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HIGH HEAT TRANSFER OXIDIZER HEAT EXCHANGER DESIGN AND ANALYSIS

FINAL REPORT

CONTRACT NAS3-24738

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Lewis Research Center
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16. Abstract The RL-10 IIB engine, a derivative of the RL10, is capable of multimode thrust operation. This engine operates at two low thrust levels: tank head idle (THI), which is approximately 1 to 2 percent of full thrust, and pumped idle (PI), which is 10 percent of full thrust. Operation at THI provides vehicle propellant settling thrust and efficient engine thermal conditioning; PI operation provides vehicle tank pre-pressurization and maneuver thrust for low-g deployment.

Stable combustion of the RL10-IIB engine during the low thrust operating modes can be accomplished by using a heat exchanger to supply gaseous oxygen to the propellant injector. The Oxidizer Heat Exchanger (OHE) vaporizes the liquid oxygen using hydrogen as the energy source. This report presents the design, concept verification testing and analysis for such a heat exchanger. The design presented herein uses a high efficiency compact core to vaporize the oxygen, and in the self-contained unit, attenuates any pressure and flow oscillations which result from unstable boiling in the core. This approach is referred to as the high heat transfer design. An alternative approach which prevents unstable boiling of the oxygen by limiting the heat transfer is referred to as the low heat transfer design and is reported in Pratt & Whitney report FR-19135-2 (i.e., CR-179488).

This report, and report FR-19135-2 (CR-179488), together represent a second iteration of the RL10-IIB heat exchanger investigation program. The design and analysis of the first heat exchanger effort is presented in more detail in NASA CR-174857. Testing of the previous design is detailed in NASA CR-179487.

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FOREWORD

This report summarizes the design, analysis, and concept verification testing of the Alpha United high heat transfer oxidizer heat exchanger concept for the RL10-IIB rocket engine and is submitted in compliance with the requirements of NASA Lewis Research Center Contract NAS3-24738.

The preliminary design effort was begun in January 1985 by Alpha United in response to a Request For Quotation (RFQ) for a heat exchanger defined by Pratt & Whitney Preliminary Purchase Performance Specification (PPS) F-654. The design, analysis and unit fabrication was accomplished by Alpha United Incorporated, El Segundo, California. Analytical support was given to Alpha United by Mr. Fred Faulkner of Thermodynamics Analysis Service, Lomita, California and Consulting Engineer, Mr. Samuel Tepper, of Palos Verdes, California. The effort was headed by Thomas D. Kmiec, Assistant Project Engineer, Pratt & Whitney Government Products Division (P&W/GPD).

The following individuals have made significant contributions to the preparation of this report: Paul G. Kanic and Richard J. Peckham, P&W/GPD.

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SUMMARY

Stable combustion of the RL10-IIB engine during low thrust operating modes (Tank Head Idle and Pumped Idle) can be accomplished by using a heat exchanger to supply gaseous oxygen to the propellant injector. The Oxidizer Heat Exchanger (OHE) vaporizes the liquid oxygen using hydrogen as the energy source. This report presents the design, concept verification testing and analysis for such a heat exchanger. The design presented herein uses a high efficiency compact core to vaporize the oxygen and, in the self-contained unit, attenuates any pressure and flow oscillations which result from unstable boiling in the core. This approach is referred to as the high heat transfer design. An alternative approach which prevents unstable boiling of the oxygen by limiting the heat transfer is referred to as the low heat transfer design and is reported in Pratt & Whitney report FR-19135-2.

SECTION I
INTRODUCTION

A. BACKGROUND

The RL10-IIB engine, a derivative of the RL10, is capable of multi-mode thrust operation. This engine operates at two low-thrust levels: tank head idle (THI), which is approximately 1 to 2 percent of full thrust, and pumped idle (PI), which is 10 percent of full thrust. Operation at THI provides vehicle propellant settling thrust and efficient engine thermal conditioning. Pumped idle (PI) operation provides vehicle tank prepressurization for transition to rated thrust or can be used to provide maneuver thrust for low-g deployment.

This is a second iteration of the RL10-IIB heat exchanger investigation conducted under the RL10 Product Improvement Program. The design and analysis of the first heat exchanger effort is presented in Pratt & Whitney (P&W) report FR-18046-3 (CR-174857) (Reference 1). Testing of that design is detailed in FR-19134-3 (CR-179487) (Reference 2) for the component level test and FR-18683-2 (CR-174914) (Reference 3) for the engine test.

B. PURPOSE

Stable combustion of the RL10-IIB engine at THI and PI thrust levels can be accomplished by providing gaseous oxygen at the propellant injector. Using gaseous hydrogen, returning from cooling the thrust chamber jacket, as an energy source, a heat exchanger can be used to vaporize the liquid oxygen. The vaporization must be accomplished without creating flow instability due to unstable boiling of the oxygen. In addition, the heat exchanger can also be used to provide gaseous oxygen for vehicle tank pressurization during full thrust operation. A flow schematic depicting the heat exchanger position in the engine cycle is presented in Figure 1.

C. APPROACH

Performance, structural, and quality requirements were established by P&W for the RL10-IIB Oxidizer Heat Exchanger (OHE) and are defined in Appendix A, Purchase Performance Specification (PPS) F-654. This specification was used to solicit responses from prominent suppliers experienced in heat exchanger design and manufacturing, and resulted in proposals from two companies. The concept discussed herein is identified as a high heat transfer OHE and was proposed by Alpha United, Inc. The remaining design is a concurrent effort incorporating a low heat transfer approach and is presented in P&W Report FR-19135-2 (CR-179488) (Reference 4).

Alpha United has selected a high heat transfer approach in designing the OHE. This approach is intended to provide a high rate of heat transfer in a compact core and attenuate any oscillations which may occur due to unstable boiling of the oxidizer. (The low heat transfer approach avoids the onset of unstable boiling.) In this design the core is enclosed by a pressure vessel which attenuates any oscillations encountered and also serves to contain the required high full thrust operating pressures without the additional weight that a pressure-sustaining core would require.

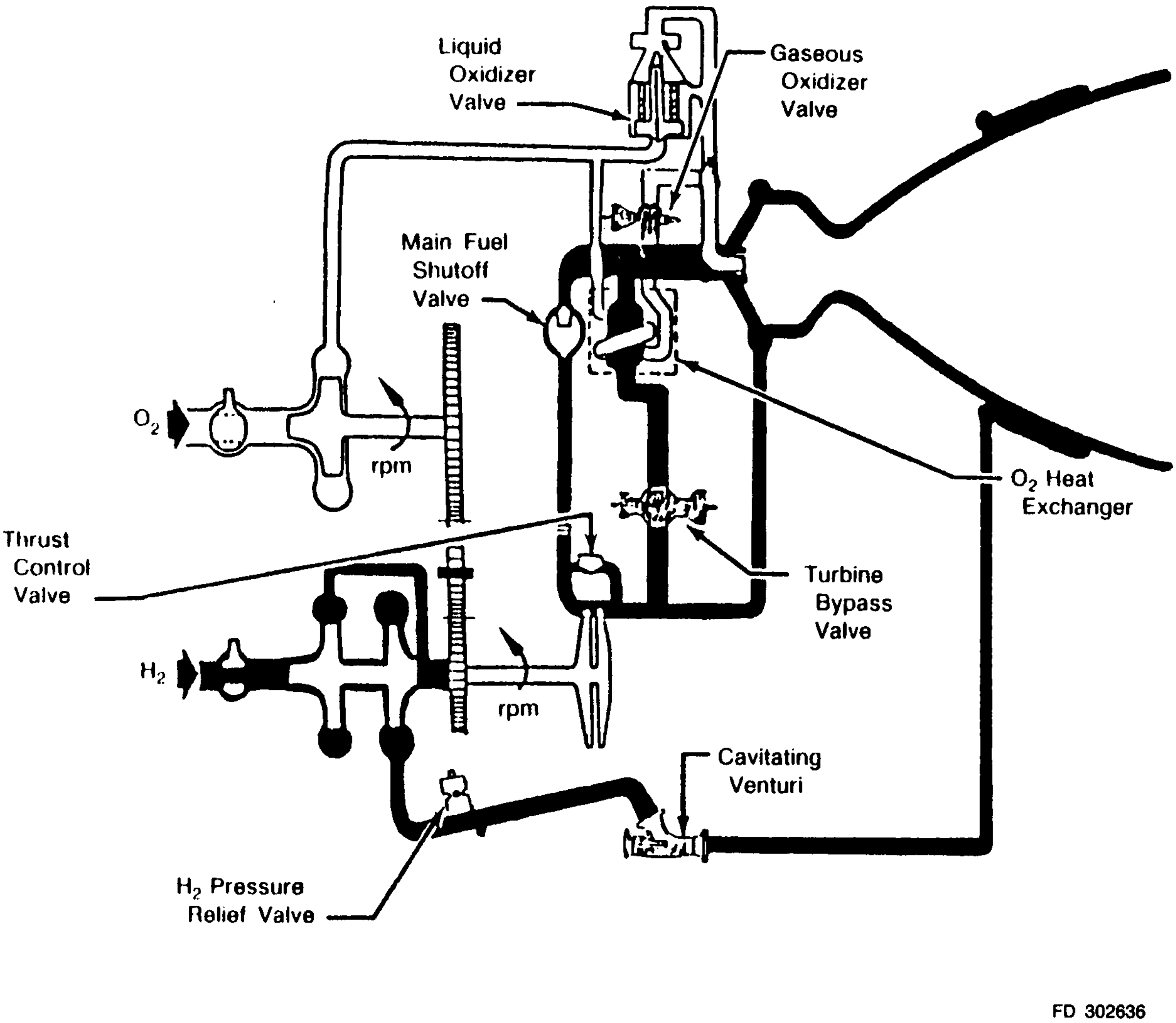

Figure 1. RL10-IIB Engine Flow Schematic

To verify that the required high heat transfer rate could be obtained and oscillation damping accomplished, a concept test was performed on an individual oxidizer flow panel and a scaled damping volume. The information from that test series was used in the final design.

At appropriate intervals during the design process, preliminary and critical design reviews were conducted by P&W during which areas of concern were discussed and potential problems were identified. Additional investigation and analysis were performed where necessary.

D. SCOPE

This report presents the design, analysis, and concept verification testing of a high heat transfer OHE for the RL10-IIB rocket engine. The design and analysis was completed for P&W by Alpha United in December 1985, and fabrication of two OHE units is currently in progress. Two OHE units will be tested at the component level to verify performance and manufacturing repeatability, and then one will be mounted on an experimental breadboard RL10-IIB engine for system testing.

SECTION II
OXIDIZER HEAT EXCHANGER CONFIGURATION

This design consists of a two stage high efficiency compact core suspended in a pressure vessel outer shell. This configuration permits the use of a lightweight core to accomplish the heat transfer while the pressure vessel contains the required high operating pressure. In addition, half of the pressure vessel serves as a damper volume to attenuate any oscillation which may result from unstable boiling of the oxygen in the core. This configuration is shown in Figures 2 and 3.

The core is composed of alternating hydrogen and oxygen flow panels which are brazed together in a vacuum braze process. The core is supported in the pressure vessel by a ring which surrounds it. The ring also serves to segregate the oxygen and hydrogen and thereby creates the separate damper volume on the oxygen discharge side of the core which is used to attenuate oscillations. The oxygen is introduced into the core through a lined bellows which compensates for the thermal expansion differential between the core and outside shell. The hydrogen is introduced to the core through a tube on the side of the shell. The hydrogen and oxygen gases are discharged through flanges located directly on the shell. This arrangement permits flexibility in configuration for mounting on the engine, since the discharge flanges can be located nearly anywhere on each half of the pressure vessel.

The overall length of the unit is 24.25 inches, with a width of 17.00 inches and pressure vessel diameter of 8.5 inches. The calculated weight of the unit is 35.75 pounds.

The following sections present the detail configurations of the oxygen and hydrogen circuits. The design and analysis leading to this configuration is presented in Section III.

A. OXYGEN CIRCUIT

Liquid oxygen enters the heat exchanger through a tube and bellows passing through the H_2 section of the pressure vessel before reaching the core inlet manifold. It then progresses through the core. Gaseous oxygen discharges from the core into the O_2 damping volume and then leaves the OHE through the O_2 discharge flange.

There are several individual layers which allow straight line oxygen flow through the core. Each layer contains four different offset fin arrangements of equal width with fin density increasing from the hydrogen inlet side of the core to the H_2 turnaround side as shown in the schematic of Figure 4.

B. HYDROGEN CIRCUIT

Hydrogen enters the heat exchanger through the H_2 inlet flange and flows through a short tube into the stage 2 core inlet manifold. H_2 then enters the individual passages of stage 2 and transitions into stage 1 through the H_2 turnaround manifold. The stage 1 passages discharge into the H_2 discharge volume side of the pressure vessel, allowing H_2 to exit the OHE through the discharge flange.

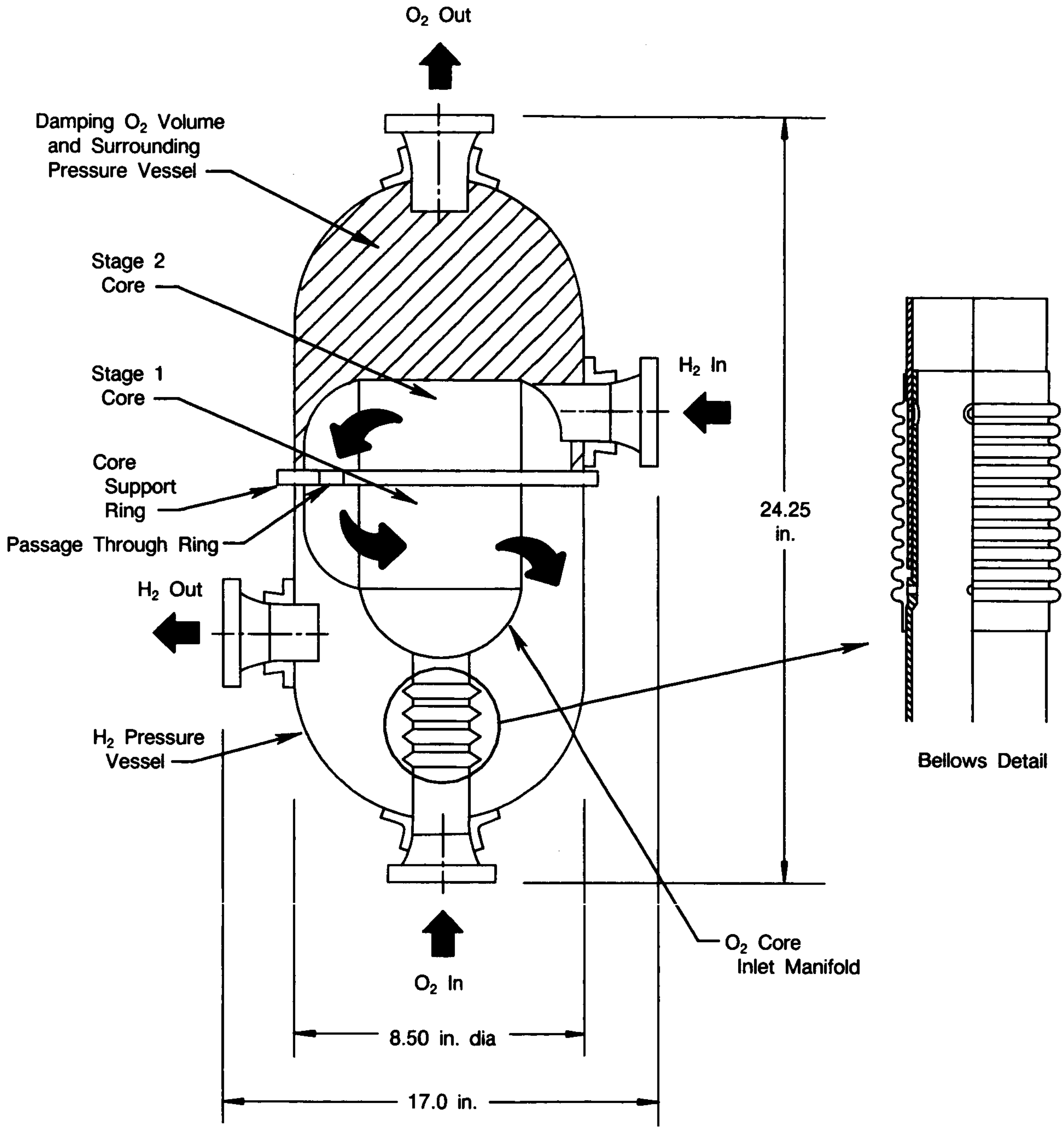

Figure 2. High Heat Transfer Oxidizer Heat Exchanger

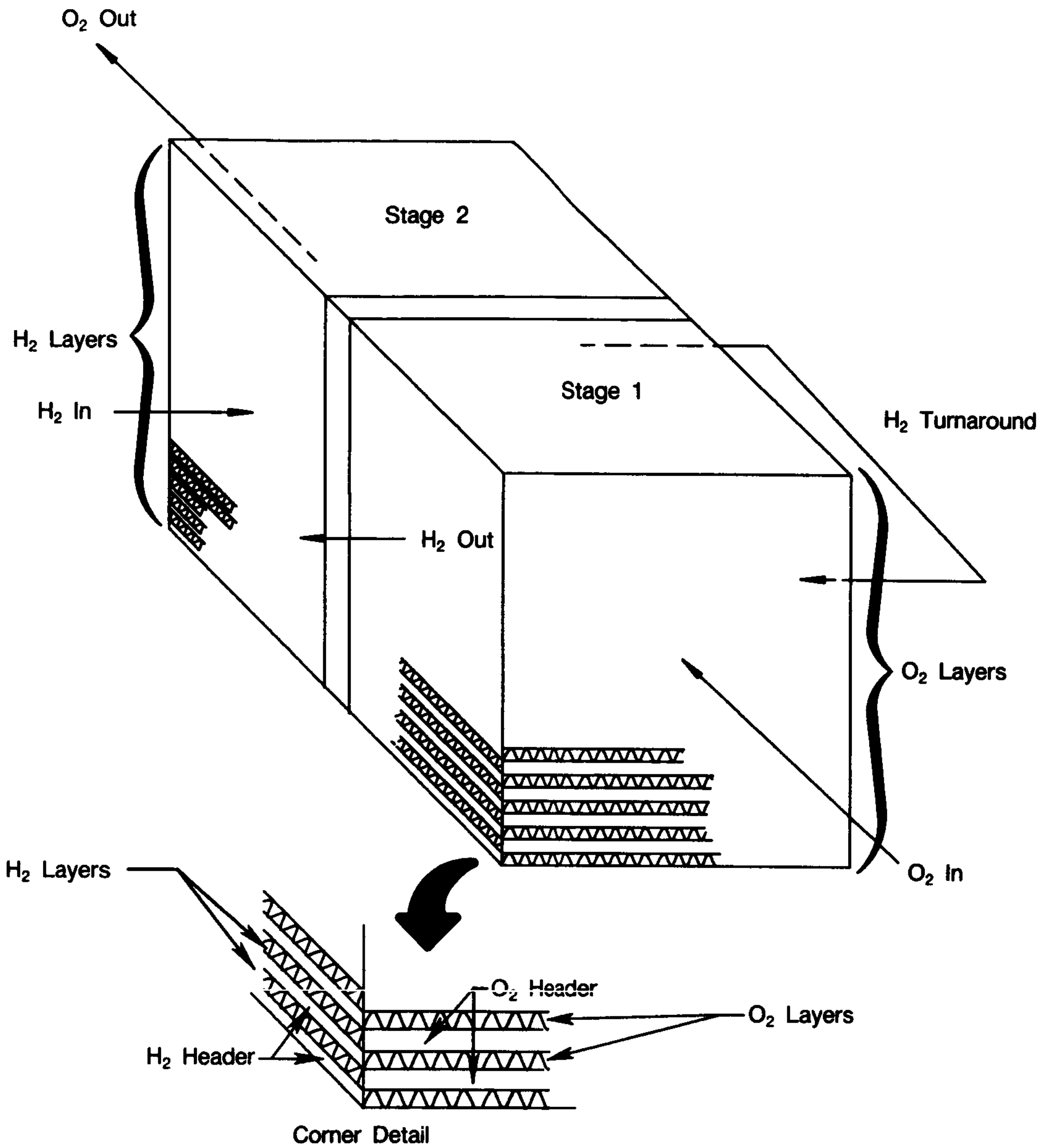

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Figure 3. High Heat Transfer Oxidizer Heat Exchanger Core Configuration

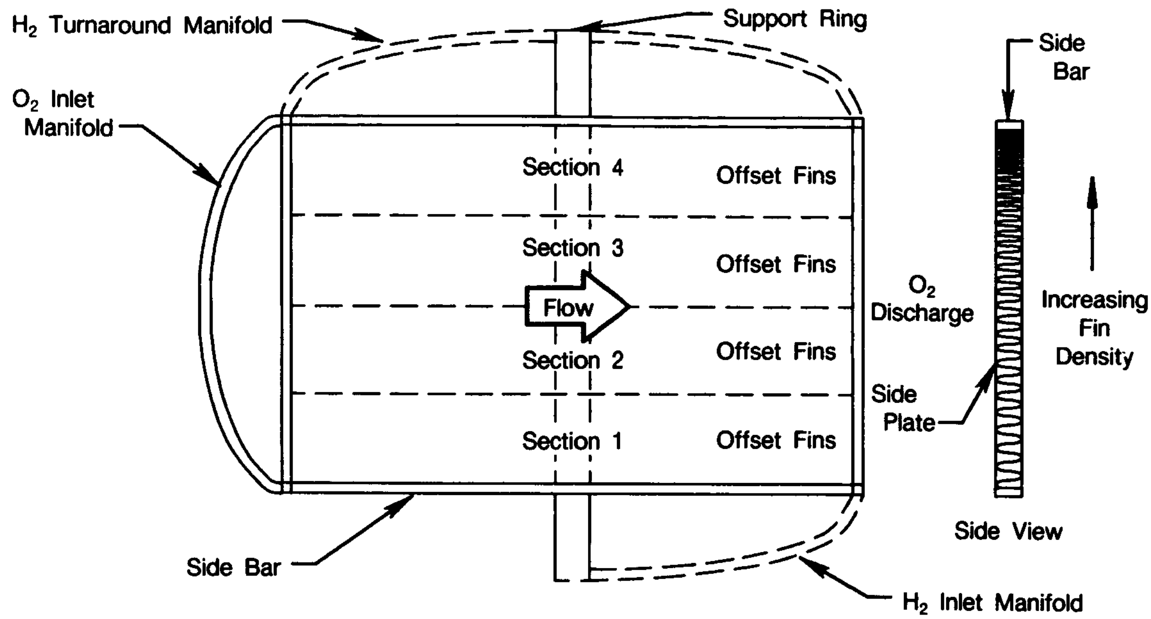

Figure 4. Oxygen Layer Configuration

Both stages each have numerous layers of flow passages. Within each passage, the fin configuration is the same throughout stages 1 and 2. The outer (H_2) layers, i.e., those on the top and bottom of the core, contain a shorter, higher density fin arrangement to maintain heat-transfer consistent with the center (inner) layers since the outer passages have oxygen flow on only one side. A schematic representation of the H_2 layers is shown in Figure 5.

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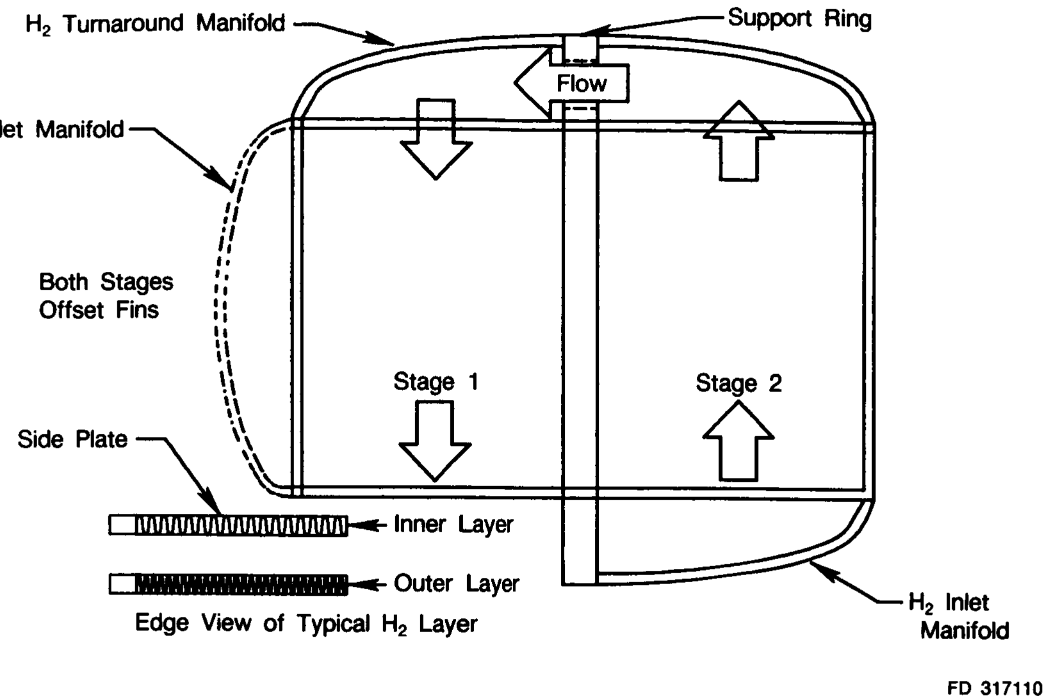

Figure 5. Hydrogen Layer Configuration

SECTION III
DESIGN

The high heat transfer OHE is a two-stage cross-counterflow unit using alternate layers of oxygen and hydrogen flowpaths. As a single self-contained unit, it is intended to vaporize the oxidizer while maintaining low core differential pressure with minimal pressure oscillations.

Design considerations were focused to meet the requirements of PPS F-654. Two design points, tank head idle (THI) and pumped idle (PI), were used as the main criteria for determining the performance characteristics. The full thrust point does not present a heat transfer performance problem due to low flow and high pressure conditions. The OHE unit is designed to meet the major criteria specified by the PPS: low pressure drop, minimum pressure oscillations, and no less than 95 percent exit quality for the oxidizer. In addition to these requirements, a possible condition of concern with high heat transfer rates is "dryout," where the OHE O_2 passage wall temperature (T_{wall}) exceeds the saturation temperature of the fluid (T_{sat}) by an excessive amount. In this situation, a thin film of gas is created against the O_2 passage hot wall, severely limiting the heat flux to the flowing liquid. Such a condition is undesirable unless the heat exchanger design compensates for the analytically predictable heat transfer degradation. Although dryout conditions were predicted to exist in some areas of the high heat transfer OHE, the effects are not detrimental to the overall OHE performance. This is discussed in greater detail in the Thermal Analysis section.

The following sections present a description of the design analysis.

A. THERMAL ANALYSIS

The thermal analysis performed in support of this design effort was conducted by constructing a thermal model for use with a thermal analyzer computer program. The program was modified for this analysis to include boiling heat transfer and two-phase flow in the fluid streams. This program provides for elemental analysis of the core with three dimensional conduction, convection, or radiation heat transfer. The output of the analyses for the Pumped Idle and Tank Head Idle operating modes is presented in the following. A description of the program can be found in Appendix B.

The OHE thermal analysis was performed in two steps. A preliminary design effort was done using the conditions and requirements defined by PPS F-654 and assumptions based on previous similar work. The second step involved remodeling using information obtained from the concept verification tests. These tests used a single O_2 layer configured to investigate the assumptions made in the preliminary design. Liquid nitrogen tests reflecting the THI and PI conditions were run to establish heat transfer and pressure drop characteristics and to evaluate the effect of the damping volume. The final design then incorporated all the information and conclusions deduced from this testing. Complete details of the tests are presented in Section IV.

1. Pumped Idle

Design point thermal performance was based on the PI condition, with subcooled liquid oxygen entering the heat exchanger to be vaporized to at least 95 percent quality. The OHE performance characteristics at Pumped Idle are shown in Table 1. Preliminary design calculations at the PI condition showed that superheated oxygen would discharge from the OHE as 100 percent gas at 207°R. The hydrogen discharges at 226°R. Pressure drops for the oxygen and hydrogen were at or below the allowed maximums at 4.7 psid and 0.98 psid, respectively. The heat transfer rate for the preliminary design was 970,060 Btu/hr.

Table 1. *Oxidizer Heat Exchanger Characteristics at Pumped Idle (PI) Conditions*

	Preliminary Design	*Final Design*	*Specification Requirement*
Cold Side (1 pass)			
Fluid	LO_2	LO_2	LO_2
Flow Rate (lb/sec)	2.84	2.84	2.84
Inlet Temperature (deg R)	168	168	168
Boiling Temperature (deg R)	207	207	—
Outlet Temperature (deg R)	207	256	—
Inlet Pressure (psia)	110	110	110
Pressure Drop (psid) (Including inlet and exit fittings)	4.7	4.3	4.7 maximum
Exit Quality (% gaseous oxygen)	100	100	95 minimum
Heat Transfer Rate (Btu/hr)	970,060	1,115,730	—
Flow Length (in.)	8.25	8.625	—
Hot Side (2 pass cross counter flow)			
Fluid	GH_2	GH_2	GH_2
Flow Rate (lb/sec)	0.190	0.190	0.190
Inlet Temperature (deg R)	659	659	659
Outlet Temperature (deg R)	226	209	—
Inlet Pressure (psia)	46.7	46.7	46.7
Pressure Drop (psid) (Including inlet and exit fittings)	0.98	2.1	2.4 maximum
Flow Length (per pass) (in.)	5.5	5.5	—

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As a result of the concept verification testing several changes were made to the preliminary design. The testing showed that 20 to 90°F of superheat in the oxygen at the core discharge seemed to greatly reduce the oscillations. To accommodate this result, a higher density, more efficient fin was selected for use on the hydrogen circuit. This change on the hydrogen side also made it necessary to change the fins on the oxygen side to more evenly distribute the flow. With the more efficient hydrogen fins, the oxygen nearest the hydrogen inlet would be superheated beyond the desired 90°F, increasing the pressure drop and thus forcing more of the oxygen flow toward the other side of the core where the hydrogen temperature was no longer great enough to cause full vaporization. The final design configuration has the oxygen core layers evenly divided into four sections. The section nearest to the hydrogen inlet has the least number of fins per inch to allow the greatest oxidizer flow to occur where the hydrogen temperature is the highest, thus preventing an excess of superheat to occur. The fin density is progressively increased away from the hydrogen inlet to decrease the oxidizer flow as the hydrogen temperature is reduced. This allows the least flow where the hydrogen temperature is the lowest thus permitting vaporization to occur.

Another change made during the final design was to reduce the thickness of the flow passages in the two outer hydrogen flow panels. Shorter, more dense fins were used in these passages to limit the hydrogen flow in the outer passages to provide a better heat transfer balance between it and the flow of the oxidizer similar to that in the inner layers which have oxidizer on both sides. The higher density fin also provides for more conduction from the side plate to the oxygen passage for lower transient thermal gradients between the side plate and the parting sheets, which enclose the flow layers.

In addition to those changes required for thermal performance, a minor change was made to the overall length of the oxygen circuit. The length of the OHE was increased by 0.375 inch to accommodate an increased thickness divider between the first and second stages. The fluid stream node temperatures from the thermal analysis are shown in Figures 6 and 7.

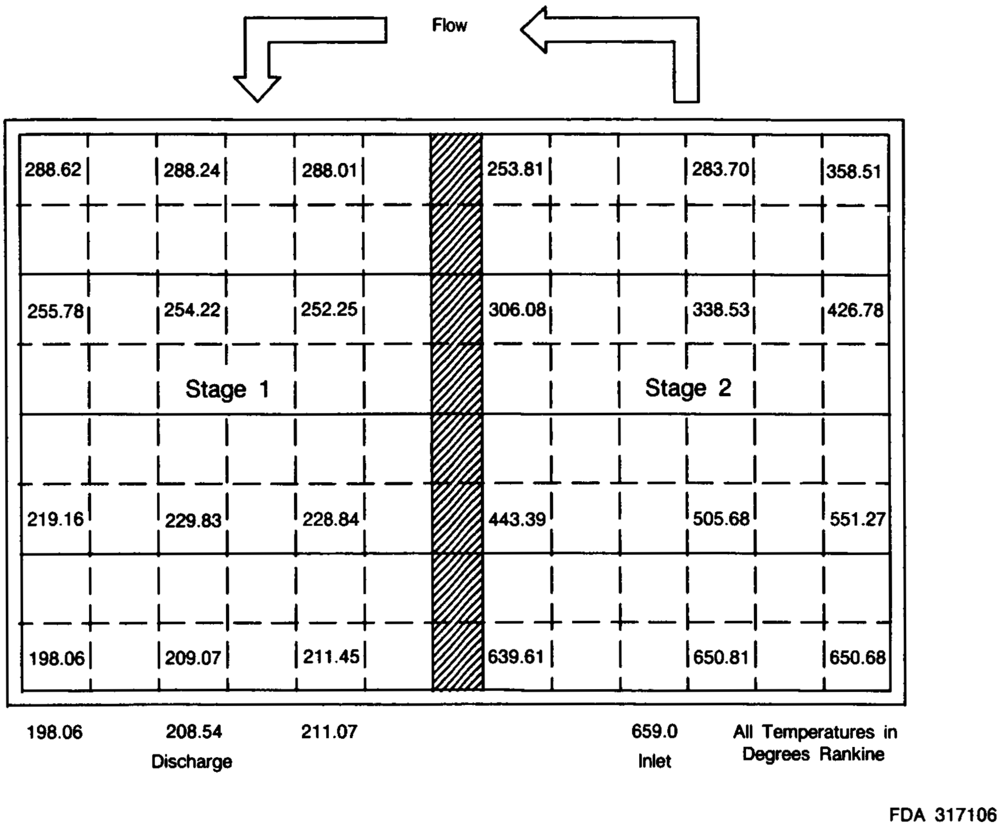

Figure 6. Hydrogen Circuit Fluid Stream Node Temperatures (Pumped Idle Condition)

The introduction of hot hydrogen into the second stage of the core results in large temperature differences between the flowing oxygen and the heat exchanger hot wall. Past analysis and experience indicate that dryout becomes evident when flowing liquid through an area where T_{wall}-T_{sat} exceeds 30°R (Ref. 2). While dryout conditions are normally considered an undesirable characteristic when associated with cryogenic heat exchangers, in this design the oxygen at the location where that occurs has already reached 80 percent quality. This means that heat transfer impairment is minimal, since 80 percent of the oxygen is already gas when it enters that area.

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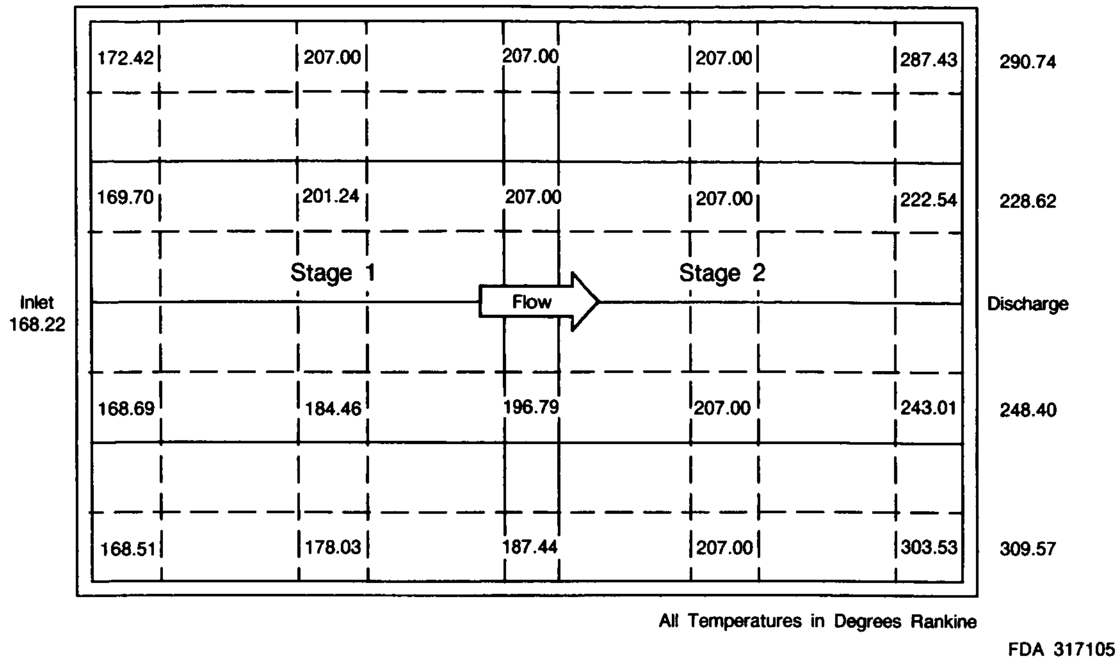

Figure 7. Oxygen Circuit Fluid Stream Node Temperatures (Pumped Idle Condition)

2. Tank Head Idle

At THI, the oxygen will be superheated to 311°R at a heat transfer rate of 151,338 Btu/hr, resulting in 100 percent gas at the OHE exit. OHE characteristics at THI are listed in Table 2. The calculated pressure drops with a H_2 bypass are well below the allowed maximums. Hydrogen and oxygen fluid stream temperatures at THI are shown in Figures 8 and 9, respectively.

To control the amount of oxygen superheat during THI operation, an OHE bypass leg in the H_2 circuit is required as indicated in Table 2. This requirement resulted from observations during the concept verification tests which showed that excessive superheat (greater than 150°R) caused an onset of unacceptable oscillations. The configuration required to meet the pumped idle performance criteria would not allow for this threshold to be completely observed during tank head idle, however, with the hydrogen bypass it is possible to completely vaporize the oxygen while limiting the excessive superheat to only a small area. It is felt that the high superheat which occurs in the area near the hydrogen inlet will not significantly affect the unit performance. Design calculations showed that to accomplish this at the THI condition, 69 percent of the hydrogen flow must be bypassed. This amount of bypass flow also alleviates a high pressure drop problem which would be present if 100 percent of the H_2 flow is directed through the heat exchanger. The bypass would be provided by external plumbing with a shutoff valve, rather than a system integral with the heat exchanger. The OHE performance with and without bypass will be investigated during testing to determine if the bypass will actually be required to meet engine performance requirements.

Table 2. *Oxidizer Heat Exchanger Characteristics at Tank Head Idle (THI) Conditions*

	Preliminary Design	*Final Design*	*Specification Requirement*
Cold Side (1 pass)			
Fluid	LO_2	LO_2	LO_2
Flow Rate (lb/sec)	0.31	0.31	0.31 ±0.05
Inlet Temperature (deg R)	165.8	165.8	165.8
Boiling Temperature (deg R)	168	168	—
Outlet Temperature (deg R)	570	311	—
Inlet Pressure (psia)	20	20	20
Pressure Drop (psid) (Including inlet and exit fittings)	1.4	0.88	2.3 maximum
Exit Quality (% gaseous oxygen)	100	100	95 minimum
Heat Transfer Rate (Btu/hr)	201,380	151,338	—
Flow Length (in.)	8.25	8.625	—
Hot Side (2 pass cross counter flow)			
Fluid	GH_2	GH_2	GH_2
Flow Rate (lb/sec through heat exchanger)	0.94	0.029	0.094 total
(lb/sec bypass flow)	None	0.065	
Inlet Temperature (deg R)	594	594	594
Outlet Temperature (deg R)	415	167.9	—
Inlet Pressure (psia)	9.0	9.0	9.0
Pressure Drop (psid) (Including inlet and exit fittings)	2.5	0.4	2.1 maximum
Flow Length (per pass) (in.)	5.5	5.5	—

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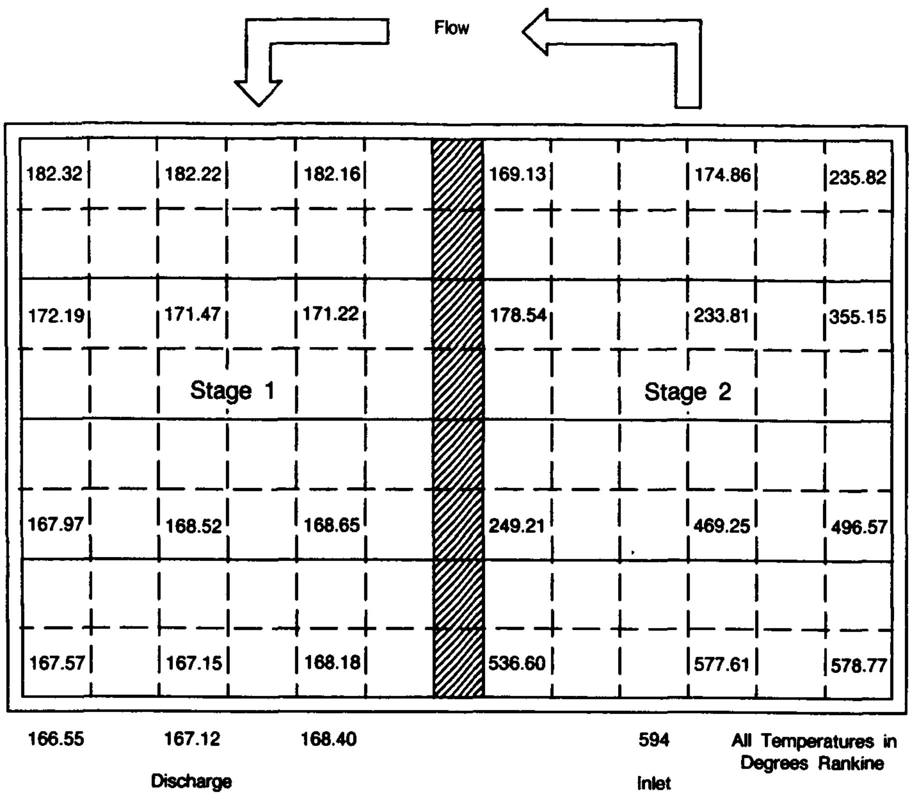

Figure 8. Hydrogen Circuit Fluid Stream Node Temperatures (Tank Head Idle Condition)

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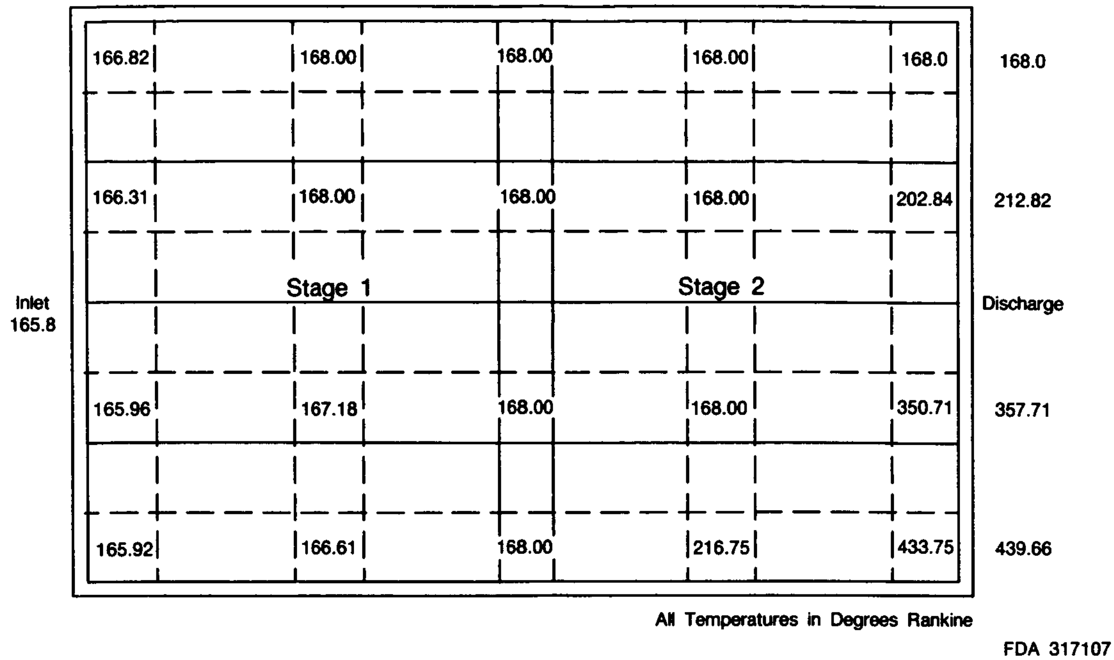

Figure 9. Oxygen Circuit Fluid Stream Node Temperatures (Tank Head Idle Condition)

3. Full Thrust

Although the primary use of the Oxidizer Heat Exchanger is to allow stable engine operation at low thrust levels without an active control system, it is also intended for use during the Full Thrust operating mode to vaporize the oxygen for autogenous vehicle tank pressurization. As stated earlier, the design drivers were the requirements at PI and THI and the performance at full thrust was not considered to be a problem due to the low flow rates and high pressures. For this reason, no specific requirements were established in the PPS F-654 for full thrust conditions. Some operating guidelines, however, were provided for design purposes. The major consideration at full thrust was the operating pressures which made it necessary to provide a higher strength structure than would be required for the low thrust operating points. The unit performance at full thrust is presented in Table 3.

4. "Off Design" Evaluation

In addition to the design requirements established in the PPS, Alpha United was asked to evaluate conditions which were considered "off-design." This was done to evaluate the sensitivity of the proposed concept to changes in the engine mixture ratio and chamber pressure. In addition, Alpha United was asked to evaluate the sensitivity to unit operation in a low "g" environment as would be expected during flight operation at Tank Head Idle and Pumped Idle.

Table 3. Oxidizer Heat Exchanger Characteristics at Full Thrust Conditions

	Preliminary Design	*Final Design*	*P&W-Provided Guideline*
Cold Side (1 Pass)			
Fluid	LO_2	LO_2	LO_2
Flow Rate (lb/sec)	0.1	0.1	0.1
Inlet Temperature (°R)	171	171	171
Boiling Temperature(°R)	276.3	276.3	—
Outlet Temperature (°R)	425	381	—
Inlet Pressure (psia)	701	701	701
Pressure Drop (psi)	0.012	0.003	—
Exit Quality (% Gaseous Oxygen)	100	100	100
Heat Transfer Rate (Btu/hr)	49,360	37,640	—
Flow Length (in.)	8.25	8.625	—
Hot Side (2 Pass Cross-Counterflow)			
Fluid	GH_2	GH_2	GH_2
Flow Rate (lb/sec)	0.046	0.011	0.046
Inlet Temperature (°R)	430	430	430
Outlet Temperature (°R)	354	183	—
Inlet Pressure (psia)	452	452	452
Pressure Drop (psi)	0.011	0.002	—
Flow Length (in.)	5.5	5.5	—

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Engine cycle points were established by P&W to correspond with changes in the chamber pressure and mixture ratio as shown in Table 4. The actual OHE inlet conditions which resulted from these engine operating points are presented in Appendix C along with the resulting OHE performance points. The most significant result was that incomplete vaporization of the oxidizer occurred at the PI low O/F points due to the low hydrogen inlet temperatures. The worst case was for the highest chamber pressure and lowest mixture ratio which resulted in 55 percent oxidizer exit quality. These results were not unexpected, since the unit was designed to operate at one point, however, the results indicated that at least 75 percent quality could be achieved if the mixture ratio was kept to no lower than 5.0. Previous engine testing (Ref. 3) showed that acceptable engine operation could be achieved even with incomplete vaporization of the oxidizer. There was no problem achieving complete vaporization at all of the THI points. It is expected that some off-design points will be tested during the planned performance testing of the completed units.

Table 4. Cycle Points Established to Correspond With Changes in Chamber Pressure and Mixture Ratio

	Tank Head Idle		*Pumped Idle*	
	Chamber Pressure (psia)	*Mixture Ratio (O/F)*	*Chamber Pressure (psia)*	*Mixture Ratio (O/F)*
Baseline	5.4	3.3	40	6.0
High Pc	6.5	3.0	45	4.0
	—	—	45	5.0
	6.5	4.0	45	7.0
Low Pc	4.5	3.0	35	4.0
	—	—	35	5.0
	4.5	4.0	35	7.0

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Operation in a low "g" environment was seen as no problem for the heat exchanger since the unit is designed for forced convection evaporation. However, the preferred orientation of the OHE is with the oxidizer entering opposite of the direction of engine thrust, i.e., the nozzle end, to avoid forcing excess oxygen through the unit. It is anticipated that performance testing of the unit will be accomplished with the unit mounted vertically and the effects of gravity will be checked by testing with the inlet both at the bottom and at the top.

B. STRUCTURAL ANALYSIS

During the design of this OHE a complete structural analysis was performed in parallel to the thermal analysis. Like the thermal analysis, the structural analysis was performed in two phases. The first phase concentrated on the dynamic behavior of the design in response to engine induced vibration and included an analysis of the stresses in the structure due to steady state operating conditions. The second phase was directed toward analyzing the structure of the design in response to the transient operating conditions predicted for the unit. The steady state operating stresses examined during the first phase were also reviewed in the second to take into account the final material selection and final operating temperatures. These analyses were conducted by Mr. S. Tepper, a consulting engineer for Alpha United, and were verified by P&W structural engineers.

Dynamic Analysis

This phase of the structural analysis was accomplished during the preliminary design of the OHE to verify that the basic concept of a core suspended in a pressure vessel would be capable of withstanding the loads imposed by engine induce vibrations. The vibration input was as defined in the PPS. This work was intended to define the relative motion between the various OHE components (i.e. core, shell, bellows, manifolds).

For the purposes of the analysis, it was assumed that the OHE was supported primarily at the oxidizer inlet flange with an additional support at the discharge flange. The plumbing which interfaced with the OHE was also assumed to give support. The plumbing interfaces were supplied by P&W to the vendor and were based on the anticipated mounting for the Breadboard II-B engine.

The analysis showed that there were 10 natural frequencies within the random vibration specified range and 14 frequencies within the sinusoidal range. The maximum stress found in response to the random vibration excitation was 31.6 ksi and occurred at the hydrogen return header near the ring which supports the core. For the sinusoidal vibration excitation, the maximum stress was found to be 29 ksi and occurred at the sides of the hydrogen inlet header. A complete report of the dynamic analysis can be found in Reference 5.

Structural Analysis

The structural analysis was completed in two phases. First, the structure was analyzed for operation at steady state conditions, based on the preliminary design. When the design was finalized for thermal performance, the steady state stresses were reviewed and updated for the configuration changes. Analyses of the stresses induced by thermal gradients during transient operations were also accomplished.

During the first phase stress analysis, the following elements were examined: the O_2 inlet bellows, the pressure vessel (shell), the core, and the headers. The bellows was examined for the stresses due to the pressure loading of the specified differential pressure of 300 psid and for the stresses created by its extension due to the thermal differences between the shell and the core. A parametric study was also done to optimize the bellows wall thickness and this resulted in a selected wall thickness of 0.010 inch. The shell was examined for the effects of pressure and its structure was analyzed for the effects of a doubler "belt" around it at the midpoint where the core is attached. This area was found to have the highest stress due to bending induced by the ring that supports the core. The effects of varying the reinforcing belt were analyzed and the belt was optimized at 0.5 inch wide. The core was analyzed only for the effects of the maximum differential pressure since the required maximum operating pressure is contained by the pressure shell. The stress were all found to be well within acceptable limits for the candidate material. The headers were also analyzed for the effects of the pressures expected and stresses were found to be acceptable.

The second phase in the structural analysis was to perform a stress analysis to examine the effects of the thermal gradients based on the information generated during the thermal analysis. Two computer programs were used to analyze the stresses during this phase. The ELPLAC code is a finite element — finite difference proprietary code to solve general elasto-plastic creep problems. The SAP IV program was developed at the University of California at Berkeley and is used to solve linear elastic structural problems. Brief descriptions of these programs can be found in Appendix B. The critical items examined were the parting sheets (the sheets separating the oxygen and hydrogen passages), the side bars, and the headers. The two steady state conditions analyzed were the THI and PI operating points. Maps of the effective stresses and strains were generated for the critical elements. A typical map for stresses in the parting sheet at the beginning of THI operation is shown in Figure 10. The stresses generated during the steady state operation were shown to be acceptable.

After the transient thermal analysis was completed, it was possible to perform an analysis to examine the structural effects caused by the transient operation of the OHE. The same finite element models used for the steady state analysis were used for the transient analysis. For the transient analysis, it was assumed that THI would last for approximately three minutes and PI would last for one hour.

This analysis was performed on the parting sheets, side plates, headers, and core fins. It was found that the parting sheet was the hardest stress-working element and achieved an effective stress of 12.6 ksi after five seconds at PI operation. The plastic strain was insignificant, and the creep strain after one hour was 0.33 percent. Another area of similar stress was found in the side plates which showed an effective stress of 12.6 ksi after one hour with no plastic strain and creep of 0.21 percent. The other area showed lower stresses, or stresses which did not exceed those during steady-state. All stresses were considered acceptable.

Following the transient stress analysis a Low Cycle Fatigue (LCF) analysis was performed for the parting sheet, side plate, and headers. With a safety factor of five applied, the LCF life was 896 cycles for the parting sheet, 3087 for the side plate, and greater than 3000 for all of the headers.

A life cycle analysis was also performed to take into account the effects of the interaction of LCF and creep. With a safety factor of five for the LCF life and 2.5 for the creep, it was found that the target life of 300 cycles could be achieved.

Complete reports of all of the structural analyses are included in References 6, 9, and 10.

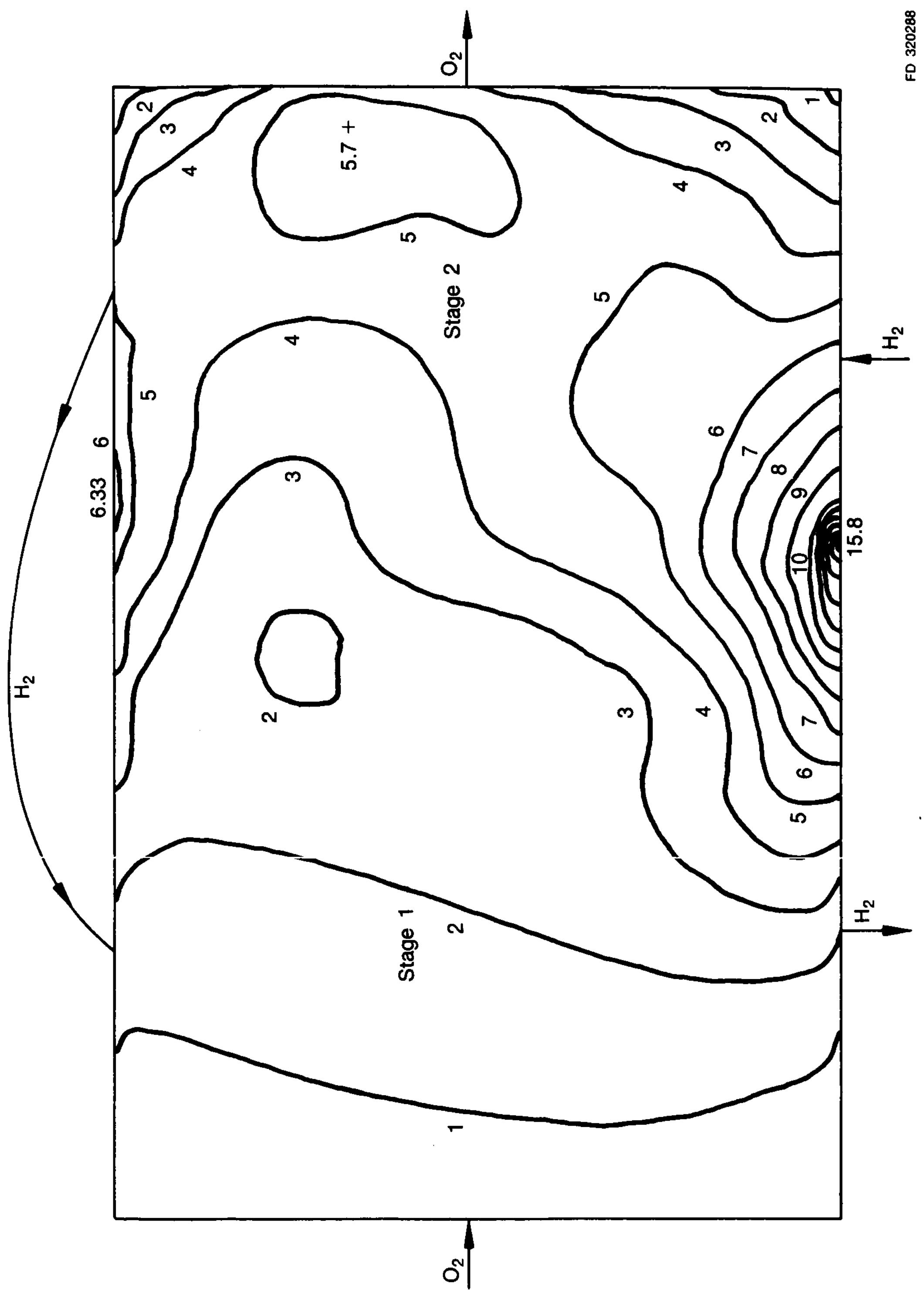

Figure 10. Parting Sheet THI Effective Stresses (ksi) Nominal Elastic Analysis

SECTION IV
DESIGN CONCEPT VERIFICATION TESTING

A. GENERAL

Following the initial design evaluation, a representative bench test using liquid nitrogen (LN_2) in a sample O_2 layer was devised. The objectives of the test were to verify assumptions made in the preliminary heat exchanger design concept and determine any necessary changes to that design. Specifically, the following assumptions were to be evaluated: 1) high heat transfer rates were achievable, 2) low pressure drop was possible; 3) damping of oscillations could be achieved in a volume downstream of the core. Once the test article was completed, a series of "shakedown runs" were made to observe system operation and reactions. Data system calibrations and heat leak calculations were made during these flows.

These preliminary runs were followed by three days of running actual test cases to simulate THI and PI operation. Modifications were made to the test program and test bench where necessary as indicated by a preliminary data review. The testing activity is described in detail in the Test Summary section.

B. TEST SECTION

The test employed a single one-inch wide O_2 layer of the original design length (8.0 in.) with electrical heaters mounted on both sides to simulate heat input from the H_2 layers. The heater elements were embedded in two aluminum blocks, each 0.5 in. thick, to provide even heat distribution from the elements to the O_2 channel walls. These blocks were brazed to the outside of parting sheets which contained the flow. At the discharge of the test section was a variable expansion volume and a variable exit orifice, both of which are designed to investigate attenuation of the flow and pressure oscillations commonly associated with a cryogenic heat transfer system. The test section was suspended in the ullage of the subcooler which was used to assure subcooled liquid nitrogen at the test section inlet. This configuration provided an insulating layer of GN_2 to prevent vapor condensation on the test piece and to permit calculation of the unit heat loss to the environment. The core section configuration is shown in Figure 11. A pictorial representation of the test section is shown in Figure 12. A photo of the test section prior to installation in the flow bench is shown in Figure 13.

C. FLOWBENCH

The flowbench for the design verification tests was constructed and operated at the Alpha United plant in El Segundo, California. It consisted of a LN_2 supply system, a subcooler, associated instrumentation and valves, and plumbing to supply the test fluid and purge flow. Separate LN_2 dewars supplied the subcooling reservoir and the test section flow. Relief valves at appropriate locations provided safety from overpressurization. A data logger was used to record the necessary temperatures and pressures; a high speed chart pen recorder provided a record of transient events. A schematic of the test section flowbench is shown in Figure 14.

A coil of the inlet line was submerged in a LN_2 bath to cool the inlet flow to assure subcooled liquid at the test section inlet. A flowmeter at the inlet measured liquid flow through the test section. After passing through the test section, the nitrogen passed through a vaporizer coil to prevent any possible liquid nitrogen discharge, and then discharged through a back-pressure valve to atmosphere.

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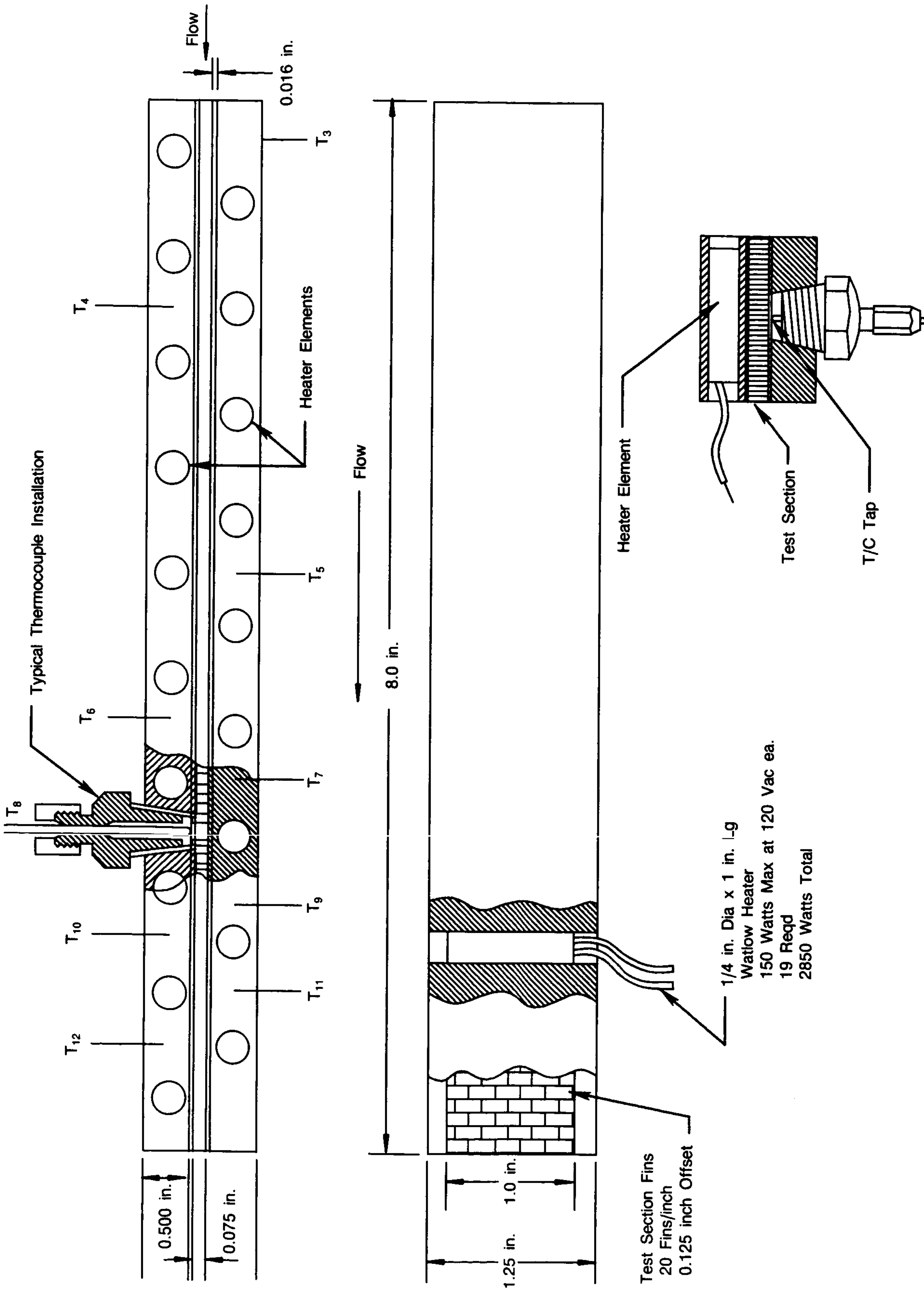

Figure 11. OHE Concept Verification Core Section Schematic

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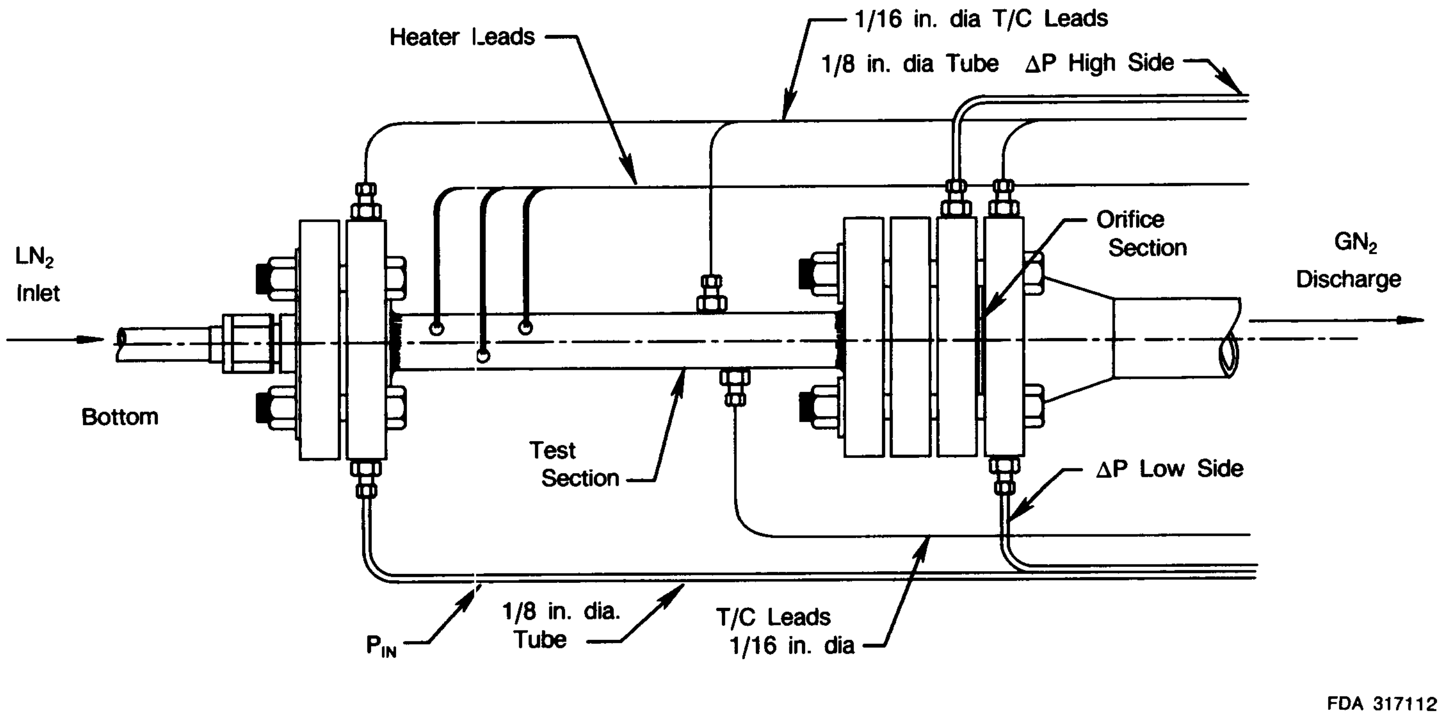

Figure 12. OHE Test Section (Pictorial View)

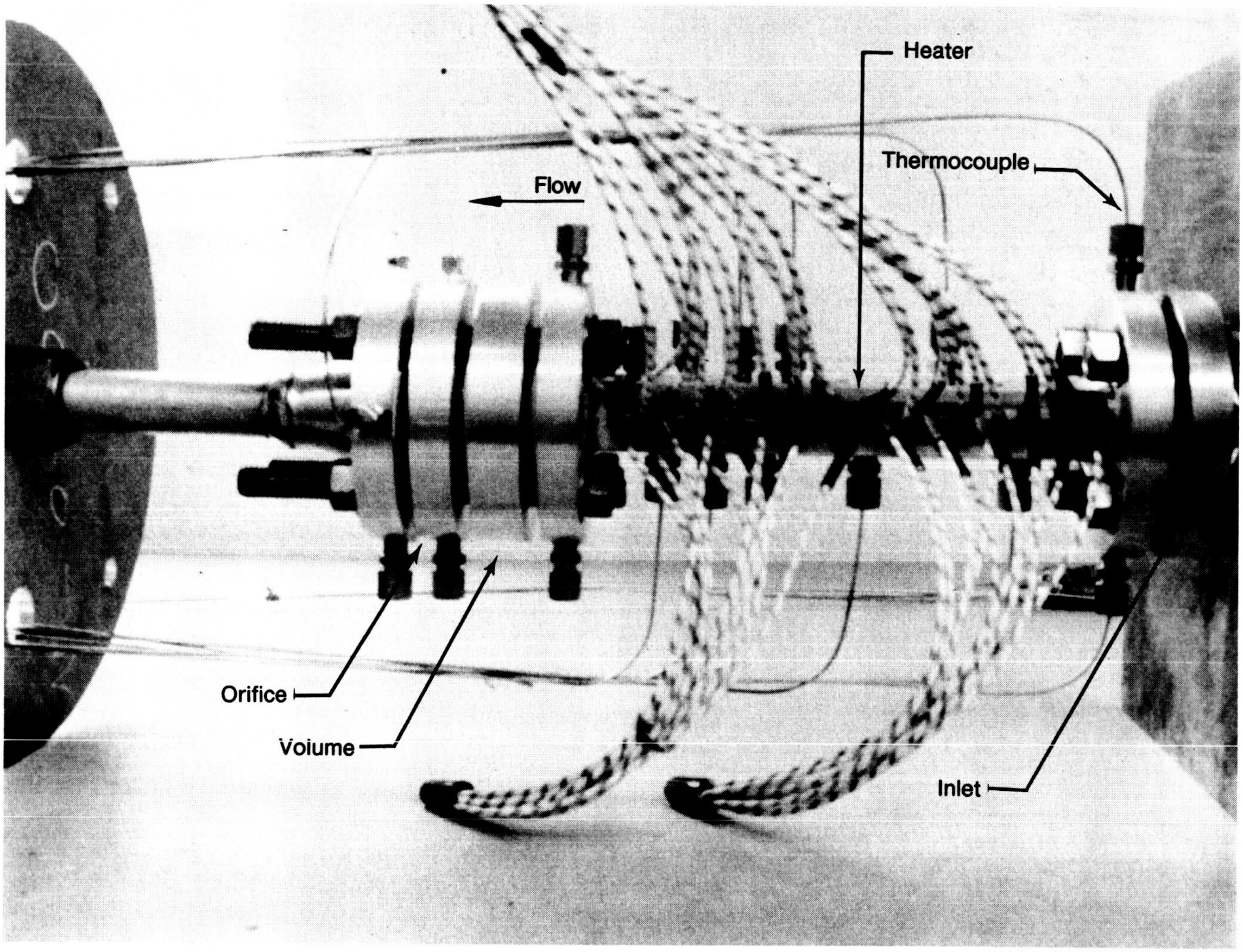

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Figure 13. Test Section Prior to Installation in Flow Bench

D. INSTRUMENTATION

Instrumentation for the test section consisted of calibrated Type T (copper-constantan) thermocouples for low temperature measurements and standard pressure transducers for pressure measurements. Thermocouple locations on the test section are shown in Figure 10. Watts transducers were used to measure heater input; a calibrated turbine flowmeter provided flow measurement data. All data was channeled into a data logger unit, which was used to display and record data for analysis. In addition, the differential pressure across the discharge orifice and across the test section core were recorded on a high-speed chart recorder so that pressure and flow oscillations due to any unstable boiling could be observed.

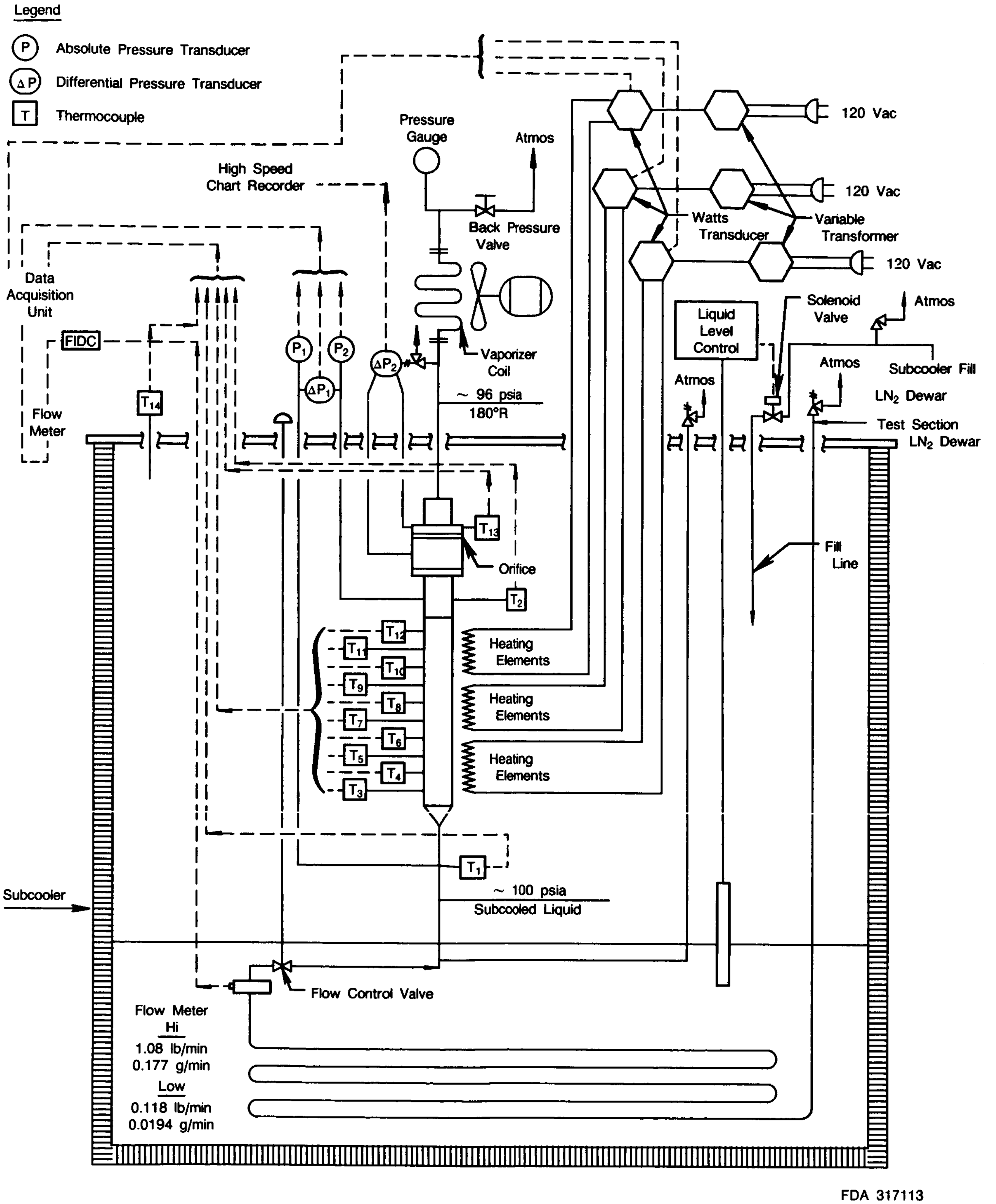

Figure 14. Test Section Flow-Bench Schematic

A list of instrumentation provisions is shown in Table 5.

Table 5. *Design Verification Test Instrumentation*

Measurement Item	*Measurement Device*	*Range*	*Record On*
Outside Ambient Temp	Type K T/C	°F	Datalogger
Test Section Inlet Temp	Type T T/C	−300 to −70°F	Datalogger
Test Section Inlet Temp	Type T T/C	−300 to −70°F	Datalogger
Test Section Temp Loc 3	Type T T/C	−300 to −70°F	Datalogger
Test Section Temp Loc 5	Type T T/C	−300 to −70°F	Datalogger
Test Section Temp Loc 6	Type T T/C	−300 to −70°F	Datalogger
Test Section Temp Loc 7	Type T T/C	−300 to −70°F	Datalogger
Test Section Temp Loc 8	Type T T/C	−300 to −70°F	Datalogger
Test Section Temp Loc 9	Type T T/C	−300 to −70°F	Datalogger
Test Section Temp Loc 10	Type T T/C	−300 to −70°F	Datalogger
Test Section Temp Loc 11	Type T T/C	−300 to −70°F	Datalogger
Test Section Temp Loc 12	Type T T/C	−300 to −70°F	Datalogger
Orifice Downstream Temp	Type T T/C	−300 to −70°F	Datalogger
Subcooler Ullage Temp	Type T T/C	−300 to −70°F	Datalogger
Core Inlet Pressure	Pressure Xducer	0-150 psia	Datalogger
Orifice Differential Pressure	ΔP Xducer	0-5 psid	Hi-speed chart recorder
Core Differential Pressure	ΔP Xducer	0-5 psid	Hi-speed chart recorder
LN_2 Flow	Flowmeter	0.015-0.4 gal/min	Datalogger
Heater Power H1-H5	Watts Xducer 50 watts/volt	40 V FS	Datalogger
Heater Power H6-H10	Watts Xducer 50 watts/volt	40 V FS	Datalogger
Heater Power H11-H19	Watts Xducer 50 watts/volt	40 V FS	Datalogger

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E. TEST PROCEDURE

The concept verification test procedure is defined by Alpha United Document No. TP 11060-1 which is shown in Appendix D. This procedure details the following items:

- Scope
- Test Conditions
- Test Equipment
- Instrumentation Hardware
- Flow Calculation Requirements
- Calibration
- Flowbench Operation
- Data Recording.

Test conditions for tank head idle and pumped idle are also included in the test procedure. THI testing included points with both uniform and non-uniform heating along the test section to simulate the effects of passing through the two hydrogen stages.

F. TEST POINTS

Points for the THI and PI runs during the test were taken from the conditions predicted for the full-size heat exchanger. Flows were scaled down due to the reduced flow area of the test piece instead of an entire core. The mass flux, fluid velocity, and film coefficients therefore remain unchanged. Power supplied to the heaters was based on heat that would be supplied by two typical sandwiching H_2 layers. The test data is presented in Table 6. A detailed description of the test activities can be found in Appendix E.

Table 6. *LN_2 Heat Exchanger Test Section Test Data*

Test Point	*Flow (lbm/min)*	*Inlet Conditions Temp (°R)*	*Inlet Conditions Press. (psia)*	*Exit Conditions Temp (°R)*	*Exit Conditions Press. (psia)*	*Heat Flux (Btu/min) From Heater*	*Heat Flux (Btu/min) To LN_2*	*Flow Condition*
(8/8/85)								
10	1.264	150.4	104.0	185.0	103.2	105.3	109.2	unstable
11	1.4556	150.4	100.7	184.3	99.2	105.1	125.9	unstable
12	1.1402	152.9	102.3	185.4	101.9	94.4	97.4	unstable
13	1.309	149.9	99.7	185.4	99.2	94.1	113.9	unstable
14	0.6623	150.9	112.2	276.9	113.7	93.8	72.8	stable
15	0.6242	150.5	114.4	303.4	113.8	93.8	72.9	stable
16	0.4877	151.7	115.7	188.1	115.8	58.7	41.9	unstable
17	0.3860	151.9	114.1	293.6	115.3	58.7	43.8	stable
(8/21/85)								
6	0.115	155.5	22.1	543.6	22.8	31.8	20.7	unstable
7	0.112	156.6	22.6	551.6	22.0	31.8	20.3	unstable
(8/22/85)								
6	0.659	151.9	115.8	262.0	116.8	79.6	69.4	stable
7	0.659	151.2	116.1	272.3	116.7	79.3	71.4	stable
8	0.938	152.2	108.2	205.1	109.9	79.9	85.0	stable
15	0.114	151.9	23.0	235.8	23.4	20.1	12.0	stable

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G. TEST RESULTS

A summary of the test results and the conclusions which were used to modify the preliminary design are presented below:

- The heat transfer conductance of boiling liquid nitrogen at the PI condition was 26 percent to 90 percent higher than the value used in the design.

- The pressure drop of the boiling liquid nitrogen was 60 percent to 90 percent of that calculated for the design with a large pressure drop oscillation in the core.

- To reduce the flow oscillations leaving the test section, it is necessary to have a small amount of superheat (20°F to 90°F) for both the PI and THI conditions.

- A large amount of superheat (150°F to 300°F) caused a greater flow oscillation in the THI condition.

- The larger volume and higher flow restriction for the flow oscillation damping system helped reduce the flow oscillations, but were not as effective as controlling the superheat.

- Based on these results, a smaller volume may be used with proper control of the superheat to reduce flow oscillations.

At the simulated PI conditions, the total heat provided by the heater elements compared to the heat absorbed by the flowing oxygen showed a close balance. At the simulated THI conditions, however, the balance was not so good. This was due in part to flowmeter error at the extremely low THI flowrates, and the resolution of the instrumentation at THI conditions.

The complete report of all testing is presented in Reference 11.

SECTION V
MATERIALS

The High Heat Transfer OHE is constructed of all aluminum parts. Alloys for specific parts are listed in Table 7.

Table 7. *Heat Exchanger Alloys*

Part		Aluminum Alloy
Tube Sheets	MD177 ALCLAD Sheet	3003
Braze Alloy		4104
Side Bars		3003
O_2 Fins		3003
H_2 Fins		3003
Manifolds		2219
Flanges		6061
Bellows		6061
Support Ring		2219
Containment Vessel		2219

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Core placement inside the containment vessel allows use of a lower strength material. Aluminum alloy 3003 was chosen because of its excellent braze characteristics, ductility, and its large margin for plastic flow development. This allows considerable stress margin between the yield (plastic initiation) and rupture.

All non-core parts other than the flanges and bellows are made of heat-treatable aluminum alloy 2219. The high strength of this heat-treatable alloy was required since these parts must contain high pressures. At the operating temperatures, the minimum ultimate yield stress is approximately 40 ksi. Aluminum 2219 alloy exhibits good resistance to stress corrosion cracking and is readily weldable.

Aluminum 6061 was chosen for the bellows fabrication because of its excellent formability, weldability, and high strength. Likewise, aluminum 6061 is used for the flanges because of its high strength, machinability, and availability in the size and form required.

A complete report on the materials selection is presented in Reference 12.

A. WEIGHT

The total calculated dry weight of the heat exchanger is 35.75 lb. Of this total, 31 percent is due to the weight of the core and 69 percent is due to manifolds, flanges, doublers, and the containment vessel. A weight breakdown is presented in Table 8. A small amount of additional weight (approximately 2 lb) may be added due to instrumentation requirements for development units.

B. HEAT TREATMENT

Since the core consists of non-heat-treatable aluminum 3003 parts, no further strengthening processes are required. The manifolds, bellows, flanges, support ring and containment vessel are made from heat-treatable 2219 aluminum alloy. These parts will be solution heat treated prior to assembly by heating to 995°F ±10°F and quenching immediately. Precipitation heat treatment of the detail parts will then follow by artificially aging at 375°F for 36 hours, resulting in a T62 temper. All parts will be heat treated prior to welding onto the assembly; the OHE design has the necessary margin to allow some strength degradation due to heating in the weld affected zones.

Table 8. *Heat Exchanger Calculated Weight Breakdown*

	Weight (lb)
Core	11.2
Containment Vessel	15.8
Vessel Reinforcing Bands	0.78
Bellows	0.3
O_2 Inlet Header + Doubler	0.59
H_2 Inlet Header + Doubler	0.36
H_2 Turnaround Manifold	0.72
Support Ring	2
O_2 Flanges, Doublers	1.25
H_2 Flanges, Doublers	2.75
Total	35.75

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SECTION VI
FABRICATION

All OHE fabrication activities will take place at Alpha United Inc. in El Segundo, California. Once all detail parts are completed, they will be cleaned and stacked into the configuration outlined in Section II. Braze joints within the core will be provided by the MD177 core sheet, which are clad on both sides with braze material comprising 15 percent of the total 0.016 inch thickness of the sheet. Once the core is stacked, it will be fixtured and loaded to assure contact at all joints. The core will then be placed into a furnace for the fluxless vacuum braze process, which will then be followed by core pressure test. The manifolds, bellows, containment vessel, and flanges will then be welded on. Final machining will provide the required flange interface dimensions. The assembly will have an anodized finish to help prevent corrosion.

REFERENCES

1. Design and Analysis Report for the RL10-IIB Breadboard Low Thrust Engine, Final Report FR-18046-3 (CR-174857)

2. Oxidizer Heat Exchanger Component Testing, Final Report FR-19134-3 (CR 179487).

3. Breadboard RL10-II-B Low Thrust Operating Mode, Final Test Report FR-18683-2 (CR 174914).

4. Low Heat Transfer Oxidizer Heat Exchanger Design and Analysis Report FR-19135-2 (CR-179488)

5. "Pratt & Whitney RL10-IIB Engine O_2/H_2 Heat Exchanger Dynamic Analysis," by Alpha United, Inc., El Segundo, CA, 7 May 1985.

6. "Pratt & Whitney RL10-IIB Engine O_2/H_2 Heat Exchanger Phase 1 Stress and Vibration Analysis Report" by Alpha United, Inc., El Segundo, CA.

7. "Detailed Report of Steady State Thermal Analysis Including Design Flow Distribution for RL10 Oxidizer Heat Exchanger" by Alpha United, Inc., El Segundo, CA.

8. "Final Design Report, Transient Thermal Analysis for RL10 Oxidizer Heat Exchanger," by Alpha United, Inc., El Segundo, CA.

9. "Preliminary Final Design Report to Define Structure for Steady-State and Thermal Analysis Data," by Alpha United, Inc., El Segundo, CA.

10. "Final Design Report, Thermal Stress Analysis Transient Operation," by Alpha United, Inc., El Segundo, CA.

11. "Concept Verification Test Report for Pratt & Whitney RL10-IIB Engine Oxidizer Heat Exchanger, Phase I," Alpha United Test Report TR 11060-1 9 Sept. 1985 by Alpha United, Inc., El Segundo, CA.

12. "Hydrogen/Oxygen Heat Exchanger Fabrication and Materials Report for the Pratt & Whitney RL10-IIB Engine" 15 Jan. 1986 by Alpha United, Inc., El Segundo, CA.

APPENDIX A
PURCHASE PERFORMANCE SPECIFICATION (PPS) F-654
FOR AN OXYGEN/GASEOUS HYDROGEN HEAT EXCHANGER FOR THE RL10-IIB ENGINE

1.0 SCOPE

This specification establishes requirements for an Oxygen/Gaseous Hydrogen Heat Exchanger for the RL10-IIB rocket engine. All deviations from the requirements of this specification must be submitted in writing. Approval of deviations by the cognizant P&W Project Engineer must be obtained in writing prior to starting manufacture.

2.0 APPLICABLE DOCUMENTS

2.1 General

The following documents which have a specific revision notice shall form part of this specification as shown. When no revision notice is shown, the document in effect on the date of issue of this specification shall apply.

2.2 Government Documents

MIL-R-5149B	Rocket Engine, Liquid Propellant, General Specification for
MIL-STD-889B	Military Standard, Dissimilar Materials
MIL-P-25508E-3	Propellant, Oxygen — Type II, Grade A or Equivalent
MIL-P-27201B	Propellant, Hydrogen — Type II or Equivalent
MIL-STD-130A	Identification Marking of U.S. Military Property
DOD-D-1000B	Drawings, Engineering and Associated Lists

2.3 Non-Government Documents

2.3.1 Industry Specifications

AMS 2645	Fluorescent Penetrant Inspection
AMS 3159	Leak Test Solution — Liquid Oxygen Compatible
AMS 5620	Bars and Forgings — 13 Cr (0.30 - 0.40C) Free Machining
AMS 5621	Bars and Forgings — 13 Cr (0.30 - 0.40C)
AMS 5630	Bars and Forgings — 17 Cr 0.5 Mo (0.95 - 1.20C)
AMS 5632	Bars and Forgings — 17 Cr 0.5 Mo (0.95 - 1.20C) Free Machining

2.3.2 *P&W Specifications*

PWA 80	Cleaning, wrapping, packaging, and assembly of critical liquid oxygen system parts, assemblies, and components.
PWA 81	Cleaning, wrapping, packing, and assembly of critical liquid hydrogen system parts, assemblies, and components.
PWA 82	Liquid Oxygen Compatibility
PWA 300	Control of Materials and Processes
PWA 382A	Handling of items requiring special protection.
PWA-QA-6076	Supplier Quality Assurance Program Requirements

3.0 REQUIREMENTS

3.1 Definition

The heat exchanger defined by this specification will be used for the RL10-IIB engine. This engine model is designed to operate in a cryogenic space vehicle which must accomplish engine start at zero gravity without auxiliary propellant settling systems. This results in a wide range of propellant inlet conditions for the engine. The heat exchanger is a key element in assuring its successful operation.

The heat exchangers must gasify the oxygen at low thrust conditions specified herein without creating flow instability. Additionally, the heat exchanger may be used to provide gaseous oxygen for vehicle tank pressurization at full thrust operation. An explanation of the heat exchanger's functions follows.

During tank head idle (THI), the engine operates in a pressurized mode, (i.e., turbopumps not operating) using propellants provided from the vehicle tanks at whatever thermal conditions exist (i.e., superheated gas, saturated gas/saturated liquid of any quality, or subcooled liquid). In this mode, the engine provides approximately 1 percent of full thrust (FT) to the vehicle, which settles the propellants to eventually provide liquid at the engine interface. The liquid to the engine interface will probably not occur simultaneously in the hydrogen and oxygen feed systems.

Due to high density changes between propellant phases, the engine is confronted with significant changes in thrust chamber coolant flow and widely varying combustion mixture ratio which in turn effect combustion temperature. This process must be attenuated. The biggest change in mixture ratio would occur if the oxygen condition changed rapidly and slugs of liquid or pockets of gas were injected into the combustion chamber. This mixture ratio change can be minimized if only gaseous oxygen was available for injection. A similar problem does not occur on the hydrogen system because the hydrogen is always gasified as it cools the thrust chamber tubes before injection into the combustion chamber. Gasification of the oxygen prior to injection will provide a satisfactory level of control. The warm hydrogen gas available after thrust chamber cooling provides a source of energy for gasifying the oxygen in a gaseous hydrogen/oxygen heat exchanger.

With saturated (or subcooled) liquid propellants at the pump interfaces, the engine will be accelerated to 10 percent of rated thrust pumped idle (PI) and operated in this mode to, (1) permit pressurization of the vehicle propellant tanks using hydrogen and oxygen gases bled from the engine, or (2) satisfy mission requirements where 10 percent maximum thrust is desired. At PI, differential pressure across the oxidizer injector is too low to provide adequate injection velocity for all liquid flow to support stabilized combustion, because the injector area is sized for liquid oxygen injection at full thrust. Injection of lower density gaseous (or mostly gaseous) oxygen increases the velocity, precludes any combustion instability, and increases combustion efficiency (specific impulse). Gaseous oxygen can be supplied by using a hydrogen/oxygen heat exchanger.

Following vehicle tank pressurization, the engine may be accelerated to full thrust. In this mode, the propellant flows bypass the heat exchanger except for a small quantity which is used to gasify oxygen for vehicle tank pressurization purposes.

3.2 Characteristics

The criteria for design of the heat exchanger are shown in paragraph 6.0 of this specification and shall be used as indicated in the following paragraphs.

3.2.1 Performance

This heat exchanger shall be designed to perform at THI and PI. Design for operation at these conditions will provide the performance necessary to satisfy operation at FT, and during the transients between these modes.

3.2.1.1 Heat Transfer Rate

The heat transfer rate shall be such that vaporization of the oxygen is accomplished without creating unacceptable flow and pressure oscillations due to unstable boiling.

3.2.1.2 Inlet Conditions

The predicted fluid conditions at the heat exchanger inlets for steady state operation at each design level are shown in paragraphs 6.3 and 6.4.

3.2.1.3 Flow Rates

The predicted mass flow rates for both fluids are shown in paragraphs 6.3 and 6.4.

3.2.1.4 Pressure Drop

The maximum allowable pressure drop for each fluid during steady state operation at each design level is shown in paragraphs 6.3 and 6.4.

3.2.1.5 Oscillations

Oxygen flow oscillations induced by unstable boiling shall be limited to the extent shown in paragraphs 6.3 and 6.4.

3.2.1.6 Oxidizer Discharge Quality

The required minimum quality of the oxygen which is discharged from the heat exchanger is shown in paragraph 6.5. Complete vaporization is allowable but not required.

3.2.1.7 Hydrogen Discharge Temperature

There are no limits on the temperature of the hydrogen discharged from the unit. The discharge temperature shall be dependent on the heat transfer to the oxygen.

3.2.1.8 Pressure

The proof and burst pressures for each circuit shall be based on FT operation and are shown in paragraphs 6.7 and 6.8.

3.2.1.9 Leakage

There shall be no external leakage allowed when the unit is tested in accordance with paragraph 4.1.2.2.3. Cross circuit leakage shall be checked in accordance with paragraph 4.1.2.2.4 and limited to the extent shown in paragraph 6.6.

3.2.2 Physical Characteristics

3.2.2.1 General

The heat exchanger may be packaged as a single unit or may consist of separate modules to satisfy the design requirements for each engine operating mode. If modules are used, the system shall need no controls to accomplish the required performance at each thrust level.

3.2.2.2 Weight

The weight goal for this heat exchanger is 70 pounds. If a modular system is used, the weight of all interconnecting lines must be included as part of the total heat exchanger weight. The vendor shall identify a weight savings program to reduce the weight for the flight configuration.

3.2.2.3 Installation Envelope

The heat exchanger shall be designed to fit in an envelope between the primary nozzle and the secondary nozzle and must not interfere with translation of the secondary nozzle. Figure A-1 shows approximate dimensions for the primary nozzle and a clearance cylinder for the secondary nozzle. Specific packaging for engine installation will be coordinated with the vendor.

3.2.2.4 Interfaces

The oxygen circuit interfaces shall allow connection to nominal 1.500 in. OD tubing. The hydrogen circuit interfaces shall allow connection to nominal 2.250 in. OD tubing. Interface locations and configurations shall be per sketch CKD 10001.

3.2.2.5 Installation

Provisions for mounting of the heat exchanger shall be coordinated with P&W. Orientation of the unit shall not affect its function.

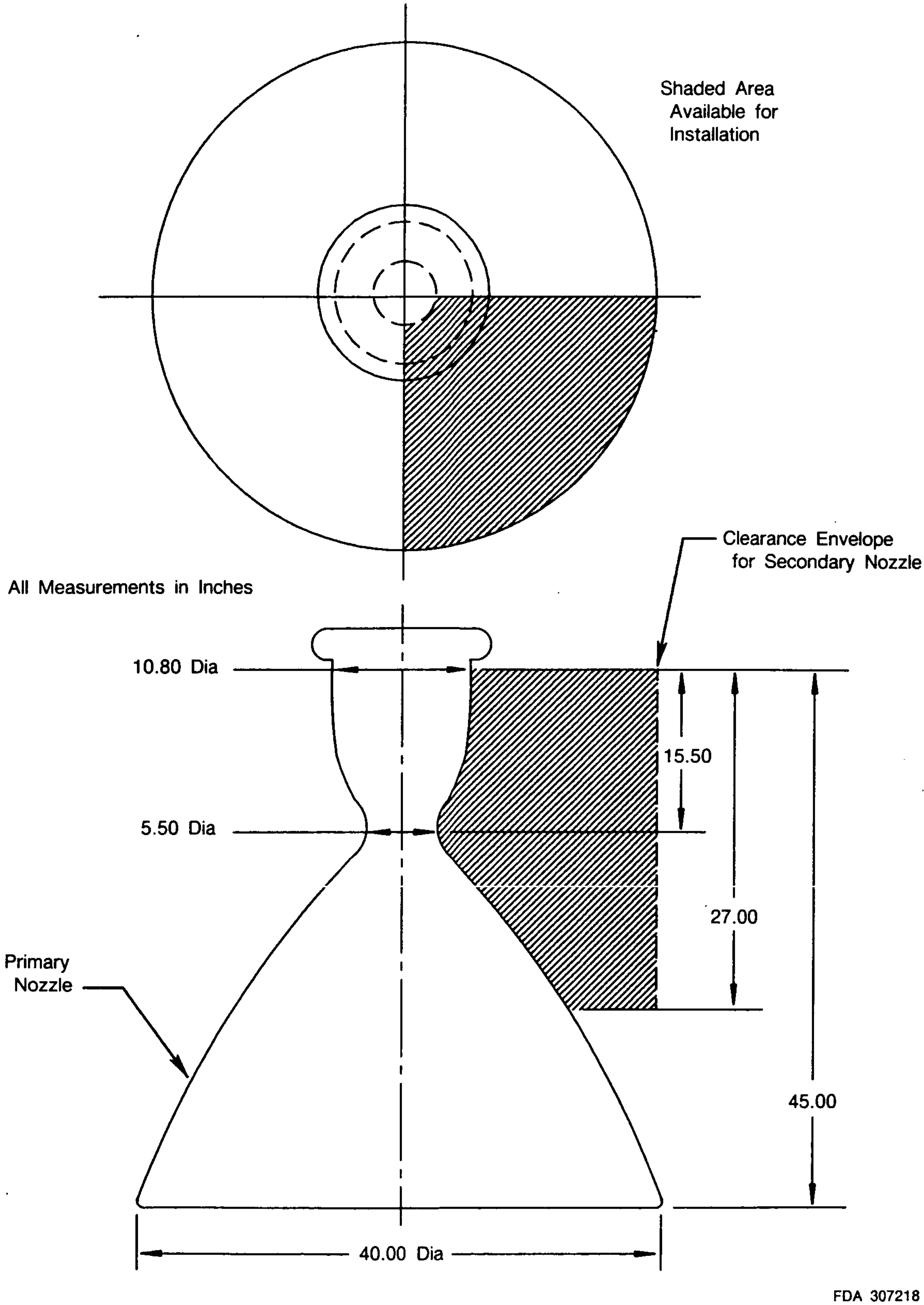

Figure A-1. Approximate Dimensions of Primary Nozzle

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3.2.2.6 Instrumentation

Provisions shall be made to allow pressure and temperature measurements to be made at various locations in the heat exchanger. The instrumentation is to be used to evaluate the heat exchanger performance. Locations and types of measurements shall be coordinated with P&W and must be approved in writing by the cognizant P&W Project Engineer prior to starting manufacture.

3.2.3 Reliability

The unit shall exhibit no degradation in performance or structural integrity during its duty life. The design goal for duty life of this unit is 300 cycles. The duty cycle for this unit is described in paragraph 7.0.

3.2.4 Maintainability

The unit shall require no service during its duty life in order to maintain performance and structural integrity. The unit shall be designed so that the fluid passages can be cleaned to meet PWA 80 or PWA 81 as applicable. Additionally, the design must allow for dehydration of the fluid passages prior to installation on the engine. The vendor shall prescribe a method for cleaning and dehydration.

3.2.5 Environmental Conditions

3.2.5.1 Altitude

The unit must be capable of operating at any ambient pressures encountered from sea level to above 100,000 feet.

3.2.5.2 Temperature

The unit must be capable of enduring storage or operating at any ambient temperature between 100°R and 600°R.

3.2.5.3 Vibration

The unit shall be designed to withstand the following sinusoidal and random vibration when mounted to simulate engine mounting. At the completion for this testing, there shall be no evidence of damage and the unit shall demonstrate satisfactory operation per paragraph 4.1.2.

3.2.5.3.1 Sinusoidal

The unit shall be vibrated sinusoidally in each of its principal axes while varying the vibration frequency slowly through the range shown in Figure A-2. All resonant frequencies shall be noted and the unit shall then be vibrated at each of these frequencies along the axis in which the resonance occurred for a period of 15 minutes at the g levels specified in Figure A-2.

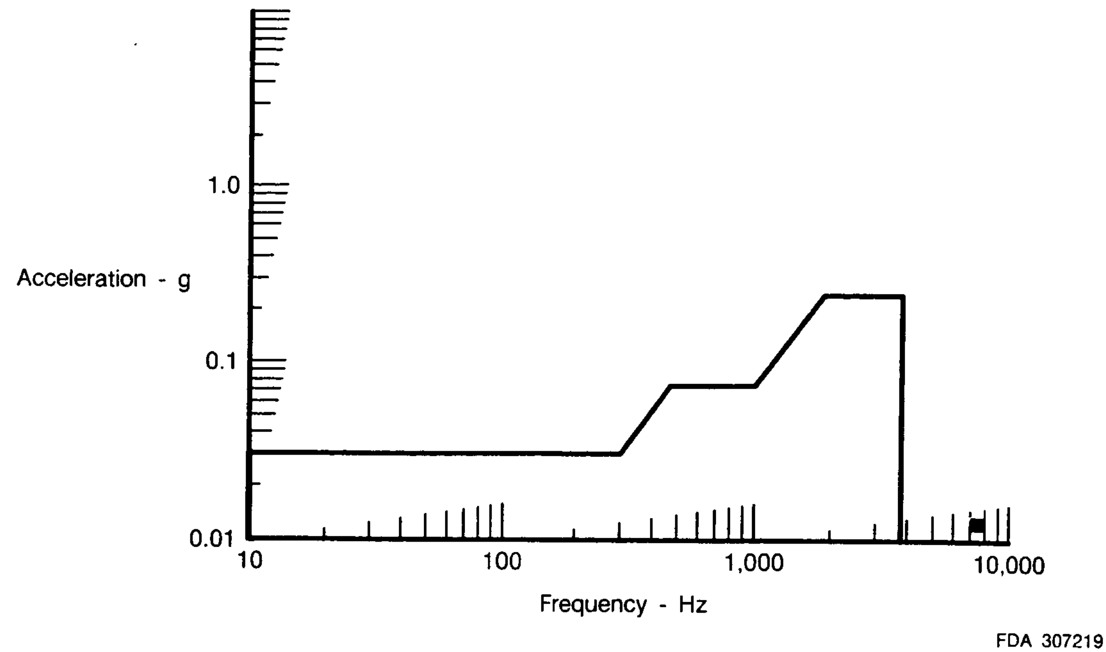

Figure A-2. Sinusoidal Vibration Schedule

3.2.5.3.2 Random

The unit shall be exposed to random vibration as specified in Figure A-3 for 15 minutes in each of its principal axes.

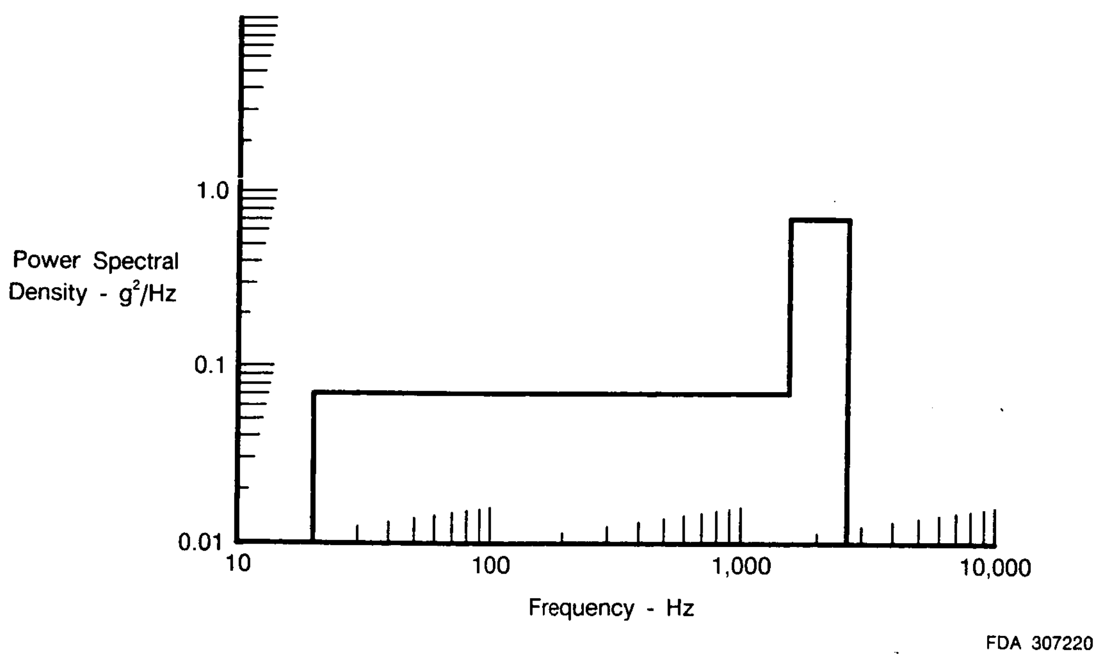

Figure A-3. Random Vibration Schedule

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3.2.5.4 Salt Spray

The unit must show no degradation in performance or structural integrity after being subjected to a salt spray test per MIL-R-5149B, paragraph 4.9.1.9.6.

3.2.5.5 Gravity/Acceleration

The heat exchanger performance shall not be affected by changes in gravity or by vehicle acceleration.

3.3 Design and Construction

3.3.1 Materials and Processes

Materials and processes used in the manufacture of the heat exchanger shall be of high quality and suitable for the purpose. Verification of required material properties of vendor supplied material shall be the responsibility of the supplier, as specified in specification PWA 300. Proof of verification will be supplied to P&W upon request.

3.3.1.1 Material Approval

All materials selected by the supplier for use in this unit are subject to review and must be approved by the cognizant P&W Project Engineer.

3.3.1.2 Dissimilar Metals

The use of dissimilar metals as defined in MIL-STD-889B shall be avoided.

3.3.1.3 Use of AMS 5620, 5621, 5630, and 5632 Material

The use of the subject heat treatable stainless steels, or equivalents, is prohibited unless agreed to in writing by the cognizant P&W Project Engineer.

3.3.1.4 Material Compatibility

All materials used in construction shall be compatible with the fluids carried by the heat exchanger such that there shall be no degradation of material or fluid properties as a result of long term contact. Any materials known to be susceptible to stress corrosion shall not be used. All materials used in the oxygen circuit shall be proven to be compatible with liquid oxygen as demonstrated by compliance with specification PWA 82.

3.3.1.5 Standards

Materials and processes which are listed in the latest edition of the SAE Aerospace Materials Specification index or which are controlled by P&W specifications shall be used whenever possible. AN, MS, or MIL standard parts shall be used, wherever possible, and identified by their standard part number. MS, AND, and AS design standards shall be used wherever applicable.

3.3.2 Marking

Part identification shall be in accordance with MIL-STD-130F and shall include at least the following:

1. Manufacturer's Name
2. Manufacturer's Part Number and latest change identification
3. Manufacturer's Serial Number
4. P&W Part Number and latest change identification
5. P&W Serial Number.

3.3.3 Quality Assurance

The supplier quality assurance program shall comply with the requirements of PWA QA-6076, Section III.

3.3.4 Interchangeability

All parts having the same manufacturer's part number shall be functionally and dimensionally interchangeable with each other with respect to installation and performance.

3.3.5 Changes in Design

All changes made in design, material, or manufacturing processes after initial acceptance must be approved in writing by the cognizant P&W Project Engineer.

3.4 Documentation

3.4.1 Design Analysis

The analysis of the design of the heat exchanger shall be available for review and must be approved by the cognizant P&W Project Engineer prior to start of fabrication of the first unit. The analysis shall include both the thermal and structural aspects of the design. All supporting test data, previous experience, or other background used as rationale for the concept selection shall also be presented. The analysis must be updated as required to support subsequent changes in design or manufacturing processes. These updates must be reviewed and approved by the cognizant P&W Project Engineer prior to incorporation of such changes.

3.4.2 Drawings

All drawings for the heat exchanger shall be prepared in accordance with Military Specification DOD-D-1000B. The supplier shall supply three copies of all drawings necessary to describe the unit. All subsequent changes must be coordinated with and approved by the cognizant P&W Project Engineer.

3.5 Precedence

In the event of conflict between this specification and referenced documents, this specification shall take precedence.

4.0 QUALITY ASSURANCE PROVISIONS

4.1 General

The supplier shall be responsible for compliance with all quality assurance provisions of this specification and all referenced specifications unless agreed to in writing by the cognizant P&W Project Engineer.

4.1.1 Responsibility for Tests

Unless otherwise agreed to, the supplier shall be responsible for all tests specified herein.

4.1.2 Tests and Examinations

4.1.2.1 Performance Tests

The supplier shall demonstrate the performance of the heat exchanger for compliance with paragraphs 3.2.1.4, 3.2.1.5, and 3.2.1.6 based on conditions shown in paragraphs 3.2.1.2 and 3.2.1.3. This test must be performed for every development unit and for the first and every tenth unit of any production lot. If the production lot is less than ten, the test shall be performed for the first and last units of the lot. The fluids used for this testing need not be hydrogen and oxygen, but must be suitable to demonstrate the performance of the heat exchanger for the design fluids. The test program, including predicted results, must be submitted for approval by the cognizant P&W Project Engineer at least 45 days prior to the first test.

4.1.2.2 Acceptance Tests

Each unit shall be subject to the following tests prior to delivery. These tests are to be performed in the order listed unless agreed to by the cognizant P&W Project Engineer. The test procedure shall be submitted to and approved by the cognizant P&W Project Engineer prior to beginning testing. Any subsequent changes must also be approved by the cognizant P&W Project Engineer.

4.1.2.2.1 Thermal Cycle

Each unit shall be subjected to thermal cycle testing. The oxygen circuit inlet shall be connected to a liquid nitrogen source and flow shall be initiated at 20 ± 2 psia. Continue flow until liquid is observed from the oxygen discharge port, and maintain for one minute following establishment of liquid flow. Following this, the unit shall be allowed to warm to ambient. Return to ambient can be assisted by an ambient gas purge which shall not return the unit to ambient in less than 15 minutes. This thermal cycle shall be repeated four additional times. The heat exchanger shall suffer no damage or permanent deformation, and shall meet leakage requirements when tested per paragraphs 4.1.2.2.3 and 4.1.2.2.4.

4.1.2.2.2 Proof Test

Each unit shall be subject to a proof test at the pressure levels indicated in paragraph 6.7. Pressure is to be held for a minimum of 5 minutes. The unit shall exhibit no permanent deformation and shall meet leakage requirements when tested per paragraphs 4.1.2.2.3 and 4.1.2.2.4.

4.1.2.2.3 External Leak Test

Each unit shall be subject to a test for external leakage. The unit shall be pressurized to 100 psig with gaseous helium and checked for external leaks. No external leakage is allowed as indicated by standard leak detector fluid (ASM 3159 or equivalent).

4.1.2.2.4 Internal Leak Test

Each unit shall be subjected to a test for internal leakage. The oxidizer circuit shall be pressurized to 100 psig with gaseous nitrogen. A leakage measuring device shall be connected to the hydrogen circuit. Pressure must be maintained for a minimum of 5 minutes. Leakage shall be limited to the extent shown in Paragraph 6.6.

4.1.2.2.5 Fluorescent Penetrant Inspection

All external welds and surfaces shall be inspected in accordance with AMS 2645 or equivalent. There shall be no evidence of cracks, pits, or porosity. Caution: Oil based penetrants shall not be used.

4.3 Test Data Reports

4.3.1 Performance Test Report

The supplier shall submit a written report of the performance test results and data analysis within 60 days of test completion.

4.3.2 Acceptance Test Report

The supplier shall supply one copy of the acceptance test data with each unit procured under this specification. This data must be provided at the time the unit is delivered to Pratt & Whitney.

5.0 PREPARATION FOR DELIVERY

5.1 Dehydration

The unit shall be dehydrated prior to shipment by a method prescribed by the supplier. This procedure shall be subject to review and must be approved by the cognizant P&W Project Engineer prior to shipment.

5.2 Shipping Closures

The unit must be packaged to prevent damage during shipment. Packaging shall be in accordance with PWA 382A.

6.0 DESIGN CRITERIA

6.1 General

The criteria shown here are to be used in conjunction with Section 3.0 of this specification as the basis for design of the heat exchanger.

6.2 Fluids

6.2.1 Hydrogen

Gaseous hydrogen per MIL-P-27201B.

6.2.2 Oxygen

Liquid oxygen per MIL-P-25508E-3.

6.3 Tank Head Idle Criteria

6.3.1 Hydrogen Inlet Conditions

Pressure: 9.0 psia
Temperature: 594/R.

6.3.2 Oxygen Inlet Conditions

Pressure: 20 psia
Temperature: 165.8/R.

6.3.3 Allowable Pressure Drops

Hydrogen: 2.1 psi maximum
Oxygen: 2.3 psi maximum.

6.3.4 Flow Rates

Hydrogen: 0.094 lbm/sec
Oxygen: 0.31 lbm/sec.

6.3.5 Allowable Oxygen Flow Oscillations

0.05 lbm/sec.

6.4 Pumped Idle Criteria

6.4.1 Hydrogen Inlet Condition

Pressure: 46.7 psia
Temperature: 659/R.

6.4.2 Oxygen Inlet Conditions

Pressure: 110 psia
Temperature: 168/R.

6.4.3 Allowable Pressure Drops

Hydrogen: 2.4 psi maximum
Oxygen: 4.7 psi maximum.

6.4.4 *Flow Rates*

Hydrogen: 0.190 lbm/sec
Oxygen: 2.84 lbm/sec.

6.4.5 *Allowable Oxygen Flow Oscillations*

0.20 lbm/sec.

6.5 Oxidizer Discharge Quality

0.95 minimum.

6.6 Allowable Cross Circuit Leakage

10 sccm.

6.7 Proof Pressure

1100 psia.

6.8 Burst Pressure

1500 psi.

6.9 Maximum Cross Circuit Differential Pressure

300 psi.

7.0 DUTY CYCLE

7.1 General

The duty cycle for the unit shall consist of operation at tank head idle, pumped idle, and full thrust levels as described below.

7.2 Tank Head Idle

7.2.1 *Prestart*

The unit will be at ambient pressure and temperature prior to start.

7.2.2 *Start to Tank Head Idle*

Pressurization of the unit to THI levels will occur within 0.5 second of propellant flow start.

7.2.3 *Tank Head Idle Operation*

Hydrogen and oxygen flows will be maintained at THI pressures until the engine temperatures stabilize. This can be from 20 to 180 seconds depending on the fluid conditions at the engine inlets.

7.3 Pumped Idle

7.3.1 Transition

Transition from the THI to PI will take place within 0.7 second from the time the signal is given.

7.3.2 Pumped Idle Operation

The unit will operate at PI for a minimum of 5 seconds and a maximum of 3600 seconds.

7.4 Full Thrust

7.4.1 Transition

Transition to the FT operating pressures will take place within 0.4 second from the time the signal is given.

7.4.2 Full Thrust Operation

The unit can operate at FT for as long as 1200 seconds.

7.5 Shutdown

Engine shutdown and ventage of the heat exchanger fluids can occur from any thrust level. Ventage will take place within 0.25 second from the time the signal is given.

APPENDIX B
DESCRIPTION OF COMPUTER PROGRAMS

I. THERMAL ANALYZER PROGRAM

A. Program Capabilities

1. Transient Heat Transfer Calculations

Transient heat transfer calculations are developed by an explicit finite difference technique using any element shape with three-dimensional conduction, convection, or radiation heat transfer.

2. Steady State Heat Transfer Calculations

Steady state heat transfer calculations are based on a modified Gauss-Seidel solution to the simultaneous equations in the thermal model. This modified technique involves "accelerated" step substitution with monotonic deceleration until successive substitutions are convergent. A method of "lumping" areas of the problem which are slow to converge is also used to accelerate the calculation procedure. This procedure also provides for any element shape with three-dimensional conduction, convection, or radiation heat transfer.

3. Conduction Heat Transfer Calculations

Conduction heat transfer is input to the program by specifying the element numbers connected by conduction, the cross sectional area for conduction between the elements, and the conduction length from the center of each element to the interface between them. A mechanical joint thermal contact resistance may also be specified between the elements if they are mechanically separated at the interface. The program obtains the thermal conductivity of each element from a table in which it may be specified as a constant value or as a function of temperature.

4. Convection Heat Transfer Calculations

Convection heat transfer is input to the program by specifying a solid element number connected to a fluid element number by convection, the cross sectional area for convection from the solid element, and conduction length from the center of the solid element to the convection surface. This program performs the important and often overlooked task of combining conduction heat transfer from the center of the solid element to the surface with convection from the solid surface to the fluid.

The convection heat transfer coefficient may be input to the program by ten different methods. In the first four methods, the heat transfer coefficient may be input as a constant, as a function of time in a table, as a function of the surface to fluid temperature difference in a table, and as a function of the "film" temperature in a table. In method five, the program calculates the natural convection heat transfer coefficient for both open and enclosed static spaces and enclosed rotating spaces. In method six the program calculates convection heat transfer coefficients for high speed laminar or turbulent flow over external surfaces including the effects of the "recovery" temperature in the boundary layer. In method seven the program calculates convection heat transfer coefficients on a free or enclosed rotating disc including the calculation of frictional "windage" heat generation. In method eight the program calculates convection heat transfer between a rotating cylinder and a static housing or from the surface of a rotating cylinder in an infinite environment. This method also includes the calculation of frictional "windage" heat generation. In method nine the program calculates convection heat transfer coefficients for flow in a duct, including the heat transfer "fin effectiveness" of extended surfaces within the duct. This method utilizes tables of Colburn J-factors input as a function of Reynolds number to the program. These tables may be generated for fluid flow in round ducts, square ducts, rectangular ducts, triangular ducts, annular spaces, dimpled tubes, and curved ducts. They may also be generated for fluid flow in tube banks, plate-fin surfaces, screen matrix surfaces, crossed rod matrix surfaces, and corrugated ceramic surfaces. Entrance effects on heat transfer may be applied using the appropriate multiplying factor at each location. In method ten the program calculates jet impingement heat transfer coefficients for impingement from a row of holes onto a concave surface or from an array of holes against a flat surface. Four techniques for evaluation of the influence of temperature-dependent fluid properties are available in the program. The appropriate fluid properties may be input in tabular form as a function of temperature.

5. *Radiation Heat Transfer Calculations*

Radiation heat transfer is input to the program by specifying a solid element number connected to a representative surrounding element number by radiation, the cross sectional area for radiation from the solid element, and the conduction length from the center of the solid element to the radiation surface. This section also includes the important combination of conduction to the radiating surface with radiation from the surface. The emissivity view factor for radiation may be estimated by methods given in "Radiation Heat Transfer" by Sparrow and Cess or by a computer program such as CONFAC II.

6. *Initial Temperature, Boundary Conditions, Heat Input, Thermal Capacitance, and Thermal Conductivity Specification*

The initial temperature, boundary conditions, heat input, thermal capacitance, and thermal conductivity may be specified for each individual element or for blocks of elements which are identical. In transient heat transfer calculation, the initial temperature, the heat input, the density, the volume, the specific heat, and the thermal conductivity of each element is specified. For elements with negligible thermal capacitance the density, the volume, and specific heat may be left blank to increase the calculation time step. For steady state calculations, the initial temperature, the heat input, and the thermal conductivity of each element is specified. The boundary condition elements are specified by having a negative value for the density times the volume. This element is then maintained at a constant temperature or may be specified as a temperature versus time function from an input table. Any element in the network may be specified as a boundary condition (constant temperature) element and any number of elements may be connected to it by conduction, convection, or radiation. The heat input for each element may be programmed as zero, as a constant value, as a function of time in a table, as a function of its own temperature or another specified element temperature, specified from the frictional "windage" heat generation calculations, or calculated from the ball and roller bearing heat generation calculation computer program which can be supplied. The specific heat and thermal conductivity of each element may be specified as a constant or as a function of temperature in tables.

7. *Fluid Stream Heat Transfer and Pressure Drop Calculations*

Fluid stream elements may be input with heat transfer to them by conduction, convection, or radiation. Fluid stream heat transfer calculations have provisions for preventing the outlet fluid temperature from "overshooting" the surrounding surface temperatures, a thermodynamic impossibility. The steady state fluid stream calculations are based on thermal capacity rate calculations, while transient fluid stream calculations may be based on the thermal capacitance of each element moving in the fluid stream to simulate "lag" conditions. The energy input of rotational flow may also be added to the fluid stream.

Both steady state compressible and incompressible fluid stream pressure drops may be calculated by the program. The pressure drop calculations include the effects of heat addition, area change, fluid friction, rotational flow, and flow addition or removal. Total head losses due to valves, bends, sharp contractions or expansions, and orifices may be included at the inlet and exit to each fluid stream.

A complete fluid stream network may be simulated with streams branching from previous streams and mixing to form new streams or even returning to a previous stream in the network. The fluid flow rate may be input as a constant, as a function of time, from a table, or as a function of specified element temperature.

8. Boiling Heat Transfer Calculations

Boiling heat transfer calculations have been included in the fluid stream heat transfer and pressure drop calculations, in the method nine convection heat transfer calculations, and in the heat transfer coefficient calculation as a function of temperature difference method for pool boiling. Six options are available in method nine for calculating forced convection heat transfer coefficients. The equations in these options are taken from Guerrieri and Talty; Dengler and Addoms; Thorsen, Dobran, and Alcorta; John C. Chen; and Altman, Norris, and Staub. The fluid stream includes subcooled liquid heating, a constant temperature boiling region, and vapor superheating. The fluid stream also includes subcooled boiling heat transfer calculations when the wall temperature exceeds the saturation temperature of the liquid flowing in the stream.

B. Program Output

1. Each element temperature, heat input, and thermal conductivity for steady state calculations is printed out. Each element temperature, heat input, weight, specific heat, and thermal conductivity for each specified printing time period in transient heat transfer calculations is printed out.

2. The fluid stream inlet temperature and the outlet temperature, the fluid stream flow rate, the fluid density, and the internal fluid heat generation for each section of each fluid stream is printed out.

3. The "free stream" temperature, the film discharge temperature, and the effective film temperature at each location specified is printed out.

4. The printing of the thermal resistance values for conduction, the thermal resistance values and heat transfer coefficients for convection, and the thermal resistance values and effective heat transfer coefficients for radiation may be included or deleted as specified.

5. The fluid stream pressure drop calculations and printout may be deleted if specified. When included, the total and static pressures, the Reynolds number, the friction factor, and the Mach number for compressible flow is printed for each element in each fluid stream.

C. Typical Applications

1. Both passive and active electronic cooling system analysis and design with or without heaters or cooling flow controllers.

2. Thermal analysis and design calculations for ambient cooled, forced air cooled, gas cooled, or liquid cooled ac or dc motors, generators, and alternators.

3. Thermal analysis and design calculations for pumps, fans, and compressors including the bearing temperatures and the analysis of the motors or turbines driving them.

4. Thermal analysis and design calculations of gas turbine engines including the axial flow and radial flow compressors and turbines, the combustor, the bearings and seals, the anti-icing system, the lubrication cooling system, the fuel supply system, and the accessory area cooling system. Also the thermal analysis of cooled and uncooled turbine blades.

5. Transient and steady state thermal analysis of heat exchangers including air-oil coolers, fuel-oil coolers, recuperators, rotary regenerators, cryogenic heat exchangers, pool boiling heat exchangers, condensers, periodic flow regenerators, and heat exchangers with more than two fluid streams. The calculations may include the effects of axial conduction, fluid bypassing, perfectly mixed or unmixed fluids, variation of fluid properties through the heat exchanger, condensation of moisture from the air or "wet" heat transfer, and the effect of the variation of fluid to wall temperature difference on local heat transfer coefficients for boiling and condensing.

6. Thermal analysis and design calculations for solar receivers and for space radiators with fluid streams and/or heat pipes. Transient calculations including thermal control elements are also included in the program.

II. STRUCTURAL ANALYSIS PROGRAMS

1. ELPLAC

This proprietary program provides elastic, plastic and creep analysis of 2-D constant or variable thickness plates used in heat exchangers for parting or side plate sheets, subjected to loads and temperatures. It handles up to 300 nodes and quad elements. A special version, running in multiple passes, uses up to 1200 elements. The program calculates stresses (directional and shear, principal and effective), and strains (elastic, plastic and creep). Data files are postprocessed by a contour plotting program (CONTOUR).

2. SAP IV

SAP IV was developed at the University of California at Berkeley by Prof. Wilson and others. It is a general program able to handle linear elastic solutions (not plasticity or creep). It is efficient, providing in many cases only stress resultants.

APPENDIX C
"OFF-DESIGN" OHE PERFORMANCE

This appendix presents the "off-design" points that were investigated to evaluate the sensitivity of the design to changes in the inlet conditions resulting from engine operation at different chamber pressures and mixtures ratios. Table C-1 presents the OHE inlet conditions that resulted from analytically varying the engine cycle operating point. Tables C-2 through C-11 present the resulting predicted OHE performance.

Table C-1. *OHE Inlet Conditions*

Pumped Idle						
Point No.	*1*	*2*	*3*	*4*	*5*	*6*
P_c (psia)	35	35	45	45	35	45
O/F*	4.0	7.0	4.0	7.0	5.0	5.0
H_2 Hex Inlet						
$\dot{W}$ (lb/sec)	0.200	0.144	0.257	0.192	0.179	0.229
P (psia)	43	41	55	53	42.1	54.1
T (°R)	460	774	434	729	573	541
O_2 Hex Inlet						
$\dot{W}$ (lb/sec)	2.15	2.66	2.75	3.39	2.32	2.97
P (psia)	108	102	124	114	105	120
T (°R)	168.7	168.0	168.6	167.6	168.3	168.3
Tank Head Idle						
Point No.	*1*	*2*	*3*	*4*		
P_c (psia)	4.5	4.5	6.5	6.5		
O/F	3.0	4.0	3.0	4.0		
H_2 Hex Inlet						
$\dot{W}$ (lb/sec)	0.08	0.07	0.12	0.10		
P (psia)	7.7	7.4	10.8	10.4		
T (°R)	557	752	519	700		
O_2 Hex Inlet						
$\dot{W}$ (lb/sec)	0.25	0.27	0.36	0.39		
P (psia)	15.6	19.5	21.3	26.6		
T (°R)	161.2	165.3	167.1	172.0		

* A portion of the pumped idle engine hydrogen flow is diverted to the turbine to drive propellant pumps.

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Table C-2. *Pratt & Whitney RL10-IIB Engine Oxygen/Gaseous Hydrogen Heat Exchanger Off-Design Pumped Idle Point No. 1*

Cold Side (one pass)	
Fluid	Liquid oxygen
Flow Rate	2.15 lb/sec
Inlet Temperature	168.7°R
Boiling Temperature	206.5°R
Outlet Temperature	206.5°R
Inlet Pressure	108 psia
Pressure Drop (Including inlet and exit fittings)	1.9 psi
Exit Quality	66.9% Gaseous oxygen
Heat Transfer Rate	528,257 Btu/hr
Hot Side (two pass cross counter flow)	
Fluid	Gaseous hydrogen
Flow Rate	0.20 lb/sec
Inlet Temperature	460°R
Hydrogen Temperature at start of oxygen boiling	282°R
Outlet Temperature	231°R
Inlet Pressure	43.0 psia
Pressure Drop (Including inlet and exit fittings)	0.78 psi
Core Size and Weight	
Hot Flow Length	5.5 in.
Cold Flow Length	8.25 in.
Stack Height	6.5 in.
Core Dry Weight	10.2 lb

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Table C-3. *Pratt & Whitney RL10-IIB Engine Oxygen/Gaseous Hydrogen Heat Exchanger Off-Design Pumped Idle Point No. 2*

Cold Side (one pass)	
Fluid	Liquid oxygen
Flow Rate	2.66 lb/sec
Inlet Temperature	168°R
Boiling Temperature	205°R
Outlet Temperature	312.4°R
Inlet Pressure	102 psia
Pressure Drop (Including inlet and exit fittings)	3.7 psi
Exit Quality	100% Gaseous oxygen
Heat Transfer Rate	935,583 Btu/hr
Hot Side (two pass cross counter flow)	
Fluid	Gaseous hydrogen
Flow Rate	0.144 lb/sec
Inlet Temperature	774°R
Hydrogen Temperature at start of oxygen boiling	307°R
Outlet Temperature	241°R
Inlet Pressure	41.0 psia
Pressure Drop (Including inlet and exit fittings)	0.74 psi
Core Size and Weight	
Hot Flow Length	5.5 in.
Cold Flow Length	8.25 in.
Stack Height	6.5 in.
Core Dry Weight	10.2 lb

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Table C-4. *Pratt & Whitney RL10-IIB Engine Oxygen/Gaseous Hydrogen Heat Exchanger Off-Design Pumped Idle Point No. 3*

Cold Side (one pass)	
Fluid	Liquid oxygen
Flow Rate	2.75 lb/sec
Inlet Temperature	168.6°R
Boiling Temperature	210°R
Outlet Temperature	210°R
Inlet Pressure	124 psia
Pressure Drop (Including inlet and exit fittings)	2.2 psi
Exit Quality	54.5% Gaseous oxygen
Heat Transfer Rate	585,677 Btu/hr
Hot Side (two pass cross counter flow)	
Fluid	Gaseous hydrogen
Flow Rate	0.257 lb/sec
Inlet Temperature	434°R
Hydrogen Temperature at start of oxygen boiling	291°R
Outlet Temperature	234.5°R
Inlet Pressure	55.0 psia
Pressure Drop (Including inlet and exit fittings)	0.92 psi
Core Size and Weight	
Hot Flow Length	5.5 in.
Cold Flow Length	8.25 in.
Stack Height	6.5 in.
Core Dry Weight	10.2 lb

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Table C-5. *Pratt & Whitney RL10-IIB Engine Oxygen/Gaseous Hydrogen Heat Exchanger Off-Design Pumped Idle Point No. 4*

Cold Side (one pass)	
Fluid	Liquid oxygen
Flow Rate	3.39 lb/sec
Inlet Temperature	167.6°R
Boiling Temperature	208°R
Outlet Temperature	208°R
Inlet Pressure	114 psia
Pressure Drop (Including inlet and exit fittings)	5.1 psi
Exit Quality	98.1% Gaseous oxygen
Heat Transfer Rate	1,139,713 Btu/hr
Hot Side (two pass cross counter flow)	
Fluid	Gaseous hydrogen
Flow Rate	0.192 lb/sec
Inlet Temperature	729°R
Hydrogen Temperature at start of oxygen boiling	325°R
Outlet Temperature	238.7°R
Inlet Pressure	53.0 psia
Pressure Drop (Including inlet and exit fittings)	0.87 psi
Core Size and Weight	
Hot Flow Length	5.5 in.
Cold Flow Length	8.25 in.
Stack Height	6.5 in.
Core Dry Weight	10.2 lb

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Table C-6. *Pratt & Whitney RL10-IIB Engine Oxygen/Gaseous Hydrogen Heat Exchanger Off-Design Pumped Idle Point No. 5*

Cold Side (one pass)	
Fluid	Liquid oxygen
Flow Rate	2.32 lb/sec
Inlet Temperature	168.3°R
Boiling Temperature	206°R
Outlet Temperature	206°R
Inlet Pressure	105 psia
Pressure Drop (Including inlet and exit fittings)	2.7 psi
Exit Quality	89.1% Gaseous oxygen
Heat Transfer Rate	717,649 Btu/hr
Hot Side (two pass cross counter flow)	
Fluid	Gaseous hydrogen
Flow Rate	0.179 lb/sec
Inlet Temperature	573°R
Hydrogen Temperature at start of oxygen boiling	294°R
Outlet Temperature	233.6°R
Inlet Pressure	42.1 psia
Pressure Drop (Including inlet and exit fittings)	0.79 psi
Core Size and Weight	
Hot Flow Length	5.5 in.
Cold Flow Length	8.25 in.
Stack Height	6.5 in.
Core Dry Weight	10.2 lb

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Table C-7. *Pratt & Whitney RL10-IIB Engine Oxygen/Gaseous Hydrogen Heat Exchanger Off-Design Pumped Idle Point No. 6*

Cold Side (one pass)	
Fluid	Liquid oxygen
Flow Rate	2.97 lb/sec
Inlet Temperature	168.3°R
Boiling Temperature	209°R
Outlet Temperature	209°R
Inlet Pressure	120 psia
Pressure Drop (Including inlet and exit fittings)	3.3 psi
Exit Quality	76.3% Gaseous oxygen
Heat Transfer Rate	814,223 Btu/hr
Hot Side (two pass cross counter flow)	
Fluid	Gaseous hydrogen
Flow Rate	0.229 lb/sec
Inlet Temperature	541°R
Hydrogen Temperature at start of oxygen boiling	304°R
Outlet Temperature	238.7°R
Inlet Pressure	54.1 psia
Pressure Drop (Including inlet and exit fittings)	0.89 psi
Core Size and Weight	
Hot Flow Length	5.5 in.
Cold Flow Length	8.25 in.
Stack Height	6.5 in.
Core Dry Weight	10.2 lb

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Table C-8. *Pratt & Whitney RL10-IIB Engine Oxygen/Gaseous Hydrogen Heat Exchanger Off-Design Tank Head Idle Point No. 1*

Cold Side (one pass)	
Fluid	Liquid oxygen
Flow Rate	0.25 lb/sec
Inlet Temperature	161.2°R
Boiling Temperature	162.5°R
Outlet Temperature	527°R
Inlet Pressure	15.6 psia
Pressure Drop (Including inlet and exit fittings)	1.2 psi
Exit Quality	100% Gaseous oxygen
Heat Transfer Rate	157,840 Btu/hr
Hot Side (two pass cross counter flow)	
Fluid	Gaseous hydrogen
Flow Rate	0.08 lb/sec
Inlet Temperature	557°R
Hydrogen Temperature at start of oxygen boiling	394°R
Outlet Temperature	394°R
Inlet Pressure	7.7 psia
Pressure Drop (Including inlet and exit fittings)	2.1 psi
Core Size and Weight	
Hot Flow Length	5.5 in.
Cold Flow Length	8.25 in.
Stack Height	6.5 in.
Core Dry Weight	10.2 lb

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Table C-9. *Pratt & Whitney RL10-IIB Engine Oxygen/Gaseous Hydrogen Heat Exchanger Off-Design Tank Head Idle Point No. 2*

Cold Side (one pass)	
Fluid	Liquid oxygen
Flow Rate	0.27 lb/sec
Inlet Temperature	165.3°R
Boiling Temperature	167°R
Outlet Temperature	714°R
Inlet Pressure	19.5 psia
Pressure Drop (Including inlet and exit fittings)	1.4 psi
Exit Quality	100% Gaseous oxygen
Heat Transfer Rate	208,127 Btu/hr
Hot Side (two pass cross counter flow)	
Fluid	Gaseous hydrogen
Flow Rate	0.07 lb/sec
Inlet Temperature	752°R
Hydrogen Temperature at start of oxygen boiling	512°R
Outlet Temperature	512°R
Inlet Pressure	7.4 psia
Pressure Drop (Including inlet and exit fittings)	2.7 psi
Core Size and Weight	
Hot Flow Length	5.5 in.
Cold Flow Length	8.25 in.
Stack Height	6.5 in.
Core Dry Weight	10.2 lb

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Table C-10. *Pratt & Whitney RL10-IIB Engine Oxygen/Gaseous Hydrogen Heat Exchanger Off-Design Tank Head Idle Point No. 3*

Cold Side (one pass)	
Fluid	Liquid oxygen
Flow Rate	0.36 lb/sec
Inlet Temperature	167.1°R
Boiling Temperature	168.8°R
Outlet Temperature	481°R
Inlet Pressure	21.3 psia
Pressure Drop (Including inlet and exit fittings)	1.5 psi
Exit Quality	100% Gaseous oxygen
Heat Transfer Rate	211,922 Btu/hr
Hot Side (two pass cross counter flow)	
Fluid	Gaseous hydrogen
Flow Rate	0.12 lb/sec
Inlet Temperature	519°R
Hydrogen Temperature at start of oxygen boiling	372°R
Outlet Temperature	453°R
Inlet Pressure	10.8 psia
Pressure Drop (Including inlet and exit fittings)	2.6 psi
Core Size and Weight	
Hot Flow Length	5.5 in.
Cold Flow Length	8.25 in.
Stack Height	6.5 in.
Core Dry Weight	10.2 lb

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Table C-11. *Pratt & Whitney RL10-IIB Engine Oxygen/Gaseous Hydrogen Heat Exchanger Off-Design Tank Head Idle Point No. 4*

Cold Side (one pass)	
Fluid	Liquid oxygen
Flow Rate	0.39 lb/sec
Inlet Temperature	172.0°R
Boiling Temperature	173.2°R
Outlet Temperature	651°R
Inlet Pressure	26.6 psia
Pressure Drop (Including inlet and exit fittings)	1.7 psi
Exit Quality	100% Gaseous oxygen
Heat Transfer Rate	276,847 Btu/hr
Hot Side (two pass cross counter flow)	
Fluid	Gaseous hydrogen
Flow Rate	0.10 lb/sec
Inlet Temperature	700°R
Hydrogen Temperature at start of oxygen boiling	476°R
Outlet Temperature	475°R
Inlet Pressure	10.4 psia
Pressure Drop (Including inlet and exit fittings)	2.9 psi
Core Size and Weight	
Hot Flow Length	5.5 in.
Cold Flow Length	8.25 in.
Stack Height	6.5 in.
Core Dry Weight	10.2 lb

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APPENDIX D
ALPHA UNITED INC. TEST PROCEDURE

CONCEPT VERIFICATION
TEST PROCEDURE
for
Pratt & Whitney
RL10 IIB Engine Oxidizer Heat Exchanger
Phase I

1.0 SCOPE

1.1 Purpose

To provide empirical design data to be used for proving and developing a heat exchanger design concept for gasifing oxygen without creating flow instability

2.0 REFERENCES

2.1 Pratt & Whitney Aircraft

2.1.1 Purchase Performance Specification PPS F-654

2.1.2 RFQ PEC 022653 (2287)-C2

2.1.3 Purchase Order 270927

2.2 Alpha United

2.2.1 Proposal 506:DPE:0121

2.2.2 Dwg no. 10624, "LN2 FLOW SCHEMATIC"

2.2.3 Dwg no. 11060, "TEST SECTION OUTLINE"

2.3 Robertson, J.M, "Boiling Heat Transfer with Liquid Nitrogen in Brazed-Aluminum Plate-Fin Heat Exchangers", AIChE Symposium Series, Vol.75, No.189,1979, pp.151-164

3.0 TEST CONDITIONS AND TEST EQUIPMENT

3.1 Test Media

Commercial liquid nitrogen

3.2 Ambient Conditions

Temperature 75 +/- 5 deg F. Relative humidity less than 80%.

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3.3 Test Set Up

Per reference 2.2.2 and 2.2.3

3.4 Test Equipment

3.4.1 Flow Loop (reference 2.2.2)

Liquid nitrogen (LN2) from a container is supplied under pressure maintained by the containers internal pressure building circuit. The container also has provisions for supplying gaseous nitrogen in place of the LN2. The LN2 flows through a subcooler coil submersed in a liquid nitrogen bath open to atmospheric pressure. The bath level is maintained by a liquid level control valve tapped into the LN2 supply line. From the subcooler coil the LN2 flows through a flow control valve and a turbine flow meter before entering the test section. The nitrogen leaving the test section is discharged through a vaporizer coil and a back pressure control valve.

3.4.2 Test Section (reference 2.2.3)

The entire test section is located in the ullage of the subcooler container. The test section assembly is oriented vertically and such that LN2 enters the bottom, through a flair connection, and flows upward. The nitrogen vapor boil-off in the subcooler container insulates the test section area and purges the area of all condensible gases. The test section has three components attached together by 1 inch flanges. The lower most component is the heat exchanger that consists of a core with flanges welded to each end. The inlet flange has pressure and thermocouple taps. The heat exchanger core is provided with 19 150 watt heating elements and 10 copper-constantan thermocouples. The middle component is a spacer flange which permits adjusting the discharge volume (by changing the flange) from less than 1 cubic inch to greater than 6.5 cubic inches. The uppermost component is a flanged orifice section. The flanges are provided with two corner pressure taps and one thermocouple tap. Three interchangeable orifice plates of 3/16, 1/4 and 5/16 inch diameter will be provided with the 3/16 inch plate installed initially.

3.5 Instrumentation

3.5.1 Thermocouples

14 "T" type (copper-constantan) thermocouples 36 in. lg 1/16 O.D. 304 cres sheath grounded with standard quick disconnect plugs. -300 F to -70 F +/- 1%.

3.5.2 Pressure transducers

2 differential pressure transducers 150 PSIG line pressure min., +/- 5 PSI differential pressure +/- 0.5% F.S. accuracy.

2 CEC strain gage transducers, 0-150 PSIG +/- 0.5% F.S.

3.5.3 Miscellaneous

1 Sponsler MF-40 cryogenic turbine flow meter.015 to .4 GPM +/- 0.25% of reading

1 Sponsler AN40 rate indicator

4 Transducer signal conditioners

1 HP 320 chart recorder

1 Fluke 2280A datalogger with two 10 channel TC thermocouple cards.

2 Voltmeters 0-150 vac 60Hz

2 Ampmeters 0-10 amps AC 60Hz

2 Variable transformers 150 vac 10 amp capacity

4.0 REQUIREMENTS

4.1 General Requirements

The general requirement for this testing is obtain sufficient pressure, temperature and flow data to enable the determination of heat transfer and flow friction variables for an analytical proof of concept and full scale prototype heat exchanger design.

4.2 Requirement - Flow Oscillation

Determine the expansion volume and flow orifice resistance required to limit the flow oscillations shown in Table 1 for liquid nitrogen evaporating in an electrically heated offset plate fin test section.

To initially select an orifice/ volume combination the Pumped Idle with uniform heating condition will be run (refer to para 4.3). The equation for pressure drop for compressible flow through orifices is shown below.

$$\omega = .525\, Y\, d_o^2\, C \sqrt{\Delta P_o\, \rho_1}$$

Where

Y = expansion factor
d_o = orifice diameter inches
C = flow coefficient = , $C = K_{Loss}$
ΔP_o = orifice pressure drop PSID
ρ_1 = fluid density lbm/cu ft
ω = flow rate lbm/sec

From this equation the following relationship between the variation in orifice pressure drop $\Delta(\Delta P_o)$ and flow rate $\Delta\omega$ can be developed.

$$\pm\Delta\omega = \left[\sqrt{1 \pm \frac{\Delta(\Delta P_o)}{\Delta P_o}} - 1\right] \omega$$

This leads to the following expression for the change in orifice pressure drop produced by flow oscillation.

$$\pm\Delta(\Delta P_o) = \Delta P_o \left[\left(1 \pm \frac{\Delta\omega}{\omega}\right)^2 - 1\right]$$

The maximum allowable orifice pressure drop oscillations are shown in Table 1.

4.3 Requirement - Steady State Flow

Verify the heat transfer and pressure drop characteristics of the finned test section flow passage for cryogenic fluid forced convection vaporization.

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Two flow rates (Pumped Idle and Tank Head Idle) with two each different heat inputs for a total of four test runs must be made to verify a selected orifice/volume combination. Thermal analysis results for the RL-10 heat exchanger showed that the heat transferred to the oxygen in the exit half of the heat exchanger was 4 to 5 times greater than in the inlet half of the heat exchanger. Therefore, in addition to uniform heat input, the test section will be tested with 4 times the electrical heat input in the exit half as in the inlet half of the test section to simulate this condition. The thermal analysis results expected for the test section with uniform heat input is shown in Table 2 and with 4 times the heating in the exit section is shown in Table 3. The node number locations in Tables 2 and 3 are shown in Figure 1

5.0 PROCEDURES

5.1 General Procedure - START UP

5.1.1 Set Up

Set up instrumentation and flow loop per figure 1 "LN2 FLOW SCHEMATIC, TEST UNIT" dwg no 10624. Initial set up for the test secton will be with the 3/16 inch diameter orifice plate and two cubic inch volume spacer.

5.1.2 Purge

Purge the flow loop and subcooler with aproximately 1.5 CFM of gaseous nitrogen for at least 30 minutes.

5.1.3 Determine Heat Losses

Fill the subcooler by opening the liquid level control valve and then the LN2 container liquid supply valve. Close the flow control valve. Apply 200 watts of power to each group of heating elements untill the test section bulk temperature reaches about 70 deg. F. Turn off the power and record the test section temperature. Allow the test section to cool for exactly 10 minutes and remeasure its temperature. Measure and record the nitrogen ullage temperature. Calculate the external heat transfer coefficient for the test section from the following equation.

$$h A_s = - \frac{C_p m}{\Delta t} \ln \left(\frac{T - T_\infty}{T_o - T_\infty} \right)$$

Where

m = test section weight in lbs

C_p = coeff of spec heat of the test section in BTU/lbm-deg F.

T_o = test section initial in temp deg F

T = test section final in temp deg F

T_∞ = gaseous nitrogen in temp deg F

Δt = cool down time in minutes

h = over all heat transfer coefficient

A_s = test section surface area

The heat loss may then be calculated for any test section temperature from the following equation.

$$q = 17.58\, h A_s (T - T_\infty)$$

where q is the heat loss in watts.

5.1.4 Calibration

Begin flow of liquid nitrogen by slowly opening the flow control valve. By adjusting the flow control valve and the back pressure valve obtain a liquid flow rate of .1 lbs/min. and test section inlet pressure of 20 PSIA (5.3 PSIG). Record all pressure and thermocouple readings. Verify that the instrumentation is responding properly.

5.2 Procedure - Flow Oscillation (ref. para. 4.2)

5.2.1 Start Up

Start up per paragraph 5.1

5.2.2 Establish Flow for Uniform Heating

From the condition of para 5.1.4, slowly increase the LN2 flow rate to 1.08 lbs/min by opening the flow control valve while maintaining the system pressure at 20 PSIA by adjusting the back pressure control valve. Apply power to both of the test section heating element groups by turning up both variable transformers equally. Each heating element group should have 840 watts applied to it. Increase the system pressure to 110 PSIA (95.3 PSIG) by closing the back pressure control valve. Readjust the flow control valve to maintain the 1.08 lbs/min flow rate if necessary. Allow the system to stabilize by running 5 minutes and readjust control valves as required.

5.2.3 Record Data

After the system has stabilezed, measure and record all thermocouples, pressure transducers and the flow rate. Record the differential pressure transducer output (orifice pressure drop) for one minute on the high speed chart recorder.

5.2.4 Establish Flow for Non-uniform Heating

By adjusting the variable transformers, change the heat loading so that the upper (downstream) group of elements is receiving 1344 watts and the lower (upstream) group is receiving 336 watts. Check flow and system pressure.

5.2.5 Record Data

Repeat para 5.2.3

5.2.6 Calculate Flow Oscillation

The frequency of the flow oscillation may be determined from the chart record of the differential pressure transducer. Use the differential pressure variation to calculate the magnititude of flow oscillation with the equation in para 4.2. Compare results with the limits shown on Tabel 1, pumped idle condition. If the compairson is unsatisfactory then install a new orifice/volume combination and repeat paragraph 5.2.

5.3 Procedure - Steady State (ref. para. 4.3)

5.3.1 Pumped Idle Condition

Once a suitable orifice/volume combination has been determined the flow, pressure and temperature data gathered in paragraph 5.2 may be used to verify the theroetical flow friction and heat transfer characteristis by comparison with the predicted performance of the test section shown in Tables 1, 2 and 3. The data will also be used to complete the preliminary thermal design of the RL-10 oxidizer heat exchanger.

5.3.2 Tank Head Idle Condition

To verify thermal performance and check for flow oscillations for the predetermined orifice/volume combination at the THI condition, repeat paragraph 5.2 with the following changes.

5.3.2.1 Uniform Heating

Flow rate	.118 lbs/min
System pressure	20 PSIA
Lower heater group power	200 watts
Upper heater group power	200 watts

5.3.2.2 Non-uniform Heating

Flow rate	.118 lbs/min
System pressure	20 PSIA
Lower heater group power	80 watts
Upper heater group power	320 watts

TABLE 1
RL10-IIB HEAT EXCHANGER MODEL TEST CONDITIONS

CONDITION		PUMPED IDLE	TANK HEAD IDLE
LN2 FLOW LBS/MIN		1.08	.118
LN2 INLET TEMP. DEG R		145.	142.
LN2 INLET PRESSURE PSIA		110.	20.
GN2 OUTLET TEMP. DEG R		179.	570.
FINNED PASSAGE PRESSURE DROP PSI		2.4	1.
HEATER POWER WATTS		1680.	400.
GN2 ORIFICE PRESSURE DROP PSI		1.6	.33
ORIFICE DIAMETER INCHES		3/16	3/16
FLOW OSCILLATION	+ LBS/MIN. - LBS/MIN.	+.076 -.076	+.019 -.019
GN2 ORIFICE PRESSURE DROP OSCILLATION	+ PSI - PSI	+.233 -.2174	+.115 -.098

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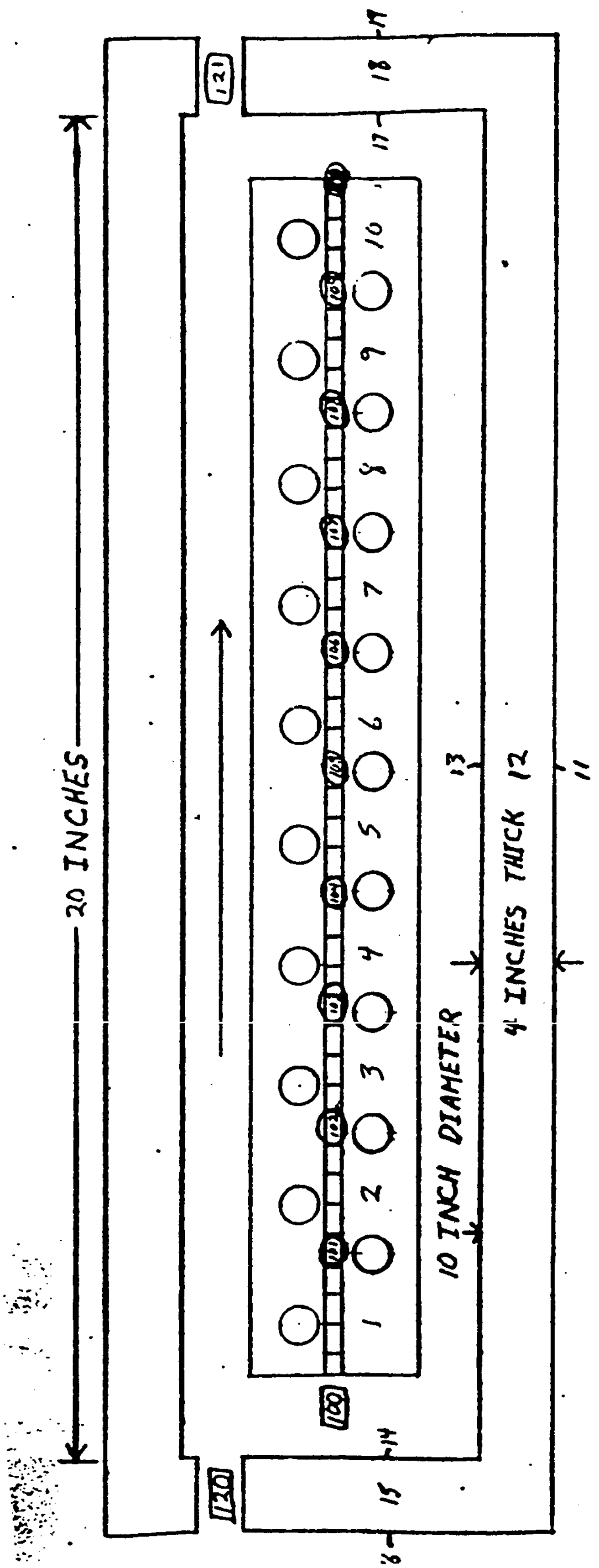

FIGURE 1 LIQUID NITROGEN TEST SECTION THERMAL MODEL

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TABLE 2

LIQUID NITROGEN TEST SECTION THERMAL ANALYSIS RESULTS FOR CONSTANT HEAT INPUT

NODE NO.	TEMP.	TEMPC.	HEAT IN.	RHOV	CPN	KN
1	238.02	132.23	168.0000	.100000	.2000	88.52079
2	235.46	130.81	168.0000	.100000	.2000	88.41814
3	223.80	124.33	168.0000	.100000	.2000	87.95190
4	214.78	119.32	168.0000	.100000	.2000	87.59134
5	210.87	117.15	168.0000	.100000	.2000	87.43494
6	210.37	116.87	168.0000	.100000	.2000	87.41496
7	214.09	118.94	168.0000	.100000	.2000	87.56340
8	228.50	126.94	168.0000	.100000	.2000	88.13981
9	247.61	137.56	168.0000	.100000	.2000	88.90421
10	255.04	141.69	168.0000	.100000	.2000	89.20166
11	194.04	107.80	.0000	.000000	.2000	86.41187
12	386.36	214.64	.0000	.000000	.2400	.01300
13	530.00	294.44	.0000	-1.000000	1.0000	.01300
14	186.78	103.77	.0000	.000000	.2000	85.73580
15	413.48	229.71	.0000	.000000	.2400	.01300
16	530.00	294.44	.0000	-1.000000	1.0000	.01300
17	186.79	103.77	.0000	.000000	.2000	85.73676
18	413.49	229.72	.0000	.000000	.2400	.01300
19	530.00	294.44	.0000	-1.000000	1.0000	.01300

TOTAL WEIGHT IS 1.0000 LBS.

FLUID STREAM TEMPERATURES
STREAM NO.= 1 NODE NO.= 100 INLET TEMP.= 142.00 QTOTAL= 1671.8530

SECTION	NODE NO.	TOUT	FLOW	RHOF	HEAT IN.	XQUAL
1	101	159.54	.0180	.0392	.000000	.000000
2	102	174.08	.0180	.0375	.000000	.000000
3	103	179.00	.0180	.0360	.000000	.095509
4	104	179.00	.0180	.0700	.000000	.233148
5	105	179.00	.0180	.0700	.000000	.366544
6	106	179.00	.0180	.0700	.000000	.501934
7	107	179.00	.0180	.0700	.000000	.653581
8	108	179.00	.0180	.0700	.000000	.790400
9	109	179.00	.0180	.0700	.000000	.885599
10	110	179.00	.0180	.0700	.000000	.990831

FLUID STREAM TEMPERATURES
STREAM NO.= 2 NODE NO.= 120 INLET TEMP.= 140.00 QTOTAL= 38.5201

SECTION	NODE NO.	TOUT	FLOW	RHOF	HEAT IN.	XQUAL
1	121	177.91	.0020	.0051	.000000	.000000

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TABLE 3

LIQUID NITROGEN TEST SECTION THERMAL ANALYSIS RESULTS FOR VARYING HEAT INPUT

NODE NO.	TEMP.	TEMPC.	HEAT IN.	RHOV	CPN	KN
1	179.01	99.45	66.0000	.100000	.2000	84.90107
2	184.29	102.38	66.0000	.100000	.2000	85.42899
3	192.23	106.79	66.0000	.100000	.2000	86.22267
4	202.80	112.66	66.0000	.100000	.2000	87.11100
5	210.98	117.21	66.0000	.100000	.2000	87.43921
6	226.10	125.61	270.0000	.100000	.2000	88.04402
7	228.77	127.10	270.0000	.100000	.2000	88.15097
8	235.15	130.64	270.0000	.100000	.2000	88.40608
9	259.30	144.05	270.0000	.100000	.2000	89.37108
10	281.87	156.60	270.0000	.100000	.2000	90.27491
11	193.23	107.35	.0000	.000000	.2000	86.33612
12	386.01	214.45	.0000	.000000	.2400	.01300
13	530.00	294.44	.0000	-1.000000	1.0000	.01300
14	185.79	103.22	.0000	.000000	.2000	85.73657
15	413.08	229.49	.0000	.000000	.2400	.01300
16	530.00	294.44	.0000	-1.000000	1.0000	.01300
17	185.83	103.24	.0000	.000000	.2000	85.74126
18	413.10	229.50	.0000	.000000	.2400	.01300
19	530.00	294.44	.0000	-1.000000	1.0000	.01300

TOTAL WEIGHT IS 1.0000 LBS.

FLUID STREAM TEMPERATURES
STREAM NO.= 1 NODE NO.= 100 INLET TEMP.= 142.00 QTOTAL= 1672.9640

SECTION	NODE NO.	TOUT	FLOW	RHOF	HEAT IN.	XQUAL
1	101	151.28	.0180	.0397	.000000	.000000
2	102	159.51	.0180	.0386	.000000	.000000
3	103	167.59	.0180	.0378	.000000	.000000
4	104	173.65	.0180	.0372	.000000	.000000
5	105	179.00	.0180	.0368	.000000	.027186
6	106	179.00	.0180	.0700	.000000	.196931
7	107	179.00	.0180	.0700	.000000	.406995
8	108	179.00	.0180	.0700	.000000	.652698
9	109	179.00	.0180	.0700	.000000	.849712
10	110	179.00	.0180	.0700	.000000	.991660

FLUID STREAM TEMPERATURES
STREAM NO.= 2 NODE NO.= 120 INLET TEMP.= 140.00 QTOTAL= 37.3890

SECTION	NODE NO.	TOUT	FLOW	RHOF	HEAT IN.	XQUAL
1	121	176.83	.0020	.0051	.000000	.000000

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APPENDIX E
TEST SUMMARY

The following presents a chronological record of the testing. The cases shown correspond to points at which it was felt that meaningful data was obtained, therefore not all cases run on a given day are presented. Refer to Table 6, Section IV for actual test data.

Day 1:

The test section was set up with a 0.188-inch diameter orifice and a spacer sized to provide a two-cubic-inch volume downstream of the flow panel. Preliminary "shakedown" runs were made. Calibrations were performed. Heat balances were determined to be acceptable, and the heat leak to the ullage was found to be between 12 and 30 watts. It was discovered that an additional LN_2 dewar would be necessary to keep refilling the subcooler to avoid reducing the LN_2 pressure in the test section to unacceptable levels.

Day 2:

Prior to starting flows, a second LN_2 dewar was installed to allow separate filling of the subcooler. For a preliminary run the subcooler was filled, and the test section was pressurized with LN_2. With little or no flow through the test piece, pressure instability was indicated on the strip chart recorder. This was probably due to boiling in the orifice section. Investigation could not pinpoint any other possible causes.

Cases 10, 11, 12, 13. These cases were run at or near the PI condition. In case 10, full heating power was applied. Unstable flow was observed in all of these cases. Liquid droplets entering the orifice cavity are suspected to be the cause of the instability. A hypothesis is made that superheating the flow prior to core discharge might prevent the problem.

Cases 14 and 15. To check out the hypothesis, the flow was reduced to approximately half the PI value, since no further heating power was available. The discharge flow became stable when the discharged nitrogen was superheated about 50°R. The flow became even more stable when the amount of superheat was increased.

Case 16. The heater power was reduced, which resulted in greater discharge flow instability.

Case 17. The discharge flow was restabilized by reducing the flowrate.

Prior to ending the second day test activities, a trial run at THI conditions was made. The data shows that the discharge flow was not being damped. As a result, modifications to the test setup were being considered.

Day 3:

As a result of the previous THI trial run, the test section was fitted with the largest practical volume (28 in.^{3}) and the smallest practical discharge orifice (0.125 in. dia). Also, the pressure relief valve downstream of the flow control valve was removed because it was suspected to be a possible source of flow oscillations. The LN_2 tank was then pressurized with a gaseous nitrogen source controlled by a two-stage regulator. The subcooler was filled, the test section pressurized, and a very small gas flow was introduced. System induced flow oscillations were still being observed. The suspected cause of the oscillations was boiling and/or condensing somewhere in the flow loop.

Cases 6 and 7. During these runs, which were at THI conditions, some flow oscillation damping took place; however, the amplitude was still not acceptable. A decision was made to re-run the PI test condition to record the effect of the different orifice/volume configuration.

Day 4:

The system was converted back to the original configuration with the pressure relief valve, and LN_2 dewar pressurization was supplied by the supply tank pressure build circuit.

Cases 6, 7, and 8. Pumped Idle tests were repeated at approximately 50 percent of the flowrate. With the small orifice/large volume combination, the flow oscillations were eliminated as before except a lesser degree of superheat was present at the test core discharge. Case 8 was run very near to the original PI condition.

Case 15. The THI condition was re-run with a significantly reduced amount of heat input to produce PI conditions. Again, the flow oscillations were damped considerably when the proper degree of superheat was achieved.

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