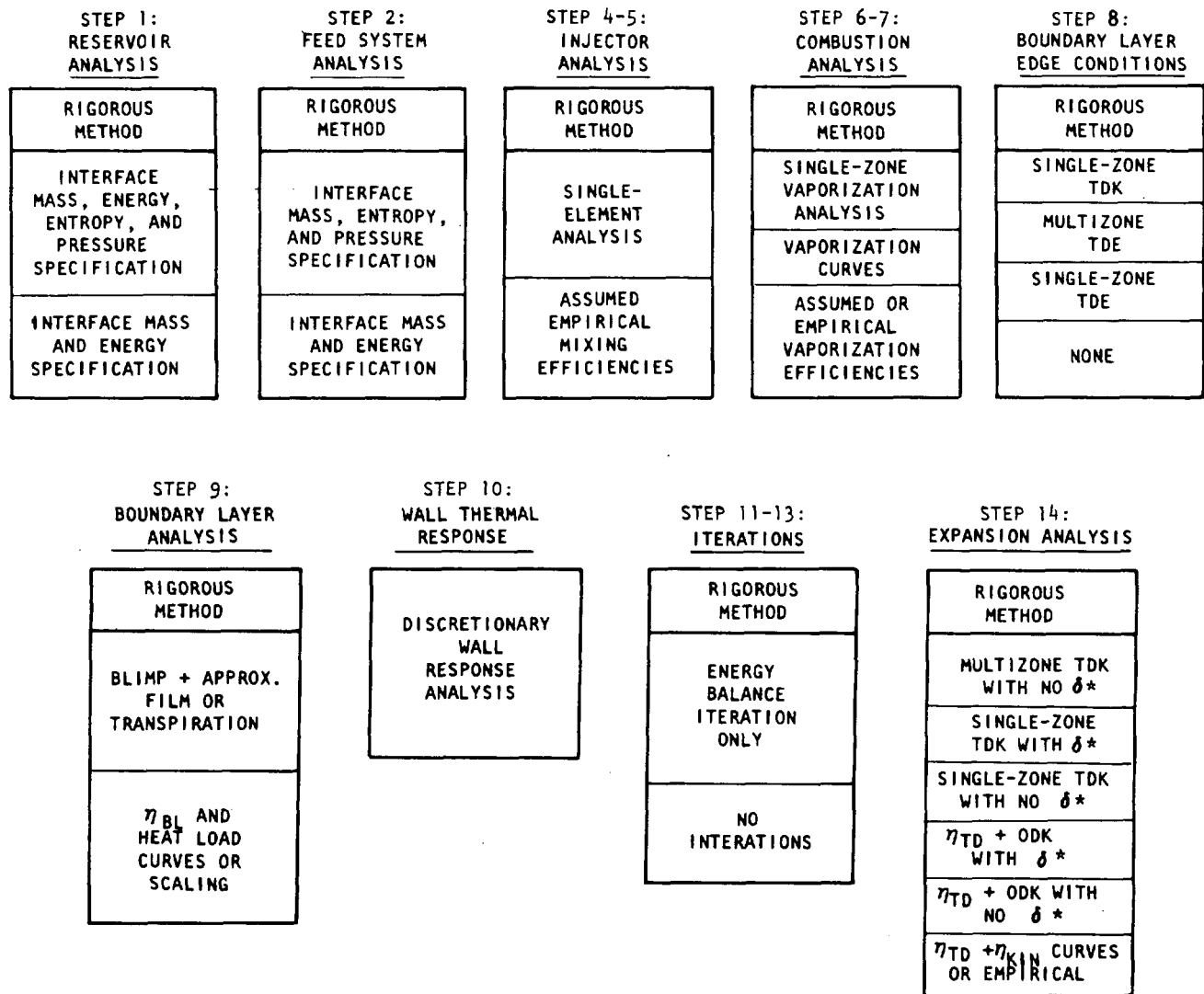
For each of the steps in the rigorous procedure, alternate calculational methods can be defined as shown in the illustration on page 4.1.1B. The optional procedures can be looked on as a spectrum of definitions of the simplified efficiencies of Section 3 ranging from exact to the most simplified.

The selection of particular methods at each step must be made in view of the information required from that step in subsequent steps. Thus, a more rigorous method may have to be employed than would otherwise be necessary just to provide the quality of input data needed later. In other words, some combinations of optional steps contain mutually exclusive elements. In any contracted or RFP effort, if an optional procedure is to be used, the exact method of calculation at each step must be explicitly detailed to preclude misunderstanding.

The steps of the optional procedures are identical to those of the rigorous. However, at each step, instead of having a specified procedure in terms of a reference computer program, a number of optional procedures or computer programs may be considered to supply the required analysis. That is, the analysis is still required, but a simple tool may be employed. The correspondence of the rigorous, optional, and simplified procedures is shown in the table below:

CORRESPONDENCE BETWEEN RIGOROUS, OPTIONAL, AND SIMPLIFIED PROCEDURES

Rigorous Procedure Step		Optional Procedures	Corresponding Simplified Efficiency
1.	Reservoir Specification	Less Complete Specification	--
2.	Feed System Specification	Less Complete Specification	--
4-5.	Injector Analysis (LISP, CICH)	Single Element or Assumed η_{MIX}	η_{MIX}
6-7.	Combustion Analysis (STC)	Single Zone, Curves or Assumed η_{VAP}	η_{VAP}
8.	Boundary Layer Edge Conditions (TDK)	Simplified TDK or TDE	--
9.	Boundary Layer Analysis (BLIMP)	Simplified BLIMP Run on Existing η_{BL}	η_{BL}
10.	Wall Thermal Response	Simplified Methods	--
11-13.	Iteration	Energy Balance Only or None	--
14.	Expansion Analysis	Various Modified Methods	η_{TD} , η_{KIN}



Analytical Components of Alternate Procedure

Section 4 Optional Procedures

Date: 11/15/74

4.1 Calculational Procedures, Reporting, and Applicability

4.1.2 REPORTING AND APPLICABILITY

Because of the flexibility of the optional procedures, reporting and applicability are largely judgemental on the part of the contractor and contracting agency, but both should be clearly specified.

The degree of reporting for the optional procedures can range from the rigorous to the simplified *at each step*. The reporting should be based on the ultimate intent of the analysis. If an optional procedure is used because of a limitation in a rigorous procedure, then full rigorous procedure reporting is desirable. On the other hand, if an optional procedure is used to obtain slightly better accuracy than the full simplified procedure in a situation normally calling for the simplified, then simplified reporting is usually acceptable.

The reporting formats outlined earlier in Sections 2 and 3 should serve as guidelines both in form and intent. The exact reporting is a matter for judgement on the part of the contracting agency. The prime ground rule applying to all procedures is that an independent analyst should have available enough information to reproduce the analysis and evaluate the assumptions used.

As outlined earlier, optional procedures must be used when a particular system falls outside the capabilities of the reference computer programs. This situation may not be obvious until the reference program has actually been tried.

Guidelines for use of optional procedures in other situations when a reference or simplified procedure would apply are:

- When use of the optional procedure can afford a significant saving in time and effort with no significant loss of accuracy from the rigorous procedure
- When use of the optional procedure can afford a significant improvement in accuracy with no significant increase in effort over the full simplified procedure

The selection of the particular optional procedure is discussed further in the following sections. The uncertainty of the optional procedure can be estimated in the same manner as for the rigorous and simplified procedures. The estimate must include the precision and bias for each of the factors included in the defining equation.

Section 4 Optional Procedures
4.2 Alternative Methods
4.2.1 SPECIFICATION STEPS

Date: 11/15/74

Three levels of detail are possible: the rigorous requiring full reporting of flows and balances; interface reporting; and abbreviated interface reporting.

The three options for specification of reservoir and feed system conditions are:

- Full reporting of interface and internal flows
- Reporting of interface flows only (enthalpy, mass flow, velocity, pressure, and temperature)
- Reduced reporting of interface conditions only (enthalpy and mass flow).

The first option is identical to the rigorous requirement. The second option provides for less extensive reporting, but still requires a thorough analysis to provide the correct details at the interface. The final option is identical to the simplified procedure requirement and can be fulfilled using a simple energy balance rather than a full reservoir or feed system analysis.

The alternatives and recommended uses are summarized in the table on page 4.2.1B.

SPECIFICATION ALTERNATIVES

OPTION	RECOMMENDED USE
RIGOROUS SPECIFICATION	SITUATIONS CALLING FOR THE RIGOROUS PROCEDURE BUT FOR WHICH THE REFERENCE COMPUTER PROGRAMS FAIL.
FULL INTERFACE SPECIFICATION	TEST DATA EXTRAPOLATION, OFF-DESIGN DATA, TEST DATA CORRELATION, THRUST CHAMBER ONLY PREDICTIONS.
SIMPLIFIED INTERFACE SPECIFICATIONS	PARAMETRIC DATA, SENSITIVITY FACTOR DETERMINATION, OFF-DESIGN DATA.

Section 4 Optional Procedures
4.2 Alternative Methods
4.2.2 INJECTOR ANALYSIS

Date: 11/15/74

In the injector analysis, the rigorous procedure includes a number of options. In addition to these options, single-element analysis can often be used to advantage.

The rigorous procedure allows the use of alternate injector analysis such as full cold-flow data. Since the empirical option is part of the rigorous procedure, the only additional alternatives included here are: (1) the use of single-element analysis in which the resulting distribution is derived from only one element spray pattern, and (2) the simplified procedure using an η_{MIX} .

Single-element analysis can be particularly useful in selecting element types. However, manifold effects must be assumed to be small or the effects must be assumed to be additive. For example, a single element analysis can be used for the central region of a film-cooled injector with any of the options for the analysis of the film cooling.

The use of the full simplified procedure (η_{MIX}) precludes the use of multizone analysis, but is recommended when the injector design has not been identified. That is, past experience with the propellants of interest may indicate an achievable level of mixing for well-designed injectors. This level can be assumed for preliminary analysis and nozzle design studies prior to the actual designing of the injector.

The recommended uses of the alternate procedures are given in the table on page 4.2.2B. The three optional methods are indicated and the usual instances for employing each option are discussed.

INJECTOR ANALYSIS ALTERNATIVES

OPTION	RECOMMENDED USE
RIGOROUS	● DESIGN POINT CALCULATIONS, MAJOR MIXING LOSSES ● LARGE-SCALE MANIFOLD UNBALANCE
SINGLE-ELEMENT	● ALL ELEMENTS SIMILAR WITH NO MAJOR MANIFOLD EFFECTS (MUCH LESS THAN 0.1 PERCENT) ● PRELIMINARY DESIGN CALCULATIONS (SINGLE-ELEMENT COLD-FLOW DATA AVAILABLE, ELEMENT TYPE INVESTIGATION)
SIMPLIFIED (η_{MIX})	● NEGLIGIBLE MIXING EFFECTS (LESS THAN 0.1 PERCENT) ● PRELIMINARY DESIGN CALCULATIONS (NO COLD-FLOW DATA AVAILABLE, NO INJECTOR DESIGN AVAILABLE--USE η_{MIX} FROM SIMILAR ENGINE) ● PREVENTS USE OF MULTIZONE TDK AND STC

Section 4 Optional Procedures
4.2 Alternative Methods
4.2.3 COMBUSTION ANALYSIS

Date: 11/15/74

The use of a single-zone combustion analysis is a recommended alternative with the mixture ratio distribution reinstituted at the TDK interface.

The alternative combustion analysis procedures are summarized in the table on page 4.2.3B.

For many thrust chamber and injector designs, the percentage of mass vaporized as a function of droplet size is only very weakly a function of differences from streamtube to streamtube. Therefore, a single average zone can be used to determine the vaporization fraction for various dropsizes groups, greatly simplifying and shortening the STC analysis. The curves developed can then be used with the streamtube data (droplet sizes and mixture ratio) to establish the vaporized mass and mixture ratio zones for TDK.

The use of vaporization curves is similar to a single-zone analysis except that the actual design conditions (pressure, contraction ratio) may fall between curves or require extrapolation.

Finally, the simplified method (η_{VAP}) can be used together with the mixture ratio zones. This procedure makes the assumption that the combined effects of dropsizes and vaporization rate are identical from zone to zone. The distinct zones can still be preserved for use in TDK.

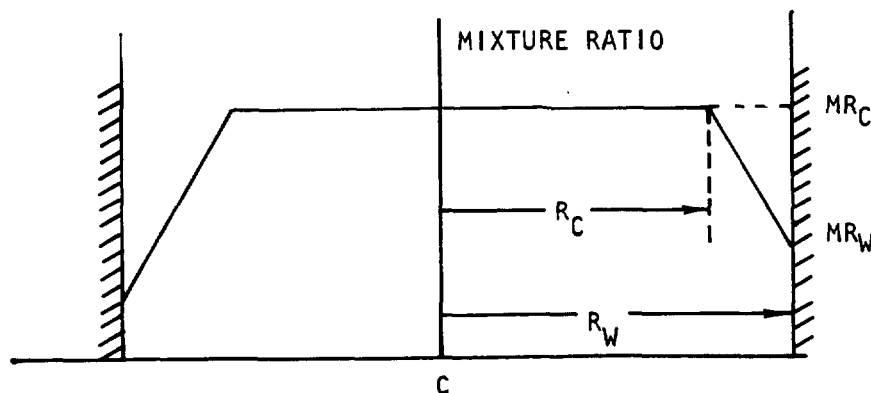
COMBUSTION ANALYSIS ALTERNATIVES

OPTIONS	RECOMMENDED USE	LIMITATIONS
RIGOROUS	● STRONG VARIATIONS IN DROPLET SIZE FROM REGION TO REGION ● STRONG MIXTURE RATIO IMPACT ON VAPORIZATION RATES	NONE
SINGLE-ZONE VAPORIZATION ANALYSIS	● NEGLIGIBLE DIFFERENCES IN VAPORIZATION EFFECTS BETWEEN MIXTURE RATIO ZONES	NONE
VAPORIZATION CURVES	● NEGLIGIBLE DIFFERENCES IN VAPORIZATION EFFECTS BETWEEN MIXTURE RATIO ZONES WITH EASY INTERPOLATION BETWEEN DESIGN CONDITIONS	NONE
SIMPLIFIED (η_{VAP})	● NEGLIGIBLE DIFFERENCES IN DROPSIZE OR VAPORIZATION EFFECTS BETWEEN MIXTURE RATIO ZONES	LOSES DISTINCTION BETWEEN DROPSIZE AND VAPORIZATION RATE EFFECTS

Simplified edge condition calculations are recommended. For film-cooled thrust chambers, the optional procedure may be preferable to the rigorous method currently used.

Four procedures are possible for determining edge conditions. Of these, the simplest is a single-zone run of the TDE option in TDK. The edge conditions from this computer run should be accurate enough that no difference will be observed in major boundary layer parameters except in cases having kinetic losses in excess of 10 percent.

For highly film-cooled situations, a method has been developed by M. Bensky (based on work reported in Ref.*) that has correlated experimental trends quite well. The method consists of linearly distributing mixture ratio between the wall mixture ratio and some inner zone at which the mixture ratio matches the core mixture ratio, as shown below:



The ratio of (R_C/R_W) is found by solving the quadratic equation:

$$\left[\left(\frac{2}{MR_W - MR_C} \right) - \frac{2 MR_W \ln \left(\frac{MR_W}{MR_C} \right)}{(MR_C - MR_W)^2} + \frac{1}{MR_C} \right] \left(\frac{R_C}{R_W} \right)^2 - \left[\left(\frac{4}{MR_W - MR_C} \right) - \frac{2 (MR_W + MR_C) \ln \left(\frac{MR_W}{MR_C} \right)}{(MR_C - MR_W)^2} \right] \left(\frac{R_C}{R_W} \right) + \left[\left(\frac{2}{MR_W - MR_C} \right) - \frac{2 MR_C \ln \left(\frac{MR_W}{MR_C} \right)}{(MR_C - MR_W)^2} - \frac{1}{MR_C} - \frac{\dot{M}_{FILM}}{\dot{M}_{OXIDIZER}} \right] = 0$$

*PWA FR-11-22, First Quarterly, Design Study of an Engine System for Upper Stages of Up-rated Saturn, 2 October 1964.

where

$$\frac{\dot{M}_{\text{FILM}}}{\dot{M}_{\text{OXIDIZER}}} = \left[\frac{\dot{M}_{\text{FILM}}/\dot{M}_{\text{INJ}}}{1 - \dot{M}_{\text{FILM}}/\dot{M}_{\text{INJ}}} \right] \left[\frac{MR_C + 1}{MR_C} \right]$$

The mixture ratio as a function of radius is then given by:

$$MR = MR_C - (MR_C - MR_W) \left(\frac{\frac{R}{R_W} - \frac{R_1}{R_W}}{1 - \frac{R_1}{R_W}} \right)$$

Note that when dividing the film region into zones, the mixture ratio of a zone must be calculated by integrating over the mass in the zone rather than taking the center point of the geometric position. The zones are used in TDK or ODK for the outer region. BLIMP is run with the core mixture ratio (unless an average appears more desirable to match heat transfer data). The various options, recommended use, and limitations are given in the table below:

	OPTION	RECOMMENDED USE	LIMITATIONS
EDGE CONDITIONS	RIGOROUS	ONLY IN MOST ACCURACY CRITICAL CASES	NONE
	SINGLE-ZONE TDK (AVERAGE MIX- TURE RATIO)	MOST CASES IN WHICH REACTION KINETICS STRONGLY AFFECT FLOW CONDITIONS	NOT APPROPRIATE FOR SEVERE STRATIFICATIONS NEAR WALL
	MULTIZONE TDE { SINGLE-ZONE TDE	CASES HAVING SEVERE RADIAL MIXTURE RATIO STRATIFICATION WITH MODERATE KINETIC EFFECTS MOST CASES UNLESS KINETICS/MIXING HAVE SEVERE INFLUENCE	INAPPROPRIATE FOR SEVERE KINETIC EFFECTS NOT APPROPRIATE FOR CASES HAVING SEVERE MIXING OR KINETIC EFFECTS
METHOD OF ANALYSIS	RIGOROUS	MOST CASES HAVING RELATIVELY UNIFORM WALL MIXTURE RATIO	APPEARS TO HAVE TROUBLE WITH UNMIXED FILM COOLANT
	APPROXIMATE FILM OR TRANSPIRATION	MOST CASES HAVING LARGE SCALE (>10% OF TOTAL MASS FLOW) FILM COOLANT	HEAT TRANSFER MAY BE INCONSISTENT WITH LOSSES
	SIMPLIFIED (η_{BL})	GENERALLY NOT RECOMMENDED EXCEPT FOR VERY QUICK ESTIMATES (COST OF RUNNING TDE + BLIMP IS QUITE LOW)	MAY BE INCONSISTENT WITH HEAT TRANSFER, WALL CONTOUR, MIXTURE RATIO DISTRIBUTION, ETC.

Section 4 Optional Procedures
4.2 Alternative Methods
4.2.5 ITERATIONS

Date: 11/15/74

Two alternative iteration levels are allowed: energy level only or no iteration.

The rigorous procedure requires three simultaneous interlocking iterations (nonboundary layer heat load, wall temperature, total heat load) for perfect consistency. With some sacrifice of consistency, but little loss in accuracy, the iteration on wall temperature and nonboundary layer heat load can be ignored. Therefore, only the correct energy needs iteration, and the iteration does not have to include redoing edge conditions. Thus, the edge conditions can be for an initial guess on enthalpy. The final inviscid calculation should use enthalpies consistent with the boundary layer heat load calculation. Alternatives are summarized on page 4.2.5B. In the energy only iteration, the calculations are carried out until the energy removed from the thrust chamber flow (boundary layer, etc.) matches that assumed to be added to the feed system from the thrust chamber without regard to wall temperature calculated versus that used in BLIMP.

ITERATION ALTERNATIVES

OPTION	RECOMMENDED USE	LIMITATIONS
RIGOROUS	CASES DEMANDING HIGHEST ACCURACY	NONE
ENERGY ONLY	MOST CASES IN WHICH BOUNDARY LAYER LOSS DOES NOT DEPEND STRONGLY ON EXACT WALL TEMPERATURE PROFILE	NONE
SIMPLIFIED	● SYSTEMS HAVING NEGLIGIBLE ENERGY TRANSFER (REGENERATIVE) EFFECTS ● PARAMETRIC DATA	FEED SYSTEM MAY BECOME INCONSISTENT WITH HEAT FLOW FROM THRUST CHAMBER, THUS MAKING INJECTION ENTHALPIES INCONSISTENT WITH η_{BL} VALUE.

Section 4 Optional Procedures
 4.2 Alternative Methods
 4.2.6 INVISCID FLOW ANALYSIS

Date: 11/15/74

Two basic options are possible: wall adjusted for δ^* or real wall. Within these options, a series of variations (multizone versus single zone, TDK versus single zone, TDK versus ODK) are allowable.

Two wall conditions can be used for the inviscid flow analysis: real wall or potential wall (displaced by δ^* , Section 2.9). If the potential wall is used, the boundary layer thrust correction is given by:

Potential wall ΔF_{BL}

$$\Delta F_{BL} = 2 \pi R_E \cos \alpha_E \left[\left(\rho_E V_E^2 \right)_{TDKP} \theta_E - \frac{P_E}{TDKP} \delta^* \right] \quad (1)$$

Real Wall ΔF_{BL}

$$\Delta F_{BL} = 2 \pi R_E \cos \alpha_E \left[\left(\rho_E V_E^2 \right)_{TDKR} \theta_E \right] \quad (2)$$

In other words, the correction for the artificial pressure thrust is eliminated. The error involved in using the combined real wall analysis is given by:

$$\begin{aligned} \text{Error} = & (ISP_{TDKP} - ISP_{TDKR}) - 2 \pi R_E \cos \alpha_E \\ & \times \left[\left(\rho_E V_E^2 \right)_{TDKP} - \left(\rho_E V_E^2 \right)_{TDKR} \right] \theta_E + 2 \pi R_E \cos \alpha_E \frac{P_E}{TDKP} \delta^* \end{aligned}$$

The final term essentially cancels the first term and, for small δ^* , the two ρV^2 products are identical.

Various optional procedures are summarized in the table on page 4.2.6B.

ALTERNATE INVISCID FLOW ANALYSES

OPTION		RECOMMENDED USE	LIMITATIONS
WALL	POTENTIAL	ONLY MOST HIGHLY ACCURATE CASES	NONE
	REAL	MOST CASES	ΔF_{BL} IS DIFFERENT FROM STANDARD DEFINITION (EQ. 2 RATHER THAN EQ. 1)
ANALYSIS METHOD	MULTIZONE TDK	MOST DESIGN POINT CASES	NONE
	SINGLE-ZONE TDK	CASES HAVING RELATIVELY NEGLIGIBLE MIXING EFFECTS	NONE
	η_{TD} + MULTIZONE ODK	CASES HAVING RELATIVELY UNIFORM EXPANSION THROUGHOUT THE FLOW (CONES, MANY BELLS)	RAPID NONUNIFORM EXPANSIONS CREATE VARYING KINETIC EFFECTS
	η_{TD} + SINGLE-ZONE ODK	CASES HAVING RELATIVELY UNIFORM MIXTURE RATIO AND EXPANSION	NONUNIFORM EXPANSION RATES AND MIXTURE RATIOS
	η_{TD} AND η_{KIN}	FIRST ESTIMATES	LOWEST ACCURACY

The various analysis methods are:

- Multizone TDK - discussed in rigorous procedure
- Single-Zone TDK - TDK run using average overall mixture ratio
- η_{TD} + Multizone ODK - η_{TD} calculated using TDE or TDY, or from charts, with kinetics calculated by running ODK for each zone. Then,

$$ISP_{TDK} \sim \eta_{TD} \sum \frac{\dot{M}_j}{\dot{M}_{TC}} ISP_{ODK_j}$$
- η_{TD} + Single-Zone ODK - same as previous step, with a single overall mixture ratio ODK run replacing the multiple-zone analysis
- η_{TD} and η_{KIN} - η_{TD} and η_{KIN} from parametric charts

Section 4 Optional Procedures
4.2 Alternative Methods
4.2.7 TYPICAL EXAMPLES

Date: 11/15/74

The use of optional procedures is illustrated using the example of a thrust chamber in which the key interest is the influence of wall contour on ISP.

Consider a study in which the optimum wall contour downstream of the throat is to be found by analysis and then confirmed by testing. The propellants are injected as gases in a manner to ensure complete mixing. The wall is heat sink. The area ratio and length are fixed. The radius of curvature downstream of the throat and expansion contour are variable. Feed is from facility tanks.

For this study, the use of optional procedures can provide considerable cost saving (and, also, is necessary because of gas/gas injection). For the specification steps, only the facility supply conditions at the injector inlet are necessary

The injection and combustion analysis steps are simplified by assuming complete mixing and complete vaporization. Therefore, no computer program runs are required.

The boundary layer edge condition can be found from a single-zone TDE run, saving considerable cost compared to a TDK run with virtually no difference in final answer.

The boundary layer analysis must be carried out using BLIMP in a rigorous fashion since the boundary layer thrust loss is strongly influenced by wall contour and tends to counteract gains in other areas. The wall temperature (which will vary with time for heat-sink hardware) can be estimated using a film coefficient. No iterations are necessary.

Since the interaction of boundary layer, two-dimensional, and kinetic processes are of major interest, the rigorous TDK analysis must be employed with the potential flow contour. Only a single zone is required (based on earlier assumption of complete mixing and vaporization).

An opposite example is a thrust chamber in which the nozzle is fixed and various injector designs are being studied. For this example, the rigorous injection and combustion analysis would be employed (LISP and STC). For the following steps, η_{BL} and η_{TD} would be employed with a multizone ODK option to give the mixture ratio distribution effects.

As indicated by these examples, the optional procedures can be basically the simplified procedure with additional detail inserted for the key processes being studied.

An example in which the method followed is rigorous except for one step is that where the wall contour cannot be analyzed using TDK (step contour, for example). In this case, the rigorous expansion analysis step is replaced with the η_{TD} and multizone ODK option.

SECTION 5. REFERENCE COMPUTER PROGRAMS

The reference computer programs are listed in this section. One page is devoted to each program giving availability, source, User's Manual, and description.

Boundary Layer Integral Matrix Program	5.1.1
Coaxial Injector Combustion Model	5.1.2
Liquid Injector Spray Pattern	5.1.3
Three-Dimensional Combustion	5.1.4
Streamtube Combustion	5.1.5
Two-Dimensional Kinetic	5.1.6
Auxiliary Computer Programs	5.1.7

Name: Boundary Layer Integral Matrix Program

Abbreviation: BLIMP

Date of Latest Version: September 1974

Available From: Klaus Gross, Marshall Space Flight Center, Huntsville, Alabama

Programmer: Mike Evans, Acurex Corporation, Mountain View, California

User's Manual: Interim User's Manual for Boundary Layer Integral Matrix Procedure, Version J, M. Evans and H. Morse, Aerotherm Report 6282, September 1974.

Description: The BLIMP computer program solves the chemical equilibrium boundary layer equations using an integral matrix procedure. Various problem types can be addressed including mass addition from ablation, transpiration, or direct injection. Outputs include the momentum thickness and wall displacement used in thrust chamber performance and heat loads used in system calculations.

Name: Coaxial Injector Combustion Model

Abbreviation: CICM

Date of Latest Version: July 1974

Available From: Klaus Gross, Marshall Space Flight Center, Huntsville, Alabama

Programmer: Merlin Schuman, Rocketdyne, Canoga Park, California

User's Manual: Operating Manual for Coaxial Injection Combustion Model,
R. D. Sutton, M. D. Schuman, W. D. Chadwick, July 1974.

Description: The CICM computer program treats the droplet formation and mixture ratio distribution for coaxial gas/liquid injector elements. The program interfaces with the STC subprogram of DER at the point of full jet atomization. Subcritical and supercritical pressure liquids can be handled. Data tables and correlation coefficients are currently available for O_2/H_2 injectors.

Name: Liquid Injector Spray Pattern

Abbreviation: LISP

Date of Latest Version: May 1974

Available From: Raymond Kushida, Jet Propulsion Laboratory, Pasadena, California,
or Daweel George, Air Force Rocket Propulsion Laboratory,
Edwards, California

Programmer: William Chadwick, Rocketdyne, Canoga Park, California

User's Manual: Liquid Rocket Combustion Computer Model with Distributed Energy
Release, L. P. Combs, Revised May 1974.

Description: The LISP computer program (packaged as part of the Distributed Energy Release Model) is used to determine droplet sizes and spray mixture ratio distribution for liquid/liquid injectors. Coefficients for a variety of impinging-type injector elements are built into the program. Other element types can be treated by input of coefficients. Only subcritical liquids can be treated.

Name: Three-Dimensional Combustion

Abbreviation: 3DC (sometimes 3-D CØMBUST)

Date of Latest Version: May 1974

Available From: Raymond Kushida, Jet Propulsion Laboratory, Pasadena, California,
Daweel George, Air Force Rocket Propulsion Laboratory, Edwards,
California

Programmer: William Hines, Rocketdyne, Canoga Park, California

User's Manual: User's Guide for the Three-Dimensional Spray Combustion Program,
3D-CØMBUST, W. S. Hines and K. Fertig, Rocketdyne, Revised May 1974

Description: The 3DC computer program continues the spray patterns from LISP using an averaging technique that models the intermixing from various elements and the turning of the flow to an axial direction. Initiation of vaporization of the spray is included using a simplified approach. Applicability is currently limited to special cases.

Name: Streamtube Combustion

Abbreviation: STC

Date of Latest Version: May 1974

Available From: Raymond Kushida, Jet Propulsion Laboratory, Pasadena, California
Daweel George, Air Force Rocket Propulsion Laboratory, Edwards,
California

Programmer: William Chadwick, Rocketdyne, Canoga Park, California

User's Manual: Liquid Rocket Combustion Computer Model with Distributed Energy
Release, L. P. Combs, Revised May 1974.

The STC computer program (packaged as part of the Distributed Energy Release Model) solves the simultaneous one-dimensional flow and liquid vaporization processes occurring in the combustion chamber following injection. The program is initialized with droplet sizes and mixture ratio distributions (from LISP, 3DC, or CIGM). Flow is assumed to take place in streamtubes with no additional mixing. Two-dimensional effects in the converging region are included. Outputs are vaporization efficiency and mixture ratio zones for TDK. Two versions are available, the droplet heating version for the full-pressure regime from subcritical to supercritical, and the simplified k-prime version for subcritical pressure combustion.

Name: Two-Dimensional Kinetic
(One-Dimensional Equilibrium, One-Dimensional Kinetic are subprograms)

Abbreviation: TDK (ODE, ODK)

Date of Latest Version: May 1974

Available From: Ronald Kahl, Johnson Space Flight Center, Houston, Texas

Programmer: Gary Nickerson, Ultrasystems, Irvine, California

User's Manual: Two-Dimensional Kinetic Program User's Manual

Description: The TDK program solves the simultaneous nonequilibrium reacting gas and two-dimensional method of characteristics equations to characterize the flow in an annular thrust chamber. The program uses inputs from STC as a starting point. The actual wall contour is used. Outputs are the inviscid flow C^* and specific impulse and edge conditions (ρ , P , T , U , etc.) for BLIMP. Other options are equilibrium flow or constant γ .

The ODE subprogram solves the chemical equilibrium equations and flow thermodynamic equations for one-dimensional isentropic flow. Frozen composition and constant γ options are also available.

The ODK subprogram solves the reaction kinetic and flow thermodynamic equations for one-dimensional flow. The program calculates one-dimensional specific impulse and C^* for a rigorous reaction kinetic formulation.

The ODE and ODK subprograms can be run separately as if they were individual computer programs.

AUXILIARY COMPUTER PROGRAMS

A number of auxiliary computer programs are of interest in the JANNAF methodology (for example, ablation codes). Also, the combustion computer programs require extensive thermodynamic data that must be generated by a program such as ODE or that described in: N73-15954-CEC71/TRAN72, Svehla, et al., January 1973, FORTRAN IV Computer Program Calculation of Thermodynamic and Transport Properties of Complex Chemical Systems.

This computer program also can supply transport data for BLIMP. Eventually, a reference page will be supplied to give information on these additional programs, as done for the reference programs.

SECTION 6

Section 6 Standard Input Data
6.1 THERMOPHYSICAL PROPERTIES

The following tables contain enthalpy and density data for common rocket engine propellants. The data contained are:

PROPELLANT	PAGE NUMBERS
Chlorine Pentafluoride	6.1.1
Chlorine Trifluoride	6.1.2
Diborane	6.1.3
Fluorine	6.1.14
Hydrazine	6.1.18
Hydrogen Peroxide	6.1.19
90% Hydrogen Peroxide/10% Water	6.1.20
Methane	6.1.21
Monomethylhydrazine	6.1.22
Nitric Acid	6.1.23
Nitrogen Tetroxide	6.1.24
Normal Hydrogen	6.1.25
Oxygen	6.1.26
Oxygen Difluoride	6.1.30
Parahydrogen	6.1.31
Red Fuming Nitric Acid (RFNA)	6.1.36
Unsymmetrical Dimethylhydrazine (UDMH)	6.1.37
Unsymmetrical Dimethylhydrazine/ Hydrazine (50-50)	6.1.38

The data are used in feed system calculation and for input to the ODE, BLIMP, TDK, ODK, and TDE computer programs.

COMPOUND: Chlorine Pentafluoride

EMPIRICAL FORMULA: ClF₅ MOLECULAR WEIGHT = 130.457

ASSIGNED REFERENCE ENTHALPY

	kcal/mol	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 298.15 K 1 atm	-60.5 ±6.0	-46.4	-1.94	-834.76

DENSITY

	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 298.15 K 1 atm	1.779	1779	111.010

SOURCES OF DATA

JANNAF Heat of Formation Propellant Ingredients (U), D. R. Stull, T. E. Dergazarian, I. H. Carr, Dow Chemical Co., Midland, Michigan, and revisions 1963 to 1967, CONFIDENTIAL.

COMPOUND: Chlorine Trifluoride

EMPIRICAL FORMULA: ClF₃ MOLECULAR WEIGHT = 92.457

ASSIGNED REFERENCE ENTHALPY

	kcal/mol	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 298.15 K 1 atm	-44.45 ±0.8	-48.08	-2.012	-865.38

DENSITY

	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 298.15 K 1 atm	1.807	1807	112.76

SOURCES OF DATA

JANNAF Heat of Formation of Propellant Ingredients (U), D. R. Stull, T. E. Dergazarian, I. H. Carr, Dow Chemical Co., Midland, Michigan, and revisions 1963 to 1967, CONFIDENTIAL.

COMPOUND: Diborane

EMPIRICAL FORMULA: B₂H₆ MOLECULAR WEIGHT = 27.688

ASSIGNED REFERENCE ENTHALPY

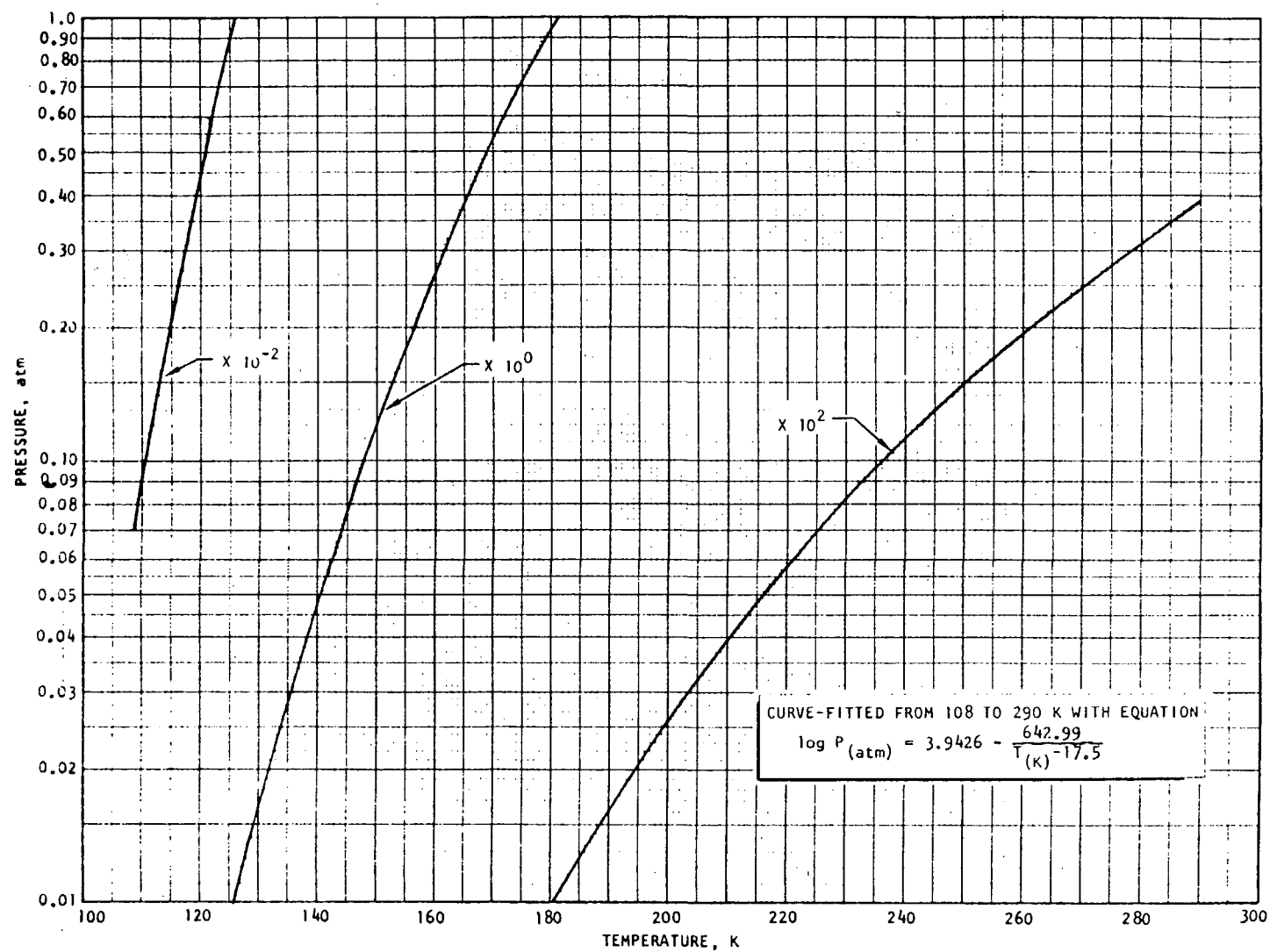
	kcal/mole	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 180.59 K 1 atm	+4.97 ±4.0	+17.94	+0.75	+323.1
GAS AT 298.15 K 1 atm	9.8	35.39	1.48	637.1

DENSITY

	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 180.59 K 1 atm	0.4371	437.1	142.76
GAS AT 298.15 K 1 atm	0.0012	1.2	0.0749

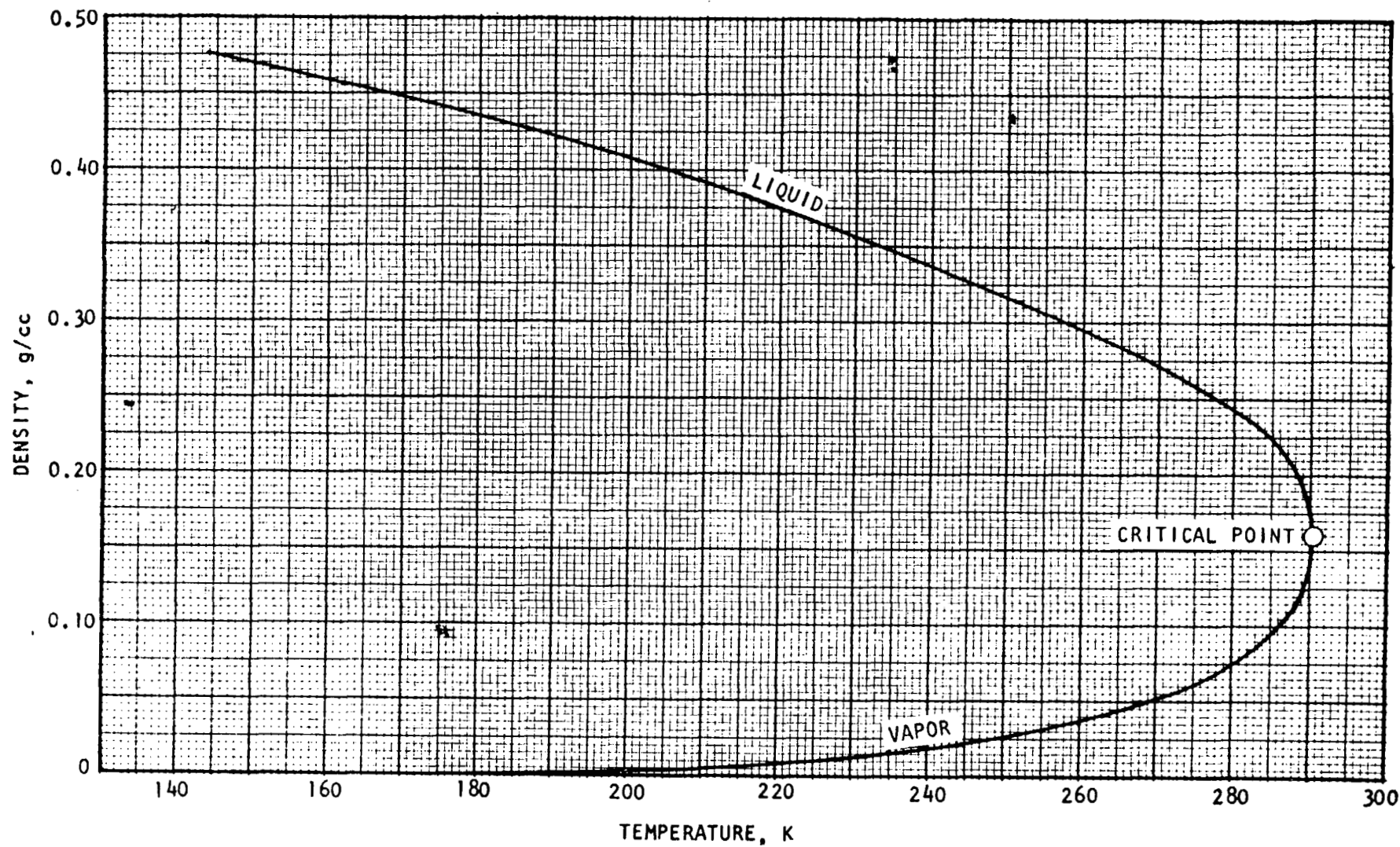
SOURCES OF DATA

1. JANNAF Heat of Formation Propellant Ingredients (U), D. R. Stull, T. E. Dergazarian, I. H. Carr, Dow Chemical Co., Midland, Michigan, and revisions 1963 to 1967, CONFIDENTIAL.
2. R-8248, Diborane Space Storable Propellant Handbook, NASA 7-769.

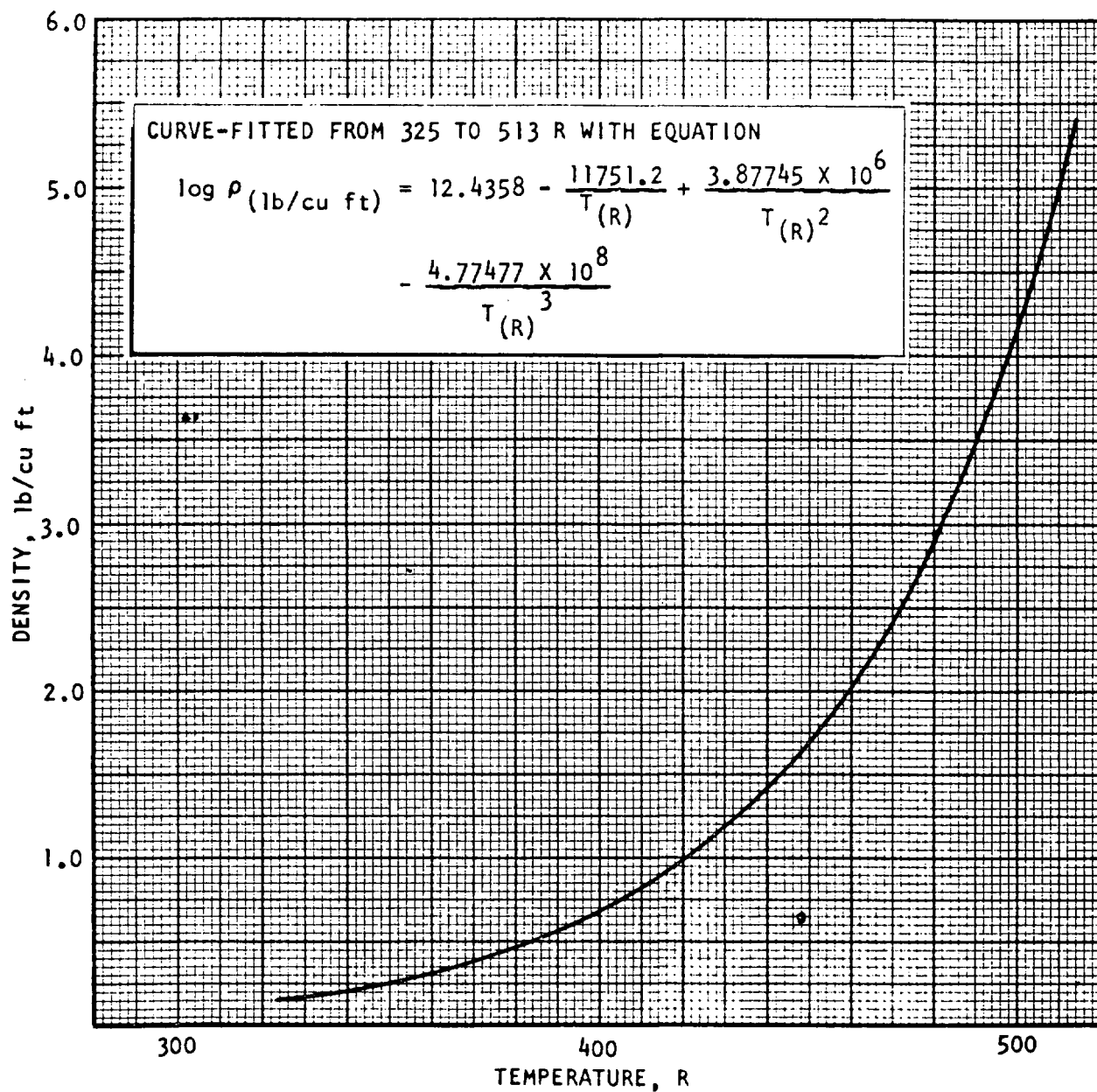


Vapor Pressure of Diborane

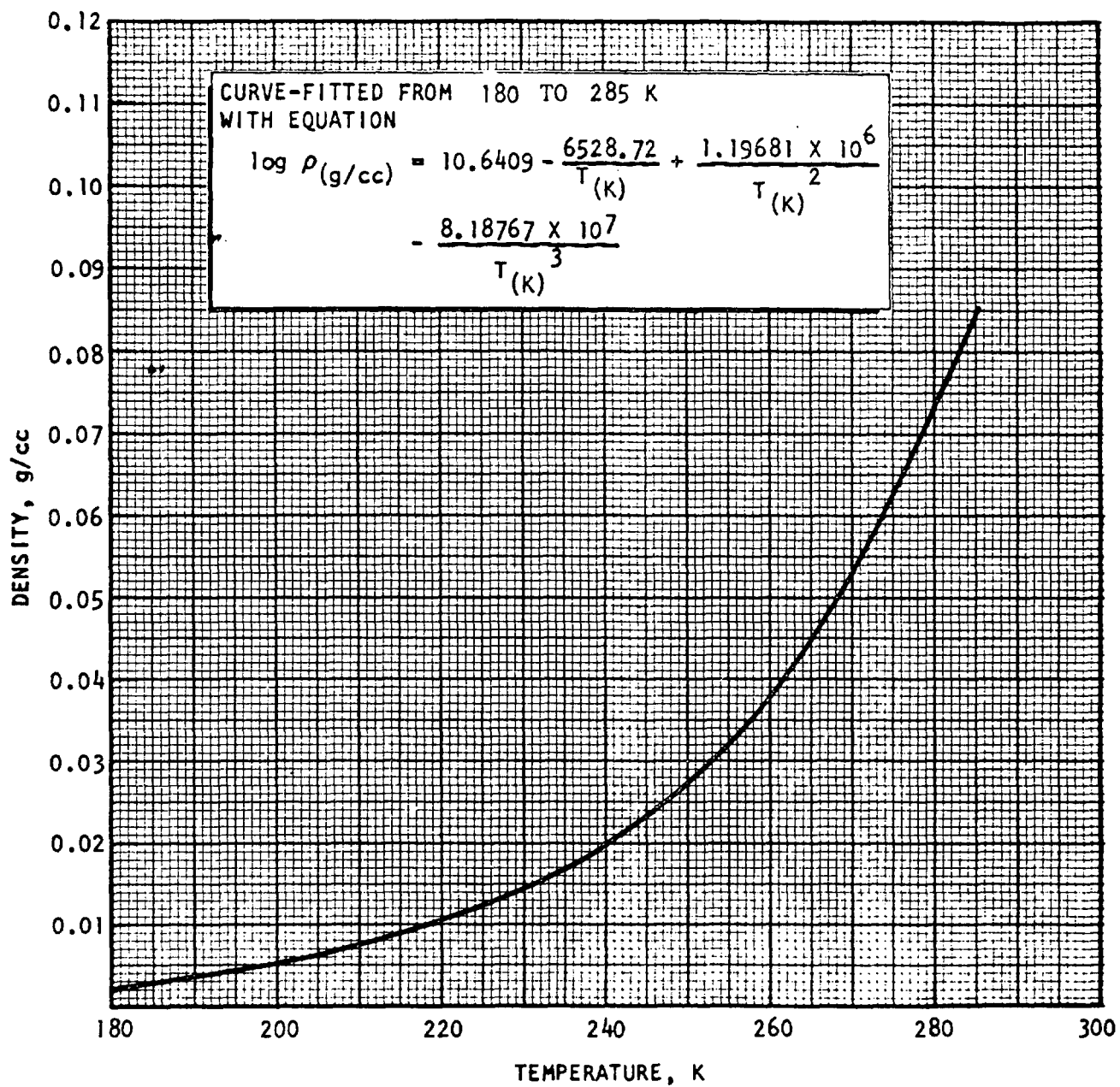
S.T.9



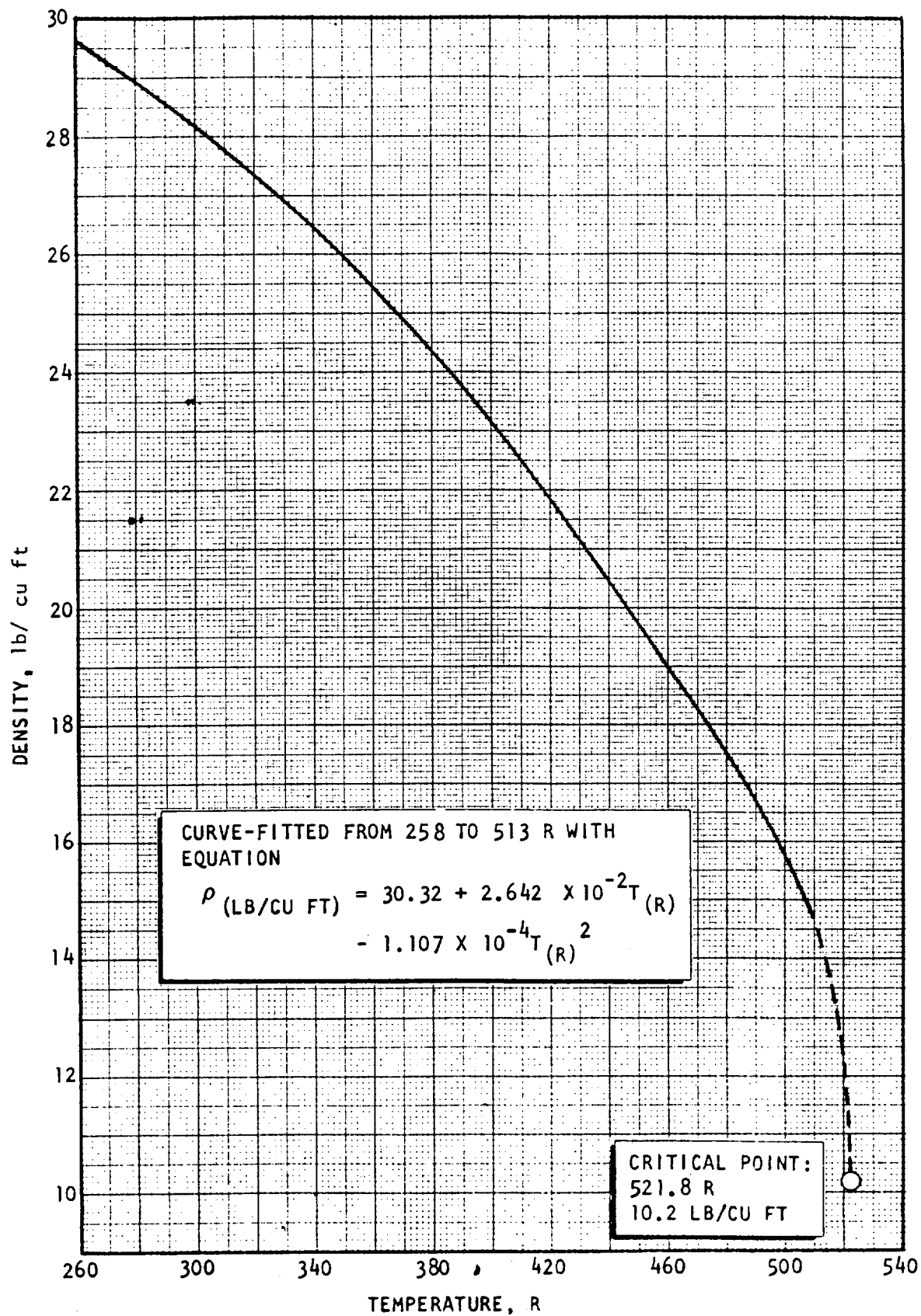
Density of Saturated Liquid and Vapor Diborane



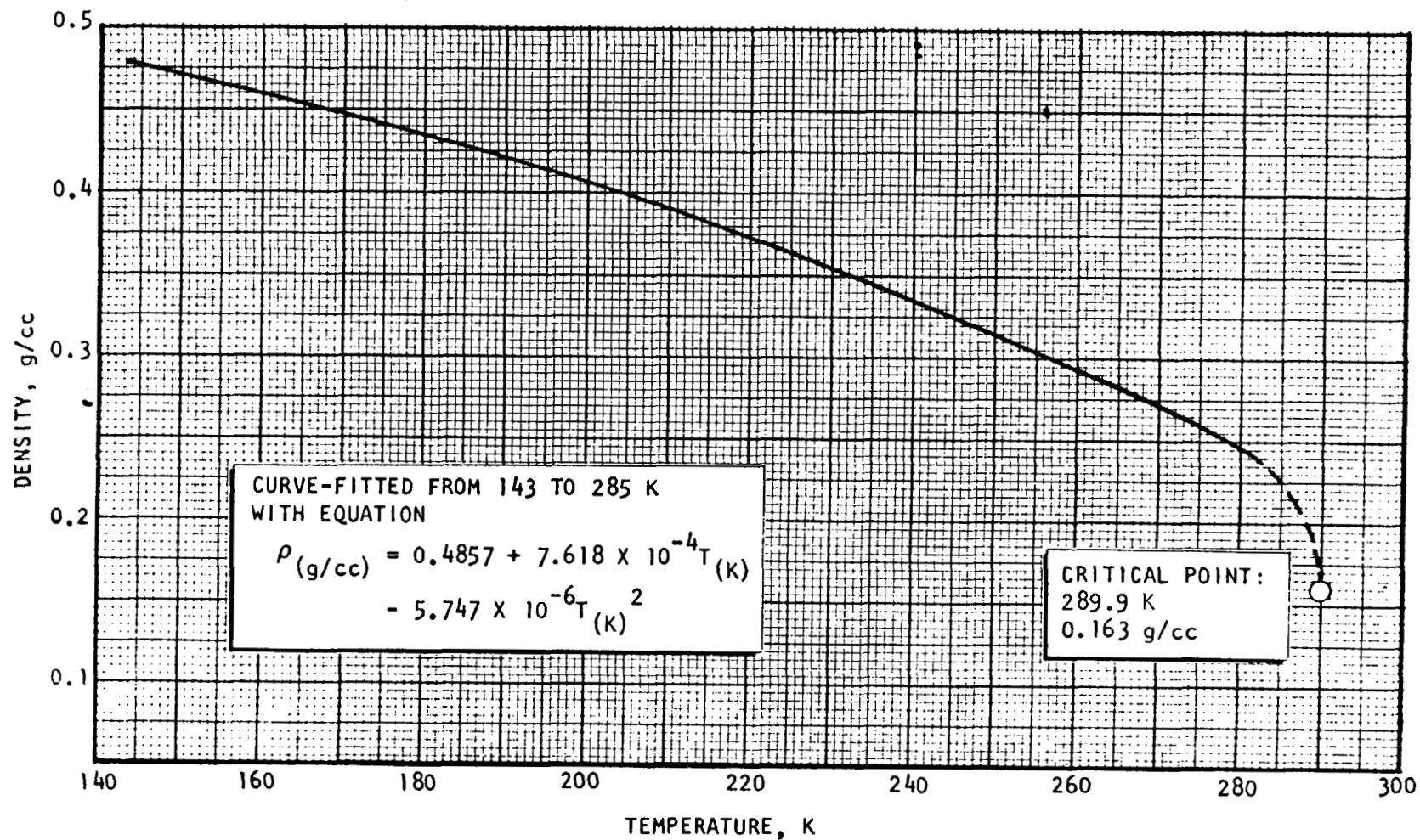
Saturated Vapor Density of Diborane



Saturated Vapor Density of Diborane



Density of Saturated Liquid Diborane



Density of Saturated Liquid Diborane

DENSITY RATIO, ρ/ρ_{O^*} OF REAL GAS DIBORANE

P(Atm.)	0.01	0.1	0.4	0.7	1	4	7	10	40	70	100
T(°K)											
130	.020820										
140	.019327										
150	.018034										
160	.016904	.17004									
170	.015907	.15983	.64975								
180	.015022	.15081	.61118	1.0842							
190	.014230	.14276	.57724	1.0215	1.4761						
200	.013518	.13555	.54706	.96621	1.3934						
210	.012874	.12902	.52005	.91713	1.3206	5.7815					
220	.012288	.12311	.49567	.87313	1.2557	5.4111					
230	.011754	.11773	.47356	.83339	1.1974	5.0983	9.6249				
240	.011264	.11280	.45338	.79728	1.1446	4.8283	8.9919	13.857			
250	.010813	.10827	.43490	.76430	1.0966	4.5913	8.4643	12.851			
260	.010397	.10409	.41789	.73403	1.0526	4.3807	8.0134	12.038			
270	.010012	.10022	.40218	.70614	1.0121	4.1920	7.6205	11.357			
280	.0096535	.096628	.38763	.68034	.97479	4.0208	7.2731	10.773			
290	.0093206	.093286	.37411	.65641	.94019	3.8646	6.9622	10.262			
300	.0090099	.090169	.36151	.63414	.90805	3.7212	6.6814	9.8093	64.403	199.33	216.33
310	.0087193	.087253	.34975	.61335	.87807	3.5892	6.4261	9.4036	54.467	173.36	201.72
320	.0084468	.084521	.33872	.59390	.85005	3.4671	5.7582	9.0365	48.644	141.94	187.43
330	.0081908	.081955	.32838	.57566	.82379	3.3536	5.9769	8.7020	44.555	114.60	172.50
340	.0079499	.079540	.31866	.55852	.79914	3.2478	5.7777	8.3951	41.411	97.252	156.70
350	.0077228	.077264	.30949	.54238	.77594	3.1488	5.5926	8.1122	38.870	85.759	140.97
360	.0075083	.075115	.30085	.52072	.75407	3.0563	5.4201	7.8500	36.747	77.617	126.86
370	.0073053	.073082	.29267	.51278	.73341	2.9690	5.2588	7.6063	34.929	71.450	115.13
380	.0071131	.071157	.28493	.49917	.71386	2.8868	5.1076	7.3787	33.343	66.567	105.60
390	.0069307	.069330	.27759	.48626	.69534	2.8092	4.9653	7.1657	31.939	62.557	97.828
400	.0067574	.067591	.27062	.47401	.67777	2.7357	4.8314	6.9661	30.684	59.172	91.397
410	.0065926	.065942	.26399	.46237	.66107	2.6662	4.7048	6.7778	29.550	56.262	85.986
420	.0064357	.064366	.25768	.45129	.64518	2.6002	4.5850	6.6002	28.518	53.718	81.361
430	.0062860	.062869	.25167	.44073	.63004	2.5376	4.4715	6.4323	27.572	51.466	77.350
440	.0061431	.061439	.24593	.43065	.61560	2.4779	4.3637	6.2733	26.702	49.452	73.829
450	.0060066	.060075	.24044	.42100	.60176	2.4211	4.2612	6.1223	25.896	47.635	70.707
460	.0058760	.058768	.23520	.41181	.58859	2.3669	4.1636	5.9790	25.146	45.983	67.910
470	.0057510	.057517	.23018	.40300	.57598	2.3151	4.0706	5.8426	24.447	44.470	65.385
480	.0056312	.056319	.22537	.39457	.56390	2.2655	3.9818	5.7126	23.793	43.079	63.091
490	.0055163	.055169	.22076	.38648	.55233	2.2181	3.8969	5.5886	23.178	41.792	60.994
500	.0054060	.054065	.21632	.37872	.54122	2.1727	3.8157	5.4701	22.600	40.598	59.065
510	.0052999	.053004	.21207	.37127	.53055	2.1291	3.7379	5.3567	22.053	39.484	57.284
520	.0051980	.051980	.20799	.36410	.52029	2.0873	3.6633	5.2481	21.537	38.442	55.633
530	.0051000	.051000	.20406	.35721	.51043	2.0471	3.5917	5.1440	21.047	37.465	54.095
540	.0050055	.050055	.20027	.35057	.50093	2.0085	3.5229	5.0441	20.582	36.546	52.658
550	.0049145	.049145	.19663	.34415	.49178	1.9713	3.4568	4.9482	20.140	35.679	51.312
560	.0048267	.048267	.19311	.33799	.48296	1.9353	3.3932	4.8559	19.719	34.859	50.047
570	.0047421	.047421	.18972	.33205	.47446	1.9008	3.3319	4.7672	19.317	34.083	48.856
580	.0046603	.046603	.18644	.32631	.46621	1.8675	3.2729	4.6818	18.933	33.346	47.730
590	.0045813	.045813	.18328	.32077	.45820	1.8354	3.2160	4.5994	18.566	32.646	46.666
600	.0045050	.045050	.18022	.31541	.45062	1.8044	3.1607	4.5200	18.214	31.979	45.656
610	.0044311	.044311	.17726	.31023	.44322	1.7744	3.1077	4.4434	17.876	31.342	44.697
620	.0043596	.043596	.17439	.30522	.43603	1.7454	3.0565	4.3690	17.552	30.735	43.784
630	.0042904	.042904	.17162	.30036	.42911	1.7174	3.0069	4.2976	17.241	30.153	42.912
640	.0042234	.042234	.16894	.29566	.42239	1.6903	2.9590	4.2286	16.941	29.595	42.084
650	.0041584	.041584	.16634	.29109	.41584	1.6639	2.9126	4.1617	16.652	29.065	41.290

P(Atm.)	0.01	0.1	0.4	0.7	1	4	7	10	40	70	100
T(°K)											
660	.0040954	.040954	.16382	.28668	.40954	1.6384	2.8675	4.0968	16.376	28.550	40.531
670	.0040343	.040343	.16137	.28240	.40343	1.6137	2.8240	4.0343	16.108	28.058	39.803
680	.0039750	.039750	.15900	.27825	.39750	1.5899	2.7820	3.9739	15.849	27.584	39.105
690	.0039174	.039174	.15669	.27421	.39174	1.5666	2.7412	3.9148	15.599	27.128	38.434
700	.0038614	.038614	.15446	.27030	.38614	1.5441	2.7012	3.8576	15.357	26.688	37.789
710	.0038070	.038070	.15228	.26649	.38066	1.5222	2.6626	3.8022	15.124	26.265	37.169
720	.0037541	.037541	.15017	.26277	.37537	1.5008	2.6251	3.7483	14.898	25.856	36.571
730	.0037027	.037027	.14811	.25916	.37022	1.4801	2.5887	3.6960	14.679	25.460	35.995
740	.0036527	.036527	.14611	.25566	.36521	1.4599	2.5533	3.6452	14.467	25.078	35.439
750	.0036040	.036040	.14416	.25225	.36033	1.4403	2.5188	3.5957	14.261	24.709	34.902
760	.0035565	.035565	.14225	.24892	.35558	1.4212	2.4853	3.5473	14.062	24.351	34.383
770	.0035104	.035104	.14040	.24569	.35096	1.4027	2.4526	3.5004	13.868	24.004	33.881
780	.0034654	.034654	.13860	.24253	.34645	1.3846	2.4209	3.4548	13.680	23.669	33.396
790	.0034215	.034215	.13685	.23946	.34206	1.3669	2.3899	3.4105	13.497	23.343	32.925
800	.0033787	.033787	.13513	.23647	.33778	1.3497	2.3597	3.3672	13.320	23.027	32.470
850	.0031800	.031800	.12718	.22255	.31789	1.2700	2.2195	3.1667	12.501	21.576	30.386
900	.0030033	.030033	.12011	.21018	.30022	1.1991	2.0953	2.9890	11.782	20.311	28.577
950	.0028452	.028452	.11379	.19911	.28438	1.1358	1.9844	2.8304	11.144	19.194	26.988
1000	.0027030	.027030	.10810	.18915	.27015	1.0789	1.8847	2.6880	10.575	18.201	25.580
1050	.0025743	.025743	.10295	.18014	.25728	1.0274	1.7947	2.5594	10.062	17.163	24.322
1100	.0024572	.024572	.098271	.17195	.24558	.98065	1.7129	2.4426	9.5989	16.509	23.189
1150	.0023506	.023506	.092998	.16447	.23490	.93787	1.6383	2.3361	9.1776	15.781	22.163
1200	.0022525	.022525	.090081	.15762	.22511	.89876	1.5699	2.2386	8.7926	15.117	21.230
1250	.0021624	.021624	.086478	.15131	.21611	.86279	1.5071	2.1489	8.4395	14.509	20.376
1300	.0020792	.020792	.083152	.14549	.20780	.82960	1.4491	2.0662	8.1143	13.950	19.591
1350	.0020022	.020022	.080072	.14010	.20010	.79887	1.3954	1.9897	7.8138	13.434	18.867
1400	.0019307	.019307	.077212	.13510	.19295	.77034	1.3456	1.9186	7.5352	12.956	18.198
1450	.0018641	.018641	.074550	.13044	.18630	.74378	1.2992	1.8525	7.2761	12.512	17.576
1500	.0018020	.018020	.072065	.12609	.18009	.71900	1.2559	1.7908	7.0346	12.098	16.997
273.16	.0098960	.099051	.39747	.69777	1.0000	4.1358	7.5064	11.164			
298.16	.0090655	.090727	.36376	.63811	.91378	3.7469	6.6312	9.8893	67.316	203.66	219.15

* ρ_0 is the density of B_2H_6 gas at 1 atm and 273.15 K. To convert ρ/ρ_0 to density in g/cc, multiply the tabular values by 1.22835×10^{-3} ; density in lb/cu ft can be obtained by multiplying ρ/ρ_0 by 7.79324×10^{-2}

ENTROPY, S/R*, OF REAL GAS DIBORANE

P(Atm.)	0.01	0.1	0.4	0.7	1	4	7	10	40	70	100
T(°K)											
130	28.177										
140	28.496										
150	28.800										
160	29.089	26.778									
170	29.368	27.058	25.649								
180	29.637	27.329	25.924	25.346							
190	29.898	27.592	26.191	25.616	25.244						
200	30.153	27.847	26.450	25.878	25.509						
210	30.403	28.098	26.702	26.133	25.767	24.275					
220	30.648	28.343	26.950	26.382	26.018	24.548					
230	30.890	28.585	27.193	26.627	26.264	24.811	24.175				
240	31.128	28.824	27.433	26.868	26.506	25.066	24.446	24.020			
250	31.364	29.060	27.670	27.106	26.745	25.314	24.706	24.295			
260	31.598	29.294	27.904	27.341	26.981	25.558	24.959	24.559			
270	31.829	29.526	28.137	27.574	27.214	25.797	25.205	24.813			
280	32.059	29.756	28.367	27.805	27.446	26.034	25.447	25.061			
290	32.288	29.985	28.596	28.034	27.676	26.267	25.684	25.303			
300	32.515	30.212	28.824	28.262	27.904	26.498	25.919	25.541	23.834	22.807	22.275
310	32.741	30.438	29.050	28.489	28.131	26.728	26.151	25.776	24.143	23.205	22.698
320	32.966	30.663	29.275	28.714	28.356	26.955	26.383	26.008	24.420	23.552	23.051
330	33.190	30.887	29.499	28.938	28.580	27.181	26.608	26.238	24.681	23.876	23.370
340	33.413	31.110	29.722	29.162	28.804	27.406	26.834	26.465	24.932	24.175	23.669
350	33.635	31.332	29.945	29.384	29.026	27.629	27.059	26.691	25.176	24.452	23.954
360	33.856	31.553	30.166	29.605	29.248	27.852	27.282	26.915	25.414	24.714	24.228
370	34.076	31.773	30.386	29.826	29.468	28.073	27.504	27.138	25.648	24.966	24.492
380	34.296	31.993	30.606	30.045	29.688	28.293	27.725	27.360	25.878	25.210	24.748
390	34.506	32.203	30.816	30.256	29.898	28.504	27.937	27.572	26.098	25.441	24.988
400	34.732	32.429	31.042	30.482	30.124	28.730	28.163	27.799	26.332	25.683	25.238
410	34.948	32.646	31.259	30.698	30.341	28.948	28.381	28.017	26.555	25.913	25.475
420	35.164	32.862	31.475	30.914	30.557	29.164	28.598	28.234	26.776	26.140	25.708
430	35.380	33.077	31.690	31.130	30.772	29.380	28.814	28.450	26.996	26.365	25.938
440	35.594	33.291	31.904	31.344	30.987	29.594	29.028	28.666	27.215	26.587	26.165
450	35.807	33.504	32.117	31.557	31.200	29.808	29.242	28.880	27.432	26.808	26.389
460	36.020	33.717	32.330	31.770	31.413	30.021	29.455	29.093	27.647	27.027	26.611
470	36.231	33.928	32.542	31.981	31.624	30.232	29.667	29.305	27.862	27.244	26.831
480	36.442	34.139	32.752	32.192	31.835	30.443	29.878	29.516	28.075	27.460	27.049
490	36.652	34.349	32.962	32.402	32.045	30.654	30.089	29.727	28.287	27.674	27.265
500	36.861	34.558	33.171	32.611	32.254	30.863	30.298	29.936	28.498	27.887	27.480
510	37.069	34.766	33.379	32.819	32.462	31.071	30.506	30.145	28.708	28.099	27.694
520	37.276	34.973	33.587	33.027	32.669	31.278	30.714	30.352	28.917	28.309	27.906
530	37.482	35.180	33.793	33.233	32.876	31.485	30.920	30.559	29.125	28.519	28.117
540	37.688	35.385	33.998	33.438	33.081	31.690	31.126	30.765	29.332	28.727	28.326
550	37.892	35.590	34.203	33.643	33.286	31.895	31.331	30.970	29.538	28.934	28.535
560	38.096	35.793	34.406	33.846	33.489	32.099	31.535	31.173	29.743	29.140	28.742
570	38.299	35.996	34.609	34.049	33.692	32.301	31.737	31.376	29.947	29.345	28.948
580	38.500	36.198	34.811	34.251	33.894	32.503	31.939	31.578	30.150	29.549	29.153
590	38.701	36.398	35.012	34.452	34.095	32.704	32.140	31.779	30.352	29.752	29.357
600	38.901	36.598	35.212	34.652	34.294	32.904	32.340	31.980	30.553	29.954	29.559

P(Atm.)	0.01	0.1	0.4	0.7	1	4	7	10	40	70	100
T(°K)											
610	39.100	36.797	35.410	34.850	34.493	33.103	32.539	32.179	30.753	30.155	29.761
620	39.298	36.995	35.609	35.049	34.691	33.301	32.738	32.377	30.952	30.354	29.962
630	39.495	37.192	35.806	35.246	34.889	33.498	32.935	32.574	31.150	30.553	30.161
640	39.691	37.388	36.002	35.442	35.085	33.695	33.131	32.771	31.347	30.751	30.360
650	39.886	37.584	36.197	35.637	35.280	33.890	33.327	32.966	31.543	30.948	30.557
660	40.081	37.778	36.391	35.831	35.474	34.084	33.521	33.161	31.738	31.143	30.753
670	40.274	37.971	36.585	36.025	35.668	34.278	33.715	33.354	31.932	31.338	30.949
680	40.467	38.162	36.777	36.217	35.860	34.470	33.907	33.547	32.125	31.532	31.143
690	40.658	38.355	36.969	36.409	36.052	34.662	34.099	33.739	32.318	31.725	31.337
700	40.849	38.548	37.159	36.599	36.242	34.852	34.289	33.929	32.509	31.917	31.529
710	41.038	38.735	37.349	36.789	36.432	35.042	34.479	34.119	32.699	32.107	31.720
720	41.227	38.924	37.538	36.978	36.621	35.231	34.668	34.308	32.889	32.297	31.911
730	41.415	39.112	37.725	37.165	36.808	35.419	34.856	34.496	33.077	32.486	32.100
740	41.601	39.299	37.912	37.352	36.995	35.606	35.043	34.683	33.264	32.674	32.288
750	41.787	39.485	38.098	37.538	37.181	35.791	35.229	34.869	33.451	32.861	32.476
760	41.972	39.670	38.283	37.723	37.366	35.976	35.414	35.054	33.636	33.047	32.662
770	42.156	39.854	38.467	37.907	37.550	36.161	35.598	35.238	33.821	33.232	32.847
780	42.339	40.037	38.650	38.090	37.733	36.344	35.781	35.421	34.005	33.416	33.032
790	42.521	40.219	38.832	38.272	37.915	36.526	35.963	35.603	34.187	33.599	33.215
800	42.703	40.400	39.013	38.453	38.096	36.707	36.144	35.785	34.369	33.781	33.398
850	43.595	41.292	39.905	39.346	38.989	37.599	37.037	36.677	35.264	34.677	34.296
900	44.464	42.161	40.775	40.215	39.858	38.469	37.907	37.547	36.135	35.550	35.170
950	45.311	43.008	41.621	41.062	40.705	39.316	38.754	38.394	36.983	36.400	36.021
1000	46.135	43.833	42.446	41.886	41.529	40.141	39.579	39.220	37.810	37.228	36.850
1050	46.938	44.636	43.249	42.689	42.333	40.944	40.382	40.023	38.614	38.025	37.657
1100	47.721	45.418	44.031	43.472	43.115	41.726	41.164	40.805	39.398	38.810	38.442
1150	48.482	46.180	44.793	44.233	43.877	42.488	41.926	41.568	40.161	39.582	39.207
1200	49.224	46.922	45.535	44.976	44.619	43.230	42.669	42.310	40.904	40.326	39.952
1250	49.947	47.645	46.258	45.699	45.342	43.953	43.392	43.033	41.628	41.051	40.677
1300	50.652	48.349	46.963	46.403	46.046	44.658	44.097	43.738	42.334	41.757	41.384
1350	51.339	49.036	47.650	47.090	46.733	45.345	44.784	44.425	43.021	42.445	42.073
1400	52.008	49.706	48.319	47.760	47.403	46.015	45.453	45.095	43.692	43.116	42.744
1450	52.662	50.359	48.972	48.413	48.056	46.668	46.107	45.748	44.346	43.771	43.399
1500	53.299	50.996	49.610	49.050	48.693	47.305	46.744	46.386	44.984	44.409	44.038
273.16	31.902	29.599	28.210	27.647	27.288	25.872	25.282	24.892			
298.16	32.473	30.170	28.782	28.220	27.862	26.456	25.876	25.498	23.770	22.723	22.184

* To convert S/R to S in units of cal/g-K or Btu/lb-R, multiply by 7.17708×10^{-2} .

COMPOUND: Fluorine

EMPIRICAL FORMULA: F₂ MOLECULAR WEIGHT = 38.00

ASSIGNED REFERENCE ENTHALPY

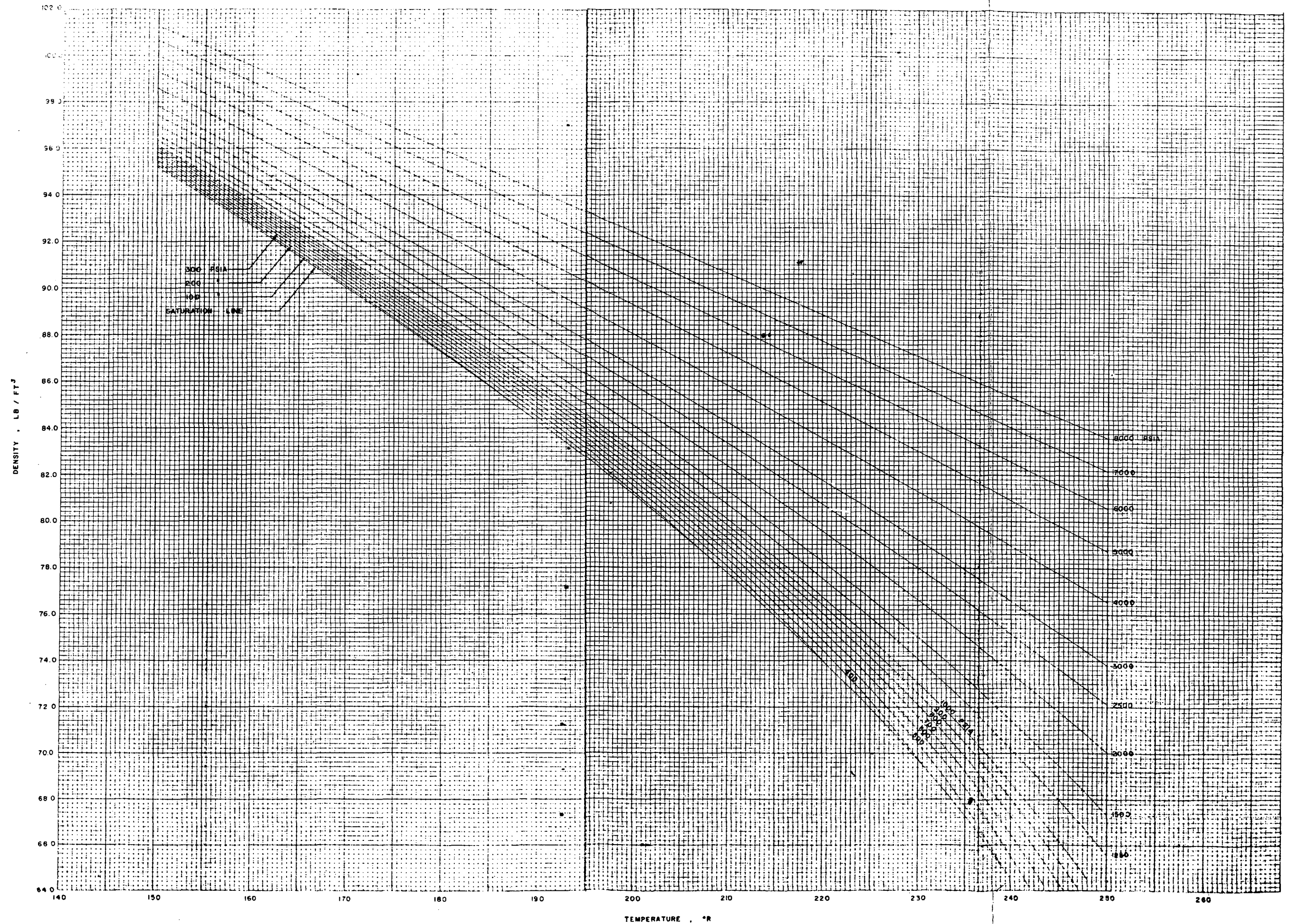
	kcal/mole	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 85.02 K 1 atm	-3.098 ±0.02	-8.153	-0.3413	-146.7474
GAS AT 298.15 K 1 atm	0	0	0	0

DENSITY

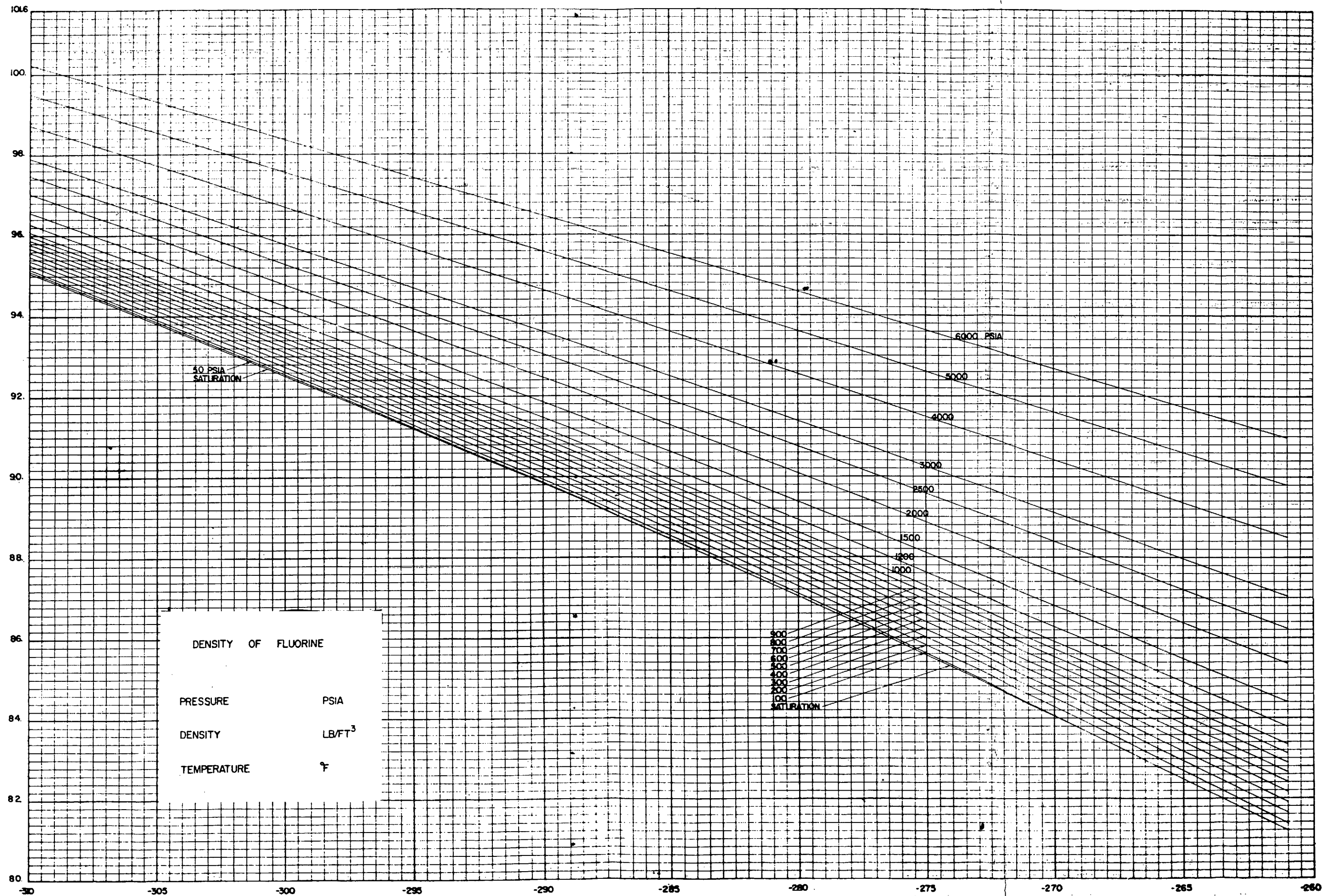
	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 85.02 K 1 atm	1.505	1505.0	93.912
GAS AT 298.15 K 1 atm	0.00155	1.5531	0.09691

SOURCES OF DATA

JANNAF Heat of Formation of Propellant Ingredients (U), D. R. Stull, T. E. Dergazarian, I. H. Carr; Dow Chemical Co., Midland, Michigan, and revisions 1963 to 1967, CONFIDENTIAL.



DENSITY, LB/FT³



COMPOUND: Hydrazine

EMPIRICAL FORMULA: N_2H_4 MOLECULAR WEIGHT = 32.048

ASSIGNED REFERENCE ENTHALPY

	kcal/mol	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 298.15 K 1 atm	+12.05	+37.60	+1.57	+676.80

DENSITY

	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 298.15 K 1 atm	1.0037	1003.7	62.63

SOURCES OF DATA

1. JANNAF Heat of Formation of Propellant Ingredients (U), D. R. Stull, T. E. Dergazarian, I. H. Carr, Dow Chemical Co., Midland, Michigan, and revisions 1963 to 1967, CONFIDENTIAL.
2. USAF Propellant Handbooks, Hydrazine Fuels Volume 1 (U), W. R. Marsh, B. P. Knox, Bell Aerospace Co., Buffalo, New York, F04611-69-C-0005, March 1970.

COMPOUND: Hydrogen Peroxide

EMPIRICAL FORMULA: H₂O₂ MOLECULAR WEIGHT = 34.016

ASSIGNED REFERENCE ENTHALPY

	kcal/mol	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 298.15 K 1 atm	-44.88 ±0.02	-131.9	-5.52	-2374.88

DENSITY

	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 298.15 K 1 atm	1.44	1440.0	89.86

SOURCES OF DATA

1. JANNAF Heat of Formation of Propellant Ingredients (U), D. R. Stull, T. E. Dergarzian, I. H. Carr, Dow Chemical Co., Midland, Michigan, and revisions 1963 to 1967, CONFIDENTIAL.
2. CPIA M/4 Liquid Propellant Manual (U), Chemical Propulsion Information Agency, Silver Spring, Maryland, CONFIDENTIAL.

COMPOUND: 90% Hydrogen Peroxide/10% Water

EMPIRICAL FORMULA: H₂O^{1.8266} MOLECULAR WEIGHT = 31.2416

ASSIGNED REFERENCE ENTHALPY

	kcal/mol	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 298.15 K 1 atm	-45.01	-144.07	-6.03	-2593.3

DENSITY

	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 298.15 K 1 atm	1.4136	1413.6	88.21

SOURCES OF DATA

1. JANNAF Heat of Formation of Propellant Ingredients (U), D. R. Stull, T. E. Dergazarian, I. H. Carr, Dow Chemical Co., Midland, Michigan, and revisions 1963 to 1967, CONFIDENTIAL.
2. CPIA M/4 Liquid Propellant Manual (U), Chemical Propulsion Information Agency, Silver Spring, Maryland, CONFIDENTIAL.

COMPOUND: Methane

EMPIRICAL FORMULA: CH₄ MOLECULAR WEIGHT = 16.043

ASSIGNED REFERENCE ENTHALPY

	kcal/mole	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 111.66 K 1 atm	-21.39 ±0.02	-133.3	-5.5812	-2399.93
GAS AT 298.15 K 1 atm	-17.895	-111.54	-4.669	-2097.03

DENSITY

	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 111.66 K 1 atm	0.4239	423.9	26.45
GAS AT 298.15 K 1 atm	0.00066	0.65573	0.04092

SOURCES OF DATA

JANNAF Heat of Formation of Propellant Ingredients (U), D. R. Stull, T. E. Dergazarian, I. H. Carr, Dow Chemical Co., Midland, Michigan, and revisions 1963 to 1967, CONFIDENTIAL.

COMPOUND: Monomethylhydrazine

EMPIRICAL FORMULA: CH_6N_2 MOLECULAR WEIGHT = 46.075

ASSIGNED REFERENCE ENTHALPY

	kcal/mol	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 298.15 K 1 atm	+12.9	+28.0	+1.17	+504.0

DENSITY

	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 298.15 K 1 atm	0.8702	870.2	54.30

SOURCES OF DATA

1. USAF Propellant Handbooks, Hydrazine Fuels Volume 1 (U), W. R. Marsh, B. P. Knox, Bell Aerospace Co., Buffalo, New York, F04611-69-C-0005, March 1970.
2. Selected Values of Chemical Thermodynamic Quantities, D. D. Wagman, et al., NBS TN 270-3, National Bureau of Standards, Washington, D.C., January 1968.

COMPOUND: Nitric Acid

EMPIRICAL FORMULA: HNO₃ MOLECULAR WEIGHT = 63.016

ASSIGNED REFERENCE ENTHALPY

	kcal/mol	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 298.15 K 1 atm	-41.46 ±0.10	-65.79	-2.75	-1184.3

DENSITY

	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 298.15 K 1 atm	1.5027	1503.7	93.77

SOURCES OF DATA

JANNAF Heat of Formation of Propellant Ingredients (U), D. R. Stull, T. E. Dergazarian, I. H. Carr, Dow Chemical Co., Midland, Michigan, and revisions 1963 to 1967, CONFIDENTIAL.

COMPOUND: Nitrogen Tetroxide

EMPIRICAL FORMULA: N₂O₄ MOLECULAR WEIGHT = 92.016

ASSIGNED REFERENCE ENTHALPY

	kcal/mol	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 298.15 K 1 atm	-4.68 ±0.4	-5.08	-0.21	-91.55

DENSITY

	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 298.15 K 1 atm	1.431	1431.0	89.29

SOURCES OF DATA

JANNAF Heat of Formation Propellant Ingredients (U), D. R. Stull, T. E. Dergazarian, I. H. Carr, Dow Chemical Co., Midland, Michigan, and revisions 1963 to 1967, CONFIDENTIAL.

COMPOUND: Normal Hydrogen*

EMPIRICAL FORMULA: H₂ MOLECULAR WEIGHT = 2.016

ASSIGNED REFERENCE ENTHALPY

	kcal/mol	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 298.15 K 1 atm	0	0	0	0

DENSITY

	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 298.15 K 1 atm	0.00008	0.082398	0.00514

SOURCES OF DATA

JANNAF Heat of Formation of Propellant Ingredients (U), D. R. Stull, T. E. Dergazarian, I. H. Carr, Dow Chemical Co., Midland, Michigan, and revisions 1963 to 1967, CONFIDENTIAL

*For hydrogen stored as a liquid, then heated without time (or catalyst) to connect to normal hydrogen) use parahydrogen (appears later).

COMPOUND: Oxygen

EMPIRICAL FORMULA: O₂ MOLECULAR WEIGHT = 32.000

ASSIGNED REFERENCE ENTHALPY

	kcal/mole	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 90.18 K 1 atm	-3.102 ±0.02	-9.694	-0.406	-174.5
GAS AT 298.15 K 1 atm	0	0	0	0

DENSITY

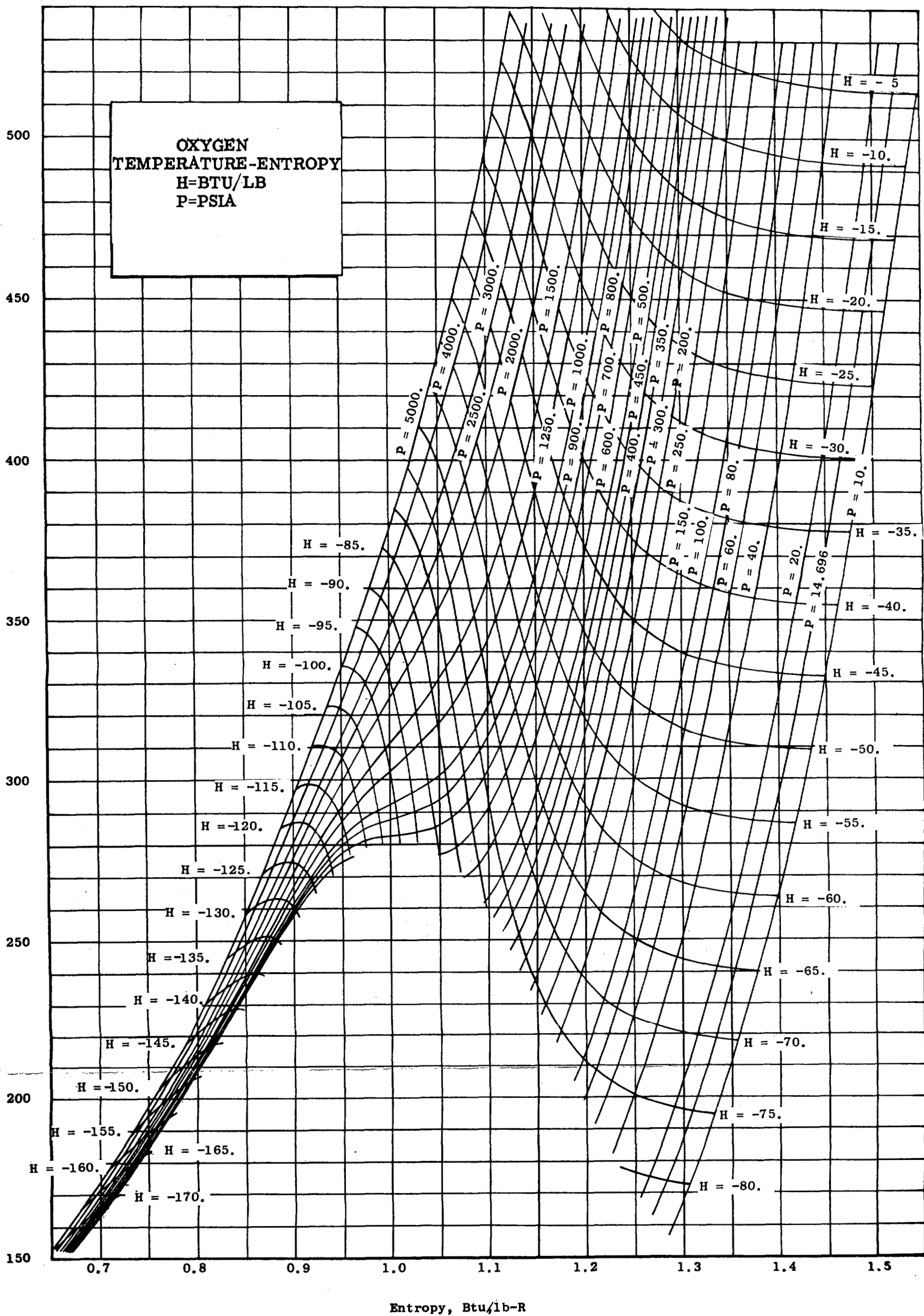
	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 90.18 K 1 atm	1.149	1149.0	71.698
GAS AT 298.15 K 1 atm	0.00131	1.3079	0.0816

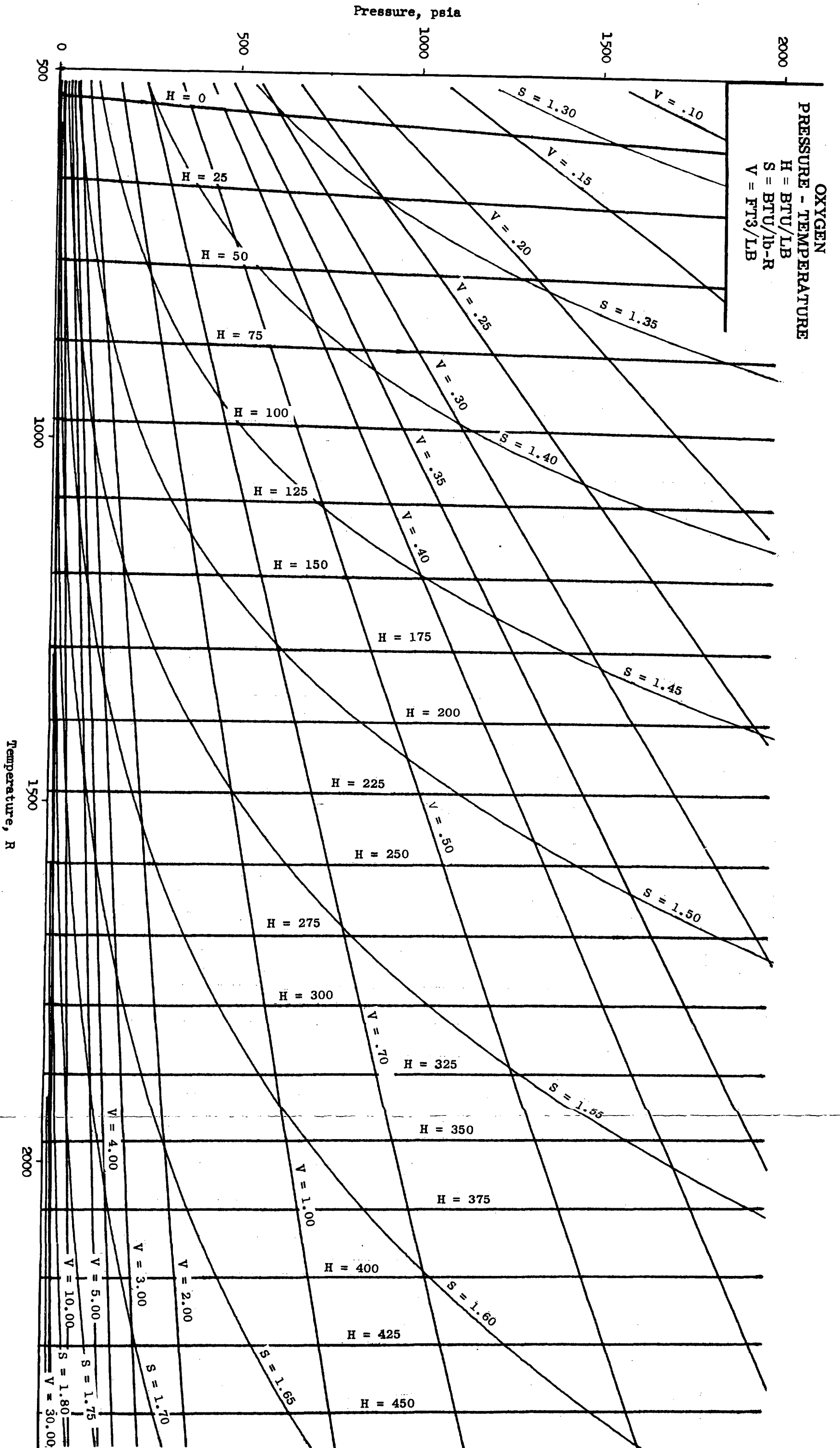
SOURCES OF DATA

JANNAF Heat of Formation of Propellant Ingredients (U), D. R. Stull, T. E. Dergazarian, I. H. Carr, Dow Chemical Co., Midland, Michigan, and revisions 1963 to 1967, CONFIDENTIAL.

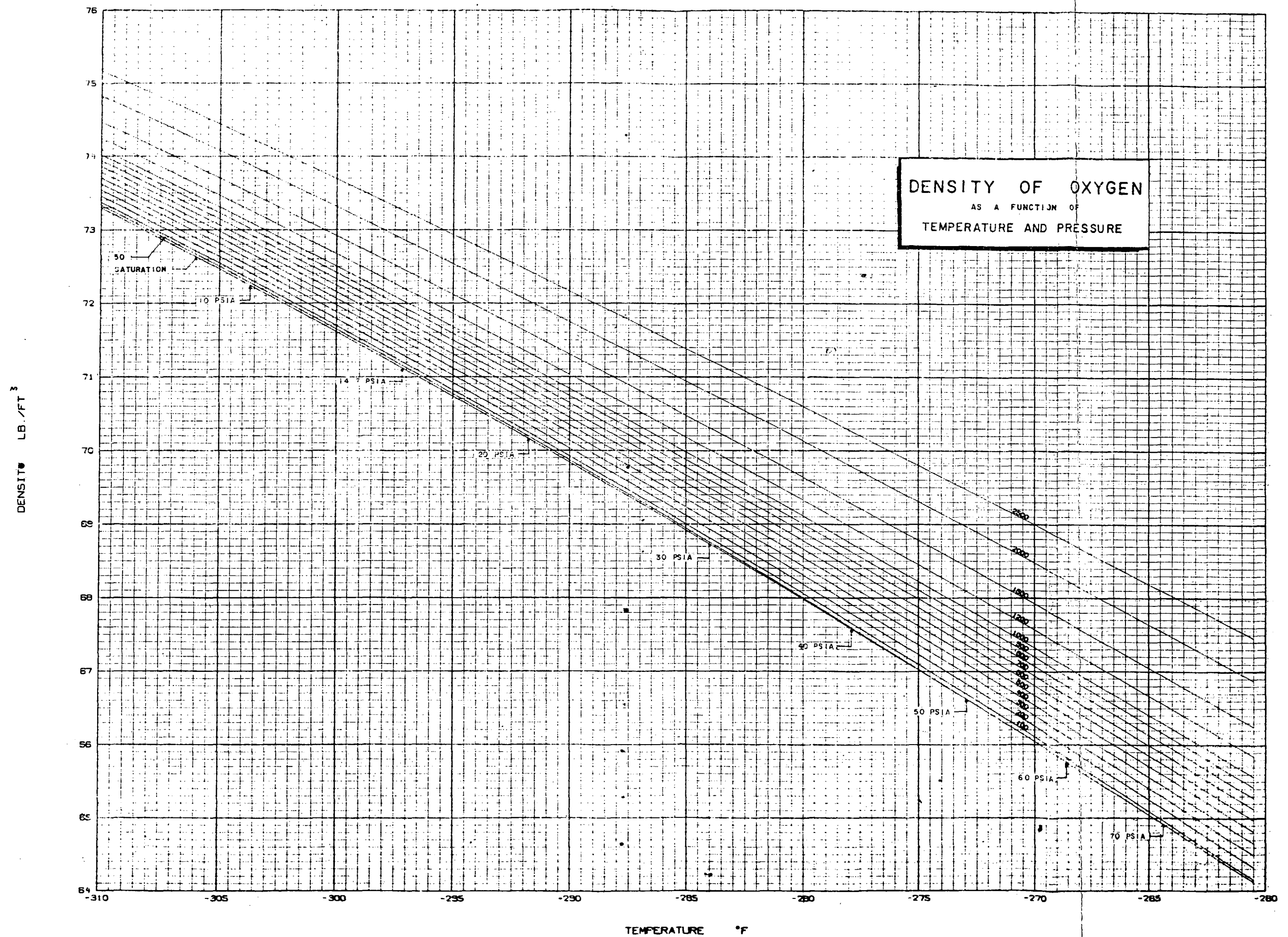
Temperature, Deg. R

Low Temperature Data - Oxygen
6.1.27





Hot Gas Data - Oxygen



COMPOUND: Oxygen Difluoride

EMPIRICAL FORMULA: OF₂ MOLECULAR WEIGHT = 54.000

ASSIGNED REFERENCE ENTHALPY

	kcal/mole	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 127.8 K 1 atm	1.95 ±0.90	3.63	0.15	65
GAS AT 298.15 K 1 atm	5.86	10.85	0.454	195.33

DENSITY

	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 127.8 K 1 atm	1.521	1521.0	94.91
GAS AT 298.15 K 1 atm	0.0022	2.2070	0.13772

SOURCES OF DATA

JANNAF Heat of Formation of Propellant Ingredients (U), D. R. Stull, T. E. Dergazarian, I. H. Carr, Dow Chemical Co., Midland, Michigan, and revisions 1963 to 1967, CONFIDENTIAL.

COMPOUND: Parahydrogen

EMPIRICAL FORMULA: H₂ MOLECULAR WEIGHT = 2.0160

ASSIGNED REFERENCE ENTHALPY

	kcal/mole	kcal/100 gm	Joules/kg	Btu/lbm	
LIQUID AT 20.27 K 1 atm	-2.154 ±0.02	-106.8	-4.4725	-1923.21	
GAS AT 298.15 K 1 atm	-0.160	-7.937	-3.322	-1.429	*

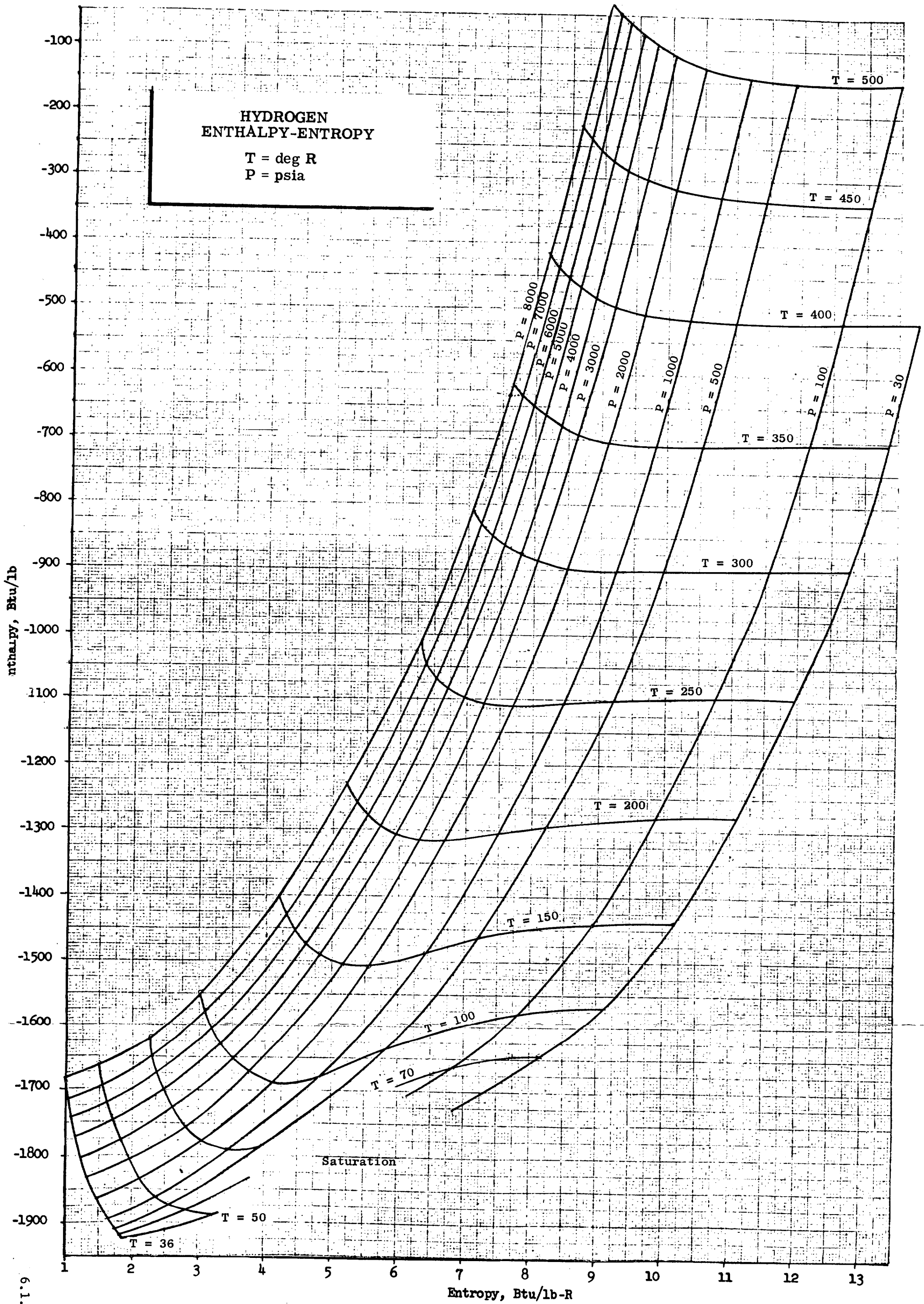
DENSITY

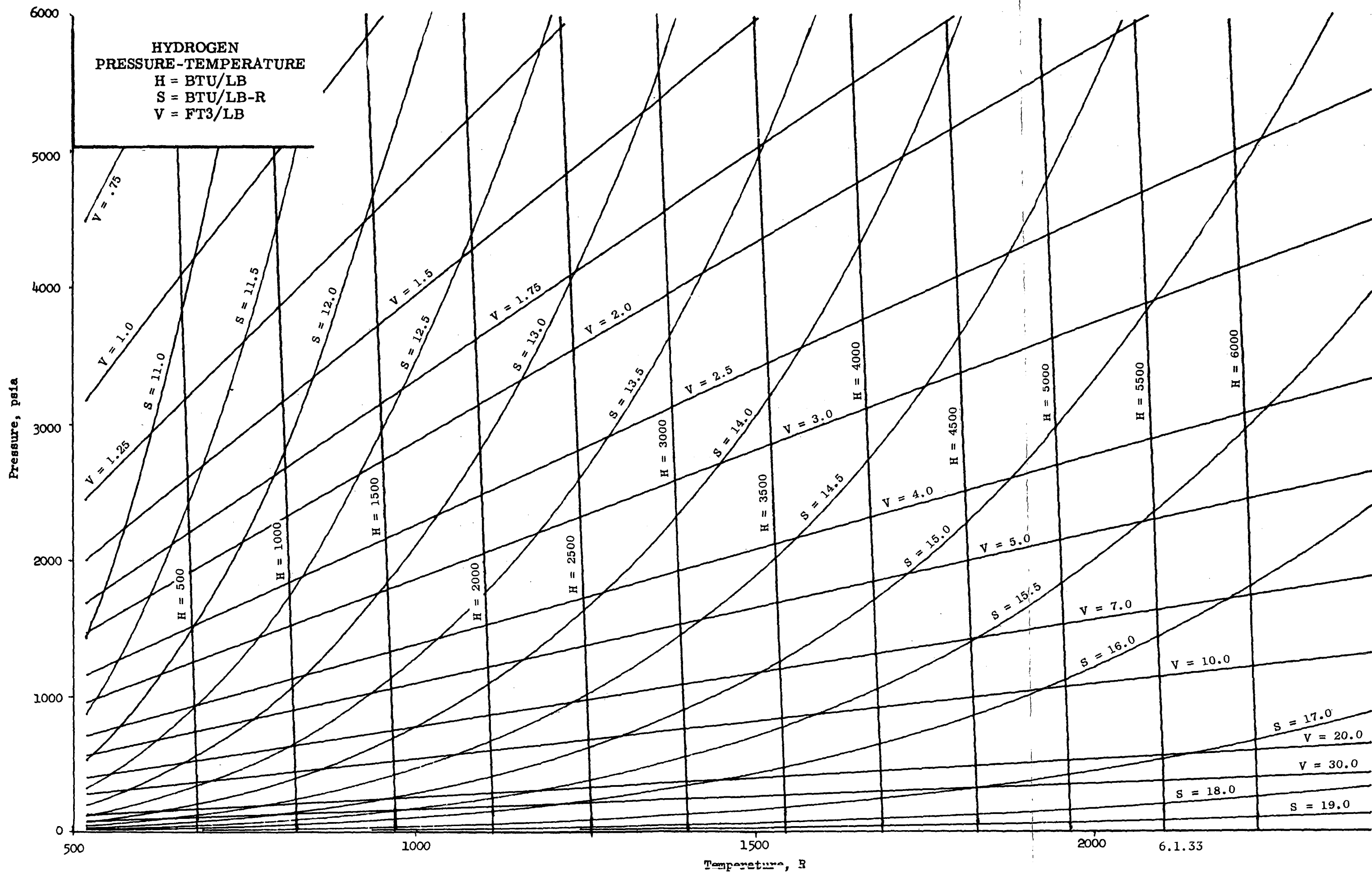
	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 20.27 K 1 atm	0.0709	70.9	4.4242
GAS AT 298.15 K 1 atm	0.00008	0.082398	0.00514

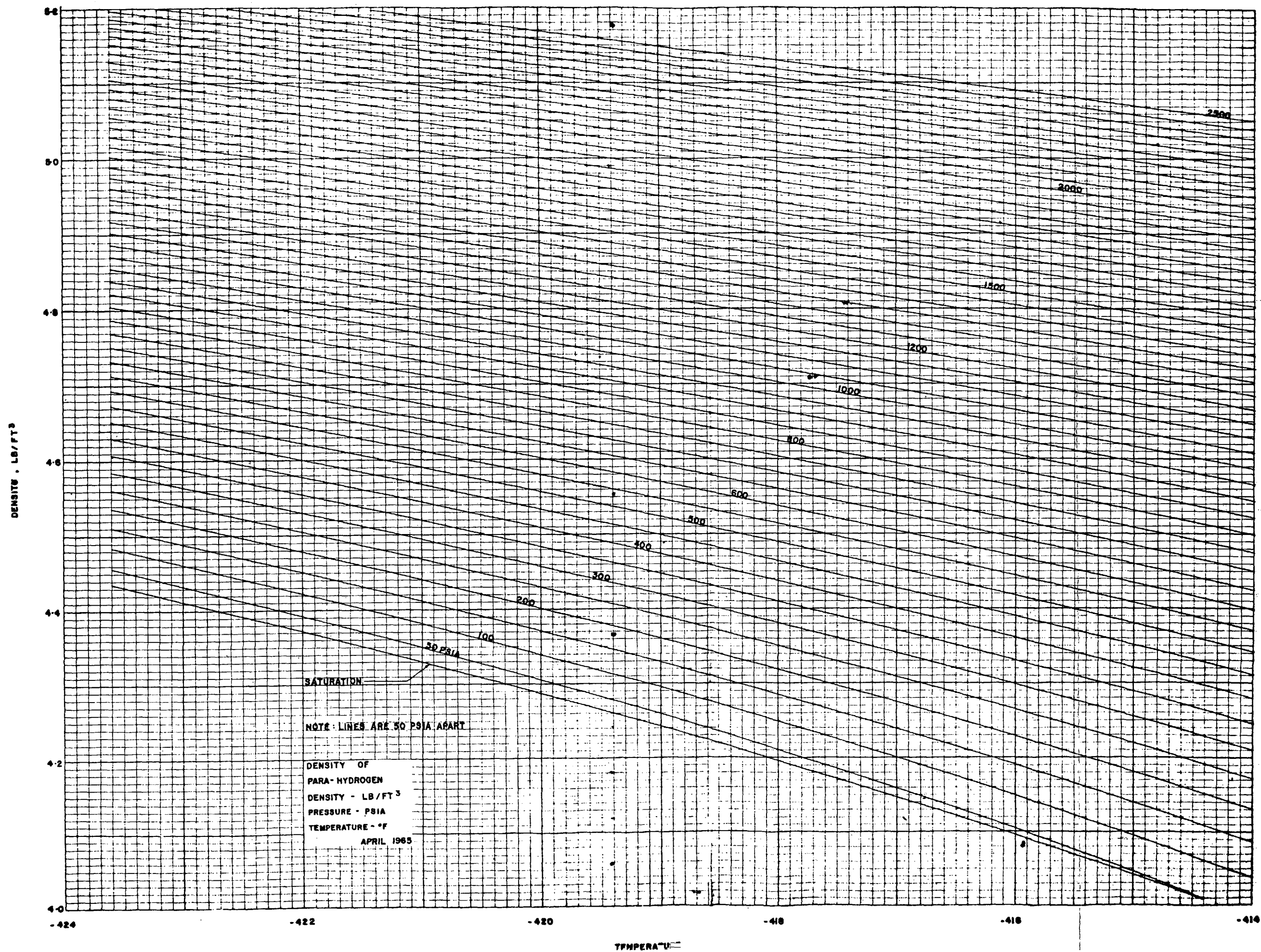
SOURCES OF DATA

JANNAF Heat of Formation of Propellant Ingredients (U), D. R. Stull, T. E. Dergazarian, I. H. Carr, Dow Chemical Co., Midland, Michigan, and revisions 1963 to 1967, CONFIDENTIAL.

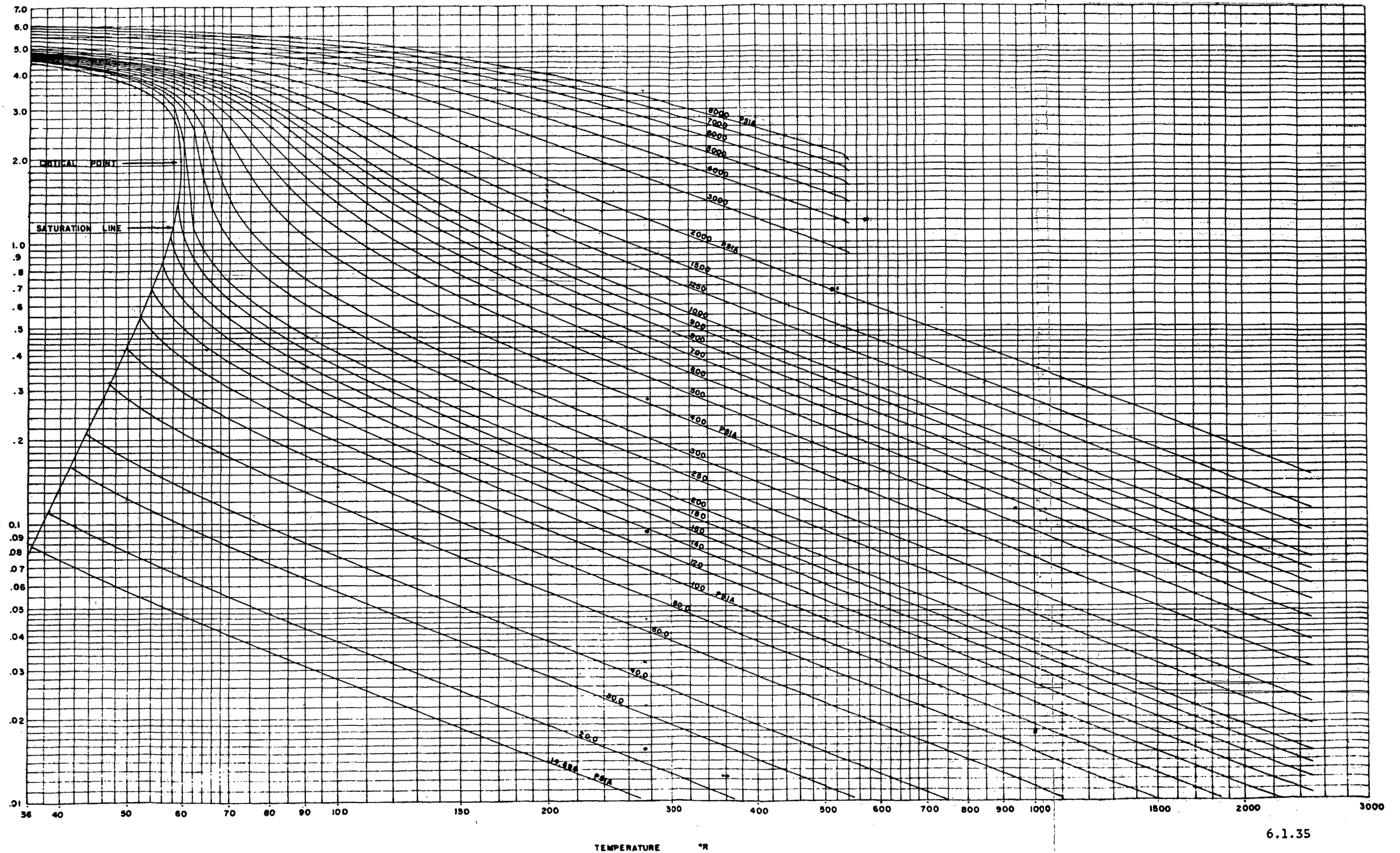
*For hydrogen stored as a liquid, then heated without time (or catalyst) to convert to normal hydrogen.







DENSITY AS A FUNCTION OF TEMPERATURE AND PRESSURE FOR PARA-HYDROGEN



COMPOUND: Red Fuming Nitric Acid (RFNA)

EMPIRICAL FORMULA: $\frac{\text{H}_{0.8894}\text{N}_{0.9365}}{\text{O}_{2.699}}$ MOLECULAR WEIGHT = 57.1990

ASSIGNED REFERENCE ENTHALPY

	kcal/mol	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 298.15 K 1 atm	-36.48	-63.81	-2.67	-1148.0

DENSITY

	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 298.15 K 1 atm	1.55	1550.0	96.72

SOURCES OF DATA

CPIA M/4 Liquid Propellant Manual (U), Chemical Propulsion Information Agency,
Silver Spring, Maryland, CONFIDENTIAL.

COMPOUND: Unsymmetrical Dimethylhydrazine (UDMH)

EMPIRICAL FORMULA: $C_2H_8N_2$ MOLECULAR WEIGHT = 60.1020

ASSIGNED REFERENCE ENTHALPY

	kcal/mol	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 298.15 K 1 atm	+11.9	+19.8	+0.83	+356.4

DENSITY

	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 298.15 K 1 atm	0.7861	786.1	49.05

SOURCES OF DATA

1. JANNAF Heat of Formation of Propellant Ingredients (U), T. E. Dergazarian, I. H. Carr, Dow Chemical Co., Midland, Michigan, and revisions 1963 to 1967, CONFIDENTIAL.
2. CPIA M/4 Liquid Propellant Manual (U), Chemical Propulsion Information Agency, Silver Spring, Maryland, CONFIDENTIAL.

COMPOUND: Unsymmetrical Dimethylhydrazine/Hydrazine (50-50)

EMPIRICAL FORMULA: $\frac{C_{0.6956}H_{5.3911}}{N_{2.0}}$ MOLECULAR WEIGHT = 41.8051

ASSIGNED REFERENCE ENTHALPY

	kcal/mol	kcal/100 gm	Joules/kg	Btu/lbm
LIQUID AT 298.15 K 1 atm	+12.31	+29.45	+1.233	+530.03

DENSITY

	g/cc	kg/m ³	lbm/ft ³
LIQUID AT 298.15 K 1 atm	0.8987	898.7	56.08

SOURCES OF DATA

USAF Propellant Handbooks, Hydrazine Fuels Volume 1 (U), W. R. Marsh, B. P. Knox, Bell Aerospace Co., Buffalo, New York, F04611-69-C-0005, March 1970.

Section 6 Standard Input Data
6.2 REACTION RATE DATA

The following tables contain reaction rate data for use in the TDK and ODK computer program.

DATA	PAGES
Three-Body Recombination/Dissociation Reactions With Specified Third Body	6.2.2
Three-Body Recombination/Dissociation Reactions With Average Third Body	6.2.4
Binary Exchange Reaction Rates	6.2.5
Important Reactions and Required Rate Constant Accuracies	6.2.8

The reaction rates re-divided into two general categories: binary exchange reactions and three-body reactions. The three-body reactions generally dominate the process since these reactions contribute to changes in thermal energy, while the two-body reactions do not.

The reaction rate constants are of the form:

$$k = A T^B e^{-C/RT} \text{ [cm}^3\text{/mole-s]}$$

where R is the gas constant and T is absolute temperature.

The A, B, and C constants are listed in Tables 1 through 3. Both forward (k_f) and backward rates (k_b) are listed for the two-body reactions. The dissociation (k_d) and recombination rates (k_r) are listed for the three-body reactions.

Three-body reactions are listed for both specific third bodies (with efficiencies given for other third bodies) and for average (M) third bodies. The use of specific third bodies is generally much more accurate.

The important reactions for typical propellant combinations and the effect of reaction rate uncertainties are shown in Table 4 (Ref. *) for a range of mixture ratios.

A listing of a greater number of reactions is given in Ref. 1. However, most of these additional reactions were found to be unimportant for most rocket engine systems.

The uncertainties are defined by:

$$\frac{1}{U} < \frac{k}{k_{REF}} < U$$

where U_{REF} is the constant corresponding to the tabularized constants.

*References are on page 6.2.9

TABLE 1. THREE-BODY RECOMBINATION/DISSOCIATION REACTIONS WITH
SPECIFIED THIRD BODY

Identification Number*	Reaction	A	B	C	Uncertainty	Ref. No.
1r	$\text{H}+\text{OH}+\text{Ar} \rightarrow \text{H}_2\text{O}+\text{Ar}$	7.5×10^{23}	-2.6	0		5
d		2.11×10^{27}	-3.199	-121384		5
2r	$\text{O}+\text{H}+\text{Ar} \rightarrow \text{OH}+\text{Ar}$	4.0×10^{18}	-1	0		3
d		6.76×10^{19}	-1.265	-103230		
3r	$\text{O}+\text{O}+\text{Ar} \rightarrow \text{O}_2+\text{Ar}$	1.2×10^{17}	-1	0		3
d		6.39×10^{20}	-1.645	-120450		3
4r	$\text{F}+\text{F}+\text{Ar} \rightarrow \text{F}_2+\text{Ar}$	5.7×10^{15}	-1			3
d						
5r	$\text{H}+\text{F}+\text{Ar} \rightarrow \text{HF}+\text{Ar}$	2.5×10^{18}	-1			3
d						
6r	$\text{H}+\text{H}+\text{Ar} \rightarrow \text{H}_2+\text{Ar}$	6.4×10^{17}	-1			6
d		3.19×10^{19}	-1.294	-105374		6
7r						
d						
8r						
d						
9r						
d						
10r	$\text{N}+\text{O}+\text{N}_2 \rightarrow \text{NO}+\text{N}_2$	6.4×10^{16}	-0.5			2
d		2.27×10^{17}	-0.5	-148830		2
11r						
d						
12r						
d						
13r						
d						
14r						
d						
15r						
d						

*r = recombination

d = dissociation

TABLE 1. (Concluded)

Identification Number	Reaction	A	B	C	Uncertainty	Ref. No.
16r						
d						
17r						
d						
18r						
d						
19r						
d						
20r						
d						

TABLE 1A. THIRD-BODY EFFICIENCIES

SPECIES	REACTION 1	REACTION 2	REACTION 3	REACTION 4	REACTION 5	REACTION 6
Ar	1	1	1	1	1	1
F ₂	-	-	-	1	1	-
HF	-	-	-	2	2	-
N ₂	4	4	4	2.8	2.8	1.5
F	-	-	-	4	4	-
H ₂ O	20	5	5	4	4	20
H ₂	5	5	5	8	8	4
O ₂	5	5	4.5	13	13	1.5
H	12.5	12.5	12.5	20	20	25
O	12.5	12.5	12.5	40	40	25
OH	12.5	12.5	12.5	40	40	25
Reference	*	*	*	3	3	*

*Recommendations of subcommittee formulated subsequent to Reference 3.

TABLE 2. THREE-BODY RECOMBINATION/DISSOCIATION REACTIONS WITH
AVERAGE THIRD BODY

Identification Number	Reaction	A	B	C	Uncertainty	Ref. No.
1r d	$\text{H}+\text{OH}+\text{M} \rightarrow \text{H}_2\text{O}+\text{M}$	1×10^{19}	-1	0	1000	1
2r d	$\text{O}+\text{H}+\text{M} \rightarrow \text{OH}+\text{M}$	2×10^{18}	-1	0	5	1
3r d	$\text{O}+\text{O}+\text{M} \rightarrow \text{O}_2+\text{M}$	1.9×10^{16}	-0.5	0	10	1
4r d	$\text{F}+\text{F}+\text{M} \rightarrow \text{F}_2+\text{M}$	1.1×10^{18}	-1.5	0	10	1
5r d	$\text{H}+\text{F}+\text{M} \rightarrow \text{HF}+\text{M}$	7.5×10^{18}	-1	0	30	1
6r d	$\text{H}+\text{H}+\text{M} \rightarrow \text{H}_2+\text{M}$	7.5×10^{18}	-1	0	10	1
7r d	$\text{O}+\text{CO}+\text{M} \rightarrow \text{CO}_2+\text{M}$	1.38×10^{34}	-5.24	-5600	300	4
8r d	$\text{C}+\text{O}+\text{M} \rightarrow \text{CO}+\text{M}$	2.7×10^{32}	-4.5	-127555	300	4
9r d	$\text{C}+\text{O}+\text{M} \rightarrow \text{CO}+\text{M}$	3×10^{16}	-0.5	0	25	1
10r d	$\text{N}+\text{N}+\text{M} \rightarrow \text{N}_2+\text{M}$	1×10^{18}	-1	0	10	1
11r d	$\text{N}+\text{O}+\text{M} \rightarrow \text{NO}+\text{M}$	6×10^{16}	-0.5	0	10	1
12r d	$\text{Cl}+\text{F}+\text{M} \rightarrow \text{ClF}+\text{M}$	3×10^{16}	-0.5	0	25	1
13r d	$\text{H}+\text{Cl}+\text{M} \rightarrow \text{HCl}+\text{M}$	3×10^{16}	-0.5	0	25	1
14r d	$\text{Cl}+\text{Cl}+\text{M} \rightarrow \text{Cl}_2+\text{M}$	1.1×10^{19}	-1	0	10	1
15r d	$\text{B}+\text{O}+\text{M} \rightarrow \text{BO}+\text{M}$	3×10^{16}	-0.5	0	25	1
16r d	$\text{BO}+\text{O}+\text{M} \rightarrow \text{BO}_2+\text{M}$	1×10^{15}	-0.5	0	25	1
17r d	$\text{B}+\text{F}+\text{M} \rightarrow \text{BF}+\text{M}$	3×10^{16}	-0.5	0	25	1
18r d	$\text{BF}+\text{F}+\text{M} \rightarrow \text{BF}_2+\text{M}$	1×10^{15}	-0.5	0	25	1
19r d	$\text{BF}_2+\text{F}+\text{M} \rightarrow \text{BF}_3+\text{M}$	1×10^{15}	-0.5	0	25	1
20r d	$\text{BO}+\text{F}+\text{M} \rightarrow \text{BOF}+\text{M}$	1×10^{15}	-0.5	0	25	1
21r d	$\text{BF}+\text{O}+\text{M} \rightarrow \text{BOF}+\text{M}$	1×10^{15}	-0.5	0	25	1

TABLE 3. BINARY EXCHANGE REACTION RATES

Identification Number*	Reaction	A	B	C	Uncertainty	Ref. No.
21f	$\text{OH} + \text{H}_2 \rightarrow \text{H} + \text{H}_2\text{O}$	2.19×10^{13}	0	-5150	10	2
b		8.41×10^{13}	0	-20100	10	2
22f	$\text{OH} + \text{OH} \rightarrow \text{O} + \text{H}_2\text{O}$	5.75×10^{12}	0	-780	10	2
b		5.75×10^{13}	0	-18000	10	2
23f	$\text{H} + \text{OH} \rightarrow \text{O} + \text{H}_2$	7.33×10^{12}	0	-7300	5	2
b		1.74×10^{13}	0	-9450	5	2
24f	$\text{OH} + \text{OH} \rightarrow \text{H}_2 + \text{O}_2$	1.41×10^{13}	-0.015	-49264	25	1
b						
25f	$\text{O} + \text{OH} \rightarrow \text{H} + \text{O}_2$	1.3×10^{13}	0	0	5	2
b		2.24×10^{14}	0	-16800	5	2
26f	$\text{H} + \text{F}_2 \rightarrow \text{HF} + \text{F}$	5.3×10^{12}	0.5	-4000	25	1
b						
27f	$\text{H}_2 + \text{F} \rightarrow \text{HF} + \text{H}$	5.0×10^{12}	0	-5700	50	1
b						
28f	$\text{H}_2 + \text{F}_2 \rightarrow \text{HF} + \text{HF}$	1.75×10^{10}	0.5	-39739	1000	1
b						
29f	$\text{H} + \text{Cl}_2 \rightarrow \text{HCl} + \text{Cl}$	3.0×10^{14}	0	-3000	25	1
b						
30f	$\text{H}_2 + \text{Cl}_2 \rightarrow \text{HCl} + \text{HCl}$	1.75×10^{10}	0.5	-45375	1000	1
b						
31f	$\text{HCl} + \text{H} \rightarrow \text{H}_2 + \text{Cl}$	6.2×10^{11}	0.5	-3100	10	1
b						
32f	$\text{HCl} + \text{F} \rightarrow \text{HF} + \text{Cl}$	1.9×10^{12}	0.68	-600	25	1
b						
33f	$\text{Cl}_2 + \text{F} \rightarrow \text{Cl} + \text{ClF}$	6.2×10^{12}	0.68	-500	25	1
b						
34f	$\text{Cl} + \text{F}_2 \rightarrow \text{F} + \text{ClF}$	7.6×10^{12}	0.68	-300	25	1
b						
35f	$\text{ClF} + \text{H} \rightarrow \text{HF} + \text{Cl}$	1.8×10^{12}	0.58	-3200	25	1
b						
36f	$\text{ClF} + \text{H} \rightarrow \text{HCl} + \text{F}$	5.6×10^{12}	0.68	-1900	25	1
b						
37f	$\text{ClF} + \text{H}_2 \rightarrow \text{HCl} + \text{HF}$	1.8×10^{10}	0.5	-46337	1000	1
b						
38f	$\text{F}_2 + \text{HCl} \rightarrow \text{HF} + \text{ClF}$	1.8×10^{10}	0.5	-39427	1000	1
b						
39f	$\text{ClF} + \text{HCl} \rightarrow \text{HF} + \text{Cl}_2$	1.8×10^{10}	0.5	-46025	1000	1
b						
40f	$\text{F}_2 + \text{Cl}_2 \rightarrow \text{ClF} + \text{ClF}$	1.8×10^{10}	0.5	-26758	1000	1
b						
41f	$\text{OH} + \text{CO} \rightarrow \text{H} + \text{CO}_2$	5.6×10^{11}	0	-1080	5	2
b						
42f	$\text{O}_2 + \text{CO} \rightarrow \text{O} + \text{CO}_2$	8.85×10^{19}	0.656	-45920	1000	2
b		1.9×10^{13}	0	-54150	1000	2
43f	$\text{CO}_2 + \text{C} \rightarrow \text{CO} + \text{CO}$	1.1×10^{11}	0.5	-6995	1000	1
b						

*f = forward

b = backward

TABLE 3. (Continued)

Identification Number	Reaction	A	B	C	Uncertainty	Ref. No.
44f b	$C+OH \rightarrow CO+H$	5.3×10^{11}	0.5	-5628	25	1
45f b	$C+NO \rightarrow CO+N$	5.3×10^{11}	0.5	-8303	100	1
46f b	$CO_2+N \rightarrow CO+NO$	1.1×10^{11}	0.5	-59618	1000	1
47f b	$C+O_2 \rightarrow CO+O$	5.3×10^{11}	0.5	-6552	100	1
48f b	$N+NO \rightarrow O+N_2$	3.1×10^{13}	0	-334	5	2
49f b	$NO+NO \rightarrow N_2+O_2$	1.36×10^{14}	0	-75400	5	2
50f b	$NO+NO \rightarrow N_2+O_2$	1.0×10^{13}	0	-79490	10	1
51f b	$N+OH \rightarrow NO+H$	5.3×10^{11}	0.5	-5628	100	1
52f b	$N+O_2 \rightarrow O+NO$	6.43×10^9	1	-6250	5	2
53f b	$OH+F \rightarrow HF+O$	1.55×10^9	1	-38640	5	2
54f b	$H_2O+F \rightarrow HF+OH$	2.9×10^{12}	0.68	-200	25	1
55f b	$B+BO_2 \rightarrow BO+BO$	1.4×10^{10}	0.68	-600	25	1
56f b	$BF+OH \rightarrow BO+HF$	1.1×10^{11}	0.5	-7585	1000	1
57f b	$BF+O \rightarrow BO+F$	1.8×10^{10}	0.5	-78036	1000	1
58f b	$B+OH \rightarrow BO+H$	5.3×10^{11}	0.5	-9865	1000	1
59f b	$B+O_2 \rightarrow BO+O$	5.3×10^{11}	0.5	-5628	100	1
60f b	$B+BOF \rightarrow BO+BF$	5.3×10^{11}	0.5	-6552	100	1
61f b	$BF_3+BO \rightarrow BOF+BF_2$	1.1×10^{11}	0.5	-9273	1000	1
62f b	$BF+BO_2 \rightarrow BO+BOF$	1.1×10^{11}	0.5	-8744	50	1
63f b	$BOF+OH \rightarrow BO_2+HF$	1.1×10^{11}	0.5	-7585	100	1
64f b	$BO+OH \rightarrow BO_2+H$	1.8×10^{10}	0.5	-75864	1000	1
65f b	$BO+O_2 \rightarrow BO_2+O$	1.1×10^{11}	0.5	-5628	100	1
66f b	$B+BF_2 \rightarrow BF+BF$	1.1×10^{11}	0.5	-6552	50	1
67f b	$BF_2+H \rightarrow BF+HF$	1.1×10^{11}	0.5	-6663	100	1

TABLE 3. (Concluded)

Identification Number	Reaction	A	B	C	Uncertainty	Ref. No.
67f b	$B + F_2 \rightarrow BF + F$	5.3×10^{11}	0.5	-2075	25	1
68f b	$B + HF \rightarrow BF + H$	5.3×10^{11}	0.5	-7468	100	1
69f b	$BO + BF_2 \rightarrow BF + BOF$	1.1×10^{11}	0.5	-8744	1000	1
70f b	$BO + BF_2 \rightarrow BF + BOF$	1.1×10^{11}	0.5	-6663	25	1
71f b	$BF + F_2 \rightarrow BF_2 + F$	1.1×10^{11}	0.5	-2075	50	1
72f b	$BF_2 + F_2 \rightarrow BF_2 + F$	1.1×10^{11}	0.5	-2075	25	1
73f b	$BF_2 + HF \rightarrow BF_3 + H$	1.1×10^{11}	0.5	-7468	100	1
74f b	$BO_2 + BF_2 \rightarrow BOF + BOF$	1.8×10^{10}	0.5	-72541	100	1
75f b	$BF_2 + OH \rightarrow BOF + HF$	1.8×10^{10}	0.5	-62579	1000	1
76f b	$BO + F_2 \rightarrow BOF + F$	1.1×10^{11}	0.5	-2075	50	1
77f b	$BF_2 + O \rightarrow BOF + F$	1.1×10^{11}	0.5	-6663	100	1
78f b	$BO + HF \rightarrow BOF + H$	1.1×10^{11}	0.5	-7468	1000	1
79f b	$BF + OH \rightarrow BOF + H$	1.1×10^{11}	0.5	-5628	100	1
80f b	$BO_2 + F \rightarrow BOF + O$	1.1×10^{11}	0.5	-7585	100	1
81f b	$O_2 + BF \rightarrow O + BOF$	7×10^{11}	0.5	0		1
82f b	$BF_2 + BF_2 \rightarrow BF + BF_2$	7.5×10^8	0.48	-1481		1

TABLE 4. IMPORTANT REACTIONS AND REQUIRED RATE CONSTANT ACCURACIES

REACTION	ESTIMATED CURRENT UNCERTAINTY	O ₂ -H ₂			F ₂ -H ₂			N ₂ O ₄ ASO			CTF N ₂ H ₄			OF ₂ -B ₂ H ₆			F ₂ -N ₂ H ₄			FLOX RP-1			LOX RP-1		
		L	C	H	L	C	H	L	C	H	L	C	H	L*	C	H*	L	C	H	L	C	H	L	C	H
H ₂ O + M = OH + H + M	10 ³	115	10.5	2.9				4.0	2.7	2.2					(1.8)							250	48	>10	
H ₂ + M = 2H + M	10	6.9	2.7	1.6	(.95)	1.07	1.1	1.9	2.1	2.6	>10	4.9		1.1			1.1	1.1	1.1	1.1	1.2	4.3	>10	>10	
H ₂ O + H = OH + H ₂	10		10.0	>10					>10	>10					*								>10	(4.4)	
H ₂ O + O = 2OH	10		>10	>10																		>10	>10	(1.4)	
O ₂ + H = OH + O	5			>5											*							>5	>5	(1.3)	
HF + M = H + F + M	10 ^{1.5}				>10 ^{1.5}	2.2	1.4					>10 ^{1.5}					1.7	1.3	(1.1)	1.4	1.2	1.6			
HF + H = H ₂ + F	(50)				>50	>50								*			>50	>50	>50	>50	>50	>50			
CO ₂ + M = CO + O + M	10 ^{2.5}								>10 ^{2.5}	13.0											1.4	1.5	.62	.64	(.85)
CO ₂ + H = CO + OH	5							>5	>5												>5	(4.7)			
Cl ₂ + M = 2 Cl + M	10										9.2	(2.0)	2.4												
HCl + Cl = H + Cl ₂	(25)										>25	>25	>25												
HF + Cl = HCl + F	25										2.5	3.9	(1.1)												
HCl + M = H + Cl + M	25											(3.4)													
HF + O = OH + F	(25)													*							>25	>25			
OH + M = O + H + M	5													*											
BO + F = BF + O	10 ³													*											
BO + BOF = BF + BO ₂	10 ²													*											
BF + HF = BF ₂ + H	10 ²																								
BOF + H = BO + HF	10 ³															(1.7)									
NUMBER OF IMPORTANT REACTIONS		2	4	5	2	3	3	3	5	4	4	5	4	11	11	11	3	3	3	3	6	6	5	6	5

* REQUIRED RATE CONSTANT ACCURACIES NOT ESTABLISHED FOR THIS CONDITION

Accuracies circled are greater than currently available, indicating added uncertainty in predictions.
L, C, H are low, center, high mixture ratio range.

SECTION 6 REFERENCES

1. Cherry, S. S., Gold, P. I., and Van Nice, L. J., Phase I Final Report - Screening of Reaction Rates, TRW Systems Report 08832-6001-T000, 22 May 1967
2. Baulch, D. L., et al., High-Temperature Reaction Rate Data, University of Leeds, May 1968.
3. Bahn, G. S., Cherry, S. S., et al., "Selection of Recombination Rate Constants for H-F-O Reactions," AiAA J., 7, 181-183 (January 1969).
4. Bahn, G. S., "The Reactions $\text{H} + \text{CO}_2 = \text{OH} + \text{CO}$ and $\text{CO}_2 + \text{M} + \text{O} + \text{CO} + \text{M}$," Pyrodynamics, 6, 101-112 (1968).
5. Homer, J. B. and Hurle, I. R., "Dissociation of Water Vapour Behind Shock Waves," Proc. Roy. Soc., A314, 585-598 (1969).
6. Cherry, S. S. and L. J. Van Nice, Phase II Final Report - Screening of Reaction Rates, TRW Systems Report 08832-6002-T000, 6 December 1967.

NOMENCLATURE

NOMENCLATURE AND DEFINITIONS

Nomenclature and definitions used throughout this Manual are consistent with those selected by the Working Group and published in Ref. *. In many instances, upper case has been used for consistency with computer output. Lower case is an acceptable substitute for many subscripts and symbols as long as the meaning is clear.

The nomenclature and definitions used are given in Tables 1 through 12, listed below:

<u>Table Number</u>	<u>Title</u>
1	Nomenclature and Definitions for Geometrical Parameters
2	Nomenclature Definitions for Performance Parameters
3	Nomenclature Definitions for Performance Efficiencies
4	Nomenclature and Definitions for Gas Dynamic Parameters
5	Nomenclature and Definitions for Thermodynamic Parameters
6	Nomenclature and Definitions for Transport Parameters
7	Nomenclature and Definitions for Uncertainty Parameters
8	Nomenclature and Definitions for Turbopump Parameters
9	Nomenclature and Definitions for Test Instrumentation Parameters
10	Subscripts
11	Standard Schematic Nomenclature
12	Conversion Factors

*Rocket Propulsion Nomenclature, CPIA Publication No. 131, ICRPG Performance Standardization Working Group, January 1967, ed. M. R. Beltran, T. C. Kozvic, Dynamic Science.

TABLE 1. NOMENCLATURE AND DEFINITIONS FOR GEOMETRICAL PARAMETERS

Symbol	Parameter	Physical Units*	SI Units	Engineering Units
A_T	Nozzle throat area	L^2	Square meters (m^2)	Square inches ($in.^2$)
A_E	Nozzle exit area	L^2	Square meters (m^2)	Square inches ($in.^2$)
R_T	Nozzle throat radius	L	Meters (m)	Inches (in.)
RWT_D	Ratio of radius of curvature of nozzle wall downstream of throat-to-throat radius	None	None	None
RWT_U	Ratio of radius of curvature of nozzle wall upstream of throat-to-throat radius	None	None	None
R/R_T	Normalized radial distance from nozzle axis	None	None	None
Z/R_T	Normalized distance along axis from throat plane	None	None	None
α	Nozzle wall angle	None	Radian (rad)	Degrees
ϵ	Ratio of exit area to throat area (area ratio, A_E/A_T)	None	None	None
ϵ_C	Ratio of injector area to throat area (contraction ratio, A_{INJ}/A_T)	None	None	None

*L = length

t = time

M = mass

T = temperature

TABLE 2. NOMENCLATURE DEFINITIONS FOR PERFORMANCE PARAMETERS

Symbol	Parameter	Physical Units	SI Units	Engineering Units	Rigorous Definition	Simplified Definition
C*	Characteristic Velocity	Lt ⁻¹	Meters/second (m/s)	Feet/second (ft/s)	$\frac{P_C A_T}{\dot{M}_T}$	Same
C* _{PRED}	Predicted Characteristic Velocity	Lt ⁻¹	Meters/second (m/s)	Feet/second (ft/s)	$\left(\frac{\dot{M}_{VAP}}{\dot{M}_T}\right) C_{TDKP}^{*} \left(\frac{A_T}{A_T - 2\pi R_E^2}\right)$ VAP MR MULTI-ZONE HL	C* _{ODE} AVG MR $\left(\eta_{C^*}^{*TD} \eta_{C^*}^{*KIN} \eta_{C^*}^{*BL} \eta_{C^*}^{*VAP}\right)$ $\eta_{C^*}^{*MIX} \eta_{C^*}^{*HL}$
C* _{TEST}	Measured Characteristic Velocity	Lt ⁻¹	Meters/second (m/s)	Feet/second (ft/s)	$\frac{P_{C_{TEST}} A_{T_{TEST}}}{\dot{M}_{T_{TEST}}}$	Same
C* _{PERF INJ}	Perfect Injector Characteristic Velocity	Lt ⁻¹	Meters/second (m/s)	Feet/second (ft/s)	C* _{TDKP} AVG INJ MR HL	C* _{ODE} AVG MR $\left(\eta_{C^*}^{*TD} \eta_{C^*}^{*KIN} \eta_{C^*}^{*BL} \eta_{C^*}^{*HL}\right)$
F	Thrust	M Lt ⁻²	Newtons (N)	Pounds force (lb _f)	Time rate of change of momentum d(MV)/dt	Same
F _{SITE}	Site Thrust	M Lt ⁻²	Newtons (N)	Pounds force (lb _f)	Measured thrust without corrections	Same
F _{TEST}	Measured Thrust	M Lt ⁻²	Newtons (N)	Pounds force (lb _f)	F _{SITE} + $\int P \cdot dA$ EXTERNAL SURFACE	F _{SITE} + P _A A _E
ISP	Specific Impulse	Lt ⁻¹	Meters/second (m/s)	Pounds force-second/pound mass (lb _f -s/lb _m)	F/M	Same
ISP _{PRED ENG}	Engine Calculated Specific Impulse	Lt ⁻¹	Meters/second (m/s)	Pound force-second/pound mass (lb _f -s/lb _m)	$\frac{F_{TC} + \Sigma F_{PROP DUMPS}}{\dot{M}_{ENG NET}} = \frac{\dot{M}_{TC}}{\dot{M}_{ENG NET}} \frac{ISP_{ODE}}{AVG MR} \left[\eta_{ISP}^{*TD} \eta_{ISP}^{*VAP} \eta_{ISP}^{*MIX} \right]$ $\left[\frac{\dot{M}_{VAP}}{\dot{M}_{ENG NET}} \frac{ISP_{TDKP}}{MR MULTI-ZONE HL} \right]$ $\frac{-\Delta F_{BL} + \Delta F_{PARTICLES} + \Sigma F_{PROP DUMPS}}{\dot{M}_{ENG NET}}$	$\eta_{ISP}^{*HL} - \left(1 - \eta_{ISP}^{*BL}\right) + \frac{\Sigma F_{PROP DUMP}}{\dot{M}_{ENG NET}}$

TABLE 2. (Concluded)

Symbol	Parameter	Physical Units	SI Units	Engineering Units	Rigorous Definition	Simplified Definition
$ISP_{PRED TC}$	Thrust Chamber Calculated Specific Impulse	Lt^{-1}	Meters/second (m/s)	Pound force-second/pound mass (lb_f-s/lb_m)	$\left[\frac{\dot{M}_{VAP} ISP_{TDKPW VAP}}{\dot{M}_{MR MULTI-ZONE}} - \frac{\Delta F_{BL}}{\dot{M}_{TC}} \right]$	$ISP_{ODE AVG MR} \left[\eta_{ISP_{TD}} \eta_{ISP_{KIN}} \eta_{ISP_{VAP}} \right]$ $\eta_{ISP_{MIX}} \eta_{ISP_{HL}} - (1 - \eta_{ISP_{BL}})$
$ISP_{TEST ENG}$	Engine Measured Specific Impulse	Lt^{-1}	Meters/second (m/s)	Pounds force-second/pound mass (lb_f-s/lb_m)	$\frac{F_{MEAS ENG}}{\dot{M}_{MEAS ENG NET}}$	Same
$ISP_{TEST TC}$	Thrust Chamber Measured	Lt^{-1}	Meters/second (m/s)	Pounds force-second/pound mass (lb_f-s/lb_m)	$\frac{F_{MEAS TC}}{\dot{M}_{MEAS TC}}$	Same
$ISP_{PERF INJ}$	Perfect Injector Specific Impulse	Lt^{-1}	Meters/second (m/s)	Pounds force-second/pound mass (lb_f-s/lb_m)	$ISP_{TDKPW AVG MR} - \frac{\Delta F_{BL}}{\dot{M}_{TC}}$	$ISP_{ODE AVG MR} \left[\eta_{ISP_{TD}} \eta_{ISP_{KIN}} \eta_{ISP_{HL}} - (1 - \eta_{ISP_{BL}}) \right]$
MR	Mixture Ratio	None	None	None	$\dot{M}_{OX}/\dot{M}_{FUEL}$	Same
P_C	Effective Thrust Chamber Stagnation Pressure	$ML^{-1}t^{-2}$	Newtons/square meter (N/m^2)	Pounds square inch (psia)	The infinite reservoir pressure for fully mixed chemical equilibrium exhaust products required to provide a given mass flow at the throat of the specific thrust chamber of interest with the infinite reservoir replacing the actual injector at the injector plane	Same using simplified calculation procedures
P^*_o	Local Throat Stagnation Pressure	$ML^{-1}t^{-2}$	Newtons/square meter (N/m^2)	Pounds square inch (psia)	The pressure that would result from decelerating a local portion of the throat flow reversibly and adiabatically (implies chemical equilibrium)	Same
ΔF_{BL}	Analytical Thrust Correction for Boundary Layer Effects	MLt^{-2}	Newtons (N)	Pounds force (lb_f)	Axisymmetric: $2 \pi R_E \cos \alpha_E$ $\left[\left(\rho_{WE} v_{WE}^2 \right)_{TDKPW} \theta_E - \left(P_{WE} \right)_{TDKPW} \delta^* \right]$	Axisymmetric: $2 \pi R_E \cos \alpha_E$ $\left(\rho_{WE} v_{WE}^2 \right)_{TDKRW} \theta_E$

TABLE 3. NOMENCLATURE DEFINITIONS FOR PERFORMANCE EFFICIENCIES

Symbol	Parameter	Rigorous Definition	Simplified Definition
$\eta_{C^*_{BL}}$	C* Boundary Layer Efficiency	$\frac{A_T}{A_T - 2R_E \delta_E^*}$	Axisymmetric $\frac{1}{\left(1 - \frac{\delta_T^*}{R_T}\right)}$
$\eta_{C^*_{ER}}$	C* Energy Release Efficiency	$\frac{C^*_{TEST}}{C^*_{PERF INJ}}$ or $\frac{C^*_{PRED}}{C^*_{PERF INJ}}$	$\eta_{C^*_{VAP}} \eta_{C^*_{MIX}}$
$\eta_{C^*_{HL}}$	C* Heat Loss Efficiency	$\frac{C^*_{TDKP VAP MR MULTIZONE HL}}{C^*_{TDKP VAP MR MULTIZONE}}$	$\frac{C^*_{ODE AVG HL MR}}{C^*_{ODE AVG MR}}$
$\eta_{C^*_{KIN}}$	C* Reaction Kinetic Efficiency	$\frac{C^*_{ODKP VAP MR MULTIZONE}}{C^*_{ODE VAP MR MULTIZONE}}$	$\frac{C^*_{ODK AVG MR}}{C^*_{ODE AVG MR}}$
$\eta_{C^*_{MIX}}$	C* Mixture Ratio Distribution Efficiency	$\frac{C^*_{ODE INJ MR MULTIZONE}}{C^*_{ODE AVG INJ MR}}$	Same as Rigorous
$\eta_{C^*_{TD}}$	C* Geometric Efficiency	$\frac{C^*_{TDKP VAP MR MULTIZONE}}{C^*_{ODKP VAP MR MULTIZONE}}$	$\frac{\dot{M}_{ODYR}}{\dot{M}_{TDYR}}$
$\eta_{C^*_{VAP}}$	C* Vaporization Efficiency	$\frac{C^*_{ODE VAP MR MULTIZONE}}{C^*_{ODE INJ MR MULTIZONE}}$	$\frac{\dot{M}_{VAP}}{\dot{M}_T}$
$\eta_{ISP_{BL}}$	Specific Impulse Boundary Layer Efficiency	$1 - \frac{\Delta F_{BL} - 2\pi R_E P_E \cos \alpha_E \delta^*}{\dot{M}_{TC} ISP_{ODER}}$	Same with simplified ΔF_{BL}
$\eta_{ISP_{ER}}$	Specific Impulse Energy Release Efficiency	$\frac{F_{TC TEST} + \Delta F_{BL PRED}}{F_{TC PREF INJ} + \Delta F_{BL PRED}}$ or	$\eta_{ISP_{VAP}} \eta_{ISP_{MIX}}$
$\eta_{ISP_{HL}}$	Specific Impulse Heat Loss Efficiency	$\frac{ISP_{TDKP VAP MR MULTIZONE HL}}{ISP_{TDKP VAP MR MULTIZONE}}$	$\frac{ISP_{ODE AVG MR}}{ISP_{ODE AVG MR NO HL}}$
$\eta_{ISP_{KIN}}$	Specific Impulse Reaction Kinetic Efficiency	$\frac{ISP_{ODKP VAP MR MULTIZONE}}{ISP_{ODE VAP MR MULTIZONE}}$	Depends on system
$\eta_{ISP_{TD}}$	Specific Impulse Geometry Efficiency	$\frac{ISP_{TDKP VAP MR MULTIZONE}}{ISP_{ODKP VAP MR MULTIZONE}}$	$\frac{ISP_{TDE}}{ISP_{ODE}}$
$\eta_{ISP_{MIX}}$	Specific Impulse Mixture Ratio Distribution Efficiency	$\frac{ISP_{ODEP INJ MR MULTIZONE}}{ISP_{ODEP AVG INJ MR}}$	$\frac{ISP_{ODE INJ MR MULTI-ZONE}}{ISP_{ODE AVG MR}}$
$\eta_{ISP_{VAP}}$	Specific Impulse Vaporization Efficiency	$\frac{\dot{M}_{VAP}}{\dot{M}_{TC}} \times \frac{ISP_{ODEP VAP MR MULTIZONE}}{ISP_{ODEP INJ MR MULTIZONE}}$	$\frac{\dot{M}_{VAP}}{\dot{M}_T}$
η_{TC}	Thrust Chamber Efficiency	$\frac{ISP_{TEST TC}}{ISP_{ODE TC}}$ or $\frac{ISP_{PRED TC}}{ISP_{ODE TC}}$	$\eta_{ISP_{HL}} \eta_{ISP_{KIN}} \eta_{ISP_{VAP}} \eta_{ISP_{MIX}} \eta_{ISP_{TD}}$ $\left(1 - \eta_{ISP_{BL}}\right)$

TABLE 4. NOMENCLATURE AND DEFINITIONS FOR GAS DYNAMIC PARAMETERS

Symbol	Parameter	Physical Units	SI Units	Engineering Units	Definition
C_D	Discharge Coefficient	None	None	None	$\frac{\dot{M}_{TDKRW}}{\dot{M}_{ODE}}$
$C_{D_{INV}}$	Inviscid Discharge Coefficient	None	None	None	$\frac{\dot{M}_{TDKPW}}{\dot{M}_{ODE}}$
M	Mach Number	None	None	None	Local velocity divided by local speed of sound (V/a)
M*	Dimensionless Velocity	None	None	None	Local velocity divided by throat speed of sound (V/a*)
V	Velocity	LT ⁻¹	Meters/second (m/s)	Feet/second (ft/s)	The rate of change of position of an identifiable entity
a	Sonic Velocity	LT ⁻¹	Meters/second (m/s)	Feet/second (ft/s)	Local speed of sound, $[(\partial P / \partial \rho)_S]^{1/2}$

TABLE 5. NOMENCLATURE AND DEFINITIONS FOR THERMODYNAMIC PARAMETERS

Symbol	Parameter	Physical Units	SI Units	Engineering Units	Definition
C_p	Specific Heat at Constant Pressure	$L^2_t - 2_T - 1$	Joule/kilogram degrees Kelvin (J/kg-K)	Btu/pound-degrees Rankin (Btu/lb _m -R)	Change in enthalpy with temperature for a constant pressure process, $(\partial h / \partial T)_p$ [NOTE: Shifting C_p allows composition changes while frozen C_p does not]
C_v	Specific Heat at Constant Volume	$L^2_t - 2_T - 1$	Joule/kilogram degrees Kelvin (J/kg-K)	Btu/pound-degrees Rankin (Btu/lb _m -R)	Change in internal energy with temperature for a constant volume process, $(\partial e / \partial T)_v$
M	Mass	M	Kilograms (kg)	Pounds mass (lb _m)	Basic parameter
P	Pressure	$ML^{-1}_t - 2$	Newtons/square meter (N/m ²)	Pounds square inch (psia)	Force exerted on a surface per unit surface area
R	Specific Gas Constant	$L^2_t - 2_T - 1$	Joule/kilogram degrees Kelvin (J/kg-K)	Btu/pound-degrees Rankine (Btu/lb _m -R)	$P/Z\rho T$
$\mathcal{R}$	Universal Gas Constant	$ML^2_t - 2_T - 1$	Joule/degrees Kelvin (J/K)	Btu/degrees Rankin (Btu/R)	$WP/Z\rho T$
T	Temperature	T	Degrees Kelvin (K)	Degrees Rankin (R)	Basic parameter
MW	Molecular Weight	M	Kilograms (kg)	Pounds mass (lb _m)	The weight of one mole of an element
Z	Compressibility	None	None	None	$\rho_{\text{PERF GAS}} / \rho_{\text{MEAS}}$
e	Specific Energy	$L^2_t - 2$	Joules/kilogram (J/kg)	Btu/pound (Btu/lb _m)	The energy content of a substance including chemical binding energy and kinetic energy
f	Specific Free Energy	$L^2_t - 2$	Joules/kilogram (J/kg)	Btu/pound (Btu/lb _m)	$h - Ts$
h	Specific Enthalpy	$L^2_t - 2$	Joules/kilogram (J/kg)	Btu/pound (Btu/lb _m)	$e + P/\rho$
s	Entropy	$L^2_t - 2_T - 1$	Joules/kilogram degrees Kelvin (J/kg-K)	Btu/pound degree Rankin (Btu/lb _m -R)	h/T or $\int \frac{qdt}{T}$
γ	Isentropic Coefficient	None	None	None	$\frac{\rho}{P} \left(\frac{\partial P}{\partial \rho} \right)_s$
ρ	Density	ML^{-3}	Kilogram/cubic meter (kg/m ³)	Pounds/cubic feet (lb _m /ft ³)	Mass per unit volume

TABLE 6. NOMENCLATURE AND DEFINITIONS FOR TRANSPORT PARAMETERS

Symbol	Parameter	Physical Units	SI Units	Engineering Units	Definition
Bi	Biot Number	None	None	None	h/k_w (indicates relative importance of film heat transfer rate to wall heat transfer rate)
Le	Lewis Number	None	None	None	$k/\rho C_p \alpha$ (indicates relative importance of heat transfer to heat capacity)
Nu	Nusselt Number	None	None	None	hx/k (indicates film heat transfer rate compared to film conductivity)
Re	Reynolds Number	None	None	None	$\rho x/\mu$ (indicates ratio of momentum to viscous effects)
St	Stanton Number	None	None	None	$h/\rho V C_p$ (indicates relative importance of film heat transfer to film heat capacity)
h	Heat Transfer Coefficient	$Mt^{-3}T^{-1}$	Joules/square meter second-degree Kelvin (J/m^2-s-K)	Btu/square foot-second-degrees Rankin (Btu/ft^2-s-R)	$q/A \Delta T$
k	Thermal Conductivity	$MLt^{-3}T^{-1}$	Joules/meter second-degree Kelvin ($J/m-s-K$)	Btu/foot-second-degrees Rankin ($Btu/ft-s-R$)	$q/(Adt/dx)$
q	Heat Flowrate	ML^2t^{-3}	Joules/second (J/s)	Btu/second (Btu/s)	Rate of energy transfer
x	Characteristic Length	L	Meters (m)	Feet (ft)	A length used to normalize or non-dimensionalize
δ	Thickness of Momentum Boundary Layer	L	Meters (m)	Feet (ft)	The point in the flow at which the momentum reaches 99 percent of free stream momentum when moving from a wall in a direction perpendicular to the wall and crossing the fluid flow
δ_T	Thickness of Thermal Boundary Layer	L	Meters (m)	Feet (ft)	The point in the flow at which the enthalpy reaches 99 percent of free stream enthalpy when moving from a wall in a direction perpendicular to the wall and crossing the fluid flow
δ_D	Thickness of Diffusion Boundary Layer	L	Meters (m)	Feet (ft)	The point in the flow at which the composition reaches 99 percent of free stream composition when moving from a wall in a direction perpendicular to the wall and crossing the fluid flow

TABLE 6. (Concluded)

Symbol	Parameter	Physical Units	SI Units	Engineering Units	Definition
δ^*	Mass Displacement Thickness	L	Meters (m)	Feet (ft)	The distance the wall would have to be displaced for an inviscid flow to have the same mass flow-rate as the actual combined inviscid and boundary layer flow. In axisymmetric coordinates for thin boundary layers: $\delta^* = \int_0^{\delta_x} \left[1 - \frac{\rho V}{(\rho_w V_w)_{TDK PW}} \right] dy$ where δ_x is the thickest of momentum, energy, or diffusion boundary layers and Y is the direction perpendicular to the wall
ν	Kinematic Viscosity	$L^2 t^{-1}$	Square-meters/second (m^2/s)	Square feet/second (ft^2/s)	μ/ρ
ϕ	Energy Thickness	L	Meters (m)	Feet (ft)	The thickness of the displaced inviscid flow having an enthalpy flux equal to the difference in enthalpy between the displaced flow and the real flow. In axisymmetric coordinates for thin boundary layers: $\phi = \int_0^{\delta_x} \frac{\rho V}{(\rho_w V_w)_{TDK PW}} \left[1 - \frac{h}{(h_w)_{TDK PW}} \right] dy$ Where δ_x is the thickest of the momentum, energy or diffusion boundary layers and Y is direction perpendicular to the walls
θ	Momentum Thickness	L	Meters (m)	Feet (ft)	The thickness of the displaced inviscid flow having an enthalpy flux equal to the difference in momentum between the displaced flow and the real flow. In axisymmetric coordinates for thin boundary layers: $\theta = \int_0^{\delta_x} \frac{\rho V}{(\rho_w V_w)_{TDK PW}} \left[1 - \frac{V}{(V_w)_{TDK PW}} \right] dy$ Where δ_x is the thickest of the momentum energy or diffusion boundary layers and Y is the direction perpendicular to the wall
μ	Dynamic Viscosity	$ML^{-1} t^{-1}$	Newton-second/square meter ($N \cdot s/m^2$)	Pound-second/square feet ($lb_f \cdot s/ft^2$)	$(F_{SHEAR}/A)/(\partial V_z/\partial Y)$

TABLE 7. NOMENCLATURE AND DEFINITIONS FOR UNCERTAINTY PARAMETERS

Symbol	Parameter	Description
B	Bias	The difference between the average of all possible measured values and the true value. Systematic or fixed error.
F(t) or F(Z)	Cumulative Probability for Probability Distribution	The integrated probability distribution. For example, the probability that a value is less than t is F(t). The probability that t is between t ₁ and t ₂ is F(t ₂) - F(t ₁). F(Z) is tabularized for normal distributions in standard handbooks.
M	Mean	The average value of a distribution $\frac{\sum x n(x)}{N} \quad \frac{\sum_i x_i n(x_i)}{N}$
N	Sample Size	The number of events included in the sample
n(x)	Distribution Frequency	The frequency of occurrence of a given measurement x
P	Probability	The relative frequency of the occurrence of events. $\frac{n(x)}{N}$
S	Precision Index	The computed standard deviation of the measurements $\sqrt{\frac{\sum_{i=1}^N (x_i - \bar{X})^2}{N - 1}}$
t	Student's t Distribution	The ratio of the difference between the true population mean and the sample mean ratioed to the estimated sample standard deviation $\frac{ M_{MEAS} - M_{ACTUAL} }{S}$
U	Uncertainty	The maximum inaccuracy expected $B + t_{95,v} S$
Z	Standardized Score	The difference between the measured value and the mean in number of standard deviations $\frac{ x - M }{\sigma} \quad \text{or} \quad \frac{ x - M }{S}$
v	Degrees of Freedom	Number of ways in which a measurement can occur randomly
σ	Standard Deviation	A measure of the dispersion or spread of a frequency distribution
Ω	Correlation Index	The closeness of agreement between the calculated value and the measured value $[1 - F(t)] \times 200\%$

TABLE 8. NOMENCLATURE AND DEFINITIONS FOR TURBOPUMP PARAMETERS

Symbol	Parameter	Physical Units	SI Units	Engineering Units	Definition
A	Inlet Area	L^2	Square meters (m^2)	Square inches ($in.^2$)	Cross-sectional area of pump inlet
H	Head	L	Meters (m)	Feet (ft)	$\frac{v^2}{2g} + \frac{p}{\rho g} + h$
I	Moment of Inertia	ML^2	Kilogram meter square ($kg \cdot m^2$)	Pound-square foot ($lb_m \cdot ft^2$)	The integral of mass times axial distance along axial distance
N	Rotational Speed	t^{-1}	Revolutions per minute (rpm)	Same	Number of complete turns about an axis in a unit time
N_s	Specific Speed	$L^{3/4} t^{-3/2}$	Meters to the 3/4 per second to the 3/2 ($m^{3/4}/s^{3/2}$)	Feet to the 3/4 per second to the 3/2 ($ft^{3/4}/s^{3/2}$)	$NQ^{1/2}/\Delta H^{3/4}$
NPSH	Net Positive Suction Head	L	Meters (m)	Feet (ft)	$\frac{(P_{STATIC} - P_{VAPOR})}{\rho_{LIQUID} g} + \frac{C_M^2}{2g} \approx \frac{P_{INLET} - P_{VAPOR}}{\rho_{LIQUID}}$
Q	Volumetric Flow	$L^3 t^{-1}$	Cubic meters/second (m^3/s)	Cubic feet/second (ft^3/s)	M/ρ
S_s	Suction Specific Speed	$L^{3/4} t^{-3/2}$	Meters to the 3/4 per second to the 3/2 ($m^{3/4}/s^{3/2}$)	Feet to the 3/4 per second to the 3/2 ($ft^{3/4}/s^{3/2}$)	$NQ^{1/2}/(H_{INLET} - H_{VAPOR})^{3/4}$
C_M	Meridional Velocity	$L t^{-1}$	Meters/second (m/s)	Feet/second (ft/s)	Q/A
u	Tip Speed	$L t^{-1}$	Meters/second (m/s)	Feet/second (ft/s)	$2 \pi RN/60$
η_p	Pump Efficiency	None	None	None	$\frac{(h_{o2} - h_{o1})_S}{(h_{o2} - h_{o1})_{CALC}}$ or $\frac{(h_{o2} - h_{o1})_S}{(h_{o2} - h_{o1})_{MEAS}}$
η_T	Turbine Efficiency	None	None	None	$\frac{(h_{o1} - h_{o2})_{CALC}}{(h_{o1} - h_{o2})_S}$ or $\frac{(h_{o1} - h_{o2})_{MEAS}}{(h_{o1} - h_{o2})_S}$
ω	Angular Velocity	t^{-1}	Radians per second (rad/s)	Same	Same as N except for units
ϕ	Pump Flow Coefficient	$L^2 t^{-1}$	Square meter/second (m^2/s)	Square foot/second (ft^2/s)	$(\frac{Q}{A})/u$ or $\frac{C_M}{u}$
ψ	Pump Head Coefficient	None	None	None	$\frac{g \Delta H_P}{u^2}$
τ	Torque	$ML^2 t^{-2}$	Newton-meter (N-m)	Foot-pound force ($ft \cdot lb_f$)	Vector product of force and radius

TABLE 9. NOMENCLATURE AND DEFINITIONS FOR TEST INSTRUMENTATION PARAMETERS

Symbol	Parameter	Description
D _A	System Zero With Ambient Pressure	Recorder deflection for a specified electrical unbalance
D _B	System Zero at Each Engine Test	
D _R	R-CAL Deflection	
D _X	Test Deflection	
D ₁	Chart Zero at Low R-CAL	
D ₂	Chart Zero to High R-CAL	Physical input to a gage or transducer corresponding to a specified electrical unbalance
KN	Key Number	

TABLE 10. SUBSCRIPTS

<u>Subscript</u>	<u>Meaning</u>
ALT	At a given altitude
AMB	Ambient
AVG	Average
B	Base
BL	Boundary layer
C	Chamber
CALC	Calculated
CONST	Constant
CON	Contraction
COR	Corrected
C*	Related to characteristic velocity
D	Discharge
DATA	Based upon test data
DIST	Distribution
E	Exit
EL	Element
ENG	Engine
EQ	Equilibrium
ER	Energy release
EST	Estimated
EXP	Experimental (test is preferred)
FS	Feed system
HL	Heat loss
INJ	Injector or injected

TABLE 10. (Continued)

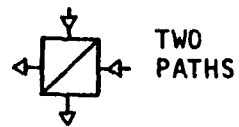
Subscripts	<u>Meaning</u>
INV	Inviscid
ISP	Related to specific impulse
KIN	Chemical reaction kinetic
MEAS	Measured
MIX	Mixing
MR	Mixture Ratio
MULTI-ZONE	Calculated in a manner similar to TDK in which a number of streamtubes are established and performed is mass averaged across the streamtubes
NET	Net value
NBS	National Bureau of Standards
ODE	Output of one-dimensional equilibrium computer program
ODIE	One-dimensional isentropic equilibrium
OX	Oxidizer
P	Constant pressure or pump
PERF INJ	Perfect injector
PRED	Predicted value (usually refers to value calculated using the Evaluation Procedures)
PROP DUMP	Propulsive dump
PW	Potential Wall
RES	Reservoir
S	Constant Entropy
STRAT	Stratification
SITE	Value as measured with no correction
T	Throat or Turbine

TABLE 10. (Concluded)

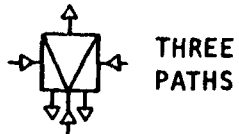
<u>Subscript</u>	<u>Meaning</u>
TC	Thrust chamber-injector inlet to nozzle exit
TD	Two dimensional
TDE	Two-dimensional equilibrium computer program output
TEST	Test measurement (alternates are EXP and MEAS), may be corrected to vacuum conditions.
TDKR	Output of TDK program for first run with real nozzle wall
TDKP	Output of TDK program for second run with virtual wall defined by boundary layer displacement thickness
THEOR	Theoretical
TOT	Total
U	Upstream of throat
UNC	Uncorrected
VAC	Vacuum
VAP	Vaporization
W	Wall
h	Constant enthalpy
i	Initial, ith
j	Jth
n	Nth
o	Stagnation conditions
s	Constant entropy
Z	Axial direction
δ^*	Displacement wall for boundary layer displacement thickness
ρ	Constant density

TABLE 11. STANDARD SCHEMATIC NOMENCLATURE

HEAT EXCHANGER



TWO
PATHS

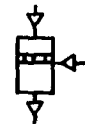


THREE
PATHS

THRUSTER



GAS GENERATION



EXPANSION



COMPRESSION



VALVES



HAND



MOTOR OR
PNEUMATIC



SOLENOID



PRESSURE OR
FLOW CONTROL



CHECK VALVE

LINES



CONNECTING



PASSING



ORIFICE

MEASUREMENTS



THERMOCOUPLE



TEMPERATURE BULB



PRESSURE



TURBINE
FLOWMETER



VENTURI
FLOWMETER

FORCE TRANSDUCER



FAN



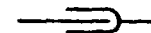
MOTOR



HEATER



COUPLING



FILTER



ROTATION



CLOCKWISE



COUNTER-
CLOCKWISE

TABLE 12. CONVERSION FACTORS

<u>Multiply</u>	<u>By</u>	<u>To Get</u>
Btu (British thermal unit)	1054.35026	J (joule)
Btu/lb _m	2324.4444	J/kg
Btu/R	1897.830469	J/K
Btu/lb _m -R	4184	J/kg-K
Btu/ft-s-R	6226.477919	J/m-s-K
Btu/ft ² -s-R	2042.07716	J/m ² -s-K
Cal (calorie)	4184	J
degree (angle)	0.01745329252	rad (radian)
ft (foot)	0.3048	m (meter)
ft ² /s	0.09290304	m ² /s
ft-lb _f (foot-pound)	1.3558179	J
gallon	0.0037854118	m ³
HP (horsepower)	746	W (watt)
in. (inch)	0.0254	m
lb _f (pound-force)	4.4482216526	N (Newton)
lb _f -s/lb _m	9.80665	m/s
lb _m (pound mass)	0.45359237	kg (kilogram)
lb _m /ft ³	16.018463	kg/m ³
lb _m -ft ²	0.04214	kg-m ²
nautical mile	1852	m
psia (pounds per square inch)	6894.7572	N/m ²
R (degrees Rankin)	0.5555555556	K (degrees Kelvin)
slug	14.5939029	kg
torr	133.322	N/m ²

For a complete list of conversion factors, see NASA SP-7012, The International System of Units/Physical Constants and Conversion Factors, by E. A. Mechtly.