PL-TR-96-1115

10 K SPACECRAFT CRYOCOOLER DEVELOPMENT PROGRAM

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July 1996

Final Report

PHILLIPS LABORATORY
Space Technology Directorate
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

UNCLASSIFIED

AD NUMBER

AD-B217 172

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PL-TR-96-1115

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1. Report Date (dd-mm-yy) July 1996	2. Report Type Final	3. Dates covered (from... to) 09/92 to 11/94

4. Title & subtitle 10 K Spacecraft Cryocooler Development Program	5a. Contract or Grant # F29601-92-C-0112
	5b. Program Element # 62601F
6. Author(s) Larry D. Crawford	5c. Project # 1101
	5d. Task # 02
	5e. Work Unit # AE
7. Performing Organization Name & Address Aerojet Electronic Systems Division P. O. Box 296 Azusa, CA 91702	8. Performing Organization Report #
9. Sponsoring/Monitoring Agency Name & Address Phillips Laboratory 3550 Aberdeen Ave SE Kirtland AFB, NM 87117-5776	10. Monitor Acronym
	11. Monitor Report # PL-TR-96-1115

12. Distribution/Availability Statement
Distribution authorized to DoD and U.S. DoD contractors only; Critical Technology July 1996. Other requests shall be referred to AFMC/STI.

13. Supplementary Notes This report is published in the interest of STINFO exchange only. The established procedures for editing reports were not followed for this technical report.

14. Abstract The purpose of this project was to develop cryocooler technology capable of providing simultaneous cooling at 80, 35, and 10 K. A contract was awarded to the Aerojet Electronic Systems Division that featured a conventional, commercial cryocooler to provide cooling at 80 K and utilized sorption technology to provide cooling at 35 and 10 K. Hydrogen was selected as the working refrigerant from 35 and 10 K, and each stage consisted of a separate circuit. The primary focus of this program was to design and develop sorption technologies capable of providing continuous, long life, cryogenic cooling required for spacecraft applications. Conventional cryocooler technologies required for cooling at 80 K were to be leveraged from existing Phillips Laboratory development programs.

15. Subject Terms Cryocooler, Cryogenic Cooling, Sorption, Joule-Thompson

Security Classification of			19. Limitation of Abstract	20. # of Pages	21. Responsible Person (Name and Telephone #)
16. Report Unclassified	17. Abstract Unclassified	18. This Page Unclassified	Limited	104	Larry D. Crawford (505) 846-5754

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EXECUTIVE SUMMARY

The purpose of this project was to extend periodic sorption cooling technology demonstrated at 10 K to continuous operation. In September 1992, Phillips Laboratory awarded contract F29601-92-C-0112 to the Aerojet Electronic Systems Division (Azusa, CA) for the development of a continuous, long life spacecraft cryocooler capable of providing simultaneous cooling at 80 K, 35 K, and 10 K.

The contract was structured in three phases. The basic phase consisted of conceptual cryocooler design and identification of critical technologies requiring additional development. Option 1 encompassed the preliminary design of the cryocooler and demonstration of critical techology components identified in the basic phase. Option 2 provided for the design, development, fabrication, and performance characterization of an engineering demonstration model (EDM). The basic phase also included a downselect of competing technologies, at which time Aerojet was selected to continue on with subsequent options.

Aerojet's concept for meeting the requirements specified in the contract (listed in table 1.0) consisted of using conventional cryocooler technology for achieving cooling at 80 K and for precooling the 35 and 10 K (lower) stages. Sorption technology was implemented in the two lower stages to achieve cooling at 10 K and 35 K. Hydrogen was selected as the working refrigerant for the two lower stages, with each stage having its own separate circuit. Cooling at 80 K was intended to be provided by any suitable commercial technology available (Stirling, Pulse Tube, Brayton, etc.). As a result, the emphasis on this program was to develop sorption technology capable of long life and continuous operation required for spacecraft applications. The conceptual design developed for this program is shown in figure 1.0.

3rd Stage Cooling Load	0.15 W @ 10 +/- 0.1 K
2nd Stage Cooling Load	2.0 W @ 35 +/- 1.0 K
1st Stage Cooling Load	5 W @ 80 +/- 2.0 K
Rejection Temperature	290 +/- 10 K
Power Supply	28 Vdc +/- 20%
Input Power (maximum)	1000 W
Cooler Weight (maximum)	100 kg
Total Vehicle Effective Weight (goal)	250 kg
Vibration (maximum)	0.05 N
Service Life (minimum)	2 Year Ground; Greater than 10 Year On-orbit

Table 1.0 Requirements for 10 K Spacecraft Cryocooler Development Program

The contract with Aeroject Electronic Systems Division was initiated on 29 Sep 1992 and was de-scoped on 4 Nov 94 due to lack of available funding to complete program objectives. This program was originally jointly funded by the Ballistic Missile Defense Organization (BMDO) as well as the Brilliant Eyes (BE) Program Office. The reduction in scope of this contract was necessitated due to a change in program priorities within those organizations. Phillips Laboratory was unable to secure adequate resources to

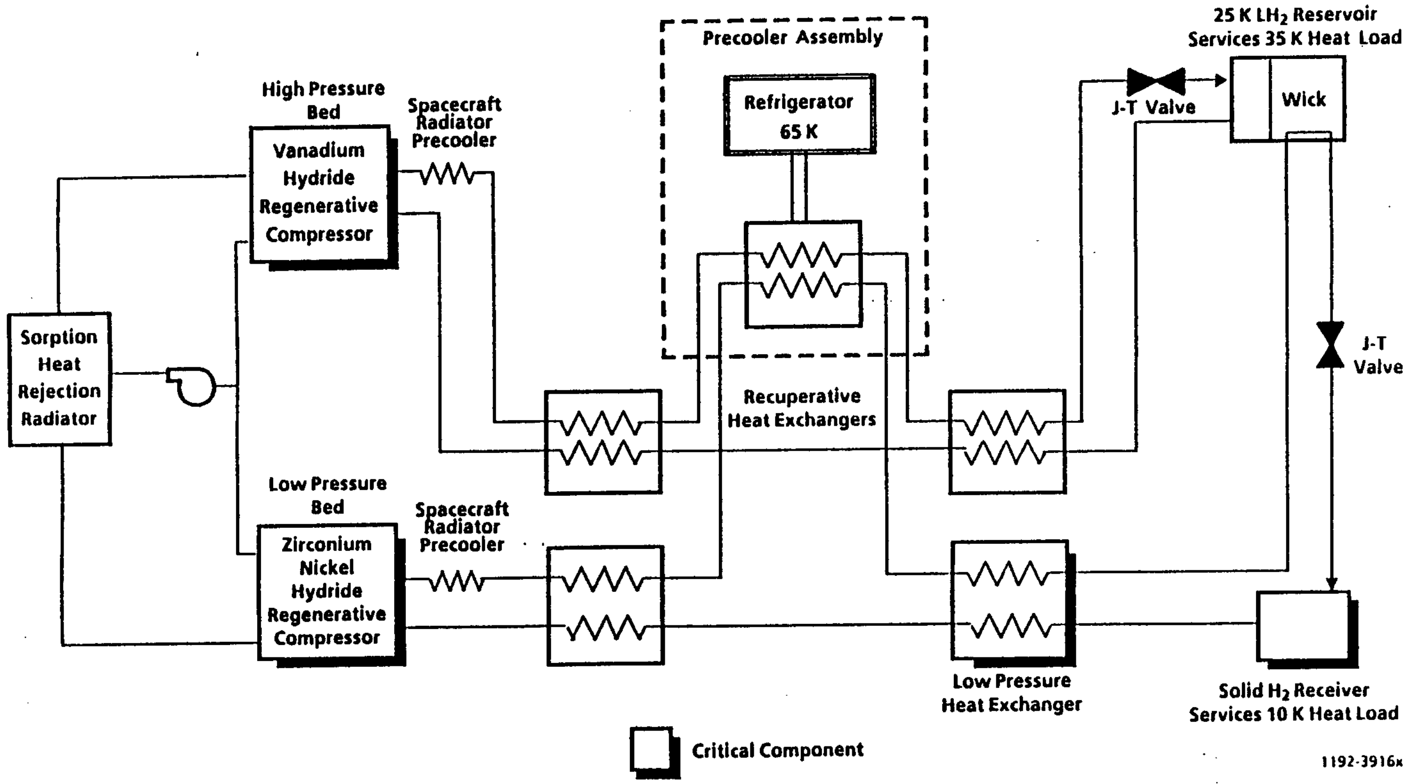

Figure 1.0 Conceptual Schematic of 10 K Spacecraft Cryocooler

continue the program using only Air Force Science and Technology funds. At the time of the reduction in scope, there were insufficient funds to complete a traditional final report. As a result, this report provides a historical summary of technical accomplishments completed during the course of this program. The body of the report contains material presented at Technical Interchange Meetings as well as a compilation of significant monthly technical progress reports.

At the conclusion of the program, Aerojet has completed the basic conceptual design activity and had been authorized to proceed with preliminary cryocooler design and critical component demonstration. Due to funding constraints, only thermal modeling of the expander and compressor components (shown in figure 1.0) were completed. At the time of commencing option 1, the program was restructured to only focus on developing a sorption cooling loop for 10 K. Table 2.0 provides a summary of performance of a cryogenic system that resulted from the conceptual studies conducted during the basic phase of this effort.

Parameter	3rd Stage	2nd Stage	1st Stage	Total
Net Cooling Load (W)	0.15	2.0	5.0	-
Parasitics (W)	0.03	0.2	0.0	-
Precooling Load (W)	0.0	0.52	5.78	-
Gross Cooling Power (W)	0.18	2.72	10.78	-
Input Power (W)	24	296	432	752
Mass (lb)	6.9	31.5	17.5	56
System Effect. Mass (lb)	12.9	105.5	125.5	244

Table 2.0 Performance Prediction of Baseline Cryocooler

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10 KELVIN CRYOCOOLER DEVELOPMENT PROGRAM

KICKOFF/STATUS MEETING

AEROJET ELECTRONIC SYSTEMS DIVISION

9 NOVEMBER 1992

Sorption Is Aerojet's Approach To Achieving 10 Kelvin Continuous Cooling

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- Use Sorption Technology For The 10K And 35K Stages

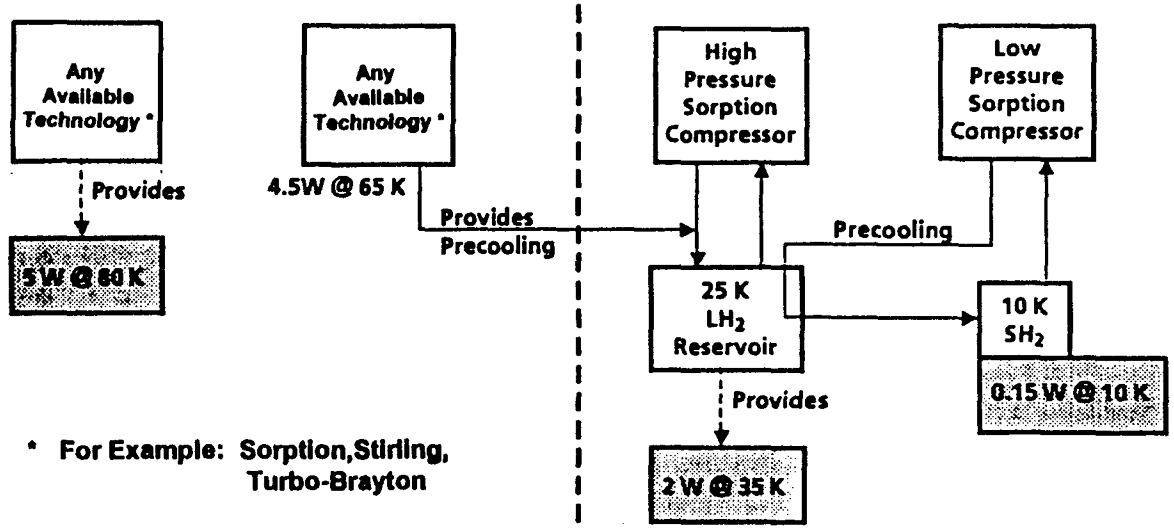
- Use Any Available Mature Technology For The 80K Stage And Precooling, For Example:
  - Sorption
  - Stirling
  - Turbo Brayton

- Our Concept:
  - Extends The Successfully Demonstrated 10K Periodic Cooling Technique To Continuous Operation

  - Utilizes An Extensive Sorption Technology Experience Base
    - Aerojet's Technical Team, Collaborative Network And Dedicated Laboratory
    - Innovative Recognized Subcontractors
    - Jet Propulsion Laboratory

Aerojet's Approach To Creating A 10 Kelvin Continuous Capability For The Government

GenCorp Aerojet



* For Example: Sorption, Stirling, Turbo-Brayton

- 5 W @ 80 K - Uses Available Government Funded Technology
- 4.5 W @ 65 K - Uses Available Government Funded Technology
  - Provides Precooling for High Pressure Sorption Compressor
- 2 W @ 35 K - Provided by 25 K LH_2 Precooling Reservoir
- 0.15 W @ 10 K - Provided by 10 Kelvin Solid Hydrogen Expander

Required Loads and Temperatures

Aerojet's Three Phase Program Provides A Logical And Low Risk Development

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- Basic Phase : Cryocooler And Critical Technology Identification/ Design
  - Concentrate On Highest Technology Risk Items
    - Critical Technology Identification
    - Critical Technology Preliminary Design (Subcontractor/AESD)
    - Cryocooler Conceptual Design
- Option 1 Phase : Preliminary Cryocooler Design And Critical Technology Demonstration
  - Demonstrate Solutions Of The Highest Risk Technologies
    - Fabricate, Test, Evaluate And Validate Critical Technology Designs
    - Complete Preliminary Cryocooler Design
- Option 2 Phase : Engineering Development Model (EDM) Design, Fab And Test
  - Incorporate All Validated Technologies Into Cryocooler System
    - Complete Detailed Design Of EDM
    - Fabricate, Test And Validate EDM Performance

A Capable And Experienced Subcontractor Team Ensures Program Success

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- The Following Critical Technologies Have Been Identified:
  - Low Pressure/Low Temperature Heat Exchanger
  - 10 Kelvin Joule-Thomson Expander
  - Regenerative Hydride Sorption Compressor
- This Program Will Concentrate On The First Two Critical Technologies
- The Regenerative Hydride Sorption Compressor Will Be Addressed As Part Of Aerojet's Ongoing IR&D Program

Subcontractor	Area Of Expertise
Alabama Cryogenic Engineering	Low Pressure/Low Temperature Heat Exchangers
APD Cryogenics	10 Kelvin Joule-Thomson Expander
General Pneumatics Corporation	10 Kelvin Joule-Thomson Expander

- Aerojet Will Also Address The Heat Exchanger, Providing Two Design Options For Each

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The Selected Key Parameters Will Track Critical System Specifications

- From The Specification Requirements:
  - Cooling Capacity: 0.15 Watt @ 10K
  - Cooling Capacity: 2.0 Watt @ 35K
  - Cooling Capacity: 5 Watt @ 80K
  - Vehicle Effective Weight < 250KG (Weight = .25 KG/Watt*Power)
  - Reliability > 0.95 For 10 Years
  - Vibration < 0.05 NT

The Selected Program Event Milestones Permit Timely Evaluation Of Technical Progress/Performance

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Program Milestone And Evaluation Technique	Date
Basic Effort Phase:	
1. Key System Level Parameters Selected	October 1992
2. Initial Performance Predictions/Analysis	December 1992
3. Requirement Allocation To Subsystems Selection/Quantification Of Indicators	February 1993
Option 1 Phase:	
4. Demonstration Tests - Critical Components	March 1994
5. System Level Performance - Update With Test Data	April 1994
Option 2 Phase:	
6. System Level Performance- Update With Revised Simulation	August 1994
7. SubSystem Acceptance Test Data	April 1995
8. Final System Level Test Results Final Reliability Update	August 1995

Program Event Milestones/Schedule Relationship

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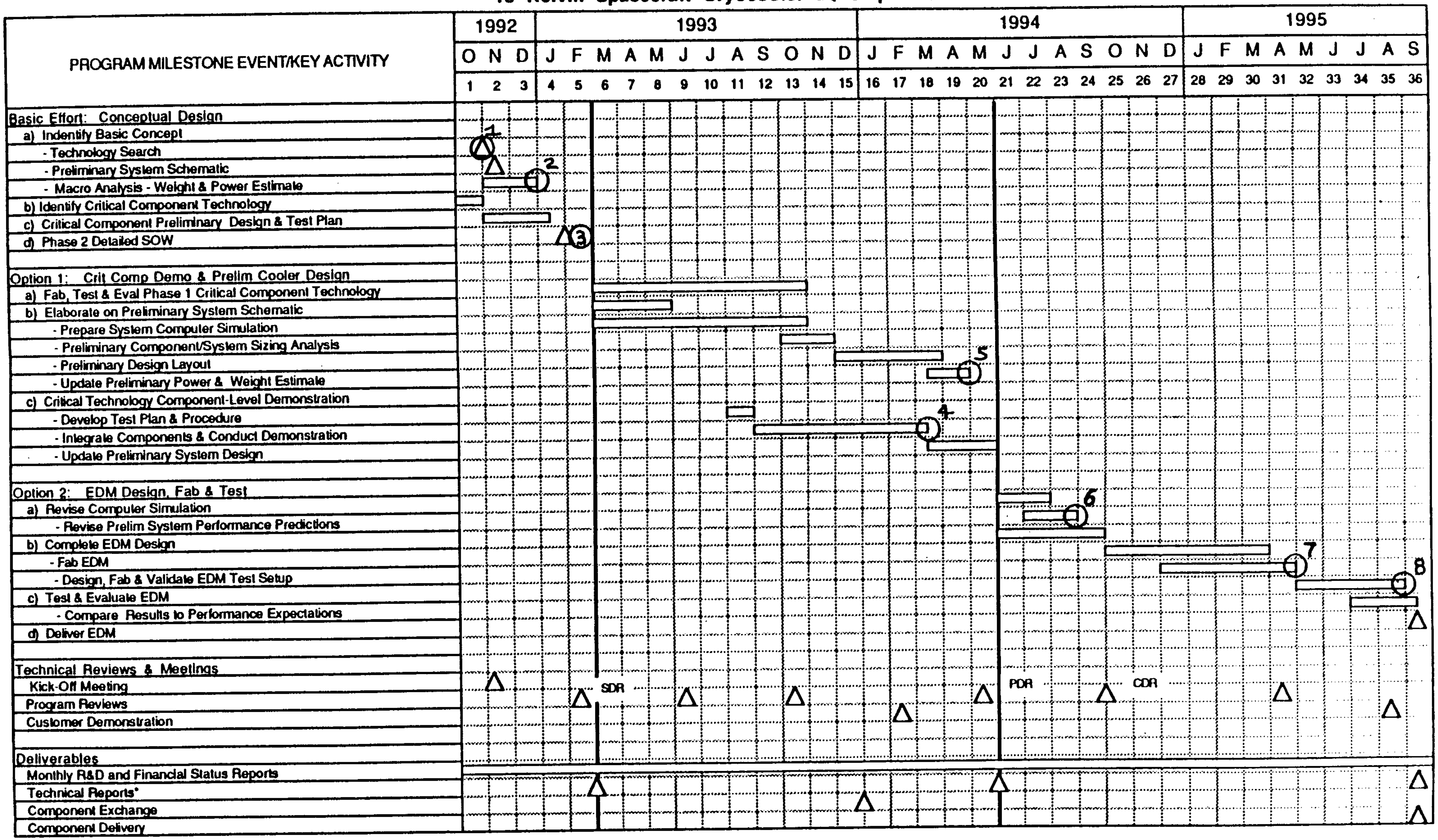
10 Kelvin Spacecraft Cryocooler Development



PROGRAM TECHNICAL STATUS AGENDA

- CRYOCOOLER CONCEPT
- SORPTION PRINCIPLES
- CRITICAL COMPONENTS
- MACROANALYSIS
- FUTURE ACTIVITIES

CRYOCOOLER CONCEPT

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- REQUIREMENTS
- CONCEPT DESCRIPTION
- SYSTEM SCHEMATIC
- HARDWARE TREE

AEROJET IS AWARE OF ALL 10 K CONTINUOUS CRYOCOOLER REQUIREMENTS

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3rd stage cooling load	0.15 W @ 10 +/- 0.1 K
2nd stage cooling load	2.0 W @ 35 +/- 1.0 K
1st stage cooling load	5.0 W @ 80 +/- 2.0 K
Rejection temperature	290 +/- 10 K
Power supply	28 Vdc +/- 20%
Input power (max)	1000 W
Cooler weight (max)	100 kg
Total vehicle effective weight (goal)	250 kg
Vibration (max)	0.05 N
Service life (min)	2 yrs ground + 10 yrs on-orbit

AEROJET'S BASELINE CONCEPT IS A HYBRID APPROACH

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- o Sorption technology is used for the two lower stages.
  - Hydrogen gas is the refrigerant.
  - Two separate hydrogen circuits are used.
  - A 2nd stage temperature of 25 K is produced (lower than required).
- o Any mature cooling technology can be used for the 1st stage.
  - Take full advantage of currently funded programs.

OUR CONCEPT IS FLEXIBLE AT THE FIRST STAGE

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- Any convenient, available cooling device can be integrated.
  - We proposed Stirling Standard Spacecraft Cryocoolers (SSC).
  - At the time, they looked promising.
- Replacement options are possible.
  - Larger capacity Stirling units are more efficient.
    - Not currently being developed.
  - Reversed Brayton is more efficient at higher loads.
    - Currently looks promising (Creare).
  - Sorption is suitable.
    - Aerojet is pursuing this separately.

SYSTEM SCHEMATIC HAS BEEN UPDATED

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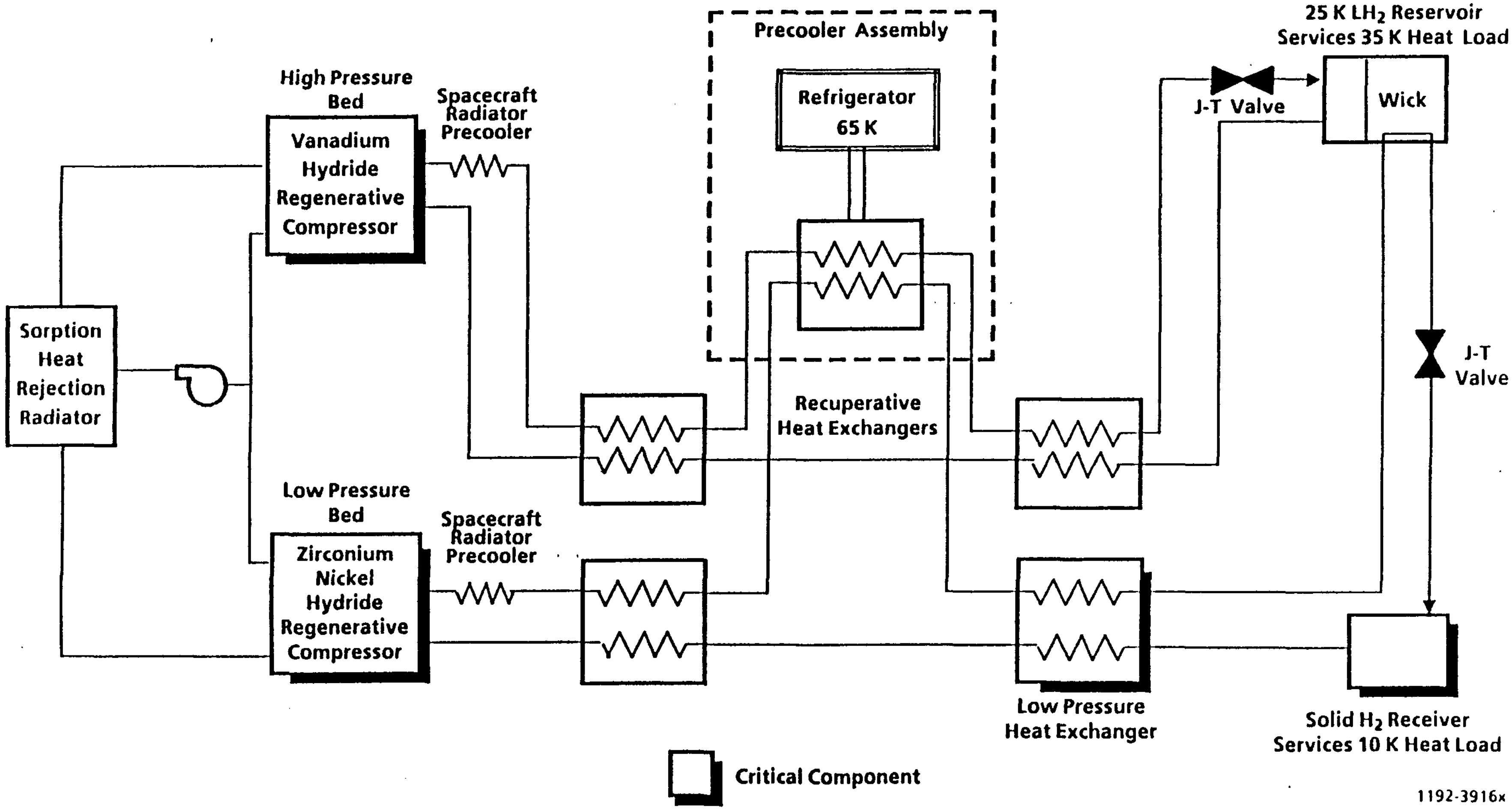

ALL KEY BUILDING BLOCKS HAVE BEEN ORGANIZED INTO A HARDWARE TREE

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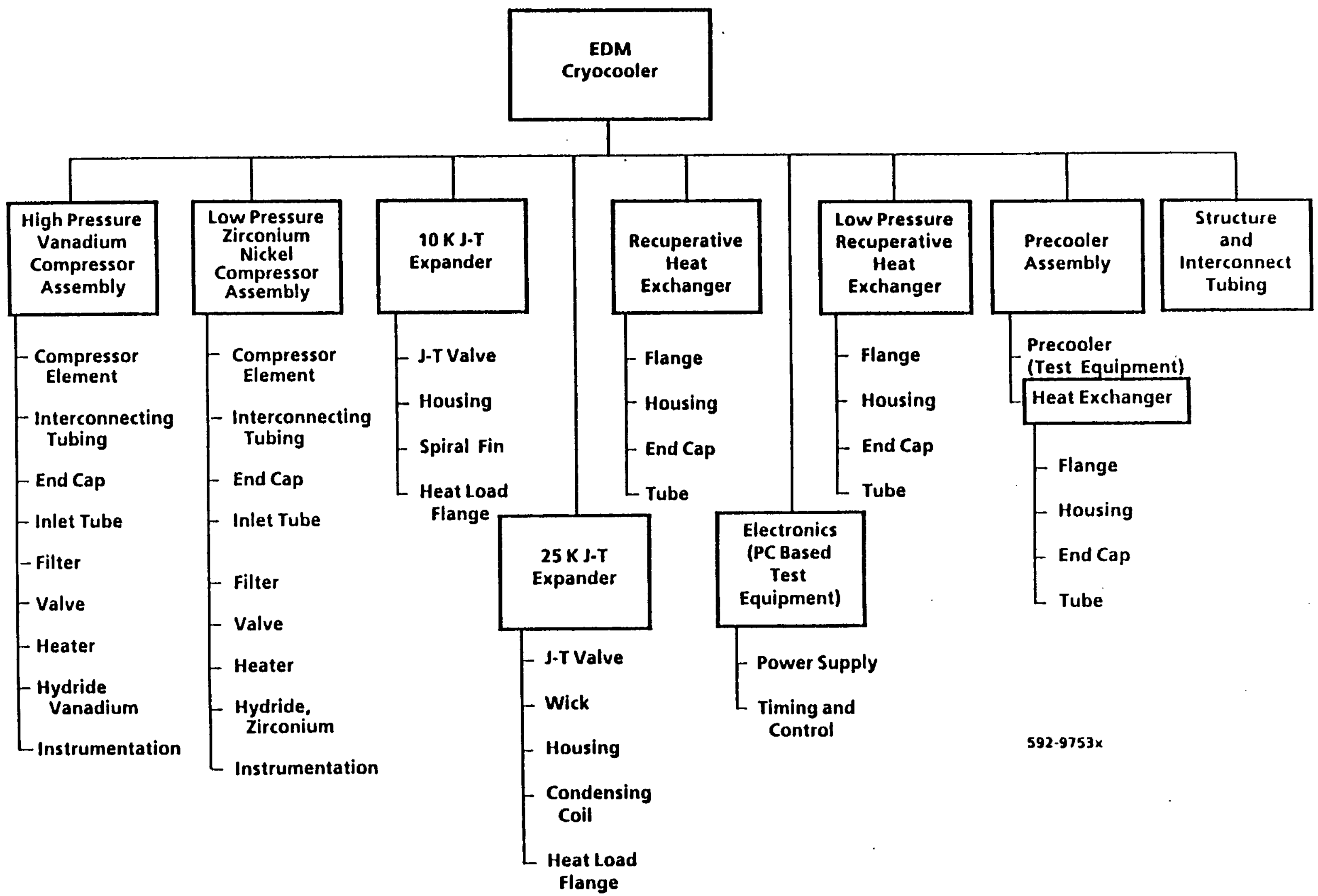

SORPTION PRINCIPLES

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- SORBENTS
- COMPRESSOR ELEMENT
- COMPRESSOR ASSEMBLY

SORBENTS ARE SPONGES FOR REFRIGERANTS

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- Sorbents are materials with a reversible affinity for gases.
  - The amount of gas they contain is temperature and pressure dependent.
- Temperature cycling sorbents is the basis for sorption refrigeration.
  - When sorbents are cooled, they store gases at low pressure.
  - When sorbents are heated, they release stored gases at high pressure.
- Compression ratios of 10's or 100's are possible.
  - Compression is accomplished thermally, not mechanically.
- A sorption compressor has no moving parts, except valves.
  - The valves operate at room temperature or above.
  - Cycle times are long.
  - Valves experience few cycles during life.

A COMPRESSOR ELEMENT IS THE HEART OF A SORPTION SYSTEM

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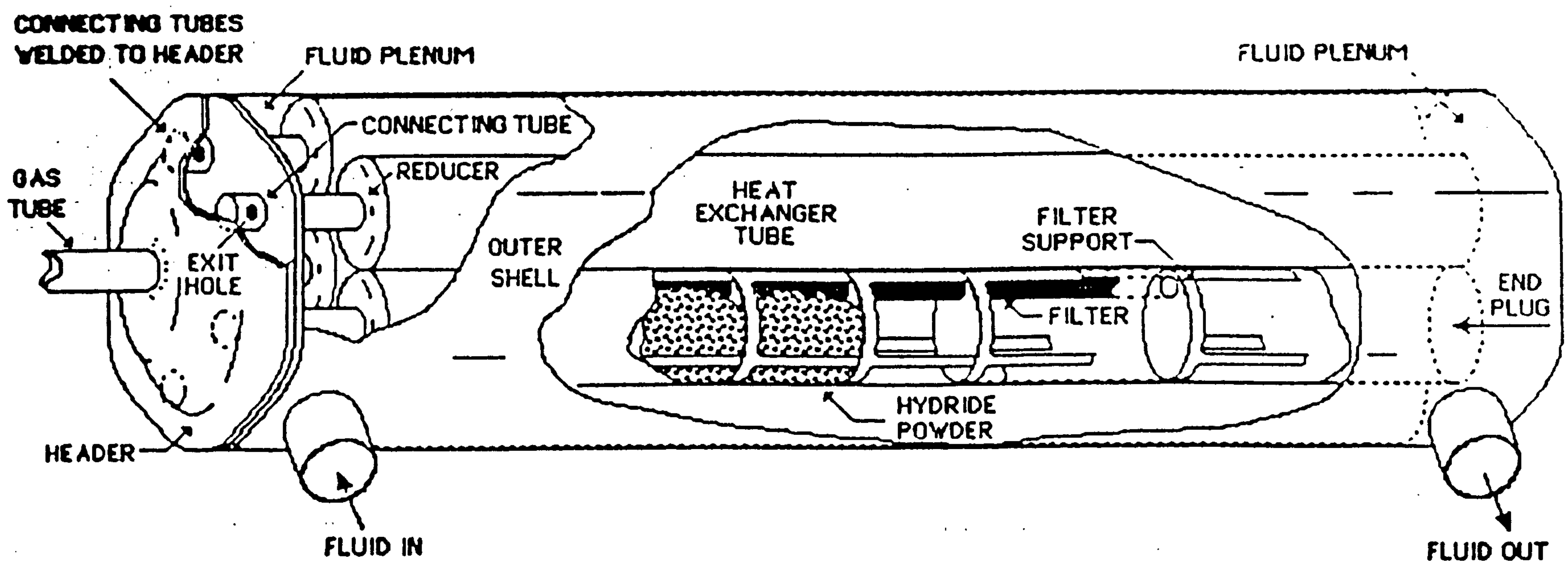

- o Must contain sorbent.
- o Must provide ingress and egress for refrigerant.
- o Must provide means to heat or cool sorbent.
- o Are developed under Aerojet IR&D.

A CONTINUOUS SORPTION COOLER CONSISTS OF MULTIPLE COMPRESSOR ELEMENTS

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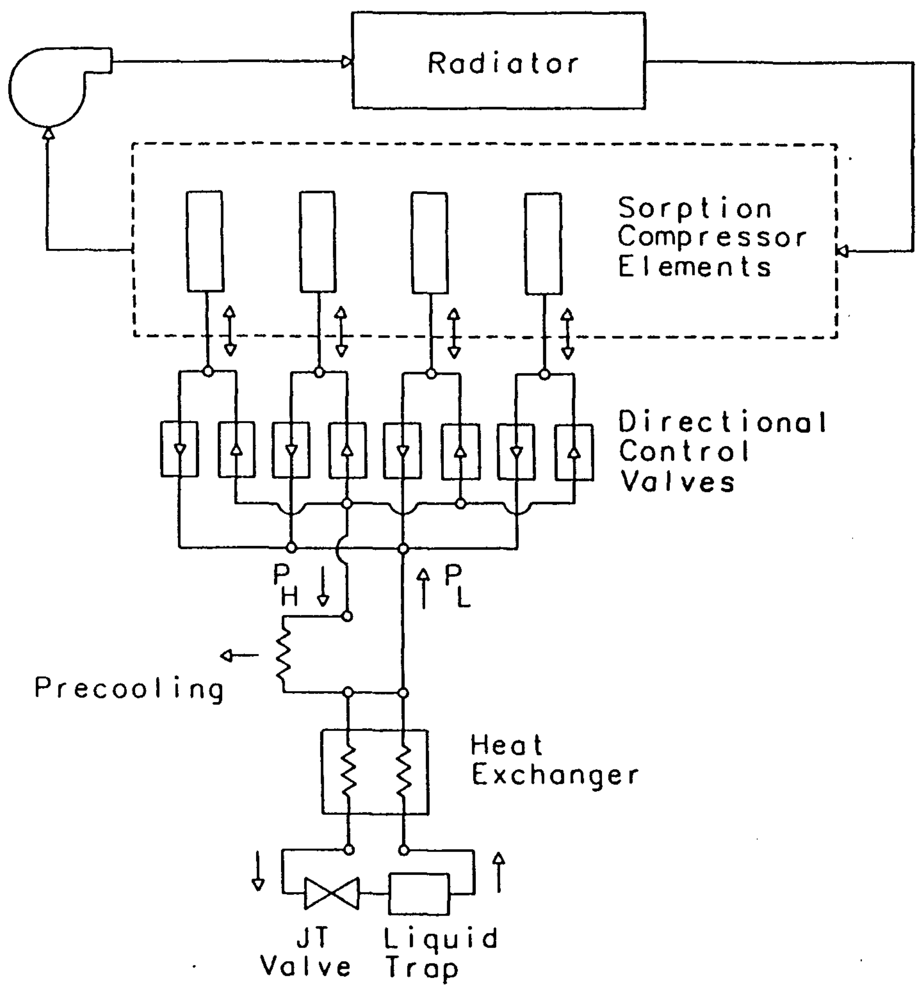

- Each sorbent element requires alternate heating and cooling.
- 4 to 6 elements are used to provide continuous refrigerant flow.
- Actual number of elements is determined by trade studies.

  This contrasts with BETSCE which is a periodic cooler.
- Sensible heat from sorbents can be recovered by regeneration.
- Regeneration conserves energy.

CRITICAL COMPONENTS

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- SUBCONTRACTORS
- 10 JT EXPANDER
- LOW PRESSURE RECUPERATIVE HEAT EXCHANGER
- SORPTION HYDRIDE COMPRESSORS
- NON-CRITICAL COMPONENTS

SUBCONTRACTORS ARE BEING CONTRACTED WITH TO DEVELOP CRITICAL COMPONENTS

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- General Pneumatics (GP) and APD Cryogenics
  - Provide conceptual designs for 10 K JT cryostat.
    - Inlet flow to JT expander: saturated liquid hydrogen at 0.3 MPa
    - Outlet flow from cryostat: saturated vapor at 260 Pa (2 Torr)
    - Mass flow: 0.8 mg/s
- Alabama Cryogenic Engineering (ACE)
  - Provide conceptual design for low pressure recuperative heat exchanger.
    - Low pressure line: 10 K and 2 Torr
    - High pressure line: 65 K and 0.3 MPa
    - Effectiveness goal: > 0.8
    - Pressure drop goal: < 15 Pa

10 K EXPANDER (SNOW BLOWER) IS A CRITICAL COMPONENT

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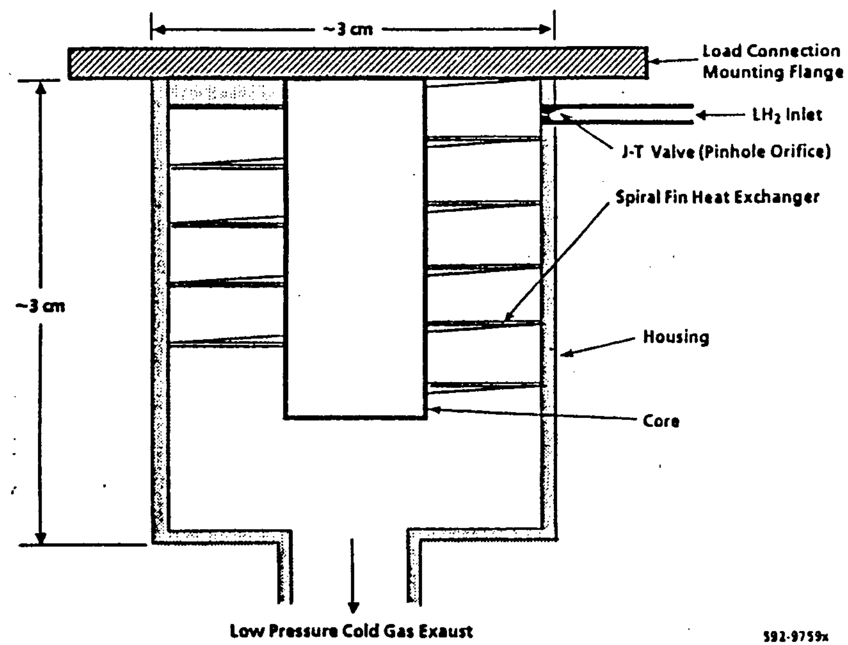
- o 10 K is achieved by expanding saturated liquid hydrogen.
  - Hydrogen "snow" is produced.

- o This was accomplished at NBS in mid Sixties.

  - NBS Report 8881, 1 October 1965
    D.B.Mann, P.R.Ludtke, et al
    Characteristics of Liquid-Solid Mixtures
    of Hydrogen at the Triple Point

- o "Snow" production and containment, and heat load servicing must be verified for our operating conditions (low flow rate).
  - Hardware will be fabricated and tested in Option 1 Phase.



LOW PRESSURE RECUPERATIVE HEAT EXCHANGER IS A CRITICAL COMPONENT

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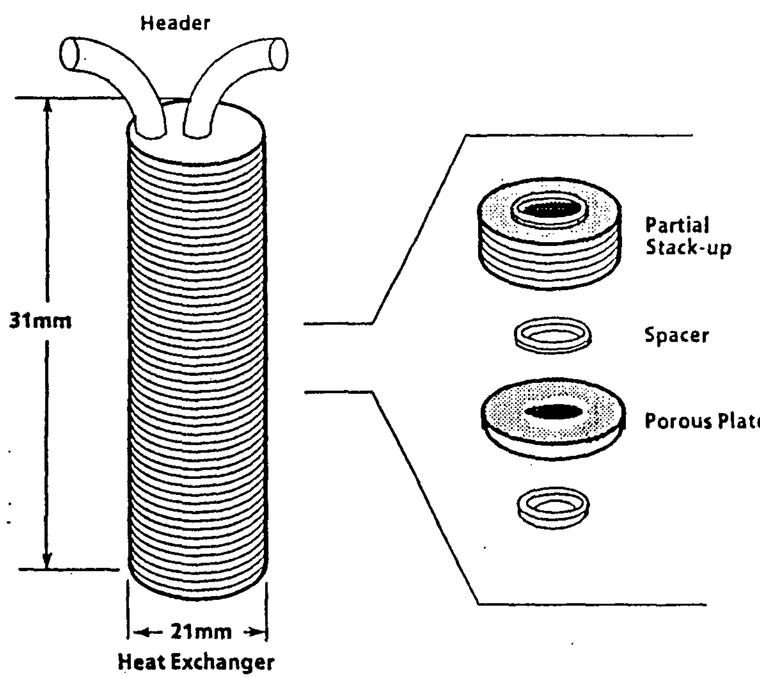
- o Recuperative heat exchangers are an important part of the system.
  - They increase operating efficiency.
- o Return pressure for the 10 K stage is 2 Torr.
  - Recuperative heat exchangers for the "snow" expander experience this pressure.
- o Recuperation at low pressure must be verified.
  - ACE will pursue perforated plate designs.
  - Aerojet will pursue tube-in-tube designs.
- o Hardware will be fabricated and tested in Option 1 Phase.



Low Pressure H_2 Flow: $\Delta P = 1.32 \times 10^{-5}$ MPa
$\dot{m} = 8 \times 10^{-4}$ gm/sec

Effectiveness = 0.90
Weight = 33 grams

592-9758x

SORPTION HYDRIDE COMPRESSORS ARE CRITICAL COMPONENTS

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- o Aerojet is pursuing hydride compressors under on-going IR&D activities.
  - Funds have been allocated for FY93.
- o Plans for FY93 include:
  - Detailed analysis of regenerative hydride compressor assembly (RHCA).
  - Detailed design of RHCA.
  - Fabrication and assembly of RHCA.
  - Design test setup.
  - Integration of RHCA into test setup.

MOST SYSTEM COMPONENTS ARE NON-CRITICAL

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Precooler	GFE, on-going development
Precooler heat exchanger	Proven technology, custom design
Check valves	Mature technology, custom design
Solenoid valves	Mature technology, custom design
2nd stage recuperators	Proven technology, custom design
25 K JT cryostat	Mature technology, custom design
Heat transport circulator	Creare, engineering development, no show-stoppers TM-1412, May 1990, W.E.Nutt and W.L.Swift Circulator Design for Sorption Compressor Refrigeration
Heat rejection radiator	Mature technology, custom design

MACROANALYSIS

GenCorp Aerojet

- o KEY INPUT PARAMETERS
- o KEY OUTPUT PARAMETERS

SPREADSHEET MODEL EXISTS FOR CRYOCOOLER SIZING

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o Key inputs:

- Precooling temperature	65 K	
- Effectiveness of heat exchangers	95% 2nd stg	85% 3rd stg
- Refrigerant concentration change	0.03 gH/gV	0.01 gH/gZrNi
- Heat of desorption	18,214 J/gH (V)	34,000 J/gH (ZrNi)
- Compressor efficiency	90%	
- Specific power for Stirling	30 w/w @ 80 K	50 w/w @ 65 K

o Key outputs:

- Input power	625 w	
- Cooler weight	85 kg	
- Sorbent mass	1.324 kg V	0.174 kg ZrNi
- Yield	48% liq 2nd stg	65% sol 3rd stg
- Specific power	161 w/w 2nd stg	357 w/w 3rd stg

FUTURE ACTIVITIES FOR BASIC PHASE

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- November
  - Update macroanalysis.
  - Start component-by-component weight allotment.
- Through February 1993
  - Complete macroanalysis.
  - Monitor, manage and complete subcontract work.
  - Produce Option 1 Phase SOW and test plans.
  - Update cost estimates for Options 1 & 2 Phase tasks.
  - Prepare and present SDR.

SUMMARY

- Our Program Approach:
  - Is Both Efficient And Aggressive, Entering EDM Development With All Key Issues Resolved
  - Ensures A High Liklihood Of Success By Teaming Aerojet's Extensive Capability With Capable, Innovative And Experienced Cryogenic Subcontractors
- Aerojet Is Excited To Participate In This Opportunity And Fully Committed To Its Success
- Aerojet Looks Forward To Delivering An EDM To Phillips Laboratory In September 1995

10 KELVIN SPACECRAFT CRYOCOOLER DEVELOPMENT PROGRAM

MONTHLY PROGRESS REPORT

DECEMBER 1992

AEROJET ELECTRONIC SYSTEMS DIVISION
1100 W. HOLLYVALE STREET
AZUSA, CA 91702

Contract No. F29601-92-C-0112
CDRL A003

Prepared By: Neil Sherman (818)812-2698

Unclassified

1.0 SUMMARY

During the month of December, the cryocooler macro-analysis tool was modified to permit accurate and conservative predictions of weight, power and performance. Analysis showed that LaNiSn is the sorbent of choice for the high pressure hydride bed, instead of vanadium. This being driven primarily by the 300K upper limit on the system rejection temperature. Analysis has also shown that the system will operate at the upper limit for vehicle effective weight (250Kg) without the third-stage low pressure heat exchangers, which have earlier been identified as critical components. Parametric trades were performed to quantize the "cost" (i.e. increase in vehicle effective weight) of variations in major operating variables. These trades were performed with the two third-stage heat exchangers removed. This provides a more conservative prediction, reflecting a system configuration without this critical component and the associated risk.

Tests conducted by Creare have validated that one Single Stage Reverse Brayton cryocooler will satisfy both the pre-cooling and 80K load requirements. This results in a less complex system and substantial savings in total vehicle effective weight.

Technical activity by all critical component subcontractors is continuing. Work will be completed in January, at which time each subcontractor will present a review of their activities. These reviews will be held at the Aerojet facility. Government participation is encouraged and welcomed. Figure 1 presents a detailed milestone schedule for this program phase.

2.0 TECHNICAL PROGRESS

2.1 BASIC CRYOCOOLER CONCEPTUAL DESIGN

2.1.1 PRELIMINARY WEIGHT, POWER & PERFORMANCE ESTIMATES

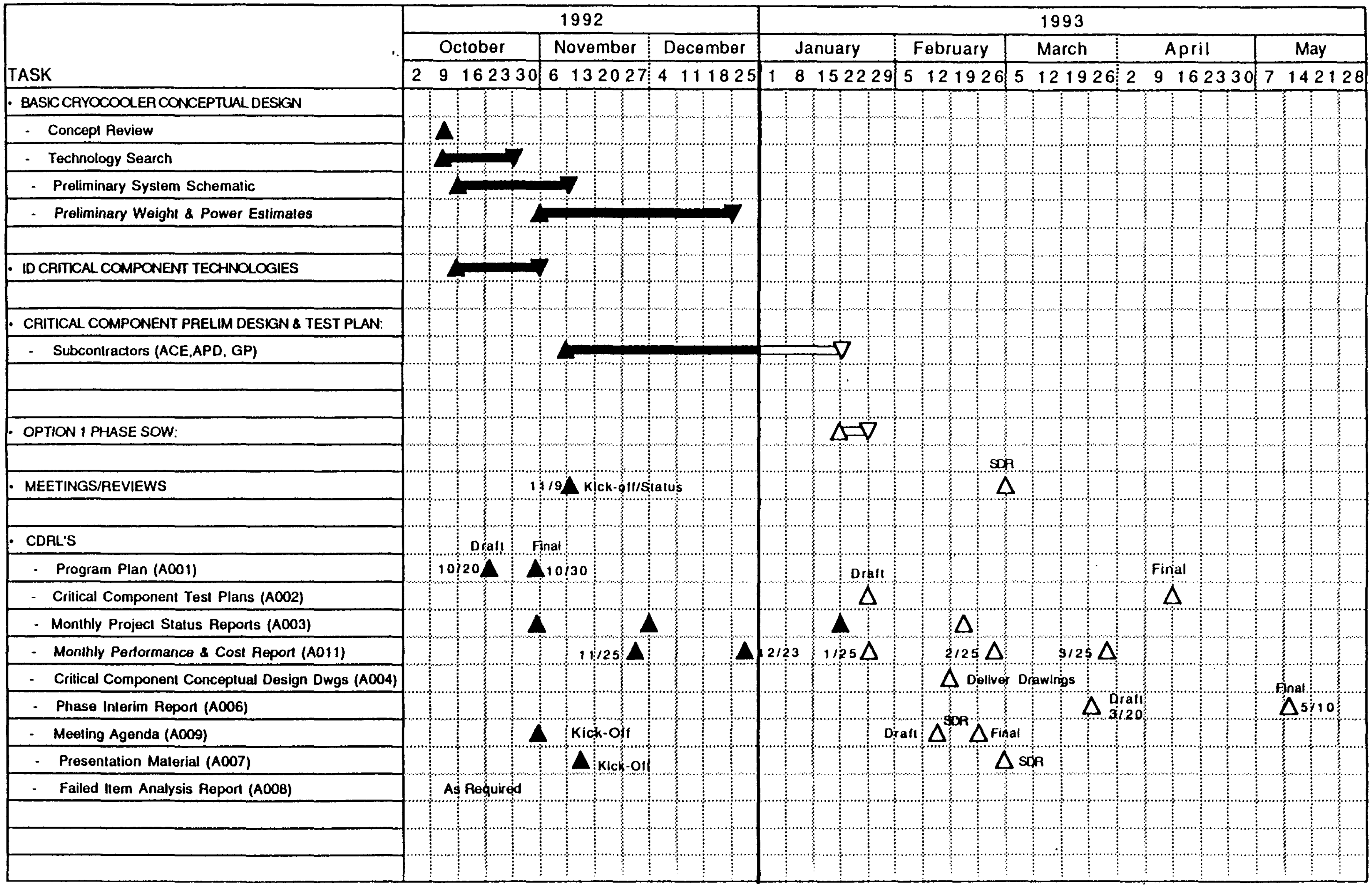
Analytical Tool Upgrade

Refinement of the macro-analysis tool to permit more accurate and conservative calculation of weight, power and performance was completed. Incorporated modifications to the tool included:

1) Actual weight and performance data were incorporated for all cryocooler components. All previously used algorithms for component weight estimates were removed.

2) A Single Stage Reverse Brayton (SSRB) cryocooler was incorporated at the upper stage. Weight, performance and power estimates for the SSRB have been provided by Creare, Inc. and have been incorporated into the analytical model.

Figure 1: **10K CONTINUOUS CRYOCOOLER - BASIC EFFORT PHASE SCHEDULE**



First-Stage Configuration

Findings have shown that a single, 65K SSRB will satisfy both the pre-cooling and the 80K load requirements. This results in a simpler and substantially lighter system, replacing the four SSC Stirling units originally envisioned for this purpose. Creare has performed additional tests on their SSRB to validate that it can provide the required cooling capacity. Tests showed that the unit can provide 8.5W of cooling at 65K with an input power of 350W (specific power = 41.2), and 10W of cooling at 65K with an input power of 410W (specific power = 41). This increased cooling capacity is achieved by increasing the operating pressure level of the unit while ensuring that the working fluid temperature rise remains within allowable limits.

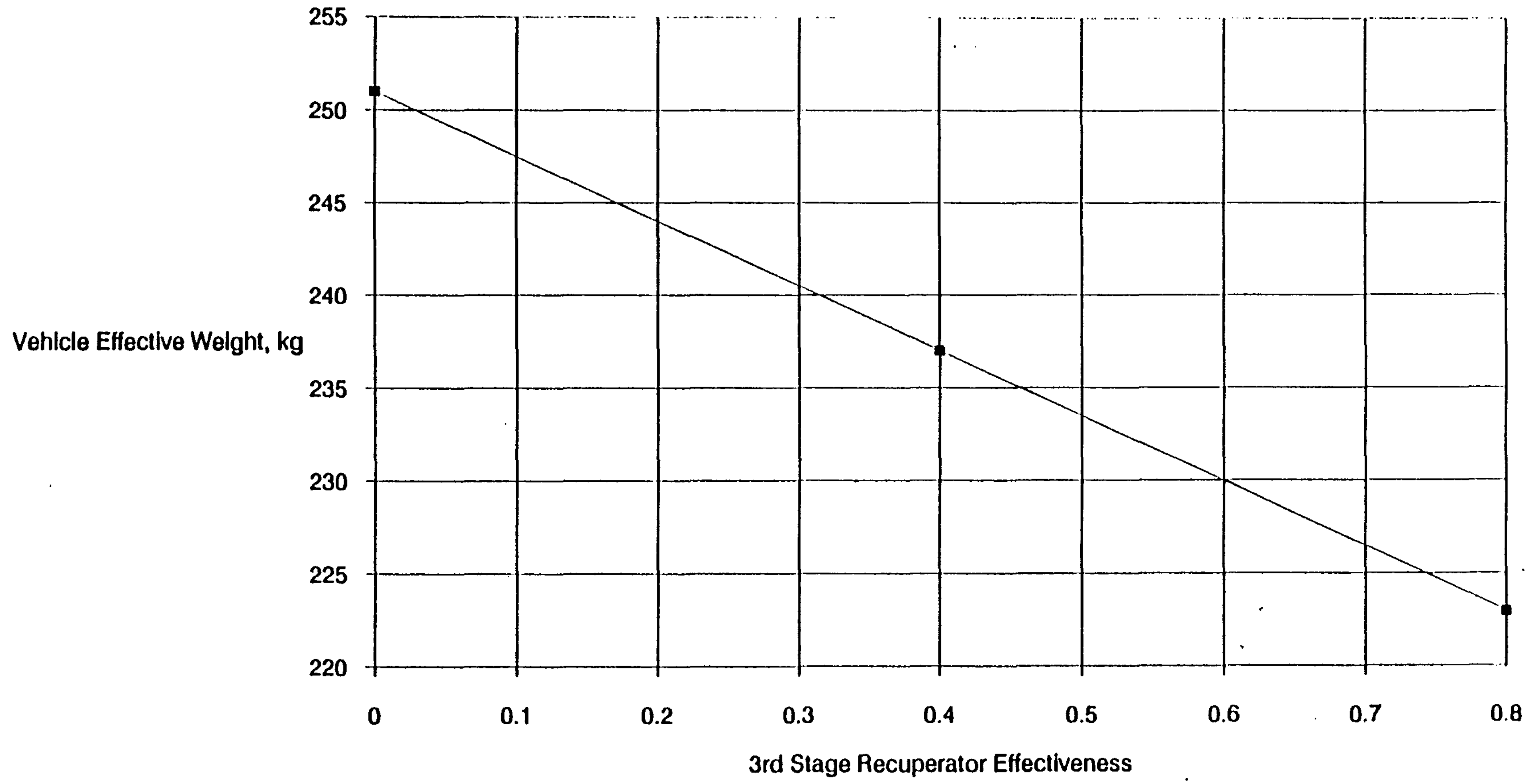
System Macro-Analysis

System macro-analysis was completed. Two major conclusions were drawn from this effort:

1) Lanthanum-nickel-tin (LaNiSn) is the sorbent of choice for the high pressure hydride bed instead of vanadium. This is driven primarily by the 300K upper limit for the rejection temperature range and the effect upon second-stage reservoir temperature. With an allowance made for the driving pressure difference within the sorbent bed during sorption, and a generous allowance made for pressure drops across the two second-stage recuperative heat exchangers, a 300K rejection temperature with vanadium translates into a 1MPa reservoir pressure, which corresponds to a 31K reservoir temperature. For LaNiSn, the same rejection temperature translates into a 0.2MPa reservoir pressure corresponding to a 23K reservoir temperature. Using LaNiSn as the sorbent, therefore, gives an 8K lower second-stage reservoir temperature. Generally, for a given hydride a higher rejection temperature translates into a higher liquid hydrogen temperature at the second-stage reservoir. The rejection temperature would have to remain at or below approximately 260K for vanadium to be preferred.

2) The System will operate at the vehicle effective weight (VEW) limit (250Kg) without the third-stage low pressure recuperative heat exchangers. Figure 2 presents the sensitivity of VEW to variation in the effectiveness of these heat exchangers. As indicated, without the heat exchangers (effectiveness = 0) the VEW is calculated to be 251Kg. This is an increase of 28Kg assuming that you have both heat exchangers, each with an effectiveness of 0.8 (VEW = 223Kg). This increase in VEW results almost entirely from a 106W increase in input power due to the loss of recuperation. Alabama Cryogenic Engineering (ACE) has indicated that of these two heat exchangers, the lower temperature unit (the one nearest the 10K reservoir) is the more feasible of the two. If only this heat exchanger is kept in the system, the calculated VEW is 238Kg for an effectiveness

Figure 2: **Variation of Vehicle Effective Weight with 3rd Stage Recuperator Effectiveness (Both Recuperators)**



of 0.8 (See Figure 3). This is a savings of 13Kg over the 251Kg system VEW which results from removing both heat exchangers.

Parametric Trades

Parametric trades were performed to conservatively quantize the "cost" (increase in VEW) of variations in major operating variables. Sensitivity coefficients derived from the trades identify key variables and permit an assessment of the impact on VEW of missing or exceeding the assumed baseline values for those variables. These trades were performed with LaNiSn as the sorbent of choice, and with the two third-stage recuperative heat exchangers removed. By not including the heat exchangers, more conservative results are obtained with the predictions reflecting a system configuration that eliminates one of the identified critical components and the associated risk. This configuration is shown in Figure 4. Trade variables were: rejection temperature (baseline 300K), precool radiator effectiveness (baseline 0.98), first-stage precool temperature (baseline 65K), hydride compressor efficiency (baseline 75%), third-stage parasitics (baseline 30mW), second-stage parasitics (baseline 0.2W), and second-stage recuperative heat exchanger effectiveness (baseline 0.98). Plots are currently being made of VEW and power input versus the trade variables. They will be available early January.

2.2 CRITICAL COMPONENT PRELIMINARY DESIGN AND TEST PLAN

Subcontracted Activities

Technical activities are continuing with each subcontractor, Aerojet is maintaining close interactive contact to ensure efficient and productive progress. The period of performance extends through mid-January. Afterwards, each subcontractor will present a detailed review (at the Aerojet Facility) of their activities. It is expected that these reviews will take place during the last week of January. Government participation at these reviews is welcomed and encouraged.

A summary of each subcontractor's progress is presented below.

Alabama Cryogenic Engineering (ACE)

ACE continues to evaluate the feasibility for the low pressure recuperative heat exchangers. In particular, ACE is concentrating efforts on the lower temperature (10K to 65K) heat exchanger, which is the unit closest to the 10K reservoir. This unit was selected because it is the more feasible of the two. Their studies indicate that the necessary heat exchanger to meet both performance and pressure drop requirements is an extension of existing technology, well within the range of feasibility and fabrication of the

Figure 3: Variation of Vehicle Effective Weight with 3rd Stage Low Temperature Recuperator Effectiveness

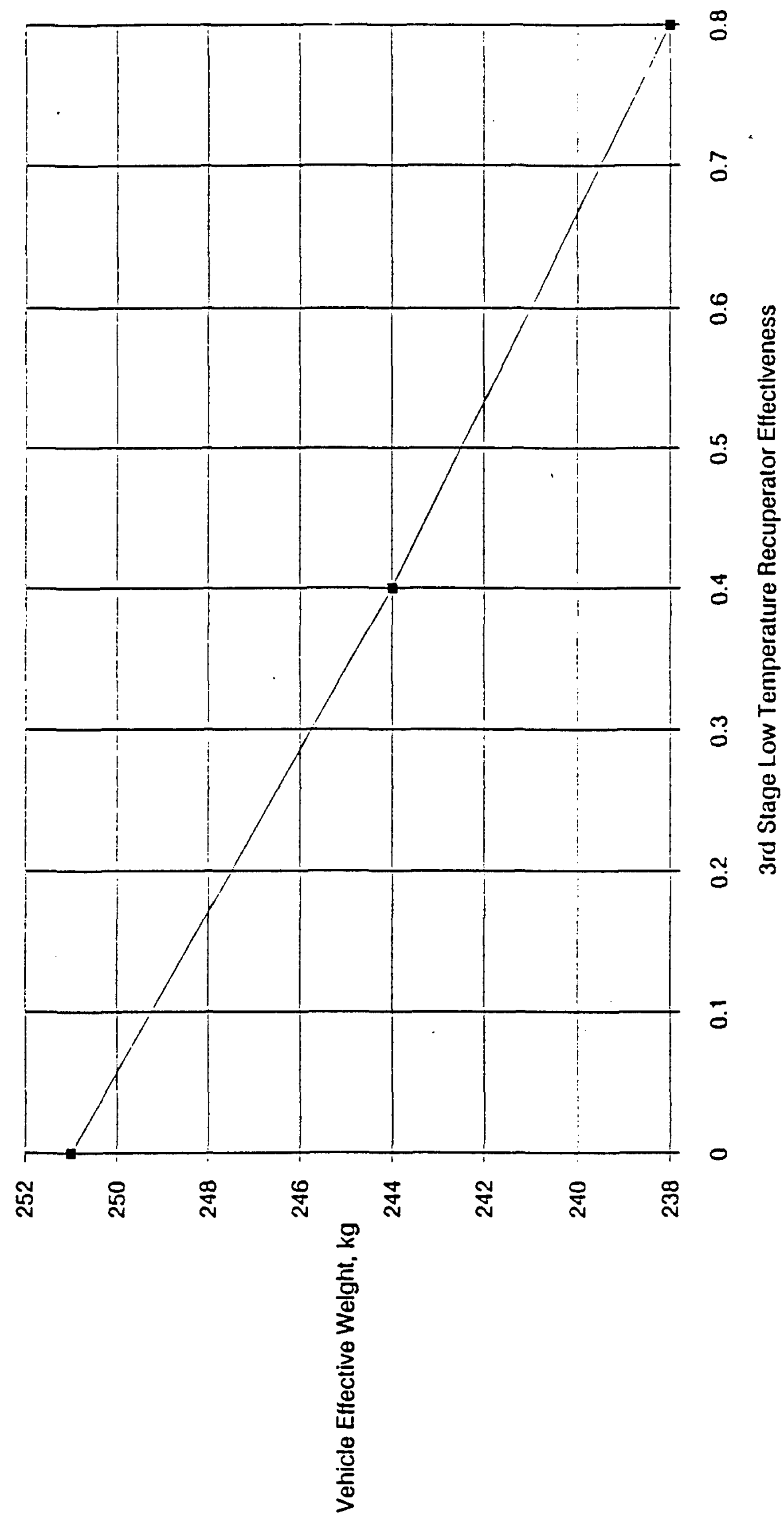
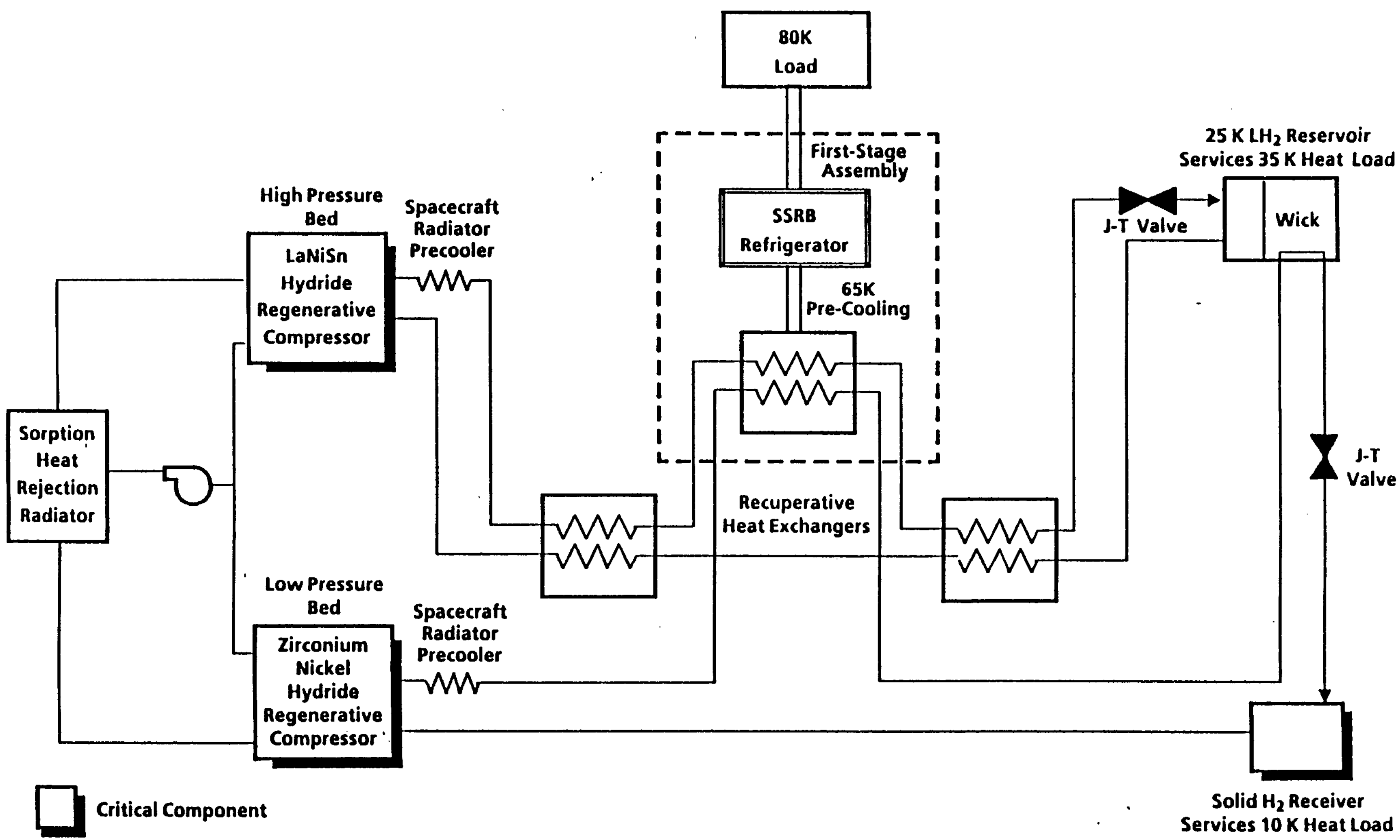


Figure 4: Baseline System Configuration for Parametric Trade Studies



individual heat exchanger components will not be a problem. ACE's monthly technical status report is presented in Appendix A.

APD Cryogenics

APD continues to evaluate design alternatives for the 10K Joule-Thomson cryostat. Work to date includes the evaluation of selected orifice size/tube length combinations to determine the optimal combination to meet performance requirements. This work is being based partially upon existing empirical data. Work will begin in January to prepare a preliminary layout. Due to funding constraints, APD was not put under contract until 23 November. It is expected that their activity will be completed by the end of January.

General Pneumatics (GP)

A computer model has been developed for analyzing the two-phase compressible flow in the Joule-Thomson expander. Preliminary parametric optimization studies have been completed, the results of which have been incorporated into a detailed design layout. The design takes into consideration both refrigerant and heat load management by taking advantage of the orifice jet fluid dynamics to collect the solid hydrogen snow. GP's technical status summary is presented in Appendix B.

Aerojet Heat Exchanger Activity

Due to the excellent progress that ACE is making, and the uncertainty regarding whether the low-pressure heat exchangers will be included in the system, Aerojet will not independently address this heat exchanger. Instead, with Phillips Laboratory concurrence, resources originally earmarked for this effort were allocated to support subcontractor activities and to conduct further parametric trades on system performance.

As discussed previously, analysis performed in December has shown that the system will operate at the upper VEW limit (250Kg) without these heat exchangers. Their ultimate inclusion in the system will depend upon the added risk of doing so weighed against predicted performance gains (as previously presented) and the potential for unexpected erosion in the margins used in the analysis. ACE has been tasked with showing the feasibility of these heat exchangers, so that they will be available should their use be chosen.

3.0 OTHER ACTIVITIES

System Design Review (SDR)

Activities to prepare for this review will start during January. A draft agenda will be developed and provided to Phillips Laboratory for comments and review.

4.0 PLANS FOR JANUARY

The following activities are planned for January:

1) Conclude technical activity with subcontractors.

2) Schedule and conduct on-site technical reviews of subcontractor activities.

3) Begin preparation for the System Design Review and establish the review date.

4) Complete documentation of the parametric trade study results.

5) Prepare the option phase 1 statement-of-work.

July 1993

10 Kelvin Spacecraft Cryocooler Development Program

Option 1 Program Phase

Contractor Progress Status And Management Report
Contract F29601-92-C-0112

CDRL A003

Submitted To:

Phillips Laboratory
Kirtland Air Force Base, New Mexico 87117-5777

Submitted By:

Aerojet Electronic Systems Division
P. O. Box 296
Azusa, California 91702

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Tables

Figures

1.0 Summary

Option 1 Phase program activities and progress continued during the month of July. A tailored Scope of Work consistent with funding limitations continues to be followed. Progress is shown in Figure 1, which presents a detailed milestone schedule for the Option 1 Phase. During the month, system thermal/thermodynamic modeling continued and efforts began to define the statement-of-work for APD Cryogenics and General Pneumatics. System thermodynamic modeling is currently centered around the expander portion of the cryocooler. It is expected that this model section will be completed 1 October. The draft SOW's are currently being finalized and it is expected that formal subcontract negotiations will commence early August. Two informal meetings were held during the month at Phillips Laboratory to provide an update on program status and to discuss computer modeling requirements. The draft Program Plan for the Option 1 Phase was also submitted.

For the remainder of GFY 1993, program activities will continue to be centered around system thermal/thermodynamic modeling, subcontractor SOW definition and subcontract negotiation, and (as necessary) updating the system baseline configuration. These activities will put the program in an optimal position to aggressively resume with expected GFY 1994 funding.

2.0 Technical Progress

The following sections status the progress accomplished during July for each of the principal technical tasks.

2.1 Cryocooler Preliminary Design

2.1.1 System Baseline Configuration Update

The system baseline configuration is shown in Figure 2. This activity (which began mid-July) includes the updating and modification of this configuration (as necessary) based upon the findings of ongoing design and analysis. Activities to date have indicated no need for any changes in the system configuration.

Future analysis using the computer simulation tool (which is under development, see Section 2.1.2) will permit detailed investigation into the impact of design modifications on performance, particularly modifications which could result in substantial risk reduction. For example, the impact of removing regeneration from the ZrNi compressor assembly will be investigated further. Preliminary calculations done during the Basic Phase show an increase in vehicle effective weight of 12 kgs if this were done. Aerojet will work closely with Phillips Laboratory and obtain concurrence prior to any updating and modification to the baseline configuration.

Figure 1: 10 Kelvin Cryocooler Development - Option 1 Phase

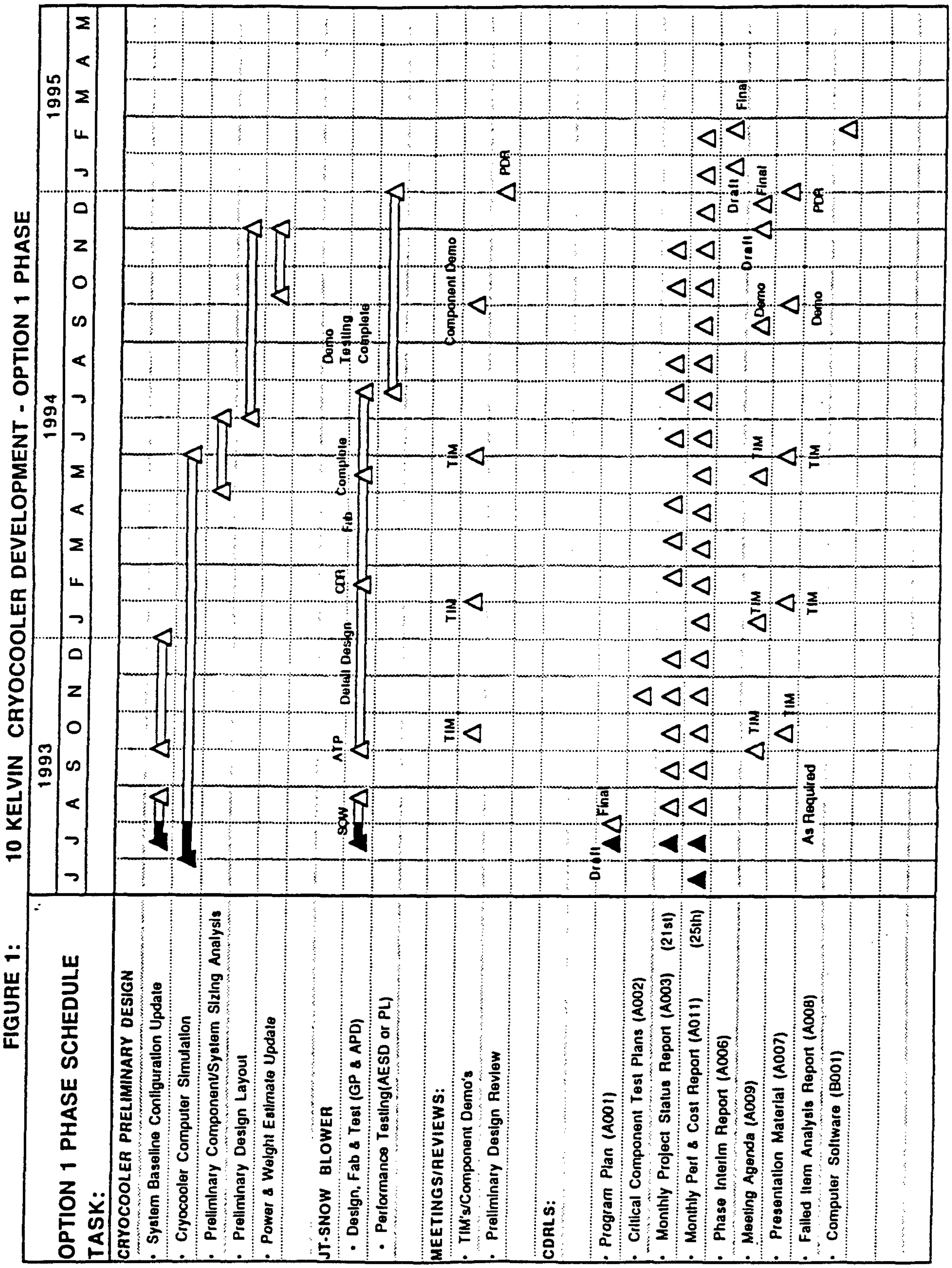
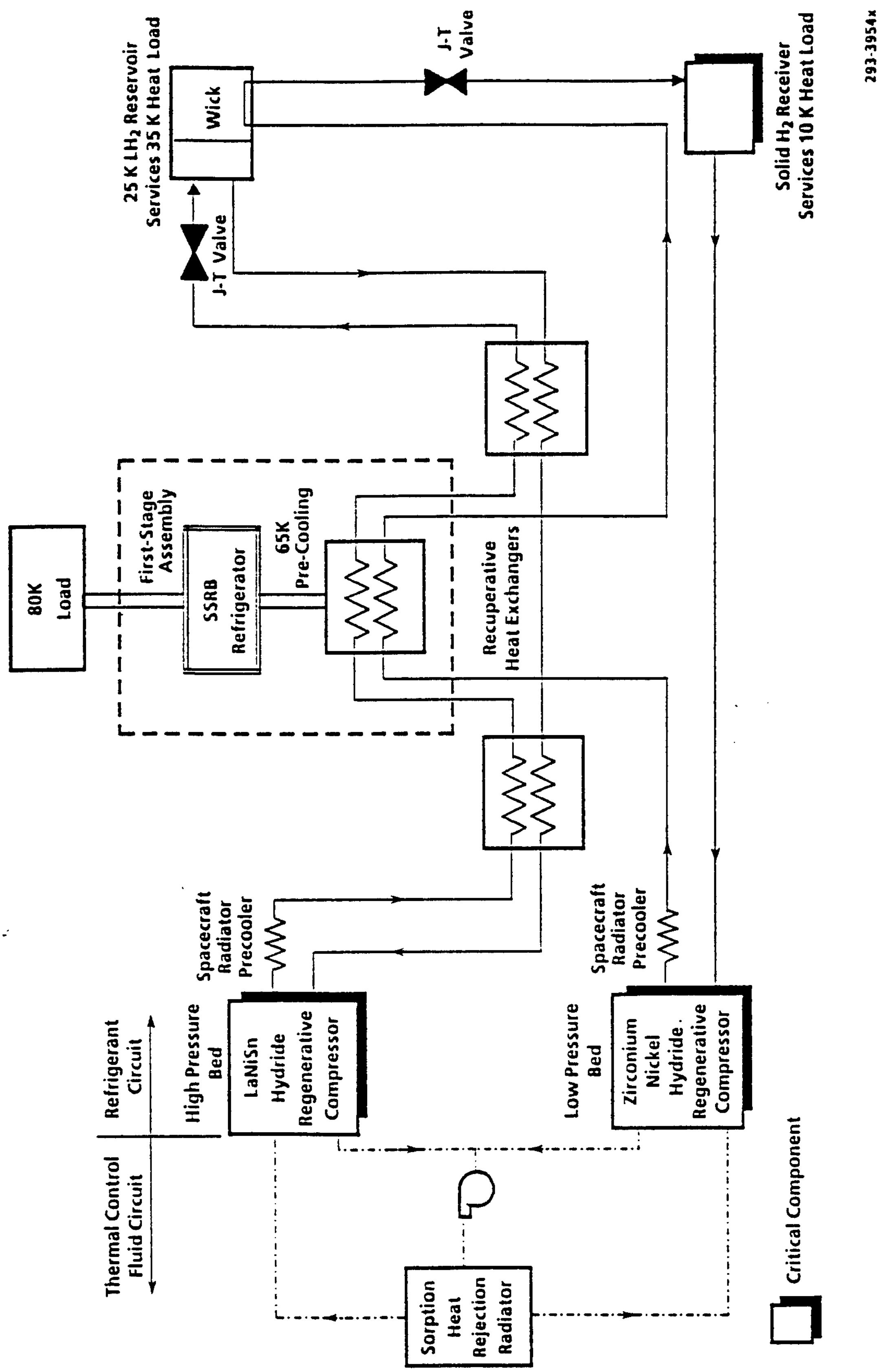


Figure 2: Baseline System Configuration



2.1.2 Cryocooler Computer Simulation

Thermal/thermodynamic modeling continued during July. The detailed model under development will permit evaluation of cryocooler steady-state and transient performance at both on- and off- design point operating conditions. This model will be updated as empirical data becomes available from subcontractor J-T Snow Blower testing and will be used to assist in preliminary design activities. At PDR, this model will be representative of the presented cryocooler preliminary design. The model will be constructed in a flexible and modular fashion to easily permit the evaluation of system configuration and component design changes. The specific development objectives and attributes for the model are summarized in Table 1.

Table 1: Computer Simulation Tool Development Objectives And Attributes
The Tool Being Developed Should: 1) Be A Design Tool 2) Be A Performance Tool 3) Be User-Friendly 4) Be Highly Modular 5) Contain Sufficient, But Not Superfluous Detail 6) Provide Component Weights

A meeting was held with Brian Whitney at Phillips Laboratory on 16 July to review these development objectives, obtain concurrence and discuss potential modeling tools to be used. A search to find the optimum tool was then initiated. Figure 3 discusses the tools available and their pro's and con's. Reviewing the objectives and evaluating each of the tools' features led us to conclude that SINDA85 best meets our objectives. The submodel capability of SINDA85 allows the user to separate the model into different modules and couple them as appropriate. Different model configurations can therefore be analyzed in a shorter turnaround time. The Fluid Flow Analysis option keeps track of the pressure drop and thermodynamic changes as the working fluid moves through the different cryocooler components. Furthermore, SINDA85 is considered an industry standard making it highly transportable.

A schematic of the cryocooler configuration being modeled is shown in Figure 4. The approach to be followed in developing the thermal model is to separate the cryocooler into three sections: The expander section, the regenerative section, and the compressor section; and develop each section as a stand alone submodel. When all sections are completed, they will be integrated into a single model. A brief description of each section is discussed below.

A) Expander Section

This section includes the recuperative heat exchangers, the precoolers and the cryostats for the second and third stages. Although removed from the baseline, the critical component low pressure heat exchangers will be included as an option. The first stage is assumed to be a mechanical cooler and its performance data will be used as input to the precooling and 80K loads.

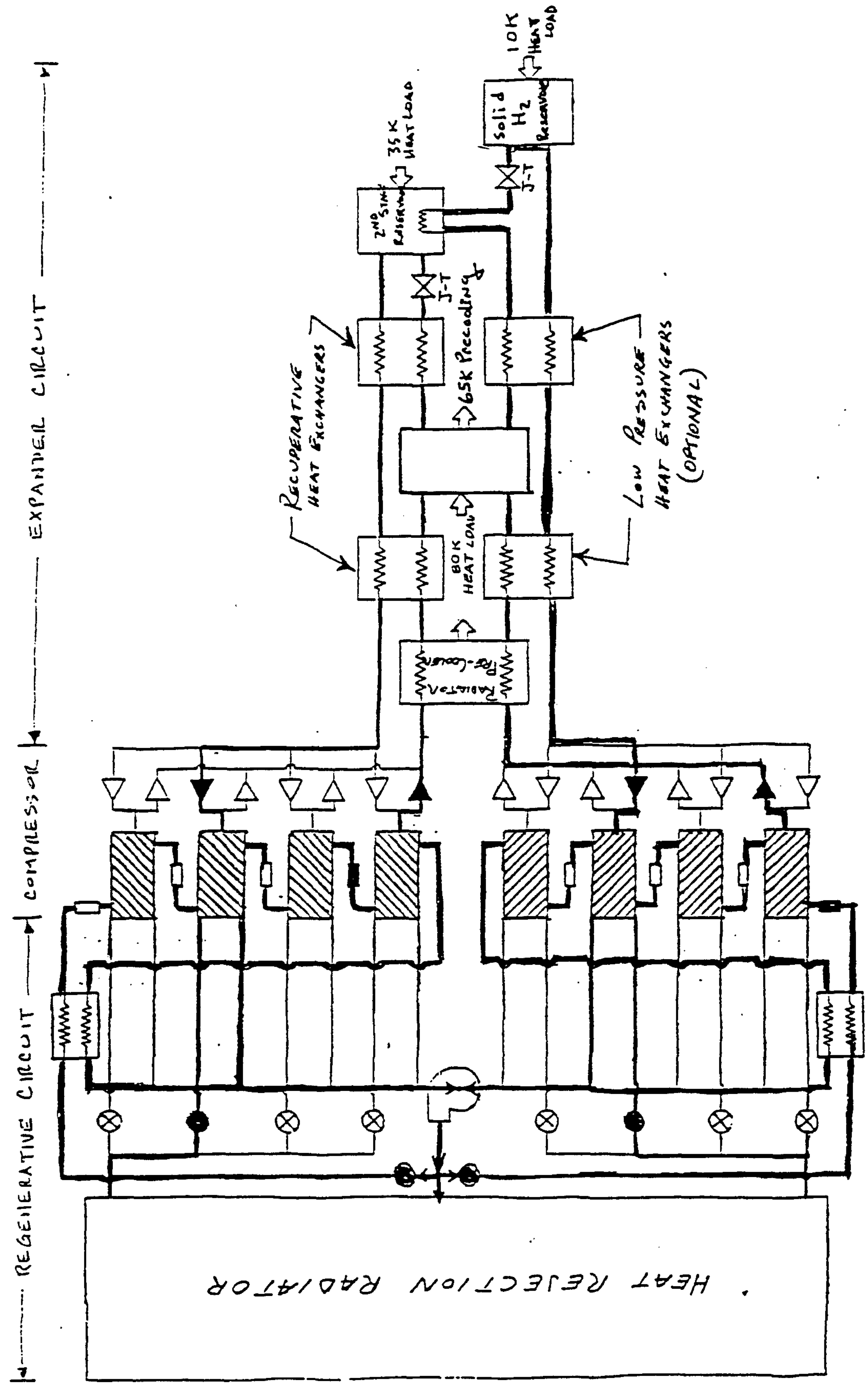
B) Regenerative Section

This section includes the heat rejection radiator, the circulator and the regenerative loop for the hydride compressors.

Figure 3: Survey of Thermal Analysis Tools

TOOL	PRO's	CON's
SINDA85	• Widely used and recognized in the thermal analysis community. • Submodel capability • Extensive fluid analysis capabilities. • Easily transportable.	• Fluid analysis option not straightforward.
FORTRAN77	• Software can be developed to meet sorption's particular needs. • Can include a model-generator through a user-friendly interface.	• Substantial development effort required.
SINDA87	• Widely used in the thermal analysis community.	• Requires license fee. • No fluid analysis option in the in-house version.
EXCEL	• Highly transportable. • User-friendly. • Suitable for top level analysis.	• Unsuitable for detailed thermal analysis; especially during transient operation. • May prove inadequate as a design tool.
STARFIRE	• Aerojet in-house thermal analyzer. • Easier to use than other analyzers. • Options allow user to write his/her own subroutines	• Thermal model needs to be translated into SINDA format when delivered to the customer. • No submodel option.

Figure 4: Schematic of Computer Simulation Model



C) Compressor Section

The Compressor Section is the most complex part of the model. The regenerative compressors are the heart of this cryocooler. It is important that the model accurately reflect the processes taking place during absorption and desorption; such as heat of reaction, concentration vs temperature and pressure, change in enthalpy, etc. Each compressor element must follow the operational sequence - heating, desorbing, cooling, absorbing - and be synchronized with the remaining elements. In order to properly simulate the compressor behavior, a very detailed modeling effort is necessary.

D) Model Integration

This effort integrates the sections discussed above into a single detailed model. This model will make extensive use of the submodel capability of SINDA85 to create modules that represent the different elements of the cryocooler. The advantage of this modular approach is that it allows for flexibility and traceability. Elements can easily be connected or disconnected using the BUILD card and some simple additional adjustments to the model. Different cryocooler configurations can be analyzed in a much shorter turnaround time.

It is intended to use GASPAK as the source of fluid properties. GASPAK is an integrated code of thermodynamic equations for properties of fluids and is available from Cryodata Inc. The source code can be modified and incorporated into other programs as a subroutine call. Thus, GASPAK will be used as a subroutine called from SINDA85.

The fluid submodel of the second-stage expander section is near completion. The entire expander section, including second- and third-stage loops, is expected to be completed by 1 October 1993.

2.2 J-T Snow Blower

2.2.1 Design, Fabricate and Test

Efforts began during the month of July to define the statement-of-work (SOW) for APD Cryogenics (APD) and General Pneumatics (GP). Preliminary discussions have been held and draft SOW's have been prepared. These drafts are currently under review by each vendor as well as Aerojet subcontract management to ensure proper compliance and flowdown with the prime contract.

It is expected that the SOW's will be finalized during early August, at which time formal subcontract negotiations will commence with both APD & GP. Subcontractor activities will be initiated as quickly as possible in GFY 1994 when additional funding is received.

The goal of the subcontract activities is to demonstrate continuous 10 Kelvin temperature by the creation and management of solid hydrogen. The temperature stability at 10 Kelvin, proper heat load management, and a producible, reliable design are the key issues in validating and demonstrating feasibility. The work will build upon the hardware concepts developed by both APD & GP during the Basic Phase. It is expected that the prototype hardware resulting from this work will be easily adaptable for integration into the Cryocooler Engineering Development Model which will be fabricated and tested during the Option 2 phase.

The current schedule (See Figure 1) shows for both subcontractors approximately 10 months elapsed time from subcontract go-ahead until completion. Preliminary discussions with both APD and GP indicate that possibly each will need less time to demonstrate the feasibility of their particular approaches. If true, this will translate into a direct Option 1 phase schedule savings as the subcontract development activities are on the critical path. Each subcontractor's development schedule will be firmed up during August. The Option 1 phase schedule will then be adjusted to reflect any identified savings.

Although each subcontractor's approach is unique, there are common tasks and features to their SOW's. This includes:

- Further design analysis - to predict performance and behavior.
- Development of a flight unit conceptual layout - to show how the prototype designs are representative of flight hardware and also to provide a basis for development.
- Prototype detailed design - followed by a CDR at Aerojet's Azusa facility prior to fabrication commitment. Government participation at the CDR is encouraged and requested.
- Prototype fabrication, assembly and test - to validate and demonstrate each approach. Testing will be conducted at both design point and off design point conditions, in accordance with an approved test plan. At the conclusion of subcontractor testing, the prototype hardware will be delivered to Aerojet for further testing. As an option, the hardware could also be forwarded to Phillips Laboratory for testing at their facility.

The subcontractors will also participate in program TIM meetings and the program PDR at the Option 1 phase conclusion. They will provide monthly progress, status and management report inputs to Aerojet which will be attached as appendices to Aerojet's monthly report to Phillips Laboratory. This will ensure that the progress of each subcontractor can be easily monitored.

3.0 CDRL's

The CDRL delivery schedule is presented in Figure 1. The following CDRL's were delivered during July:

Draft Program Plan (CDRL A001) - The draft Option 1 Phase Program Plan was delivered 8 July 1993. The Program Plan will be finalized and delivered upon receipt of government comments.

June 1993 Monthly R&D Project Status Report (CDRL A003) - delivered 8 July 1993.

June 1993 Monthly Performance and Cost Report (CDRL A011) - delivered 21 July 1993.

4.0 Other Activities

Program Evaluation for Areas of Possible Schedule Reduction

To minimize the impact of funding constraints on the overall cryocooler development schedule, the program plan and Option 1 phase schedule continue to be evaluated for areas of potential schedule savings. The goal is to reduce the current 19 month Option 1 phase schedule without incurring additional cost or risk. A key factor in shortening the schedule will be the subcontractor development efforts, which are critical path activities and will not be initiated until GFY 1994 due to funding limitations. As discussed in Section 2.2.1 the subcontractor development schedules may be shorter than originally envisioned, thus yielding a schedule savings.

Informal Meetings At Phillips laboratory

Two informal meetings were held with Brian Whitney at Phillips Laboratory during the week of 16 July. Aerojet personnel were in Albuquerque to attend the Cryogenic Engineering Conference. On 13 July Neil Sherman (Program Manager) met with Brian Whitney to provide an update on program status. On 16 July Forrest Cleveland (Program Technical Director) met with Brian Whitney for detailed discussions of computer modeling objectives and requirements.

5.0 Plans for August

The following activities are planned for August:

1) Incorporate comments and submit finalized program plan to Phillips Laboratory.

2) Continue thermal/thermodynamic modeling activity.

3) Refine baseline cryocooler configuration (as necessary).

4) Finalize subcontractor SOW's and conduct subcontract negotiations with General Pneumatics and APD Cryogenics.

5) Continue to evaluate Option 1 phase for areas of possible schedule reduction.

September 1993

10 Kelvin Spacecraft Cryocooler Development Program

Option 1 Program Phase

Contractor Progress Status And Management Report
Contract F29601-92-C-0112

CDRL A003

Submitted To:

Phillips Laboratory
Kirtland Air Force Base, New Mexico 87117-5777

Submitted By:

Aerojet Electronic Systems Division
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Appendix

Figures

1.0 Summary

Option 1 Phase program activities and progress continued during the month of September. A tailored Scope of Work consistent with funding limitations continues to be followed. Progress is shown in Figure 1, which presents a detailed milestone schedule for the Option 1 Phase. During September, system thermal/thermodynamic modeling continued and updated cost estimates for Option 1 phase subcontract activities were prepared by APD Cryogenics and General Pneumatics. At month end, subcontract negotiations with General Pneumatic were completed and negotiations with APD Cryogenics were continuing. System thermodynamic modeling continues to be centered around the expander portion of the cryocooler. Modeling of the second-stage expander loop has been completed. Modeling of the entire expander loop (i.e., including the third-stage) is expected to be completed by mid-October, at which point the basic elements will be in place to conduct expander loop trade and design studies.

2.0 Technical Progress

The following sections status the progress accomplished during September for each of the principal technical tasks. They are presented in the order which they appear on the detailed milestone schedule (Figure 1), which also provides a cross-reference with the contract WBS (CWBS).

2.1 J-T Snow Blower

2.1.1 Design, Fabricate and Test

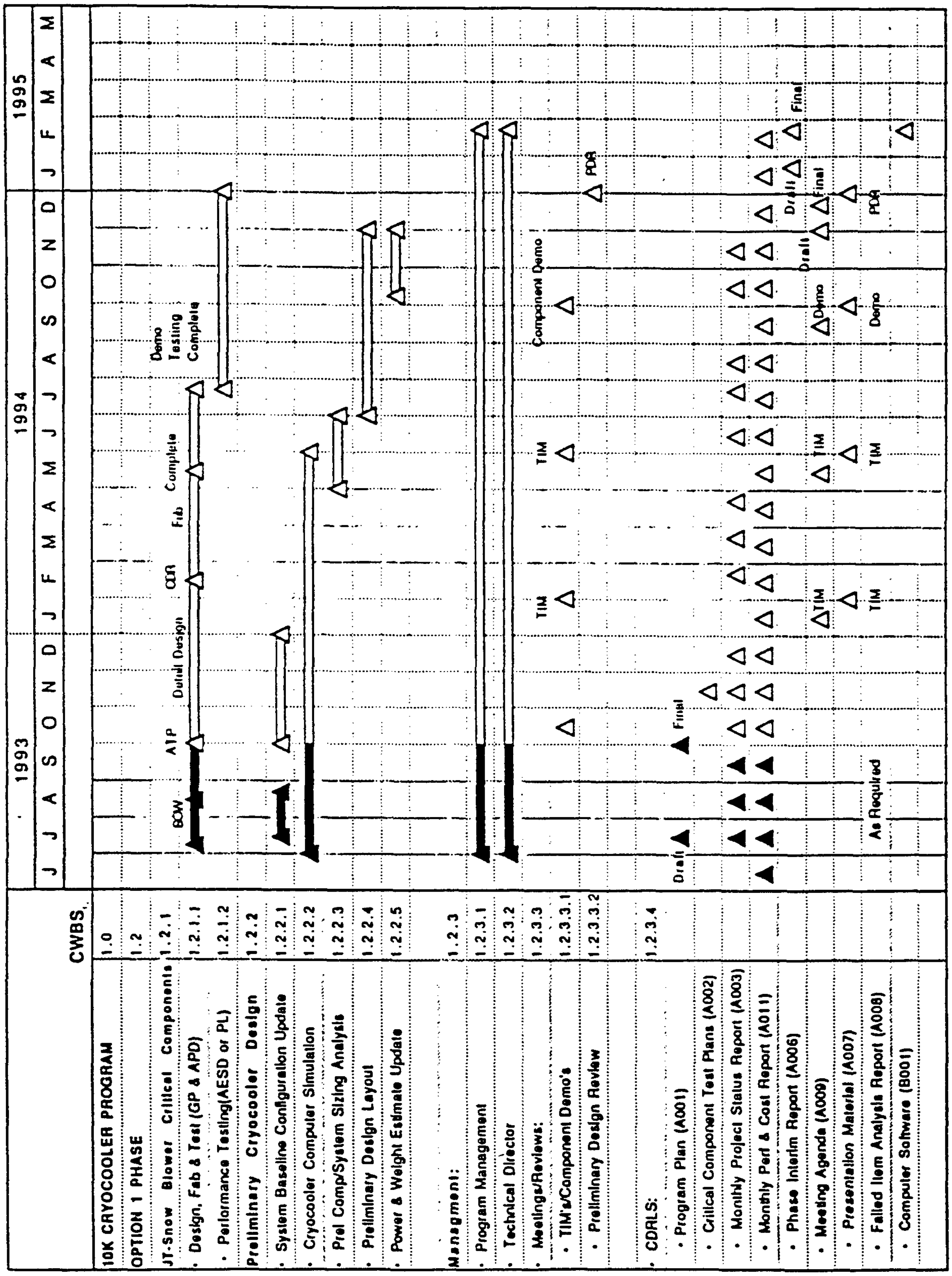
During September, updated cost estimates for the Option 1 Phase subcontract activities were prepared by APD Cryogenics and General Pneumatics. Additionally, formal subcontract negotiations with General Pneumatics were completed. Subcontract negotiations with APD Cryogenics are continuing, and are expected to be completed by mid-October. A detailed review with Phillips Laboratory personnel of each subcontractor's expected activities will be on the agenda of the informal working meeting expected to take place in October (See Section 4.0). Subcontractor efforts will commence in October upon receipt of GFY '94 funding.

2.2 Preliminary Cryocooler Design

2.2.1 Cryocooler Computer Simulation

The thermal model of the cryocooler system expander is near completion. The progress achieved during September is discussed below.

Figure 1: 10 Kelvin Cryocooler Development Schedule - Option 1 Phase



The integration of GASPAK into the SINDA85 environment has been completed. The thermodynamic and transport properties for normal hydrogen and other cryogenic fluids are now available. The integration has been validated by creating a cooling loop similar to the second-stage loop, but using a working fluid common to both SINDA and GASPAK. That fluid was Propane. A comparison of the results showed excellent agreement.

The exercise of creating a new cooling loop for comparison purposes showed the versatility of SINDA/FLUINT as an analysis tool. The thermal model, with corresponding pressures and temperature levels, was completed in less than three hours.

Upon comparing the performance between the SINDA built-in fluid and the GASPAK-supplied fluid configurations, the execution time was slower in the GASPAK run. Efforts are underway to optimize the use of GASPAK calls to speed up program execution. The difference in execution time however is not significant and will have no impact on productivity.

Once GASPAK became operational in SINDA, efforts to complete the third stage were begun. A schematic is shown in Figure 2. The third stage is thermally coupled to the second-stage reservoir just before the J-T valve and is driven by the low-pressure sorption compressor. This compressor is being simulated by two plenums representing the pressure states of the compressor as it thermally cycles. Currently, GASPAK does not handle temperatures and pressures below the triple point. Properties in this regime are necessary for modeling solid hydrogen behavior and will be incorporated as required. Modeling is expected to be completed mid-October, at which point the basic elements for expander loop trade and design studies will be in place.

3.0 CDRL's

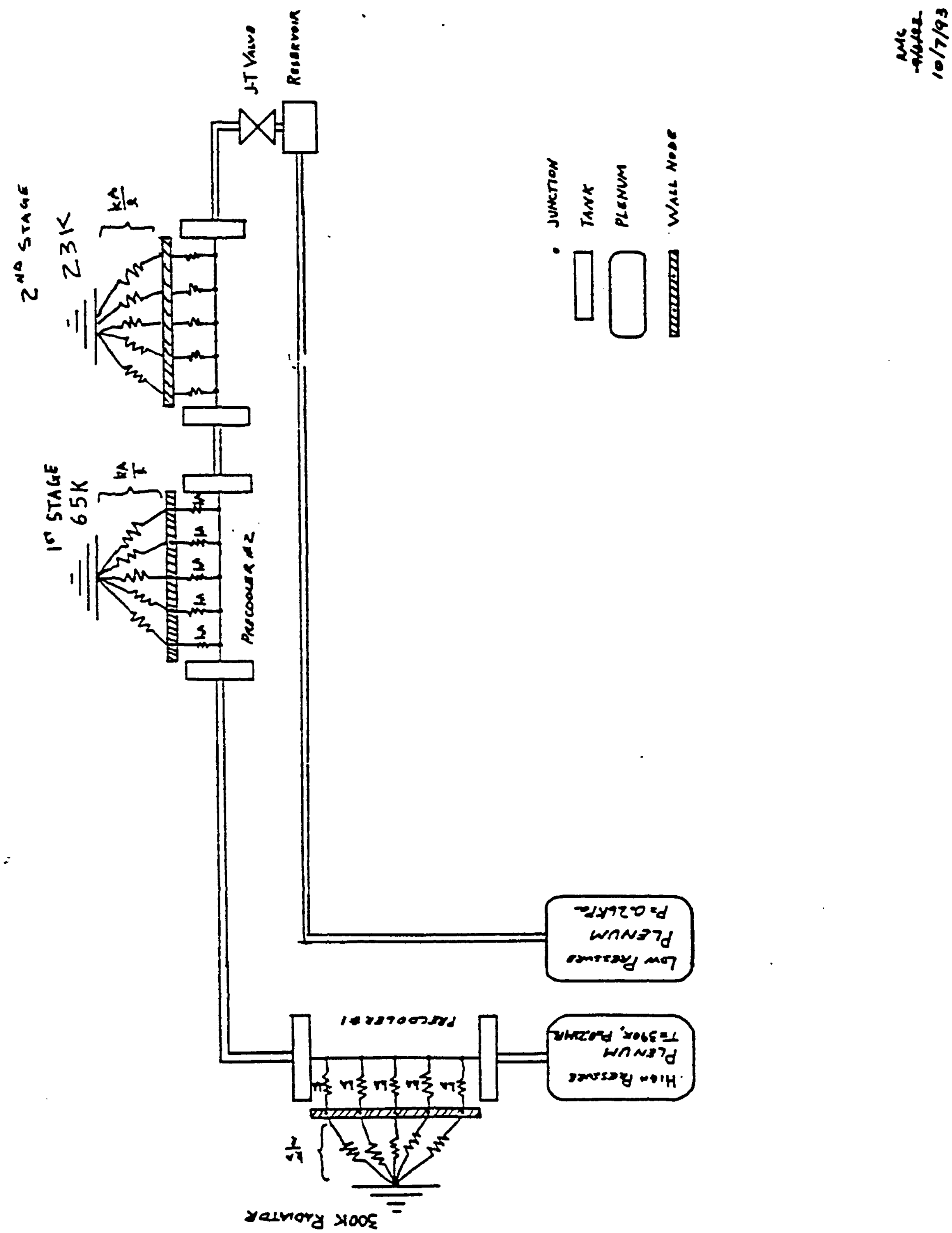
The CDRL delivery schedule is presented in Figure 1. The following CDRL's were delivered during September:

1) <u>Option 1 Phase Finalized Program Plan (CDRL A001)</u>
   Delivered 27 September 1993

2) <u>August 1993 Monthly R&D Project Status Report (CDRL A003)</u>
   Delivered 14 September 1993

3) <u>August 1993 Monthly Performance and Cost Report (CDRL A011)</u>
   Delivered 16 September 1993

Figure 2: 3rd Stage Expander Loop
(Driven by the low pressure compressor)



4.0 Other Activities

Program Evaluation for Areas of Schedule Reduction

This activity continues and it will be an ongoing program philosophy to seek improvement upon schedule without incurring additional cost or risk. As reported last month, indications are that a one to two month decrease in the Option 1 Phase will potentially result from shorter than expected subcontractor development activities. Further evaluation of the Option 1 Phase and the overall program will be permitted in October when GFY '94 funding levels are established.

Informal Working Meeting At Aerojet Facility With Phillips Laboratory Personnel

An informal working meeting with Phillips Laboratory personnel is being planned at the Aerojet Facility during October. The purpose of this meeting will be to status the program progress to date and to determine the best way to proceed with the GFY 1994 funding levels. Prior to the meeting, an agenda of discussion items will be forwarded to Phillips Laboratory for concurrence.

5.0 Plans for October

The following activities are planned for October:

1) Continue thermal/thermodynamic modeling activity.

2) Complete subcontract negotiations with APD Cryogenics.

3) Initiate subcontractor activities upon receipt of GFY '94 funds.

4) Have informal working meeting with Phillips Laboratory personnel to discuss program progress and future plans.

October 1993

10 Kelvin Spacecraft Cryocooler Development Program

Option 1 Program Phase

Contractor Progress Status And Management Report
Contract F29601-92-C-0112

CDRL A003

Submitted To:

Phillips Laboratory
Kirtland Air Force Base, New Mexico 87117-5777

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October 1993

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Appendix

Figures

1.0 Summary

Work on all Option 1 Phase technical activities was stopped early during the month due to the lack of funding. Prior to this action, a tailored Scope of Work consistent with funding limitations had been followed since May. Progress is shown in Figure 1, which presents a detailed milestone schedule for the Option 1 Phase. Indicated progress reflects the stopping of technical activities. Program management and administration work order numbers do remain open (supported on residual program funds) to maintain communications with Phillips Laboratory. Program personnel and resources are being maintained to ensure an efficient program re-start when expected GFY 1994 funding is received.

At the time when activities were stopped, subcontract negotiations with General Pneumatics were completed and negotiations with APD were continuing. Additionally, thermodynamic modeling of the cryocooler expander loop was nearing completion.

2.0 Technical Progress

Because technical activity was stopped very early in October, there was no significant progress beyond that reported in last month's Progress, Status and Management Report. The following sections briefly summarize the status of the principal technical tasks when activity was halted. They are presented in the order which they appear on the detailed milestone schedule (Figure 1), which also provides a cross-reference with the contract WBS (CWBS).

2.1 J-T Snow Blower

2.1.1 Design, Fabricate and Test

Updated cost estimates for the Option 1 Phase subcontract activities have been prepared by APD Cryogenics and General Pneumatics. Additionally, formal subcontract negotiations with General Pneumatics are complete. Subcontract negotiations with APD Cryogenics were underway when work was stopped. A detailed review with Phillips Laboratory personnel of each subcontractor's planned activities will occur during the informal working meeting expected to take place in November (See Section 4.0). Subcontractor efforts will commence as soon as possible upon receipt of GFY '94 funding.

2.2 Preliminary Cryocooler Design

2.2.1 Cryocooler Computer Simulation

The thermal model of the cryocooler system expander loop is near completion. Figures 2 and 3 present schematics of the second-and third-stage expander loops, respectively.

Figure 1: 10 Kelvin Cryocooler Development Schedule - Option 1 Phase

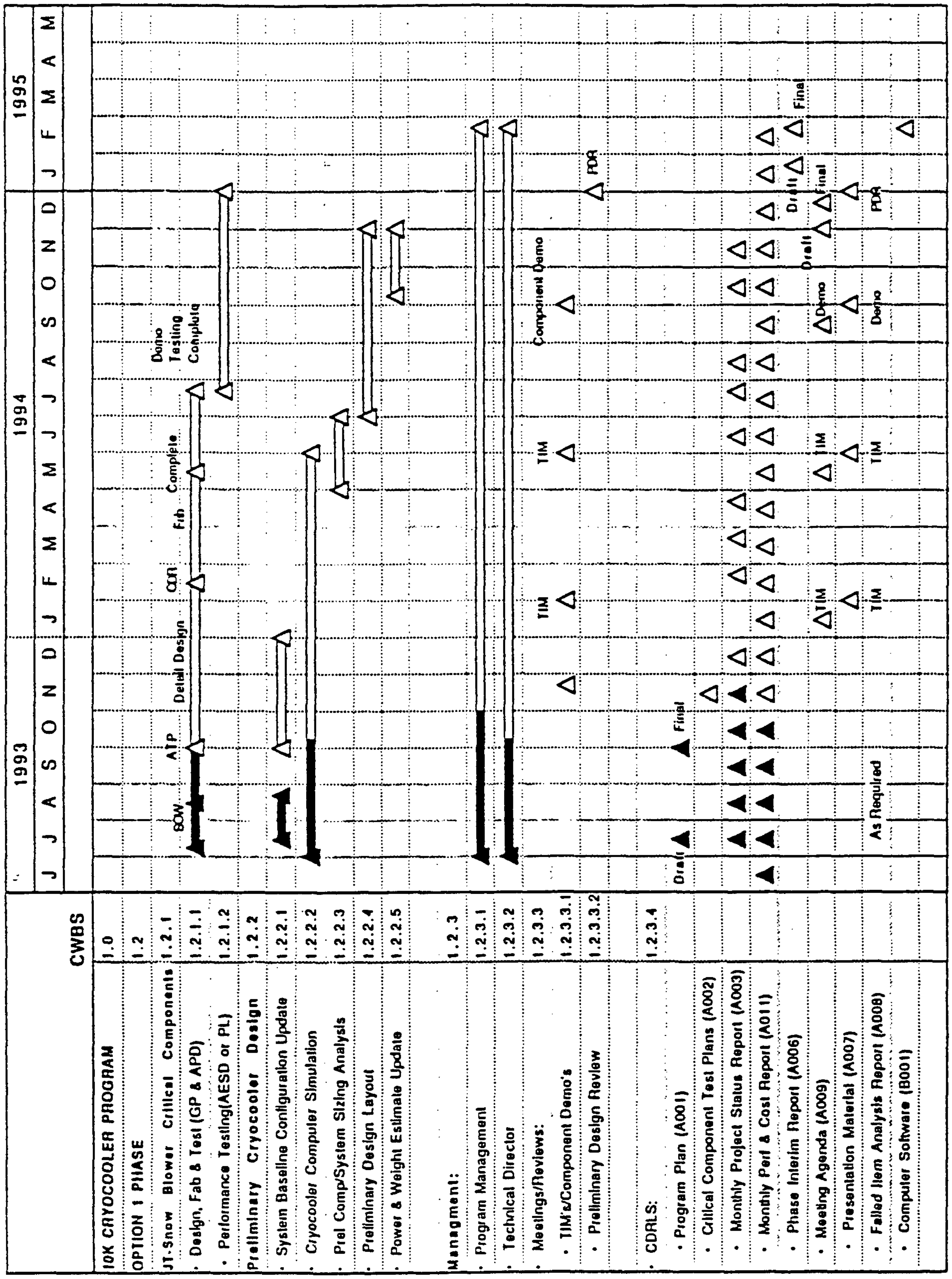


Figure 2: 2nd Stage Expander Loop
(Driven by the high-pressure compressor)

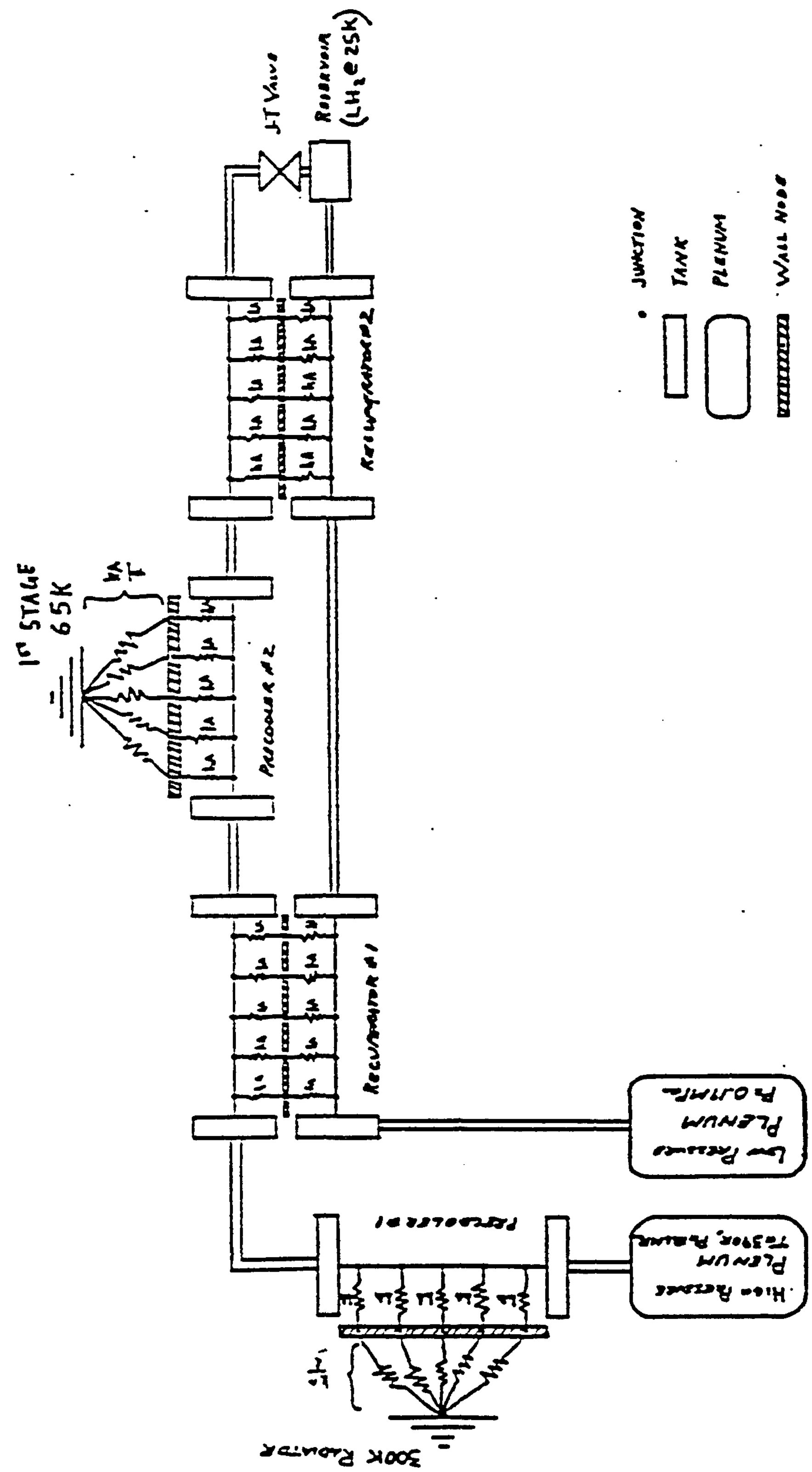
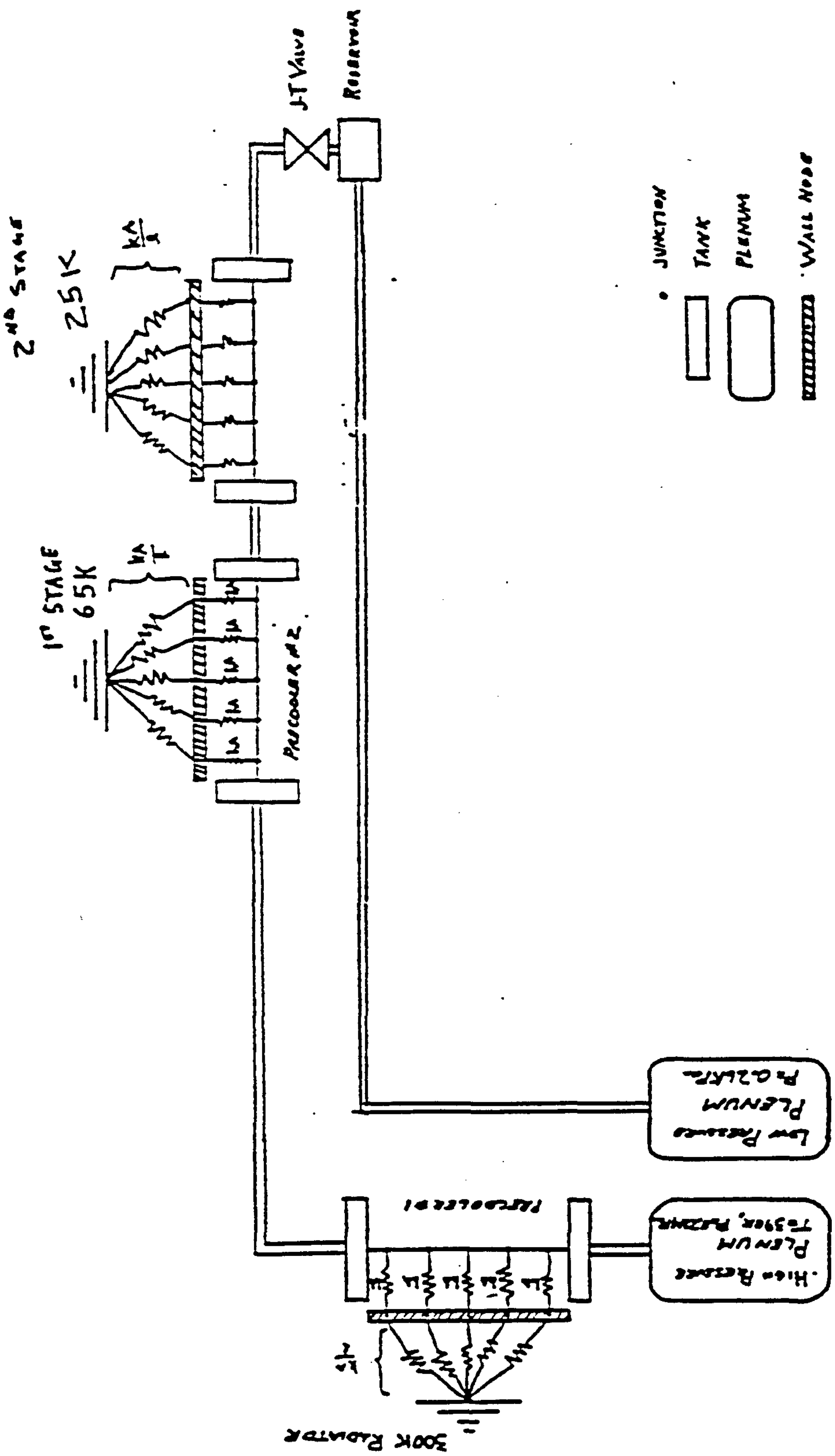


Figure 3: 3rd Stage Expander Loop
(Driven by the low-pressure compressor)



The second-stage expander loop model includes coupling to the 65 K pre-cooling first stage, the recuperative heat exchangers, the J-T

valve and a cryogen reservoir. This stage is driven by the high-pressure sorption compressor which is simulated by two plenums representing the compressor pressure states as it thermally cycles.

The third stage is thermally coupled to the second-stage reservoir just before the J-T valve and is driven by the low-pressure sorption compressor. This compressor is also simulated by two plenums representing the pressure states as it thermally cycles.

Modeling is expected to be completed shortly after work resumes, at which point the basic elements for expander loop trade and design studies will be in place.

3.0 CDRL's

The CDRL delivery schedule is presented in Figure 1. The following CDRL's were delivered during October:

1) September 1993 Monthly R&D Project Status Report (CDRL A003)
   Delivered 14 October 1993

2) September 1993 Monthly Performance and Cost Report (CDRL A011)
   Delivered 21 October 1993

4.0 Other Activities

Informal Working Meeting At Aerojet Facility With Phillips Laboratory Personnel

Upon receipt of additional funds, an informal working meeting with Phillips Laboratory personnel is being planned at the Aerojet Facility during November. The purpose of this meeting will be to status the program progress to date and to determine the best way to proceed with the expected GFY 1994 funding levels. Prior to the meeting, an agenda of discussion items will be forwarded to Phillips Laboratory for concurrence.

5.0 Plans for November

The following activities are planned for November:

1) Receive additional funding from Phillips Laboratory and resume program technical activities.

2) Have informal working meeting with Phillips Laboratory personnel to status program progress and to determine future plans.

November 1993

10 Kelvin Spacecraft Cryocooler Development Program

Option 1 Program Phase

Contractor Progress Status And Management Report
Contract F29601-92-C-0112

CDRL A003

Submitted To:

Phillips Laboratory
Kirtland Air Force Base, New Mexico 87117-5777

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Appendix

Figures

1.0 Summary

Work on all Option 1 Phase technical activities has been stopped since early October due to the lack of funding. Prior to this action, a tailored Scope of Work consistent with funding limitations had been followed since May. Progress is shown in Figure 1, which presents a detailed milestone schedule for the Option 1 Phase. Indicated progress reflects the stopping of technical activities. At the time when activities were stopped, subcontract negotiations with General Pneumatics were completed and negotiations with APD were continuing. Additionally, thermodynamic modeling of the cryocooler expander loop was nearing completion.

A small funding increment was received during November. A working meeting was held with Brian Whitney of Phillips Laboratory to discuss program progress and to determine the best way to proceed with the overall expected GFY 1994 funding levels. Detailed program replanning will commence during December based upon guidelines established at this meeting and after expected GFY 1994 funding levels are confirmed.

Program management and administration has maintained close communications with Phillips Laboratory during this work stoppage. Program personnel and resources continue to be maintained to ensure an efficient program re-start when the program has been replanned and expected GFY 1994 funding is received.

2.0 Technical Progress

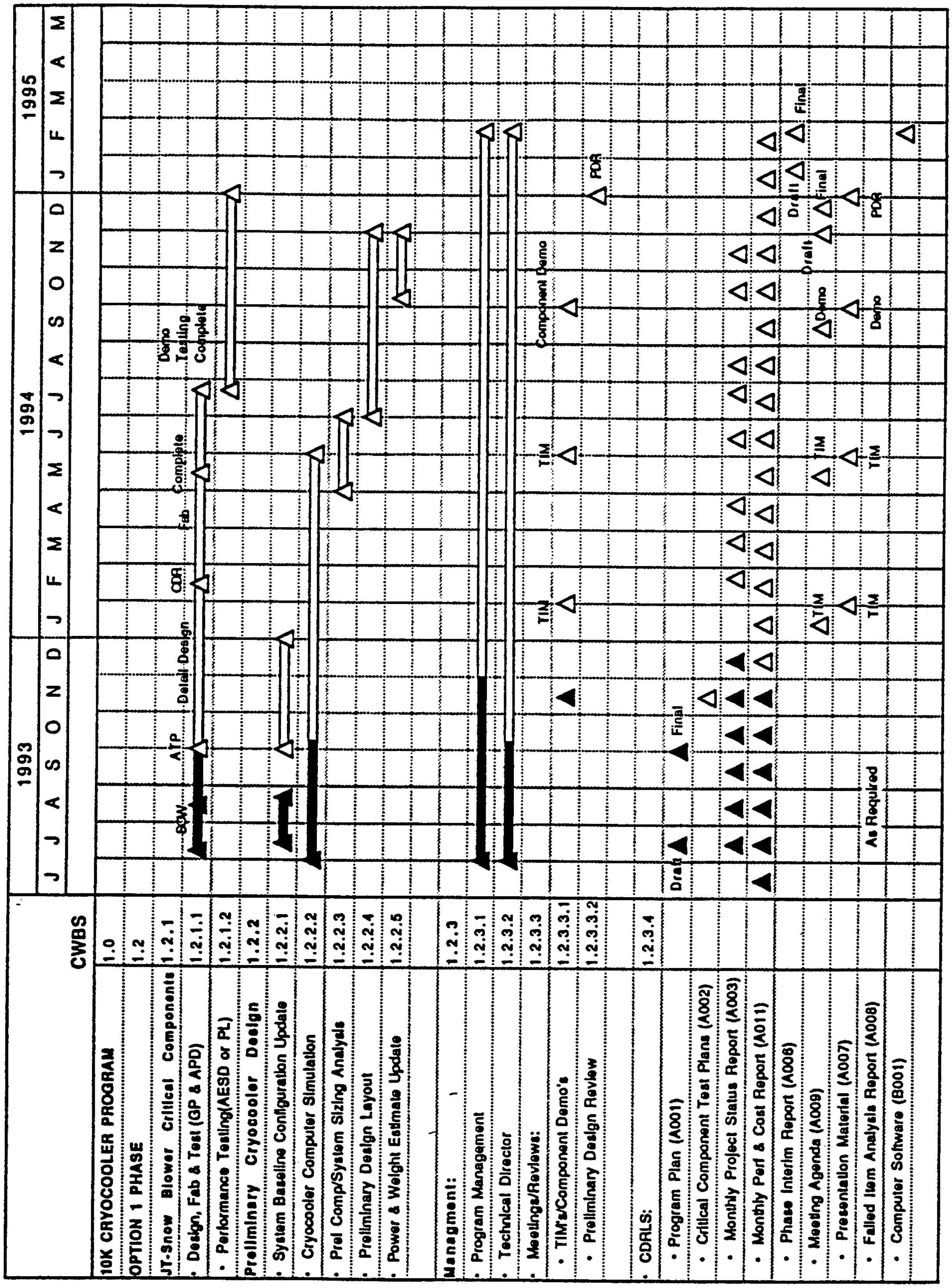
Because technical activity was stopped very early in October, there has been no progress beyond that reported in last month's Progress, Status and Management Report. In the interest of providing a reminder, the following sections briefly summarize the status of the principal technical tasks when activity was halted. They are presented in the order which they appear on the detailed milestone schedule (Figure 1), which also provides a cross-reference with the contract WBS (CWBS).

2.1 J-T Snow Blower

2.1.1 Design, Fabricate and Test

Updated cost estimates for the Option 1 Phase subcontract activities have been prepared by APD Cryogenics and General Pneumatics. Additionally, formal subcontract negotiations with General Pneumatics are complete. Subcontract negotiations with APD Cryogenics were underway when work was stopped.

Figure 1: 10 Kelvin Cryocooler Development Schedule - Option 1 Phase



2.2 Preliminary Cryocooler Design

2.2.1 Cryocooler Computer Simulation

The thermal model of the cryocooler system expander loop is near completion. Figures 2 and 3 present schematics of the second-and third-stage expander loops, respectively. The second-stage expander loop model includes coupling to the 65K pre-cooling first stage, the recuperative heat exchangers, the J-T valve and the 25K cryogen reservoir. This stage is driven by the high-pressure sorption compressor which is simulated by two plenums representing the compressor pressure states as it thermally cycles.

The third-stage expander loop is thermally coupled to the 65K pre-cooling first-stage and to the second-stage 25K reservoir, just before the third-stage J-T valve. This stage is driven by the low-pressure sorption compressor. This compressor is also simulated by two plenums representing the pressure states as it thermally cycles.

Modeling is expected to be completed shortly after work resumes, at which point the basic elements for expander loop trade and design studies will be in place.

3.0 CDRL's

The CDRL delivery schedule is presented in Figure 1. The following CDRL's were delivered during November:

1) October 1993 Monthly R&D Project Status Report (CDRL A003)
   Delivered 15 November 1993

2) October 1993 Monthly Performance and Cost Report (CDRL A011)
   Delivered 18 November 1993

4.0 Other Activities

Working Meeting At Aerojet Facility With Phillips Laboratory Program Manager

A working meeting with Brian Whitney of Phillips Laboratory was held at Aerojet's Azusa facility on 18 November. The purpose of the meeting was to status the program progress to date and to determine the best way to proceed with the expected GFY 1994 funding levels. Guidelines for replanning the program were established at the meeting. Detailed minutes of the meeting which contain these guidelines have been prepared and forwarded to Phillips Laboratory for concurrence. Replanning activities will begin during early December after expected GFY 1994 funding levels have been confirmed.

Figure 2: Second-Stage Expander Loop
(Driven by the high-pressure compressor)

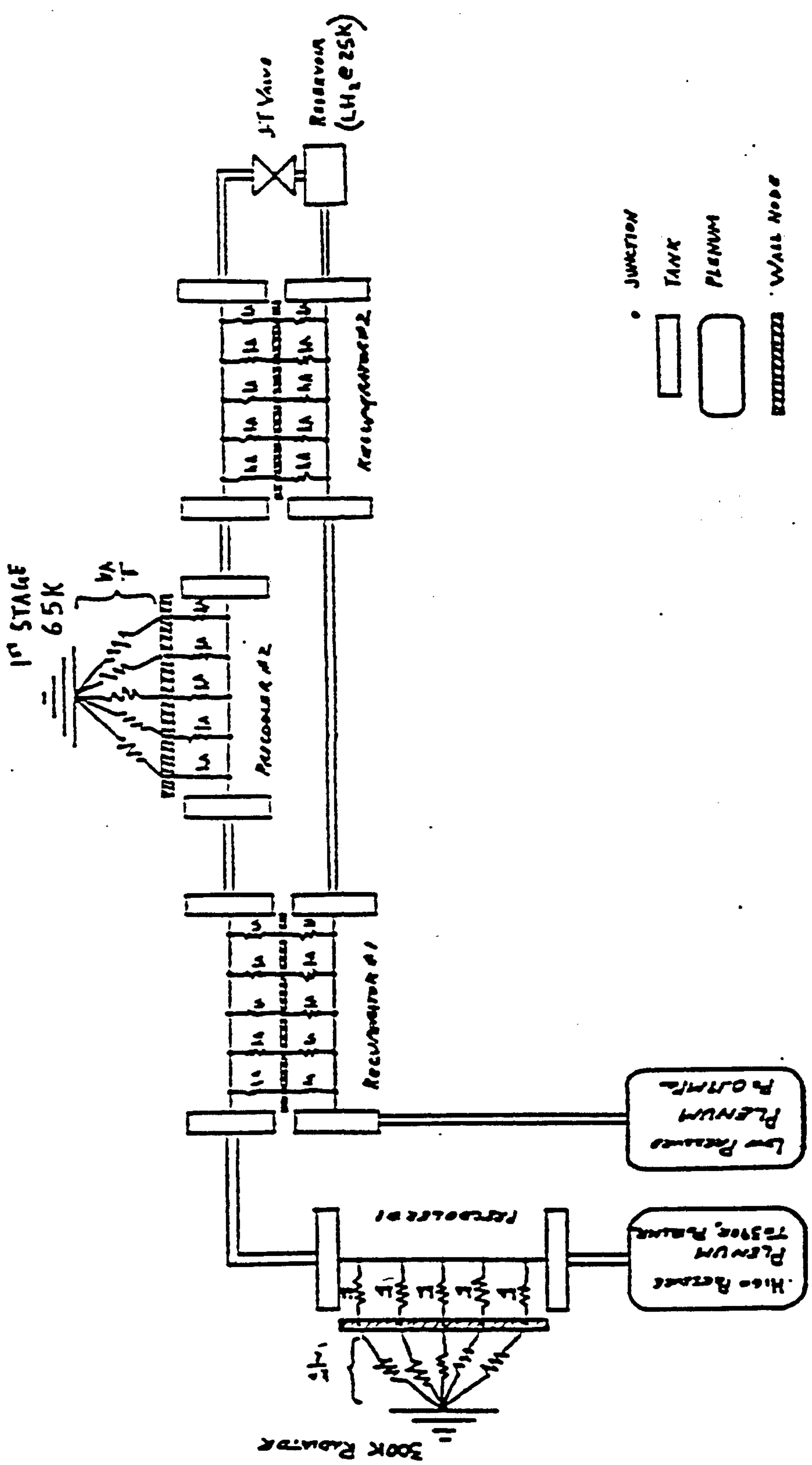
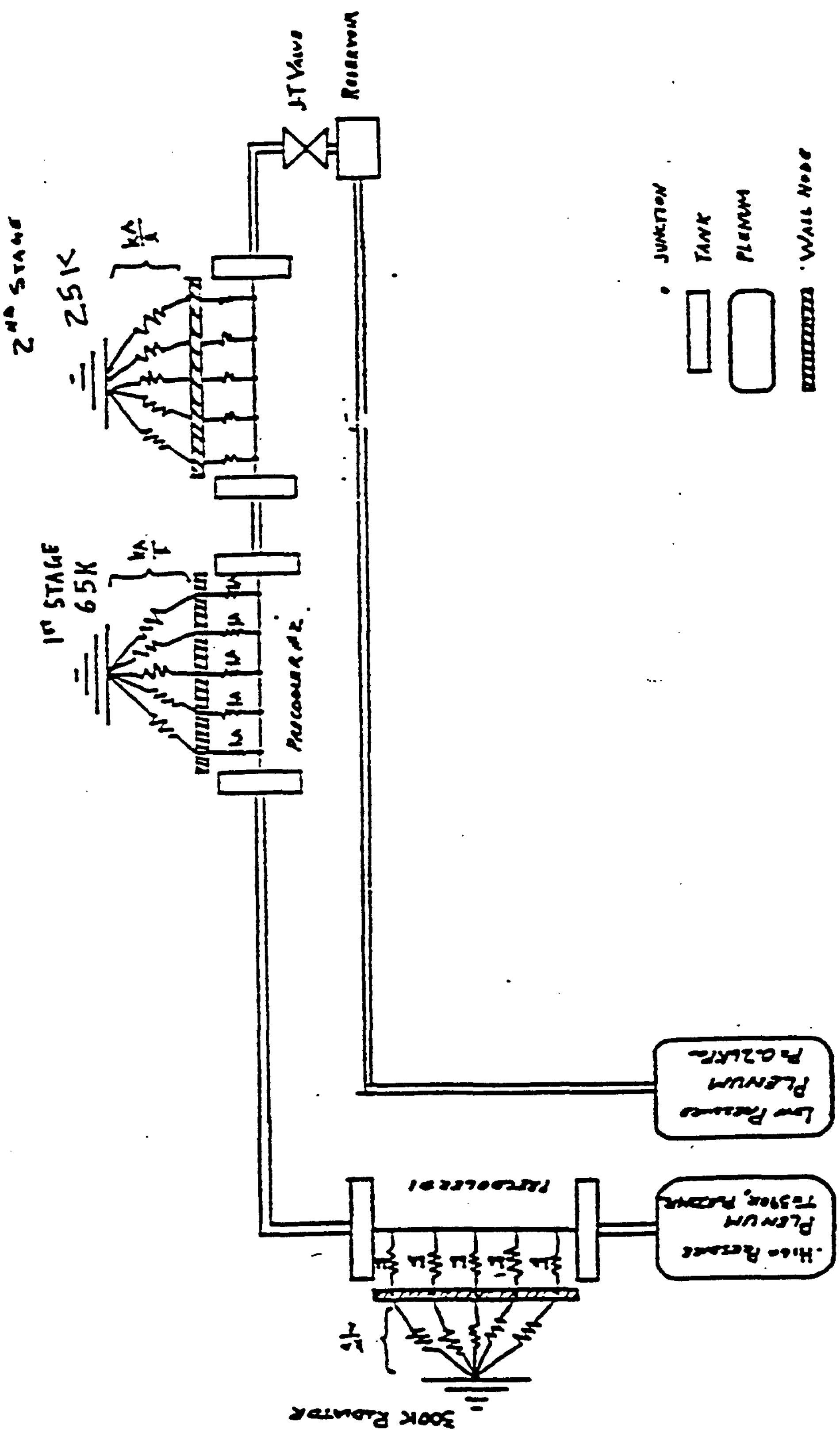


Figure 3: Third-Stage Expander Loop
(Driven by the low-pressure compressor)



5.0 Plans for December

The following activities are planned for December:

1) Replan the program based upon guidelines established at the 18 November working meeting (pending confirmation of funding levels).

2) Obtain AFPL approval for replanned program and resume technical activities.

10 K CRYOCOOLER PROGRAM REVIEW

Brian M. Whitney
Phillips Laboratory
Cryocooler Program Manager
1 Nov 94

10 K CRYOCOOLER PROGRAM STRUCTURE

THREE PHASE PROGRAM

1. Conceptual Design
2. Critical Component Development
3. Engineering Model Fabrication and Test

UP-FRONT COMPONENT DEVELOPMENT TO:

1. Concentrate resources on critical technical issues and performance drivers.
2. Evaluate component impact on the cryocooler system.

PHASED APPRACH ALLOWS FLEXIBILITY TO TAILOR DESIGN TO MEET SYSTEM NEEDS

10 K CRYOCOOLER STATUS

Conceptual Design Phase is complete. Aerojet was selected over two other competitors to continue on with Option 1 (Critical Component Development)

Option 1 was exercised in June 92, but with very little money on contract. AF 6.2 money for FY94 fell through with no BMDO or BE money to replace it.

Program has been in a holding pattern. Only thermal modeling of the expander and compressor has been worked on in Option 1.

Program is undergoing replanning to eliminate the upper stage temp/load requirements and concentrate on the load at 10 K.

10 K CRYOCOOLER TECHNICAL REQUIREMENTS

	BASELINE PREDICTION	REQUIREMENT
INPUT POWER (.150W@10K)	178W	<200W
COOLER WEIGHT	46kg	<50kg
EFFECTIVE WEIGHT	91kg	<10kg

REQUIREMENT	SOLUTION/RATIONALE
TEMP STABILITY (+ 0.1 K)	Steady Suction Pressure Plus Trim Heater
VIBRATION (0.05 N)	No Reciprocating Parts
POWER SUPPLY (28Vdc)	Sorption Stage Electronics Can Operate From Any Voltage Source
MINIMUM SERVICE LIFE (2 yr Ground Storage +10 yr On-Orbit)	Ongoing Materials Development Efforts Are Addressing LaNiSn And ZrNi Long-Life Behavior

UPDATE ON COOLER WEIGHT & POWER - 10 K CONTINUOUS					
Forrest R. Cleveland - 31 Oct 94					
1) Cooler presented in Basic Phase Interim Report - 13 Sep 93					
		3rd Stg	2nd Stg	1st Stg	Total
Net cooling load	W	0.15	2.00	5.00	
Parasitics	W	0.03	0.20	0	
Precooling load	W	0	0.52	5.78	
Gross cooling load	W	0.18	2.72	10.78	
Input power	W	24	296	432	752
Weight	#	6.9	31.5	17.5	56
System effective wt	#	12.9	105.5	125.5	244
2) Cooler without net cooling loads on 2nd and 1st stages					
		3rd Stg	2nd Stg	1st Stg	Total
Net cooling load	W	0.15	0	0	
Parasitics	W	0.03	0	0	
Precooling load	W	0	0.52	2.44	
Gross cooling load	W	0.18	0.52	2.44	
Input power	W	24	56	98	178
Weight	#	6.9	21.8	17.5	46
System effective wt	#	12.9	35.8	42.0	91

TABLE 1

PERIODIC 10 K SORPTION COOLER DESIGN SPECIFICATION

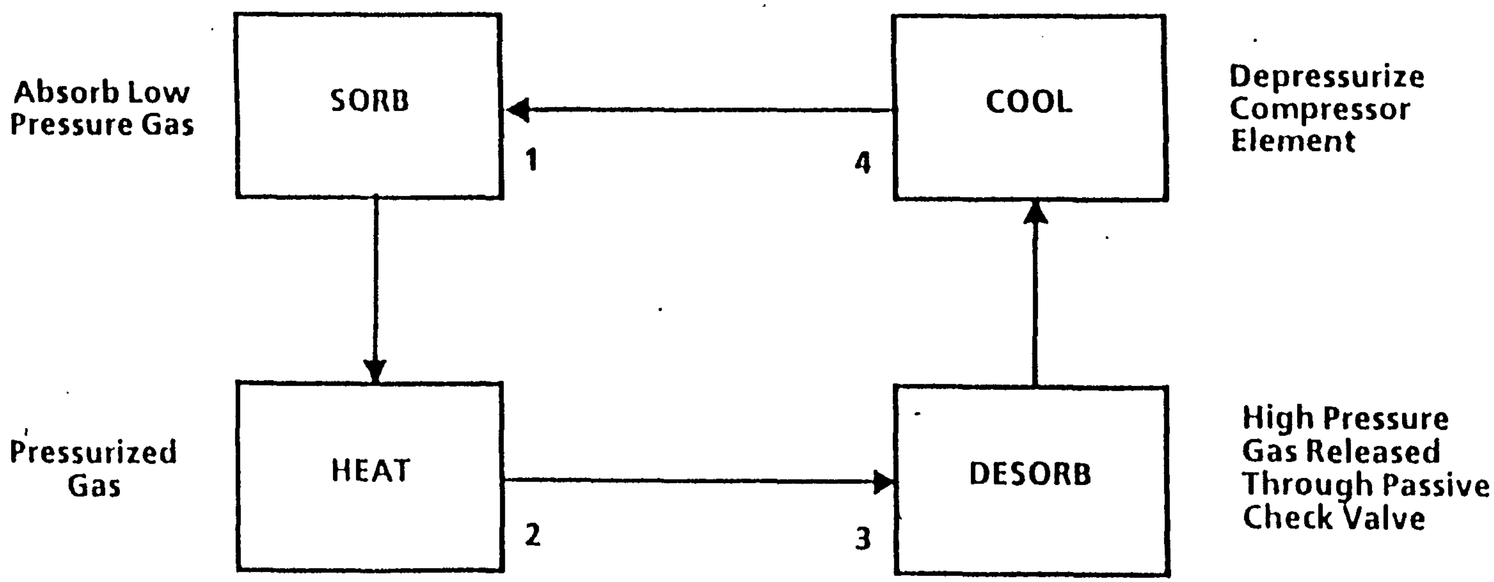
	Nominal	Study Range Minimum	Study Range Maximum	Comments
Detector temperature, K	< 11	NA	NA	
Detector temperature stability, K	± 0.1	NA	NA	
Focal plane heat load, w	0.100	0.05	0.200	Includes FPA parasitics + FR
Upper-stage temperature @ 10 K cooldown start, K	60	50	80	Max. allowable temp after heatup is 80 K
Upper-stage heat load, w	1	0	2	External heat load (e.g., optics); TSD heat load must be accounted for separately
Cooldown time to < 11 K from upper-stage temp, min	<2.0	1.5	3.0	
Cooling duration at < 11 K, min	15	5	30	
Wait period between consecutive cooldowns, min	90	5	240	No recharge between cooldowns
Consecutive cooldowns before recharge	3	1	6	
Total cycle time, hr	24	8	48	Cooldowns + operations + recharge
Heat rejection temperature*, K	250	150	300	Minimum compressor temperature = 200 K
Focal plane weight (beryllium), g	400	100	1000	Includes FPA plus cold window/baffle
Power supply, vdc	28 ± 4	NA	NA	
Service life (ground storage), yr	4	NA	NA	
Service life (orbital lifetime), yr	10	NA	NA	
Ground storage temperature, K	250 to 350	NA	NA	
Performance goals:				
Total input power from spacecraft bus, w	< 100			
Total cooler system weight, kg	<30			
Weight/power penalty factor*, kg/w	0.25			Accounts for radiators and solar array
Total vehicle effective weight, kg	<55			

*Weight/power penalty factor must be increased for radiator temperatures below 230 K.

Simple Principles Describe Sorption Refrigerator Operation

GENCORP
AEROJET

- Sorption Compressor Driven Thermally
  - Heating Compresses Refrigerant Gas
  - Large Pressure Ratio Delivered



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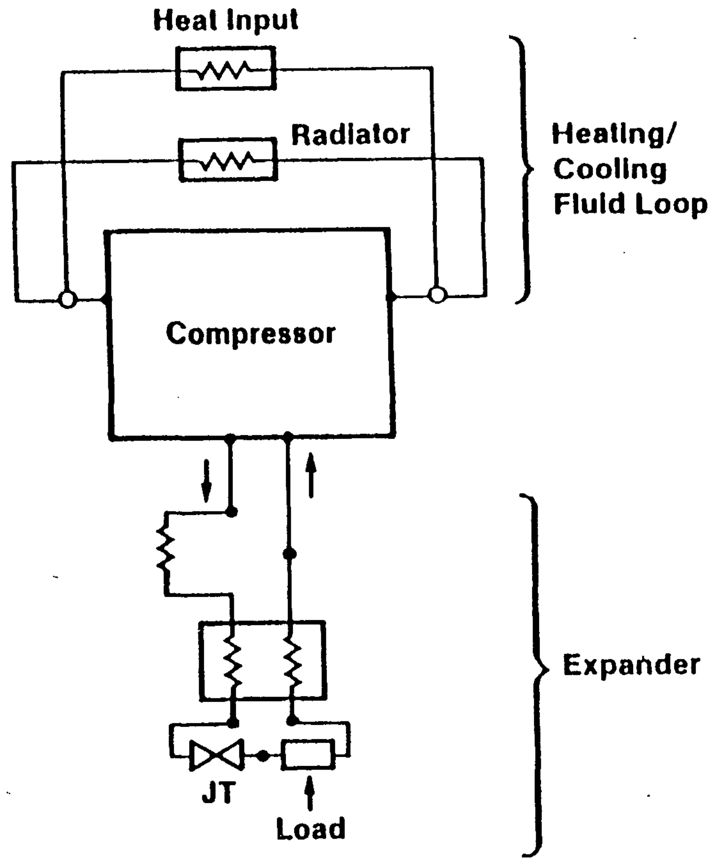
The Technology Being Developed Is Simple And Highly Reliable

GENCORP AEROJET

- Sorption Refrigerator Combines A Sorption Compressor With An Expander
- Expansion Through Joule-Thompson Orifice Provides Refrigeration
- Staging Several Sorbent/Sorbate Combinations Permits Cooling From 5 To 200K

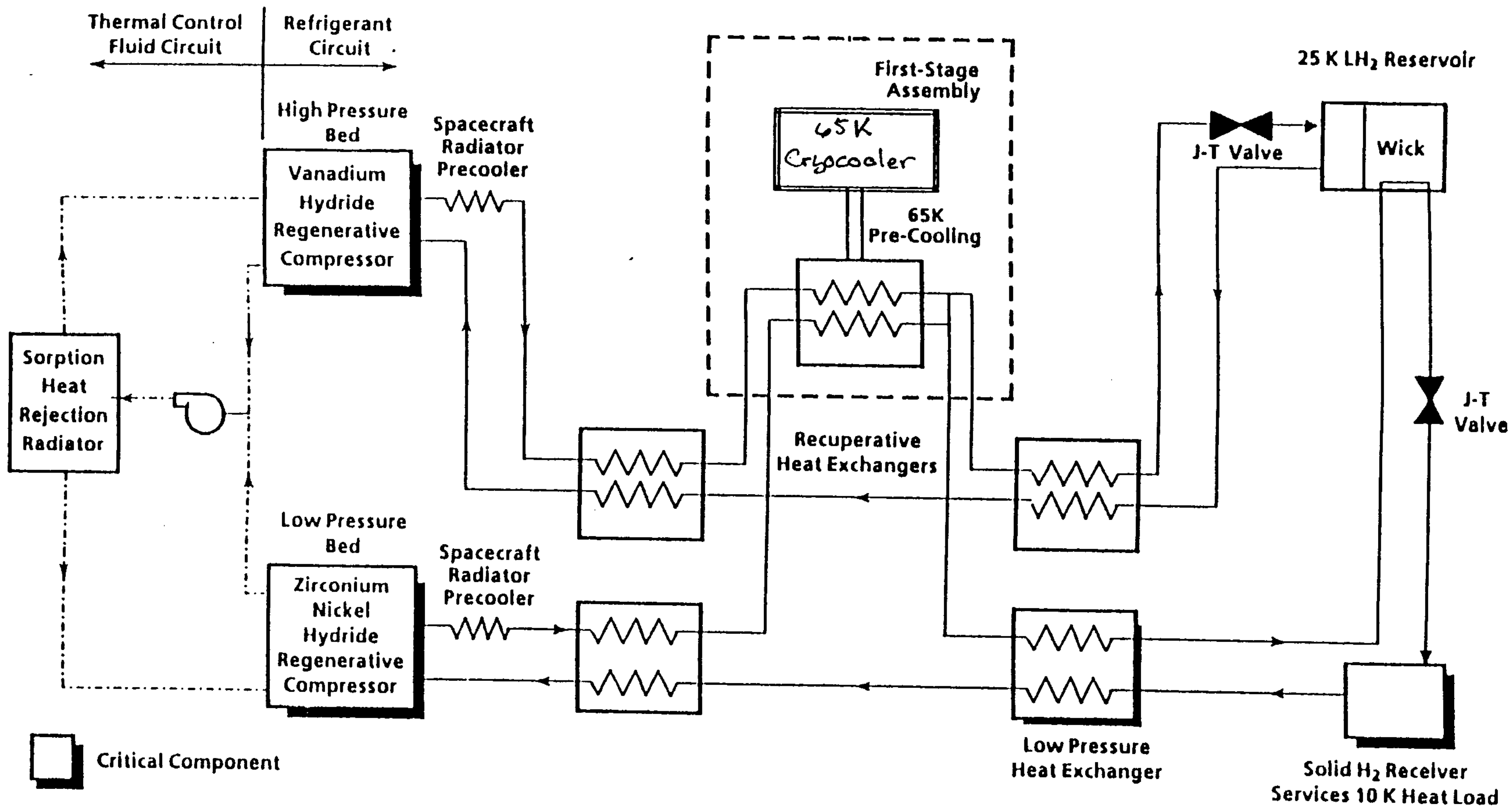


SORPTION TECHNOLOGY ADVANTAGES

GENCORP
AEROJET

- Fault Tolerant Hardware Leads To High Reliability
  - No Cold Moving Parts
  - No Close Tolerances
  - Redundancy Easily Incorporated
- Split System Allows Easy Sensor Integration
  - Cold End Can Be Located On Focal Plane (No Vibration)
  - Compressors And Heat Exchangers Can Be Located Remotely
  - Sorption Refrigerator Can Be Driven By Any Heat Source
- Development Within Any Sorbent Technology Is Generic
  - One Design Applicable Across Entire Sorbent Temperature Range
  - Hybrid System is Extremely Efficient in Sinking Off 65 K SSC

Baseline System Configuration At Kick-Off Meeting



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PHILLIPS LABORATORY

Solid Hydrogen Can Also Be Produced By Alternate Reservoir Approach

GENCORP AEROJET

- Originated By Jack Jones Of JPL & Al Johnson Of Aerospace Corp. (J/J Concept)

- Presented Publicly By Al Johnson:
  - 7th International Cryocooler Conference
    Santa Fe, NM, 17-19 November 1992

- Develop As A Three-Stage Periodic Cryocooler.

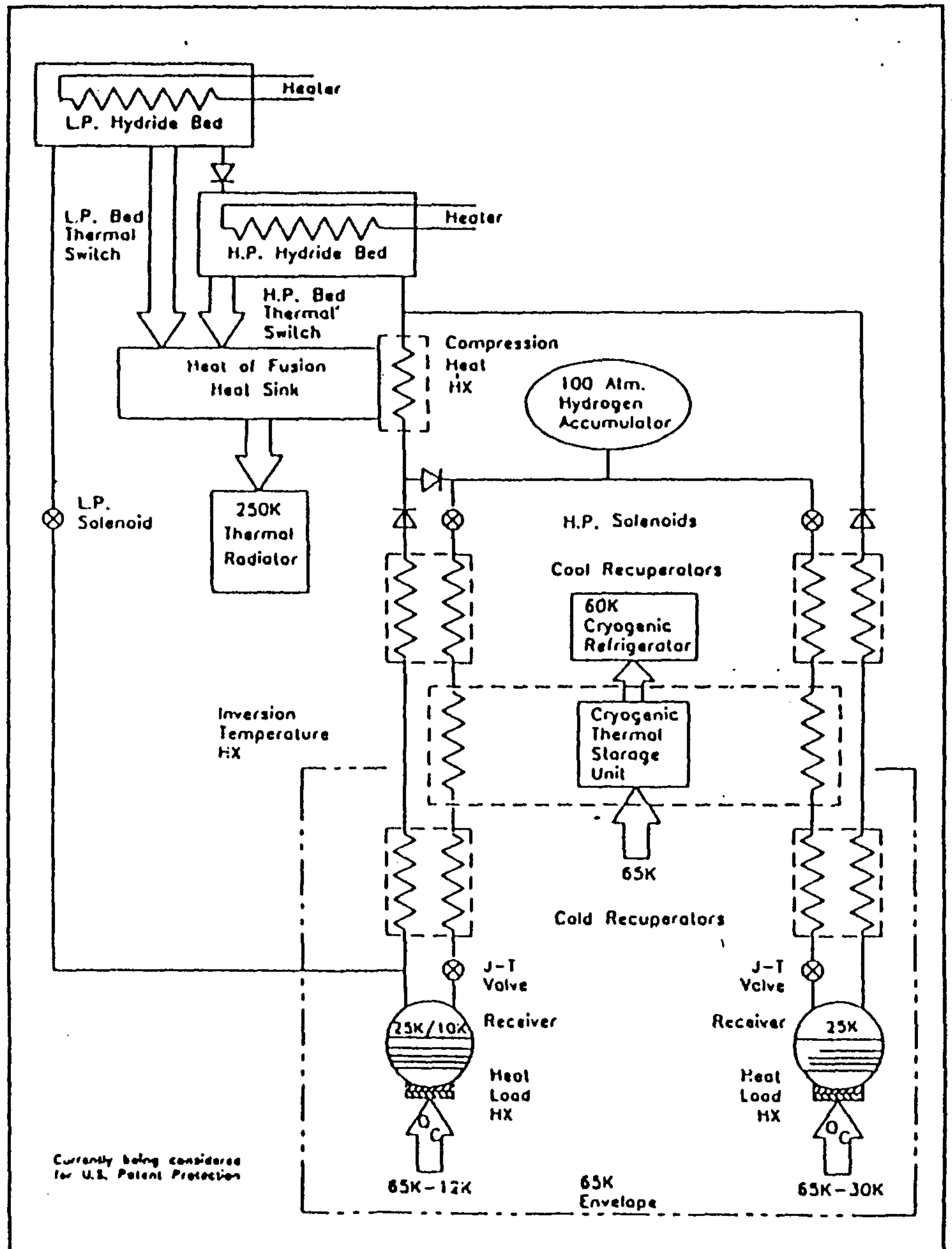
- Can Be Converted To A Three-Stage Continuous Cooler:
  - Double The Periodic Layout
  - Combine Duplicate Sorbent Beds For Weight Savings
  - Operate Expansion Circuits Consecutively

- Requires Dual Reservoirs & Thermal Switches At Second And Third Stage Loads.

- All components In Expansion Circuit Have Been Demonstrated.

Continuous Cooler Evolves From Periodic Concept

GENCORP AEROJET



The Regenerative Hydride Compressor Assembly (RHCA) Is An Extension Of Existing Technology

GenCorp
Aerojet

- All Key Issues Have Been Identified And Are Being Addressed:
  - Sorbent Material Development
  - An Efficient Regeneration Scheme To Recapture Sensible Heat.
  - High Heat Transfer/Fast Gas Kinetic Compressor Design
- The IR&D Development Schedule Results In A Proven And Validated Technology At The 10 Kelvin Cryocooler Program PDR.
- Activity Is Being Funded On Aerojet Discretionary Research And Development Funds - In Compliance With Federal Acquisition Regulations.

The IR&D RHCA's Performance Specifications Are Traceable To The 10 Kelvin Cryocooler System

GENCORP AEROJET

- LaNiSn Is The Sorbent Material
- Critical Operating Parameters Will Address Cryocooler System Requirements

	RHCA	10K CRYOCOOLER
Refrigerant Mass Flow(mg/sec)	10 -15	15
Operating Pressure(MPa)	Low: 0.3 - 0.6 High: 8 - 10	Low: 0.2 - 0.6 High: 10
Rejection Temperature(K)	260 - 310	280 - 300
Regenerative Mass Flow(g/sec)	10 - 12	10

- Demonstration Tests Will Validate Performance Under Cryocooler System Conditions.
  - Resolves All Key Issues For The High Pressure Hydride Compressor.

Key Issues Unique To ZrNi Compressors Are Being Addressed On BETSCE

AEROJET

- These Issues Are:
  - Absorbing Capacity And Bed Kinetics At Very Low Pressure
  - Materials Properties And Characterization
- Regeneration Is Not Critical For A ZrNi Compressor
  - Vehicle Effective Weight Increases 12 kg Without Regeneration
- ZrNi Compressor Design Is Less Demanding Than LaNiSn
  - Lower Operating Pressure Level
  - Lower Cooling Load (Therefore Less Sorbent Mass)
  - Less Severe Heat And Mass Transfer Characteristics

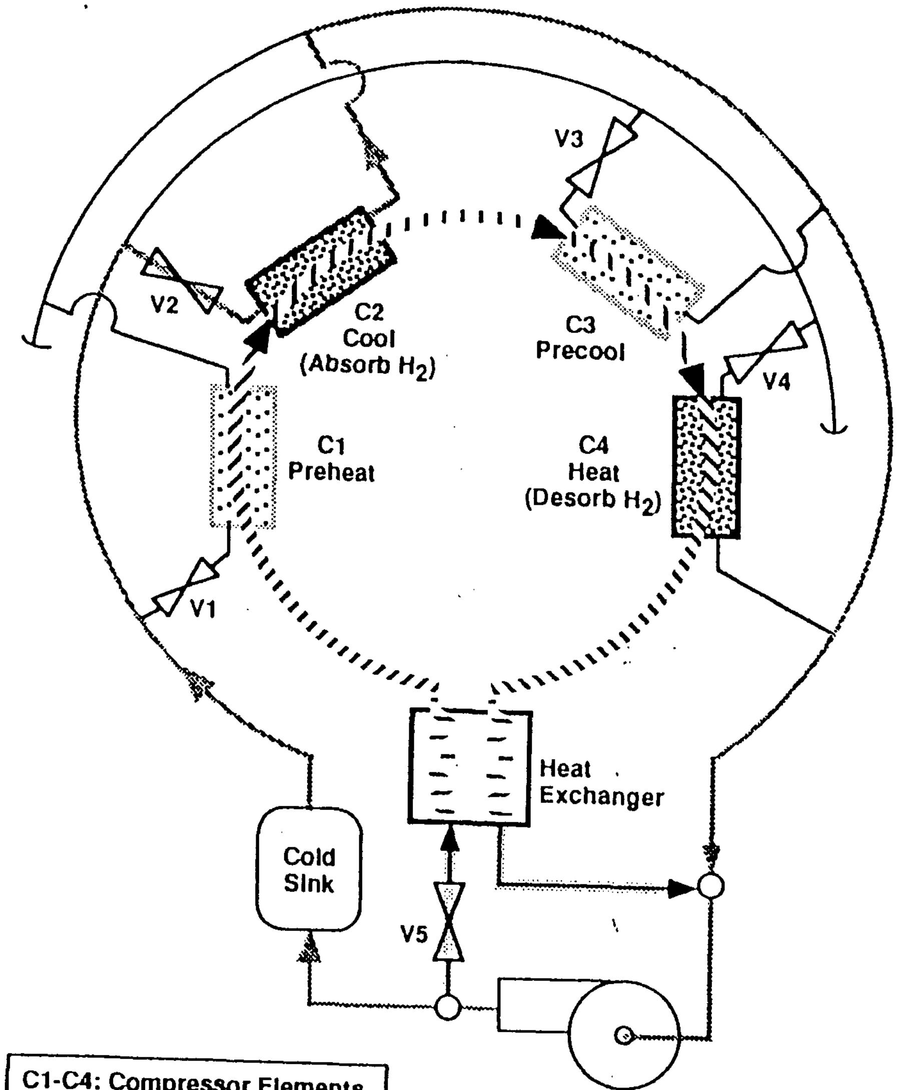
GENCORP AEROJET

BETSCE Hydride Performance Requirements, Margins And Test Results+

Functional Element	Quantity H2, In Grams	Time In Seconds	Total Capacity H2, In Grams
Low Pressure Sorbent Bed Margin	0.7 (0.55)* [27%]	40 + 0.74 gms In 40 sec	1.52 (1.03)* + 2.19 gms [48%]
Fast Absorption Sorbent Bed Margin	8.0 (5.95)* [34%]	80 + 9.4 gms In 80 sec	8.0 (5.95)* + 12.5 gms Maximum [34%]
High Pressure Sorbent Bed Margin	——	——	9.35 (6.98)* + 12.1 gms Reversible [34%]
Cooldown Time		120 Sec From 60K + 95 Sec From 70 K	
Reservoir Temp/Time		≤ 11K For ≥ 10 Min + < 11K For 20 Min	

* Note: Values In Parenthesis Are The Cryostat Assembly Flow Requirements

An Efficient And Simple Regenerative Scheme Will Be Employed

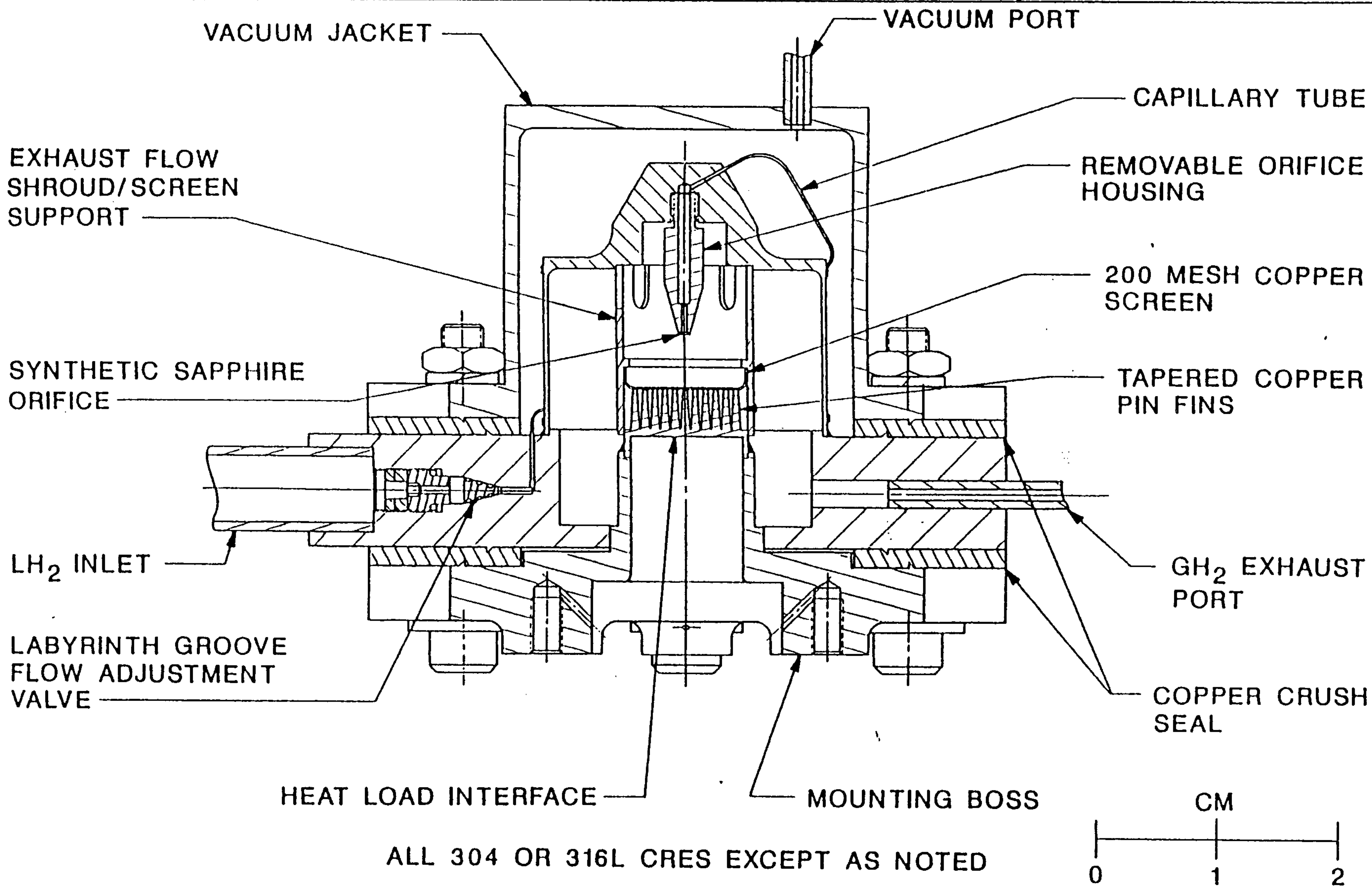


C1-C4: Compressor Elements
V1-V5: Solenoid Values

GenCorp Aerojet

ENGINEERING DEVELOPMENT MODEL CRYOSTAT PROVIDES VERSATILITY

General Pneumatics Corporation



ALL 304 OR 316L CRES EXCEPT AS NOTED

CRYOSTAT CROSS SECTION

93

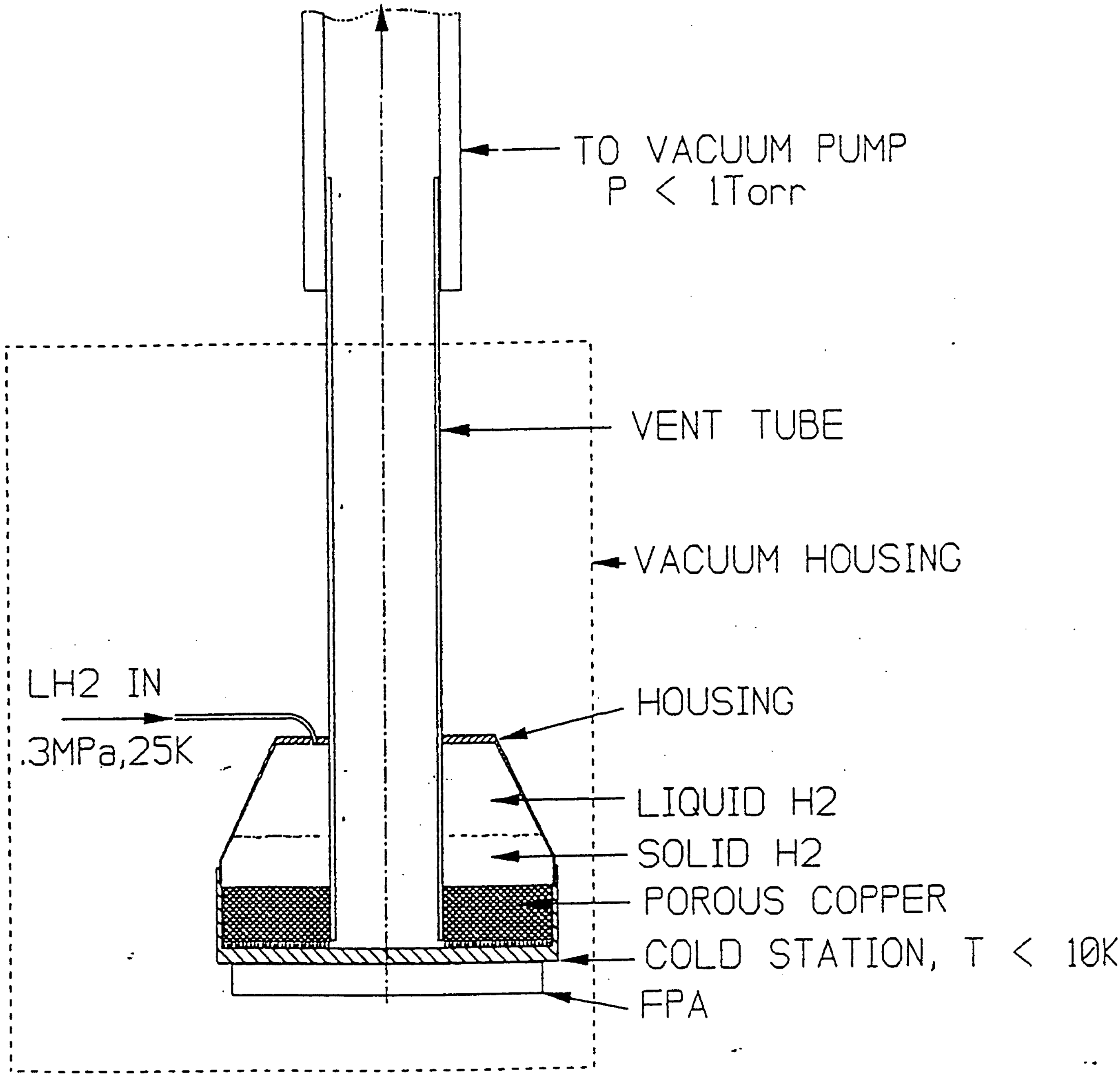
CRYOSTAT PROVIDES EFFICIENT THERMAL MANAGEMENT

10 K COLDWELL IS SURROUNDED BY RETURN FLOW ANNULUS AND VACUUM JACKET FOR ISOLATION FROM 25 K ENVIRONMENT.

CAPILLARY TUBE IS MOUNTED ON THIN 304 CRES WALL BETWEEN RETURN FLOW AND VACUUM JACKET FOR TRANSITION FROM 25 K TO 15 K WITH MINIMUM CONDUCTED PARASITICS.

ORIFICE JET DEPOSITS H_2 ICE IN ARRAY OF COPPER PIN FINS ON BACK OF COLDPLATE.

COPPER SCREEN PREVENTS H_2 ICE ESCAPE, PIN FINS AND SCREEN PROVIDE GOOD CONDUCTIVITY TO REFRIGERATION LOAD.



10 K CONTINUOUS FLOW SUBLIMATION COOLER
FINAL CONFIGURATION CONCEPT

10 K CONTINUOUS FLOW JT CRYOCOOLER CONCEPT AND FEATURES

* LH2 flows through a relatively large capillary tube at a rate about 100 times greater than steady state to cool down to 10 K and freeze H2 on a porous copper plug which blocks further liquid flow.

* SH2 in contact with the Cu plug sublimes at < 10 K and cools the FPA.

* A temperature gradient is established in the solid/liquid H2 behind the plug with heat flowing toward the 10 K surface.

* The capillary tube has only liquid in it thus a pressure difference of 300 kPa keeps the SH2 in contact with the porous Cu.

* The H2 vent rate is directly proportional to the rate of heat input.

* The SH2 has significant thermal inertia so the flow rate changes slowly.

* The porous Cu is sized to have a small ΔT between the FPA and the SH2.

* Temperature is controlled by adjusting the vent pressure.

10 K CRYOCOOLER PROGRAM CONCLUSION

- A High Payoff Conceptual Design Which Meets all Requirements Has Been Defined.
- Practical Solutions To All Critical Technologies Have Been Identified.
- The Approach Is Flexible And Risk Tolerant - The Ability Exists To Change Program Direction To a Periodic System .
- The Resourses To Execute This Program Are In Plce And Committed.
- The Program Will Deliver An Engineering Model Cryocooler By Mid CY97
- Streamlined Program Management Allows For Rapid Response To Customer Needs.

THE 10 K CONTINUOUS PROGRAM GIVES BRILLIANT EYES, BMDO, AND THE AIR FORCE THE GREATEST LEEWAY TO DEAL WITH ITS 10 K COOLING NEEDS

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