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OXIDIZER HEAT EXCHANGER COMPONENT TESTING

FINAL REPORT

CONTRACT NAS3-24238

Prepared for
National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

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References: (1) Contract NAS3-24238, Article II.F.
(2) Letter from Richard L. DeWitt/NASA to W.C. Shubert/P&W, dated 1 August 1986

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Lewis Project Manager — R. L. DeWitt

16. Abstract

As part of the RL10 Rocket Engine Product Improvement Program, Oxidizer Heat Exchanger (OHE) stages 1, 2, and 3 were designed and fabricated during late 1983 and early 1984. The purpose of the OHE is to provide gaseous oxygen to the propellant injector for stable engine operation at tank head idle and pumped idle operating modes.

This report summarizes the OHE stages 1 and 3 rig testing, and includes the separation of the stage 1-and-2 assembly and the remanifolding of stage 1. The OHE performance analysis and analytical model modifications for both stages are also presented. The flow tests were accomplished during the time period from 9 October 1984 to 12 November 1984.

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SECTION I
INTRODUCTION

As part of the RL10 Product Improvement Program (PIP), Oxidizer Heat Exchanger (OHE) stages 1, 2, and 3 were designed and fabricated during late 1983 and early 1984. The purpose of the OHE is to provide gaseous oxygen to the propellant injector for stable engine operation at tank head idle (THI) and pumped idle (PI) operating modes. The design of the OHE is reported in FR-18046-3 (Reference 1). Due to fabrication problems, the stage 1-and-2 assembly was not delivered in time for engine testing. Tests performed on the stage 1-and-2 assembly during fabrication revealed irreparable leakage in stage 2; stage 1 was subsequently separated from the assembly and modified to allow component level testing. Two OHE stage 3 units were individually mounted and run on the RL10-IIB Breadboard Engine XR201-1 in February 1984, as reported in FR-18683-2 (Reference 2). The stage 3 engine testing revealed unexpectedly high pressure drop and low heat transfer, and an investigation was conducted to determine why the design performance goals were not met.

Stage 1 and stage 3 s/n 001 were individually mounted on a modified RL10 component test stand and flowed to determine the performance characteristics of each unit. The second stage 3 unit (s/n 002) was not bench tested. The purpose of the testing was to determine why stage 3 performance did not meet design goals during engine test and to evaluate the stage 1 concept of limiting heat transfer by use of insulation to separate the two propellants. It was also intended to supply empirical data to improve the analytical models used to evaluate heat exchanger performance.

This report summarizes the OHE stages 1 and 3 rig testing, and includes the separation of the stage 1-and-2 assembly and the remanifolding of stage 1. The OHE performance analysis and analytical model modifications for both stages are also presented. The flow tests were accomplished during the time period from 9 October 1984 to 12 November 1984.

SECTION II
CONFIGURATION

A. STAGE 1

The stage 1-and-2 assembly was received from the vendor in a semi-finished condition after excessive leakage to the stage 2 insulation cavity was discovered. Since the stage 2 unit was unusable, stage 1 was removed from it. The stage 1 was designed as a low heat transfer heat exchanger to vaporize the oxidizer to approximately 5 percent quality during tank head idle operation. Complete vaporization was to be provided by the remaining two stages. The low heat transfer rate was to be obtained by providing an insulated cavity between the oxidizer and fuel passages. Atmosphere changes within the cavity (vacuum, gaseous helium, gaseous nitrogen) could also be used to further tailor the heat transfer to meet engine cycle requirements. Stage 2 was of similar design, but with higher heat transfer to provide oxygen at 5 percent quality during pumped idle, with vaporization completed by the stage 3 unit.

While the stage 1 core was exposed, the H_2 and 0_2 flow passage cross section dimensions were measured to determine if any deviations from the original drawing specifications occurred during fabrication. Slight reductions in flow areas were found. Manifolds were salvaged from the stage 1-and-2 assembly, and modified to fit the stage 1 core to allow its individual flow. The remanifolded stage 1 heat exchanger is shown in Figures 1 and 2.

A detailed description of the stage 1-and-2 assembly and stage 1 remanifolding process is presented in Appendix A. Surface roughness and cross sectional dimensions are presented in Appendix B.

B. STAGE 3

The stage 3 was designed as a high heat transfer unit to complete vaporization of the oxidizer from the stage 1-and-2 assembly. It is a compact crossflow heat exchanger intended to completely vaporize oxygen which enters at a quality of 5 percent or greater.

The OHE stage 3 unit tested was P/N CKD 1952, S/N 001 and was built per layout L-238388, sheet 10. This unit was previously tested on engine XR201-1 on runs 11.01 through 15.01 for a total of 499.8 seconds at tank head idle and 792.1 seconds at pumped idle. The stage 1-and-2 assembly was not run during this testing. The engine test results and a detailed description of the unit can be found in FR-18683-2 (Reference 2).

Pressure taps were installed on each inlet and discharge manifold, after which the heat exchanger was proof tested to a pressure of 200 psig. Flow passage cross sectional dimensions and surface roughness of this unit were also determined. As with stage 1, area reductions were found. These data are presented in Appendix B. The stage 3 OHE is shown prior to installation of the pressure taps in Figures 3 and 4.

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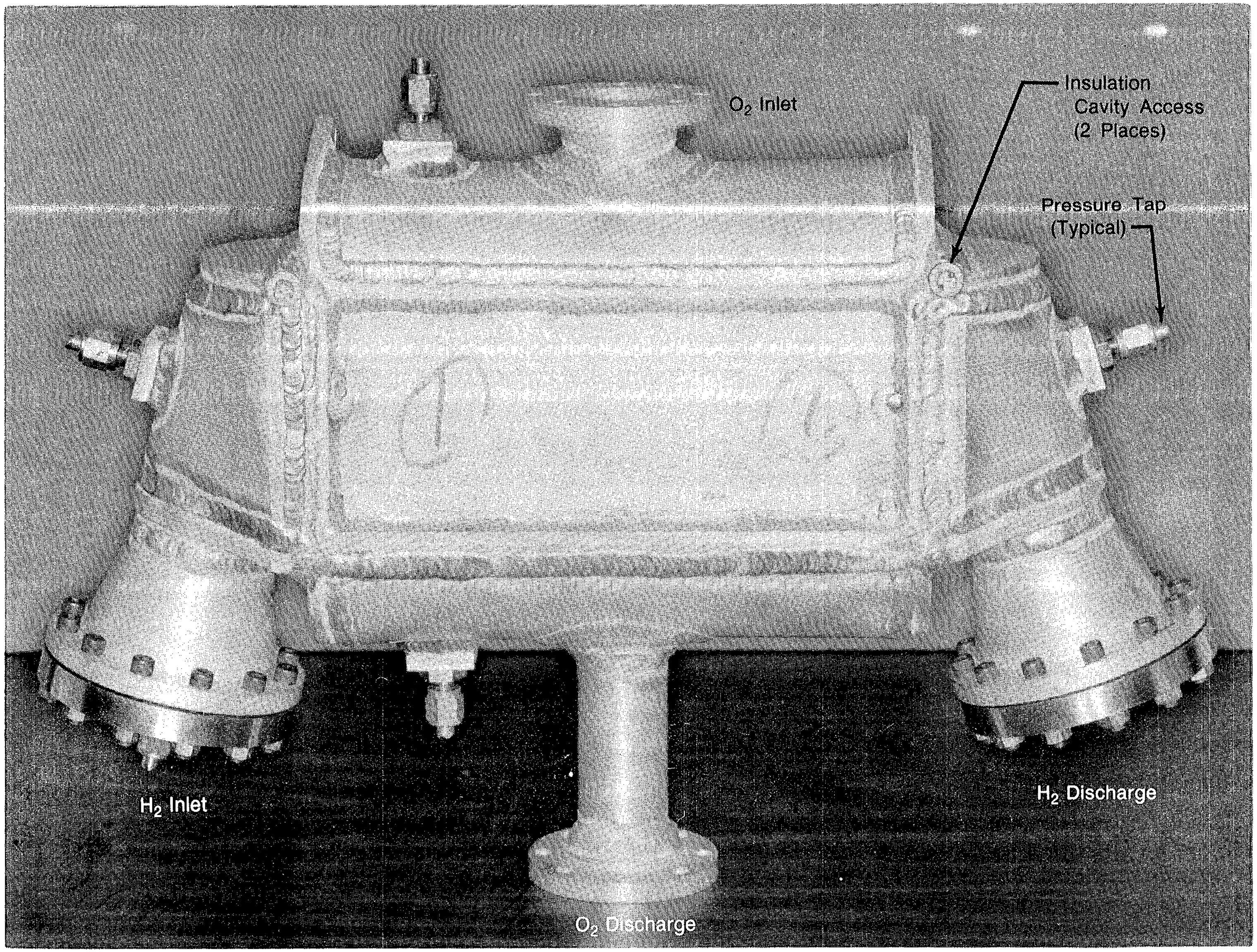

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Figure 1. Oxidizer Heat Exchanger Stage 1 (Side View)

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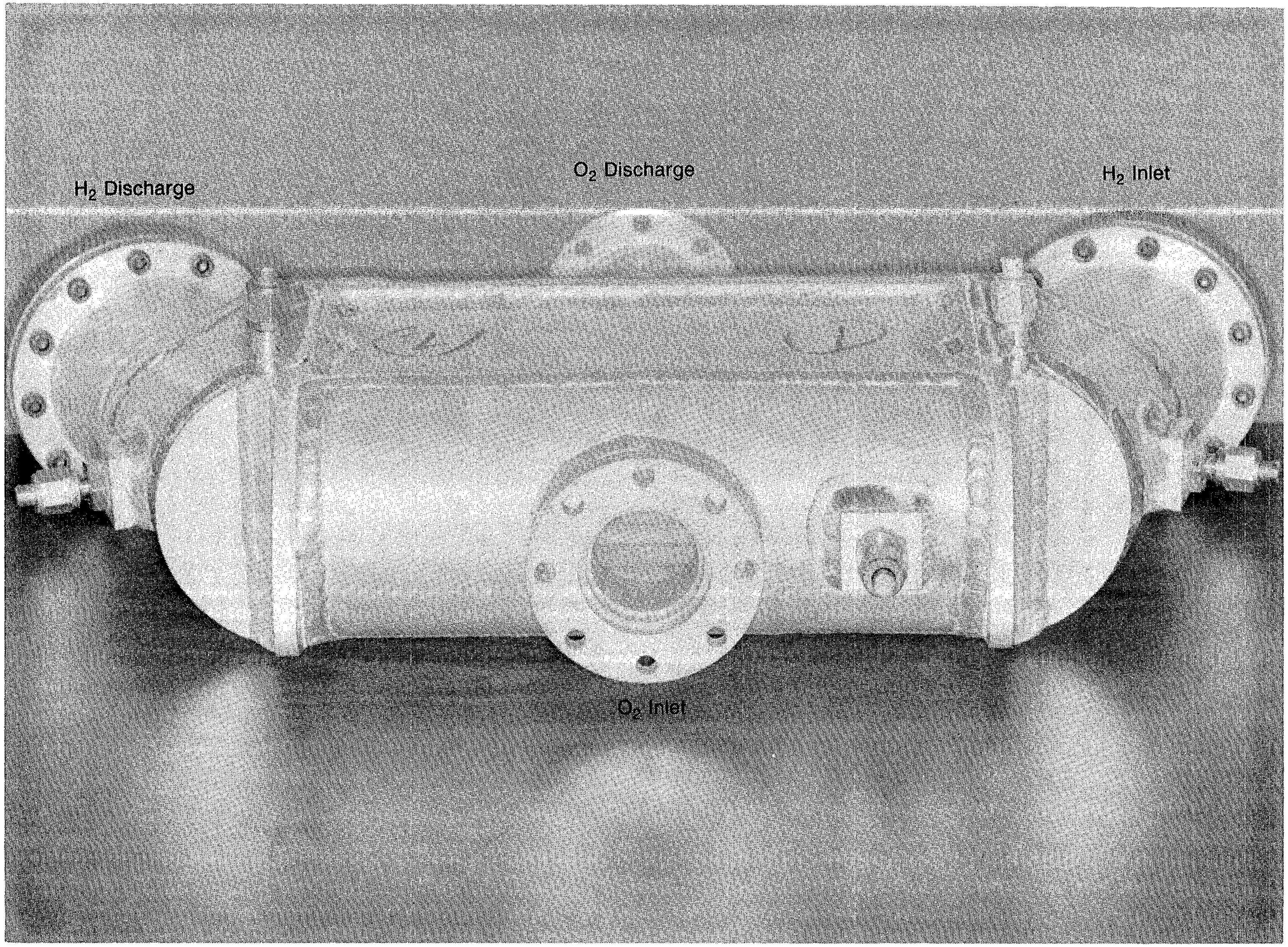

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Figure 2. Oxidizer Heat Exchanger Stage 1 (O_2 Inlet View)

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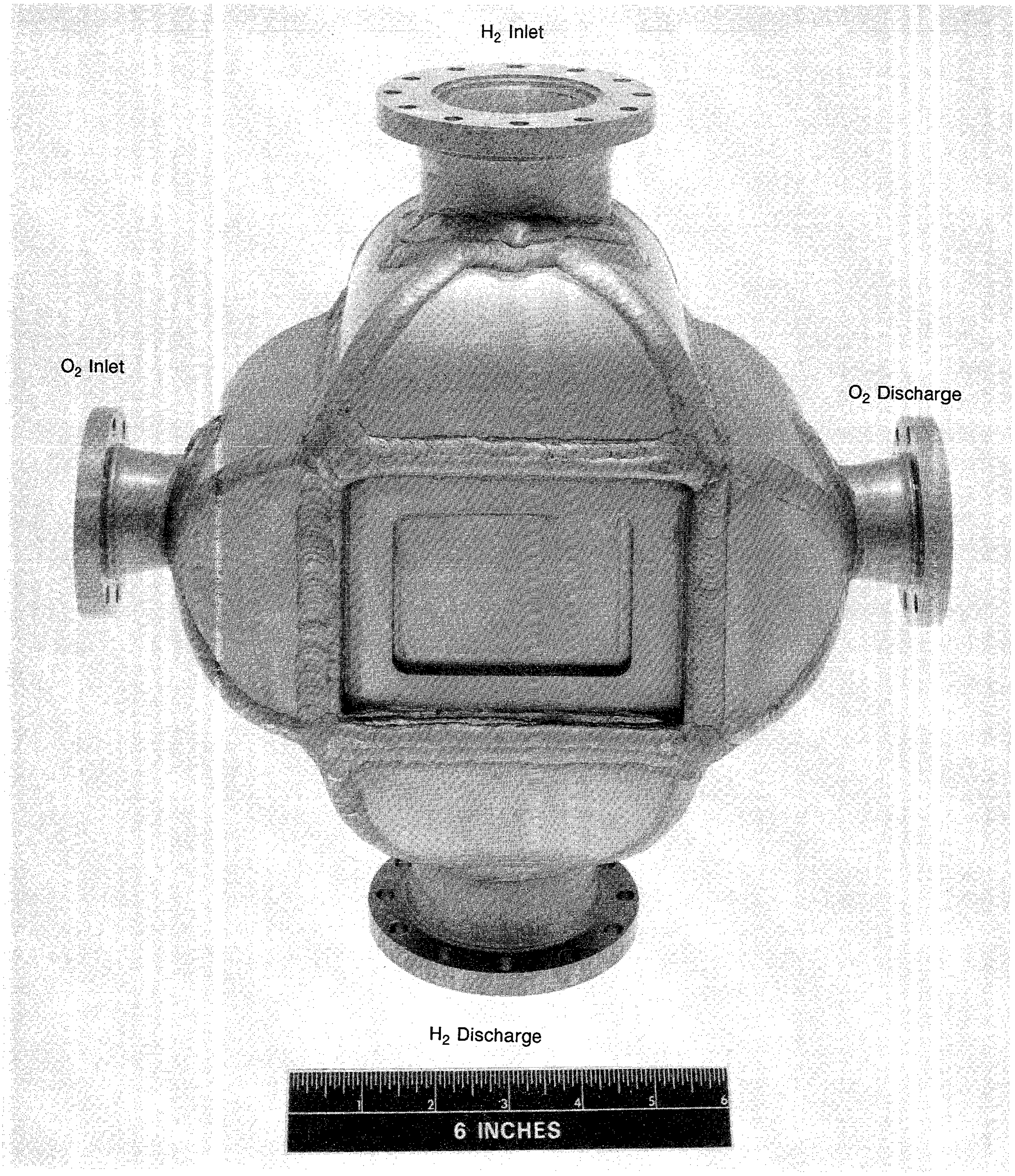

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Figure 3. Oxidizer Heat Exchanger Stage 3 (Side View)

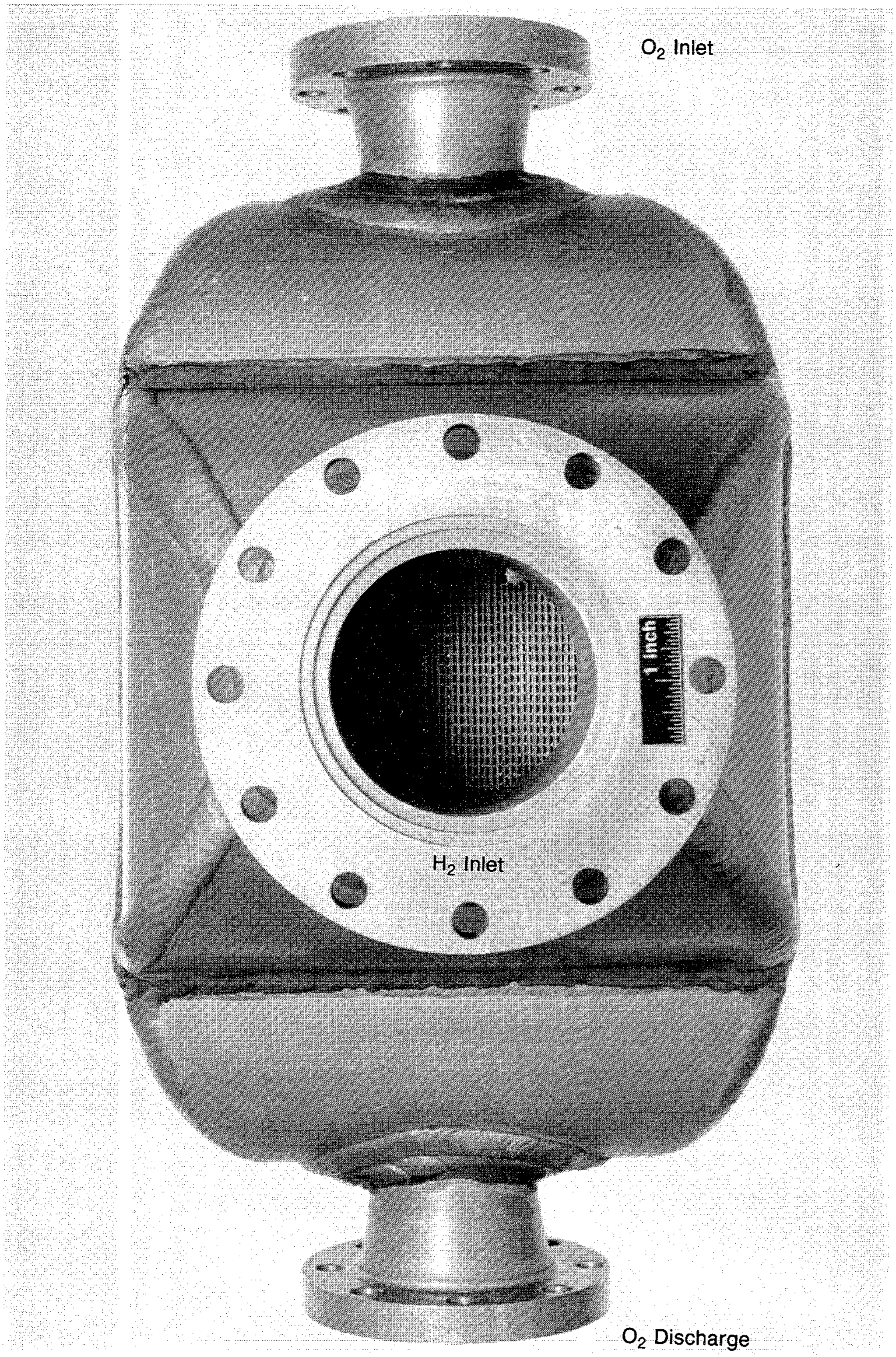

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Figure 4. Oxidizer Heat Exchanger Stage 3 (H_2 Inlet View)

SECTION III
OHE TESTING

A. FLOWBENCH CONFIGURATION

The tests were conducted on the G-1 flowbench, which is a liquid nitrogen flowbench used to test rocket engine components. The configuration was modified to provide the following:

- Gaseous, in addition to liquid, nitrogen flow through the OHE 0_2 circuit
- Heated gaseous nitrogen flow through the OHE hydrogen circuit
- Insulated plumbing to achieve and maintain liquid flow
- Capability to provide gaseous helium, vacuum, or gaseous nitrogen in the stage 1 insulation cavity.

Flowbench modifications were minimized, and existing bench equipment and instrumentation were used wherever possible. Insulation was wrapped around the OHE units to prevent heat loss for more accurate heat balance calculations. The flowbench configuration is illustrated in Figure 5. Additional instrumentation was added to supplement the existing stand measurements and to provide for accuracy at both tank head idle and pumped idle flow levels. A brief discussion of instrumentation provisions is presented in Appendix C.

Stage 1 is shown mounted in the stand in Figures 6 and 7, and stage 3 is shown in Figure 8. These photos were taken prior to insulation installation.

B. RUN SUMMARY

The stage 3 OHE was mounted in the test stand on 4 October 1984 and testing commenced on 9 October. The stage 1 unit was installed following that testing. Test of the stage 1 was concluded on 12 November 1984.

Test points were chosen for each heat exchanger stage to characterize OHE performance at simulated tank head idle and pumped idle conditions. Twelve tests were made with gaseous nitrogen in the H_2 circuit and liquid nitrogen in the 0_2 circuit of the stage 1 unit, while 9 runs were made with GN_2 in both circuits. For the stage 3 unit, 26 runs were made, of which 16 were GN_2-LN_2 and 10 were GN_2-GN_2. A detailed tabulation of the runs is presented in Appendix D.

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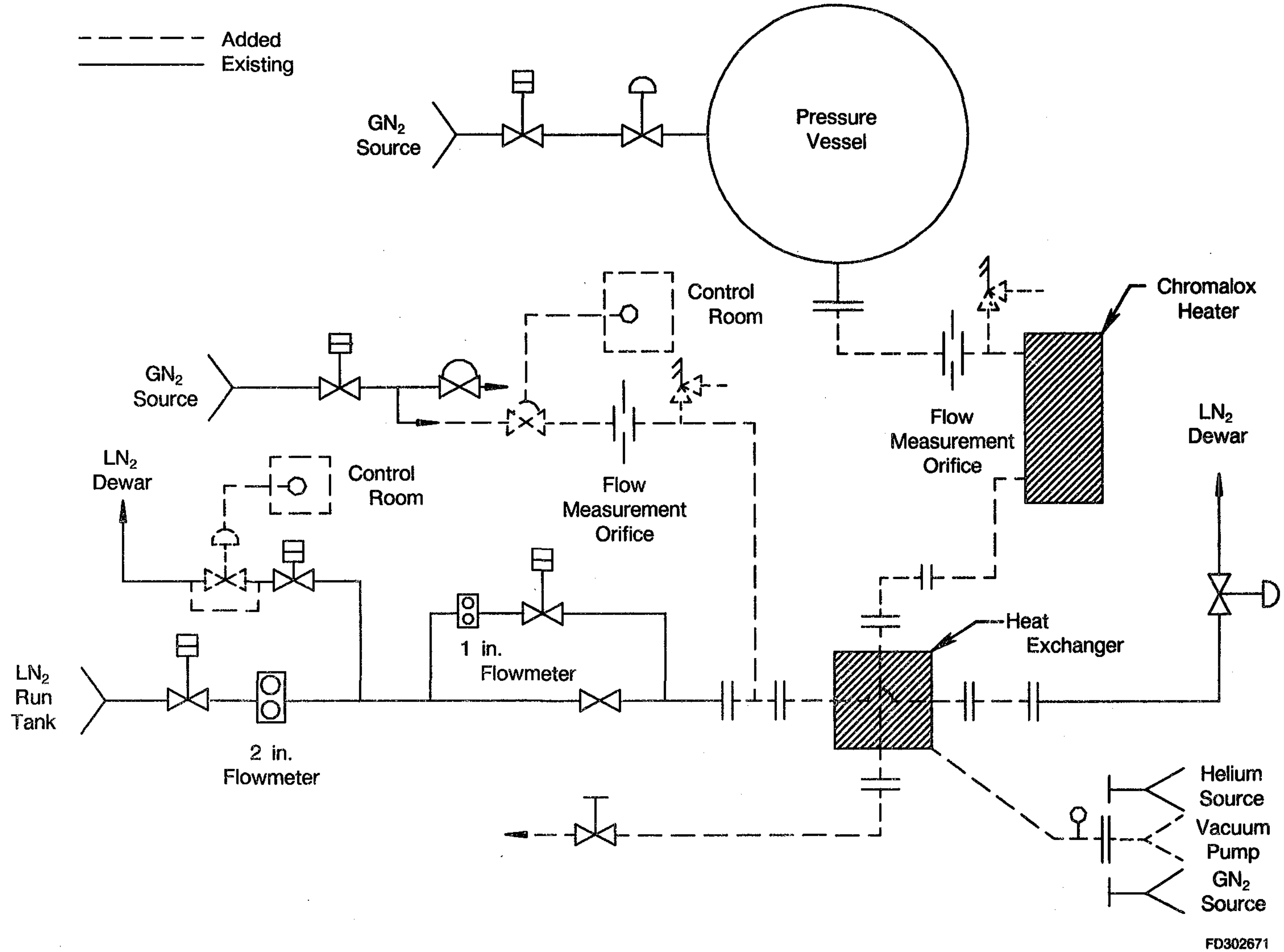

Figure 5. Oxidizer Heat Exchanger Flowbench Configuration

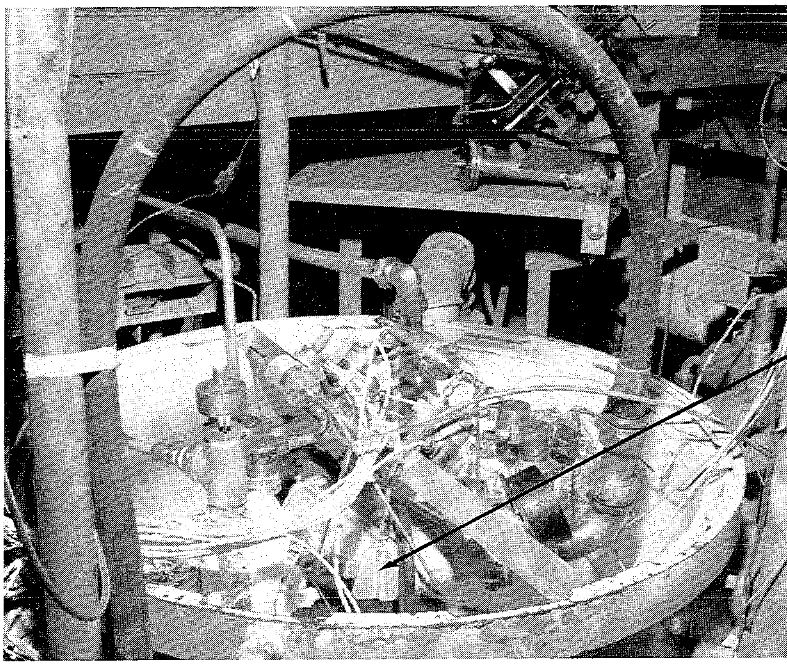

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Figure 6. Oxidizer Heat Exchanger Rig Test Flowbench — Stage 1 Mounted

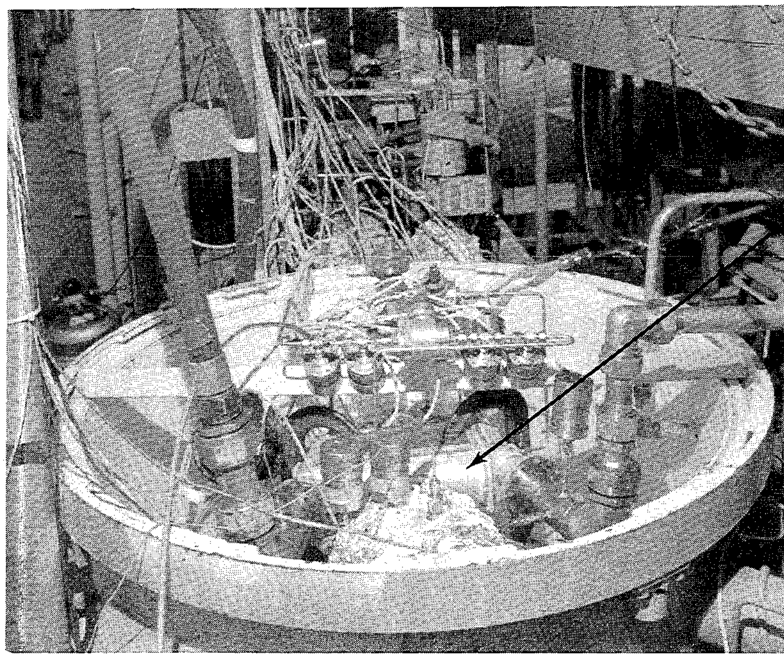

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Figure 7. Oxidizer Heat Exchanger Rig Test Flowbench — Stage 1 Mounted

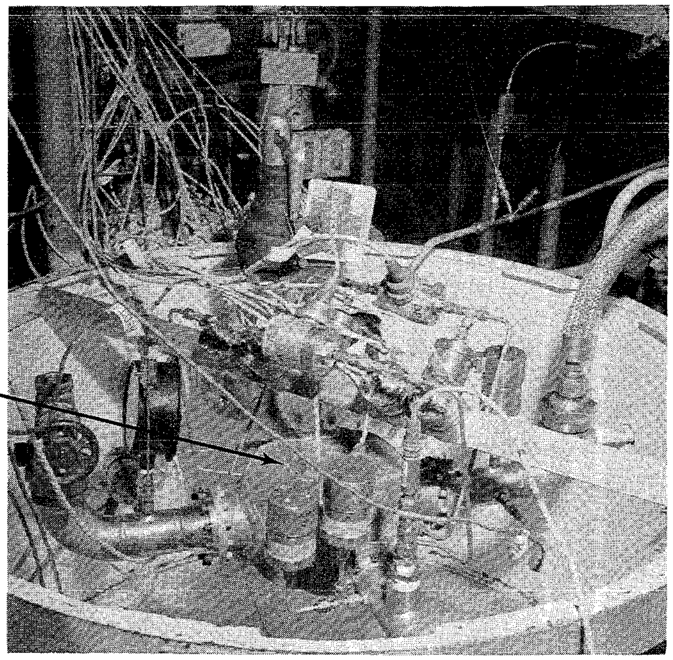

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Figure 8. Oxidizer Heat Exchanger Rig Test Flowbench — Stage 3 Mounted

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SECTION IV
PERFORMANCE ANALYSIS

Performance analysis of heat exchanger rig test data was conducted at various times both during and after the runs. Preliminary reviews were performed by the Test Engineering, Performance, and Heat Transfer Groups. These prompted minor changes to the test program, the addition of some test points, and periodic checks of the equipment to assure accuracy. The majority of the post-run analysis was performed by the United Technologies Research Center/Optics and Applied Technology Laboratory (UTRC-OATL), supplemented by some limited data review by the P&W Heat Transfer Group. Rig test results were used to: a) identify the reason for the high pressure drop and low heat transfer found during engine test of stage 3; b) evaluate the stage 1 design concept; and c) to provide data for modifications to the Crossflow Heat Exchanger Analysis Program (CHEAP). This program was developed under Contract NAS3-22902 to analyze this crossflow heat exchanger design, as reported in Reference 1. The UTRC/OATL Report No. 85R-280251-01 contains the results of the study to compare predicted and measured performance data and offers explanations for performance anomalies. The report is presented in its entirety in Appendix E.

A. TEST RESULTS

1. Stage 3

Results of the stage 3 test analysis are summarized below.

- It appears that oxygen circuit dryout of the LN_2 occurred during the high H_2 low O_2 flow point, as overall heat transfer went down despite the high GN_2 flowrate in the H_2 circuit, as shown in Figure 9. The dryout phenomenon, which occurs when a gas film forms on the passage walls due to a high temperature differential between the liquid and the hot wall, is discussed in Appendix E.

- The maximum LN_2 exit quality calculated during the tank head idle points was 0.47.

- The maximum attainable GN_2 flowrate of 0.7 lbm/sec was not high enough to initiate dryout at simulated pumped idle, as shown in Figure 10. The total heat transferred is limited by the specific heat of GN_2 which is much lower than that of the GH_2 in the engine testing.

- No flow instabilities were observed during testing.

2. Stage 1

Results of the stage 1 test analysis are summarized below.

- As expected, helium in the insulation cavity provided greater heat transfer than nitrogen or vacuum, as shown in Figure 11. The difference in heat fluxes between nitrogen and vacuum atmospheres was not noticeable. This may have been due to a fluid leakage into the insulation cavity, as discussed in Appendix A.

- The maximum LN_2 exit quality calculated at the O_2 discharge was 0.022.

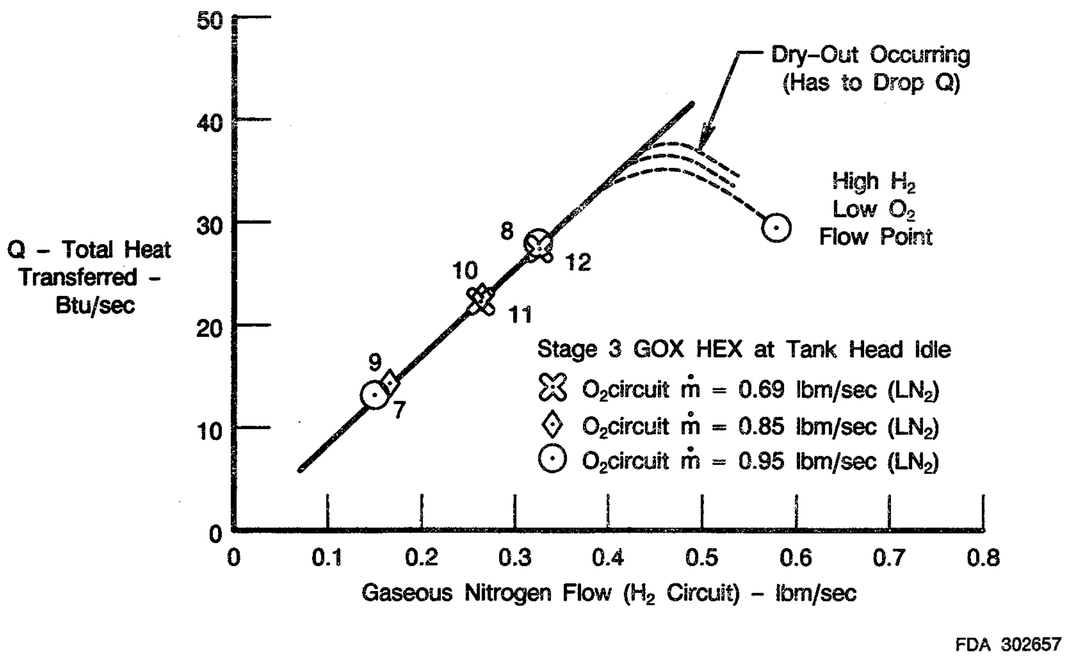

Figure 9. Stage 3 Heat Exchanger Performance — Tank Head Idle

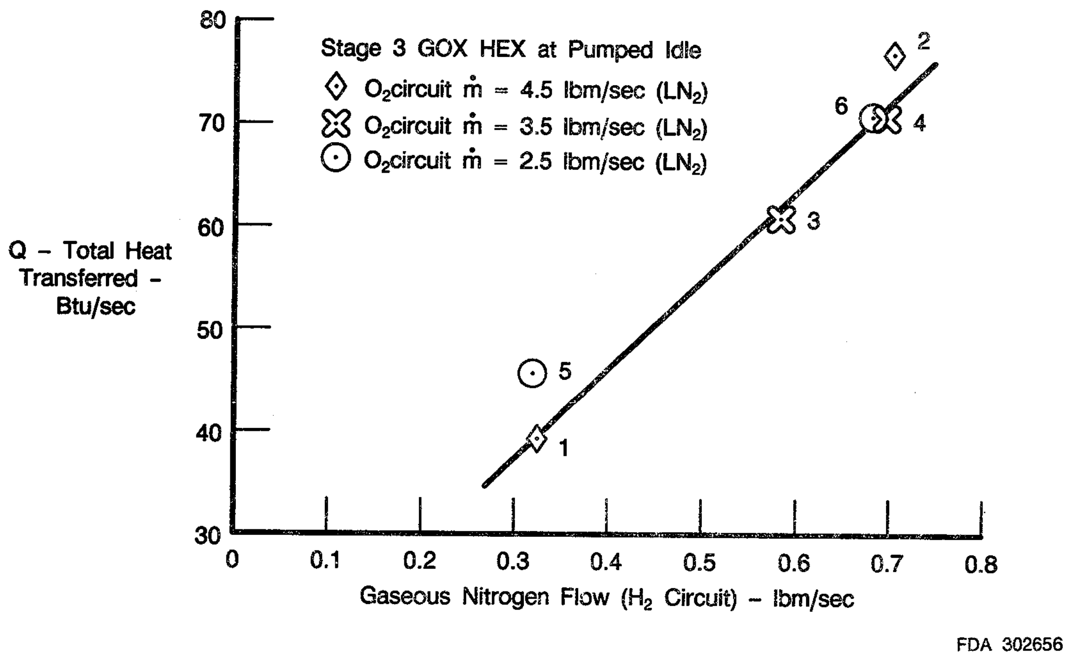

Figure 10. Stage 3 Heat Exchanger Performance — Pumped Idle

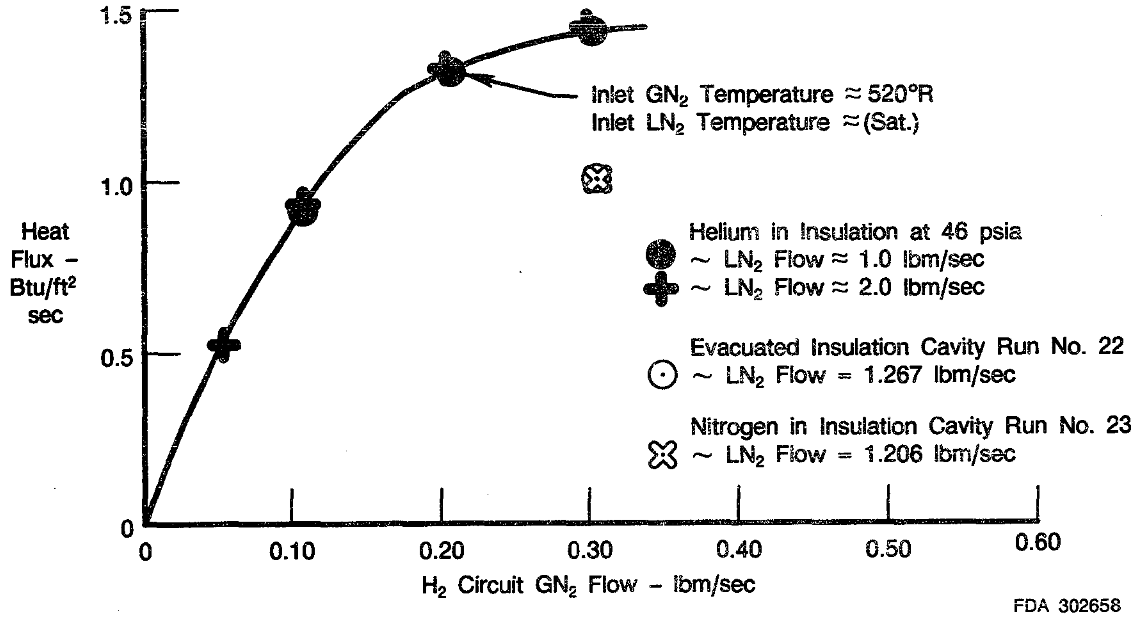

Figure 11. Stage 1 Heat Exchanger Performance

B. POST-TEST ANALYSIS

Following the completion of the initial test analysis, the test results were further analyzed by UTRC to correlate measured data with predictions and to modify the prediction program to make it a better tool for future heat exchanger analysis. Modification included the change in passage geometry as mentioned earlier and addressed the dryout condition found in the early test analysis. The following is a summary of the results of that work.

- The temperature changes across the core predicted by the CHEAP agreed well (within 10 percent) with the measured data for both hydrogen and oxygen circuits for stage 3 prior to program modifications.

- The measured pressure drops during bench tests across the stage 3 heat exchanger agreed with predictions generally within 20 percent for higher ΔP's (above approximately 0.75 psid). It is suspected that resolution of the instrumentation was partially responsible for discrepancies at the lower pressures.

- The temperature changes across the stage 1 core predicted by modified CHEAP were not in agreement with the data measured during bench testing. The measured data indicate that more heat was being transferred from the hydrogen circuit to the oxygen circuit than predicted. This may have occurred in the form of thermal short circuits, such as flow panels contacting headers. It was also possible that insulation cavity infiltration by braze wicking or fluid leakage was rendering the FELTMETAL® less effective than originally designed.

- The stage 1 pressure drops obtained during the bench tests were consistently higher than those predicted by the modified CHEAP analysis. Factors contributing to this condition include possible measurement error at the low pressure levels and the effects of the large discrepancies in predicted versus actual heat flux.

- Modifications to the program for actual geometry and dryout occurrence resulted in accurate prediction for the stage 3 pumped idle engine runs of Reference 2. Limited dryout correlations did not allow accurate tank head idle predictions for engine runs.

Although this analysis program was modified to closer predict the results of actual testing, in its present form it is limited to analysis of heat exchangers with this type of geometry only. Considerable modification would be required to make it useful for analysis of heat exchangers with different geometries (i.e., lanced or ruffled fins, or cross/counter flow).

The report of the analytical program modifications and more detailed analysis of the testing is presented in Appendix E. An investigation into possible problems with stage 1, which contributed to the discrepancies between predicted and measured performance, showed possible thermal short circuitry due to flow panel shift during braze. This is also discussed in Appendix E.

SECTION V
CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Conclusions derived from the testing of the stage 1 and 3 units and the fabrication problems encountered with the stage 1-and-2 assembly are presented in this section.

- After modifications were made to the analytical model to account for actual heat exchanger geometry, the stage 3 unit thermal performance agreed with measured engine run performance for the pumped idle runs.

- Inaccurate thermal performance predictions for tank head idle during engine runs is attributed to limited dryout correlations, which may not be accurate at tank head idle temperatures and pressures.

- Dryout occurred in stage 3 during both tank head idle and pumped idle engine operation.

- The higher-than-designed stage 3 pressure drops may be attributed at least in part to increased passage surface roughness and reduced flow area as shown in Figure B-1 due to collapsed and blocked passages.

- Even after CHEAP program modifications, the stage 1 unit test data showed considerably more heat transfer than the analytical model predicted. Thermal short circuits in the form of headers contacting flow panels and possible leakage infiltration appear to be possible causes.

- The analytical model was improved for predicting the performance of this type of heat exchanger. Inaccuracies still encountered after modifications may be attributed in part to the uncertainty of two-phase flow predictions. The analytical model is capable of predicting dryout, which is useful in identifying the associated low heat transfer and degradation in OHE performance.

- The analytical model is useful for heat exchangers of this type of crossflow heat exchangers; however, it cannot readily be used for other types of heat exchangers with non-rectangular geometries, non-continuous fins, and mitered turns now being contemplated for this application.

B. RECOMMENDATIONS

- Future heat exchanger designs should avoid dryout due to the considerable decrease in thermal efficiency when this occurs.

- A heat exchanger design employing more conventional aluminum fabrication techniques, such as plate-fin, should be used.

REFERENCES

1. Design and Analysis Report for the RL10-IIB Breadboard Low Thrust Engine, FR-18046-3, Contract NAS3-24238.

2. Breadboard RL10-IIB Test Report, FR-18683-2, Contract NAS3-24238.

3. RL10-IIB GOX Heat Exchanger Performance Evaluation, UTRC Report No. 83R-280169-3.

APPENDIX A
OHE STAGE 1-AND-2 ASSEMBLY AND STAGE 1 REWORK

1. STAGE 1-AND-2 ASSEMBLY

Each unit consisted of a set of thermal skin flow panels arranged in a crossflow configuration and separated by layers of insulation designed to limit heat transfer between the two working fluids. Since the insulation was low density felt, the design allowed for changes in the insulation cavity atmosphere to provide variations in the rate of heat transfer. A diagram detailing the core configuration for each stage is shown in Figures A-1 and A-2.

Considerable difficulty was encountered during the assembly and brazing of the stage 1-and-2 units due to the large number of detail parts and difficulty in maintaining braze clearances and preventing wicking of the braze into the insulation. Figures A-3 and A-4 show that the stage 1 core was successfully assembled and brazed. However, the stage 2 unit displayed incomplete braze joints and crushed panels after the initial braze attempt, as shown in Figures A-5 and A-6. After an attempt to rebraze the stage 2 core proved unsuccessful, the vendor pursued a salvaging process consisting of TIG welding all flow panel-header joints as illustrated in Figure A-7. The stages were then joined. Subsequent pressurization of the stage 2 insulation cavity revealed extensive leakage to the oxidizer and fuel manifolds. At this point, it was felt that all reasonable avenues of success had been exhausted, and a decision was made not to attempt any further repair. The stage 1-and-2 assembly is shown as received partially assembled in Figure A-8.

2. STAGE 1 REWORK

In order to test the stage 1 unit individually, it had to be removed from the stage 2 core and remanifolded. This was accomplished by salvaging manifolds from stage 2, modifying them, and welding them in place as shown in Figure A-9. Also, a section of tubing was added to one of the O_2 flanges to make the flange separation the same as stage 3 to simplify test bench mounting. Pressure taps were drilled and bosses welded in place on each manifold. The unit was proof tested to 50 psig in both the O_2 and H_2 circuits and the insulation cavity revealed no leaks at 4 psig internal pressure, which is the maximum pressure that could be applied to the cavity without deforming the outer O_2 panels.

3. STAGE 1 LEAKAGE

Although the insulation cavity revealed no detectable leaks when it was pressurized to 4 psig, it did collect leakage from the H_2 and O_2 circuits when these circuits were subjected to the scheduled higher pressures. Prior to initiating test sequence, GN_2 leakage into the insulation cavity at test pressures was determined. This was done by separately pressurizing the H_2 and O_2 circuits and measuring the leakage from the insulation cavity. Periodic leak checks were also made during the runs to monitor any leakage increases resulting from thermal shock. A summary of the results, shown in Table A1, revealed that thermal cycling was causing more leakage. To prevent the test fluids (LN_2, GN_2) from entering the insulation cavity during tests, the insulation cavity pressure was always maintained at a slightly higher level than the highest H_2 or O_2 circuit pressure.

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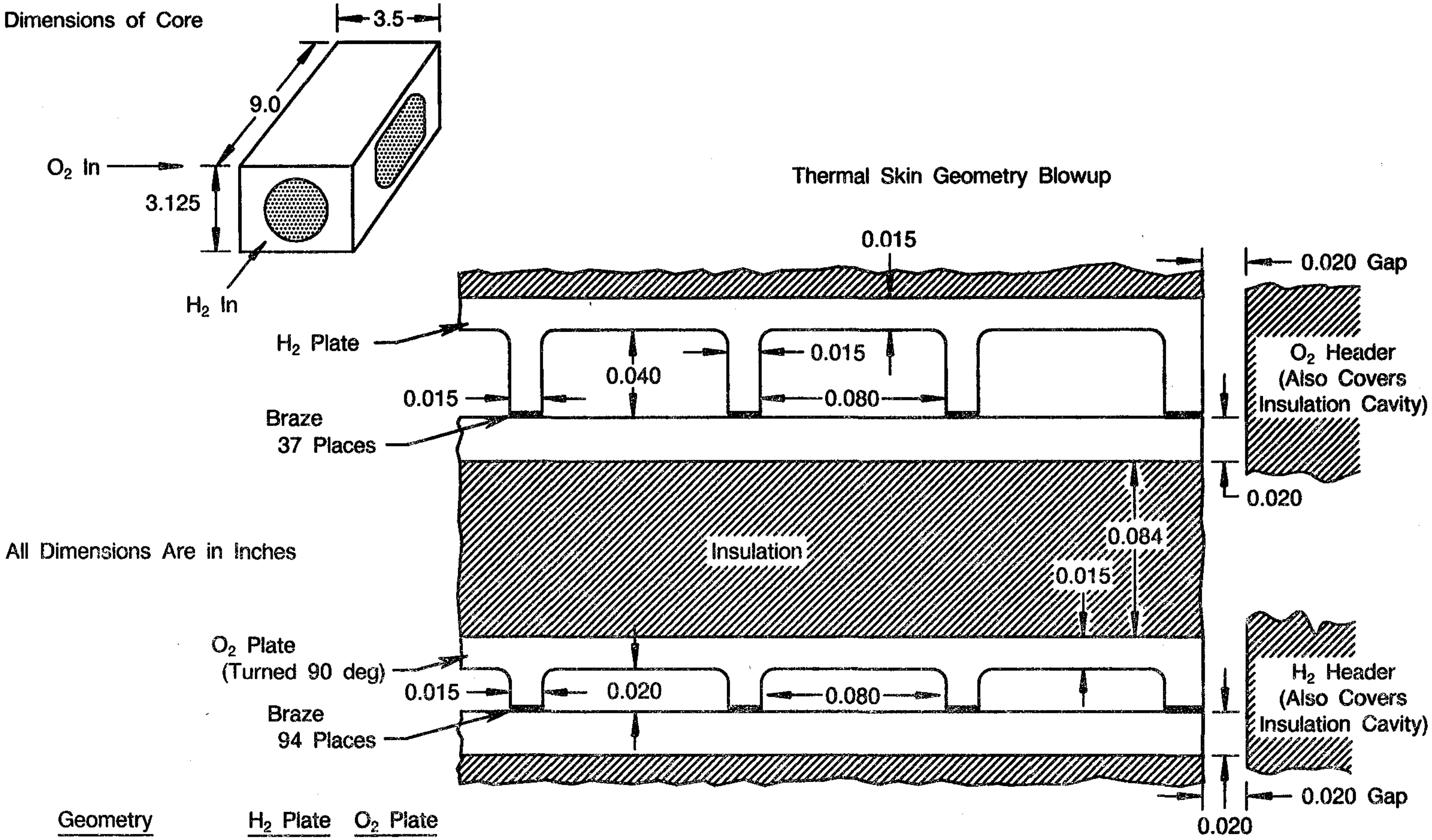
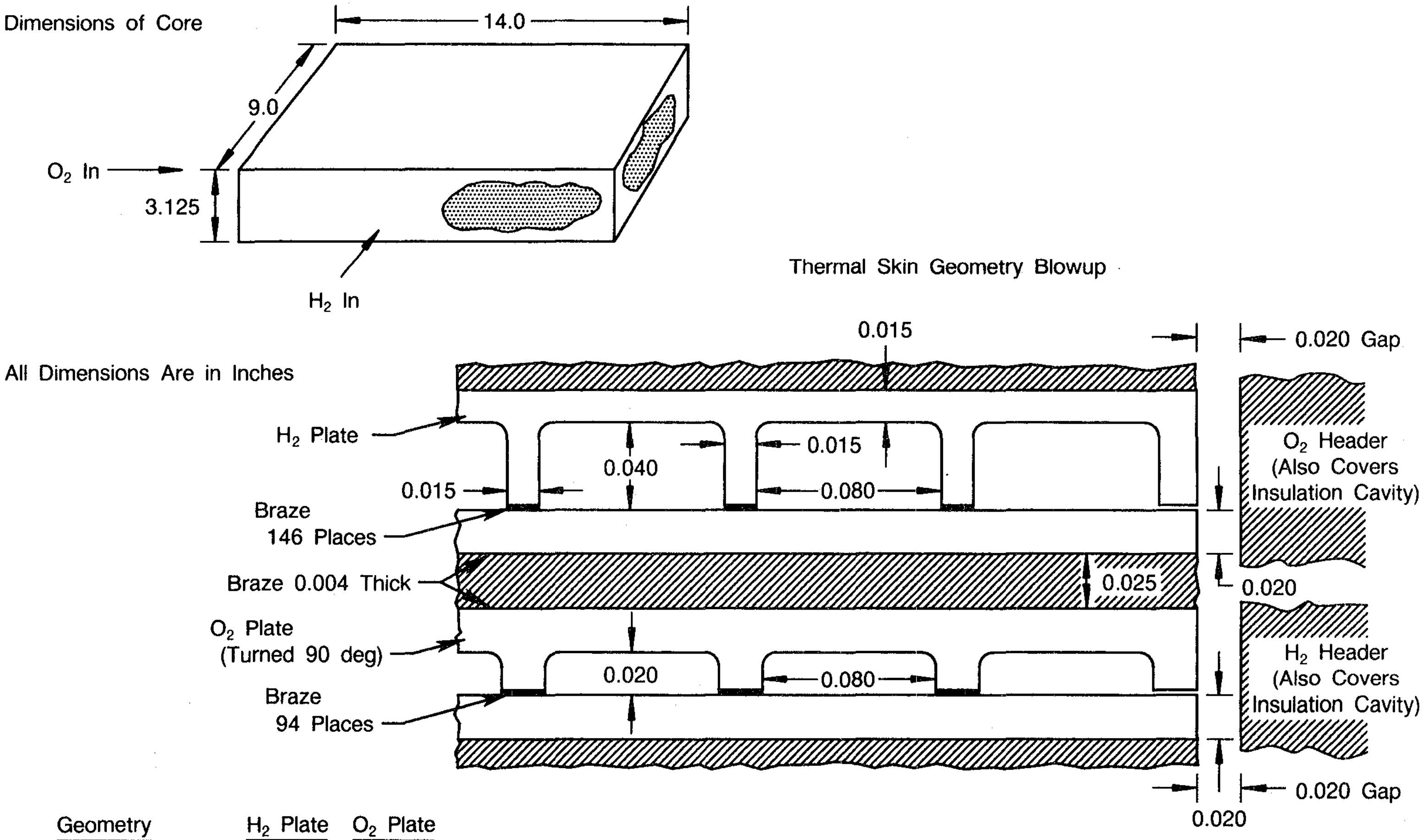


Geometry	H_2 Plate	O_2 Plate
No. Plates	12.0	11.0
Passage Diameter, in.	0.0513	0.0336
Flow Area, in.^{2}	1.213	1.602

Heat Transfer Area, ft^2	5.2
Core Weight, lb	7.5
Insulation Type	2% Dense Metal Felt (0.150 in. compressed to 0.084 in.)
Insulation Material	300 Series Stainless Steel

FDA 302661

Figure A-1. Oxidizer Heat Exchanger Stage 1 Configuration



Geometry	H_2 Plate	O_2 Plate
No. Plates	20.0	19.0
Passage Diameter, in.	0.0513	0.0336
Flow Area, in.^{2}	8.199	2.77
Heat Transfer Area, ft^2	36.6	
Core Weight, lb	53.3	
Insulation Type	5% Dense Metal Felt	
Insulation Material	Nickel 200	

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Figure A-2. Oxidizer Heat Exchanger Stage 2 Configuration

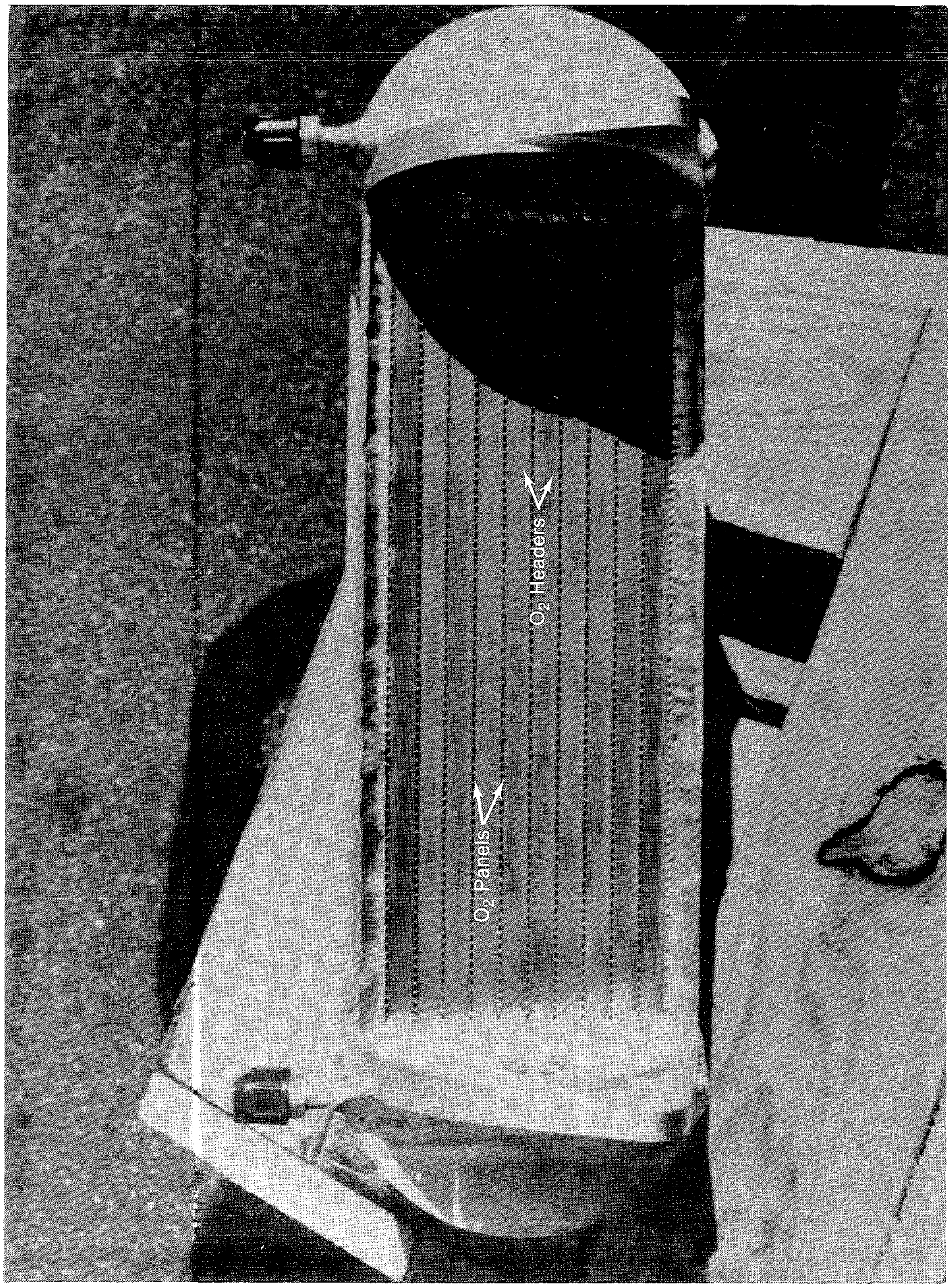

Figure A-3. Oxidizer Heat Exchanger Stage 1 Core — O_2 Inlet

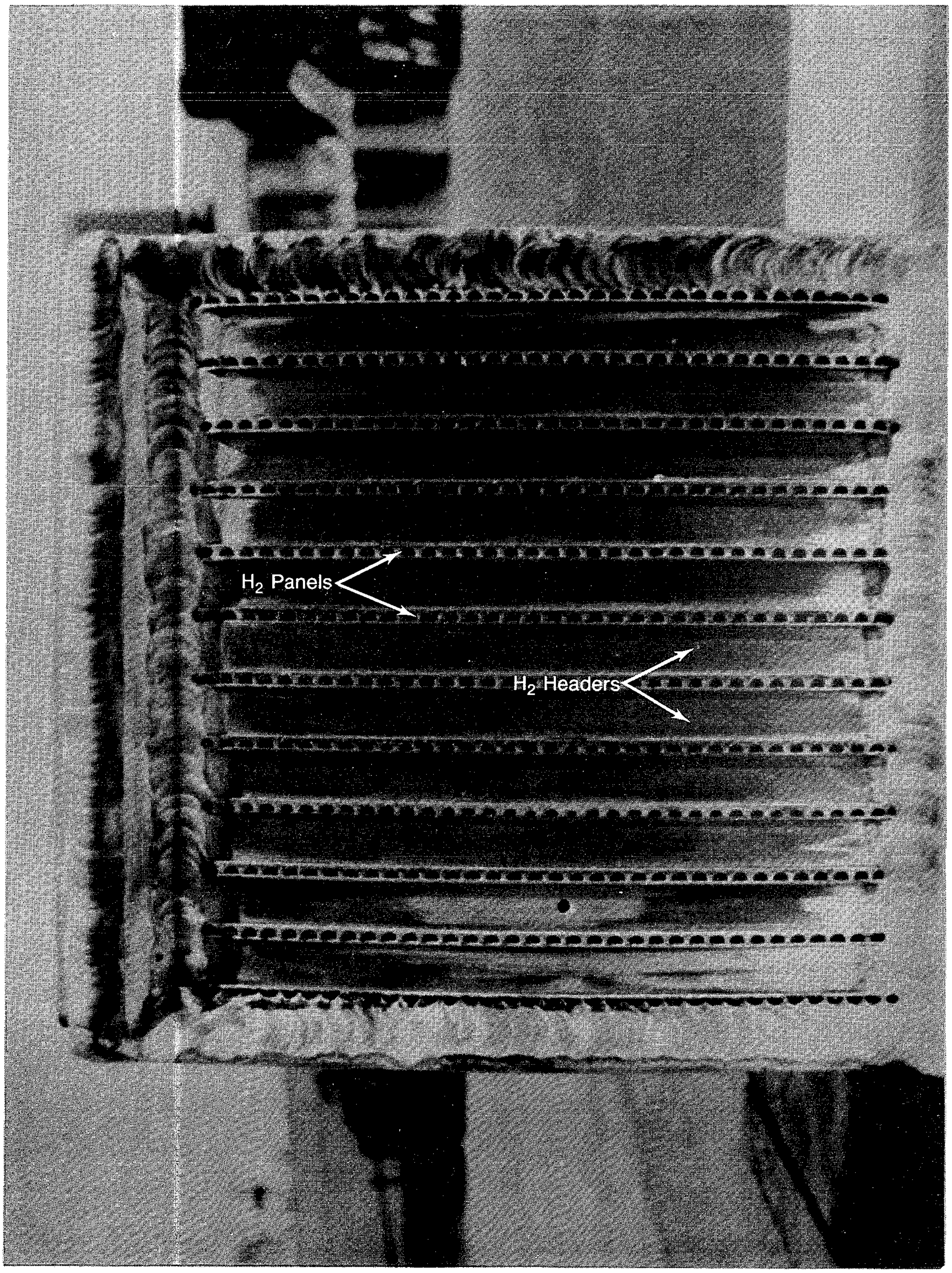

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Figure A-4. Oxidizer Heat Exchanger Stage 1 Core — H_2 Inlet

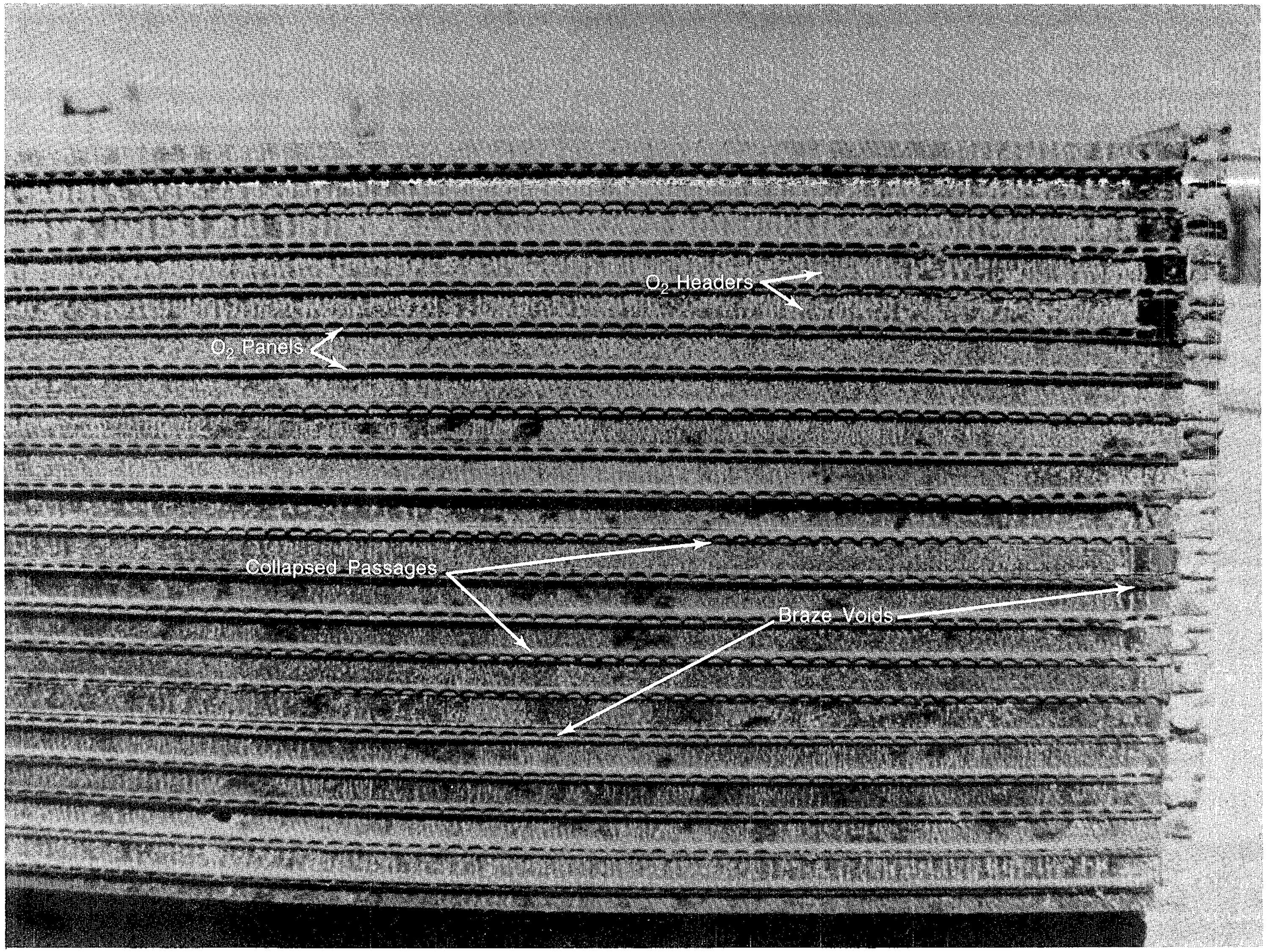

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Figure A-5. Oxidizer Heat Exchanger Stage 2 Core — O_2 Inlet

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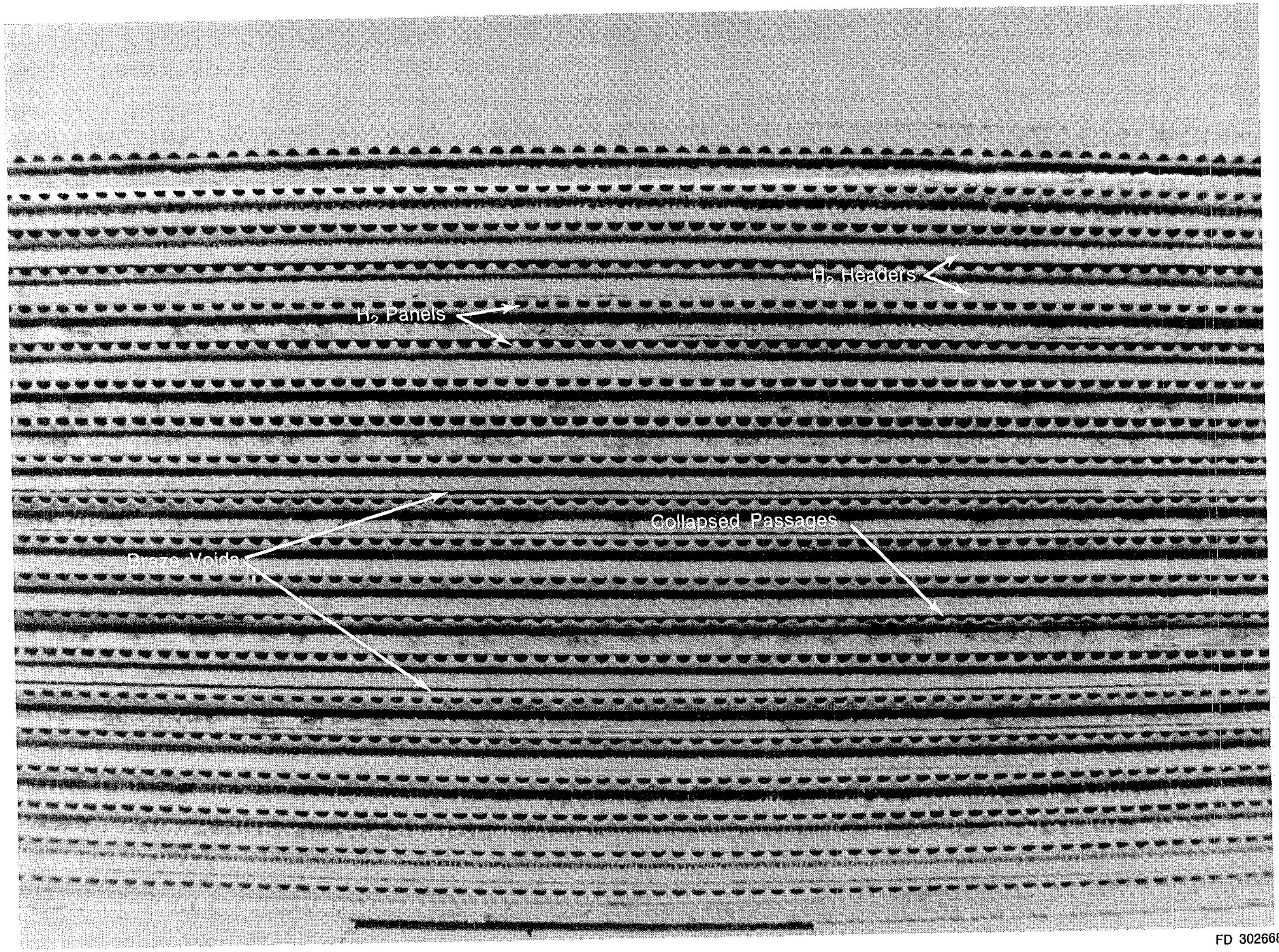

Figure A-6. Oxidizer Heat Exchanger Stage 2 Core — H_2 Inlet

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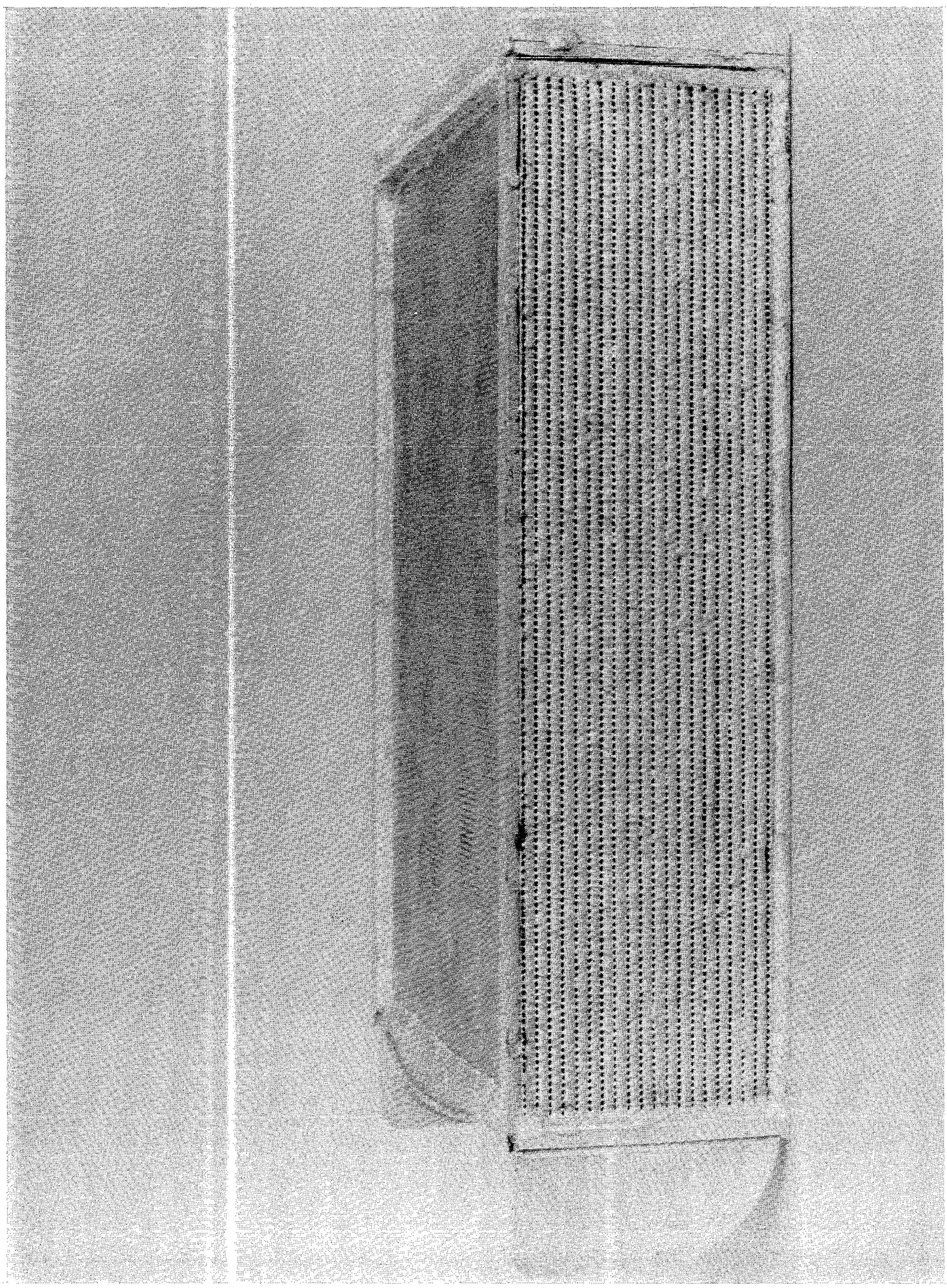

Figure A-7. Oxidizer Heat Exchanger Stage 2 Weld Repair

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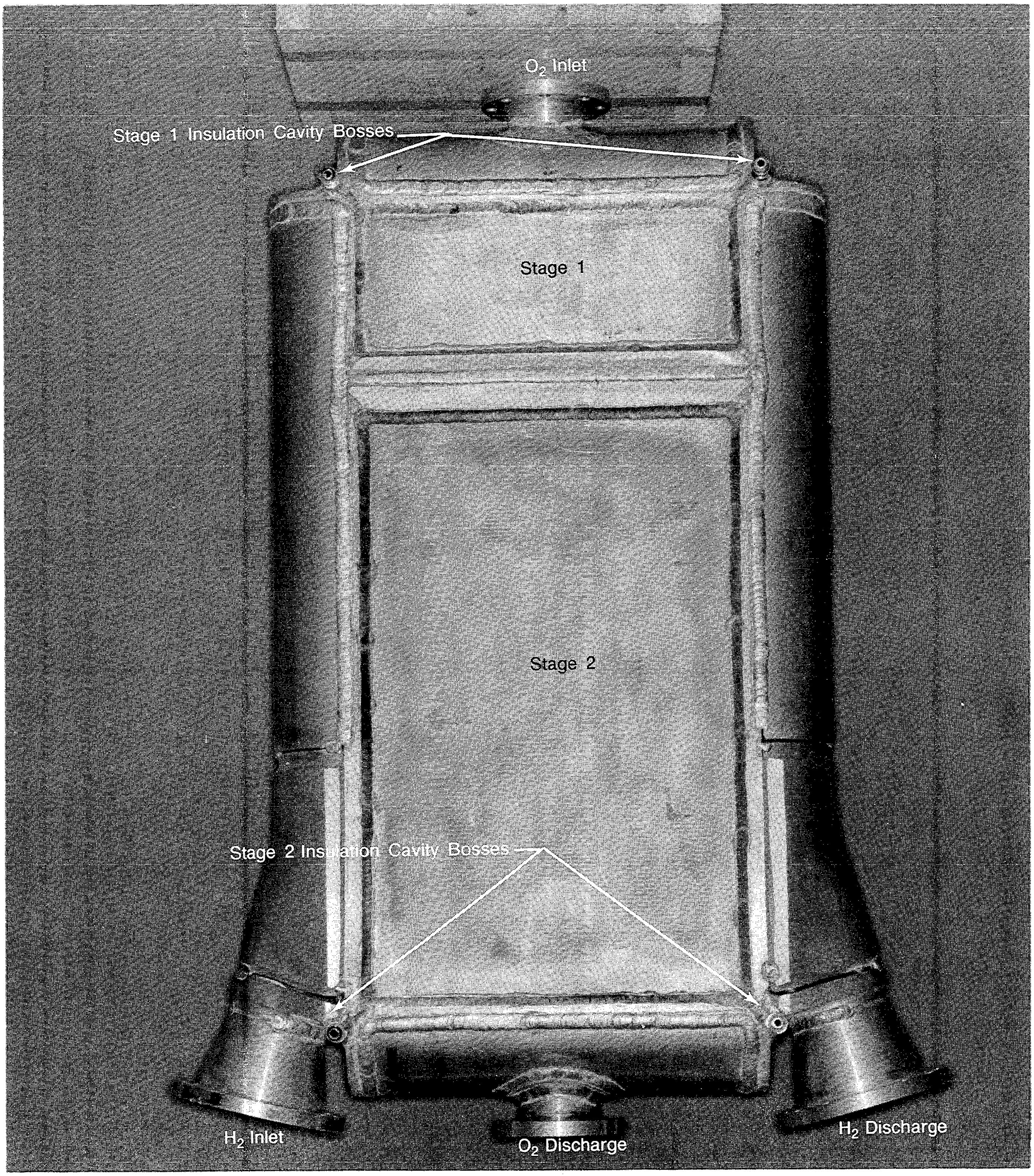

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Figure A-8. Oxidizer Heat Exchanger Stage 1-and-2 Assembly As Received

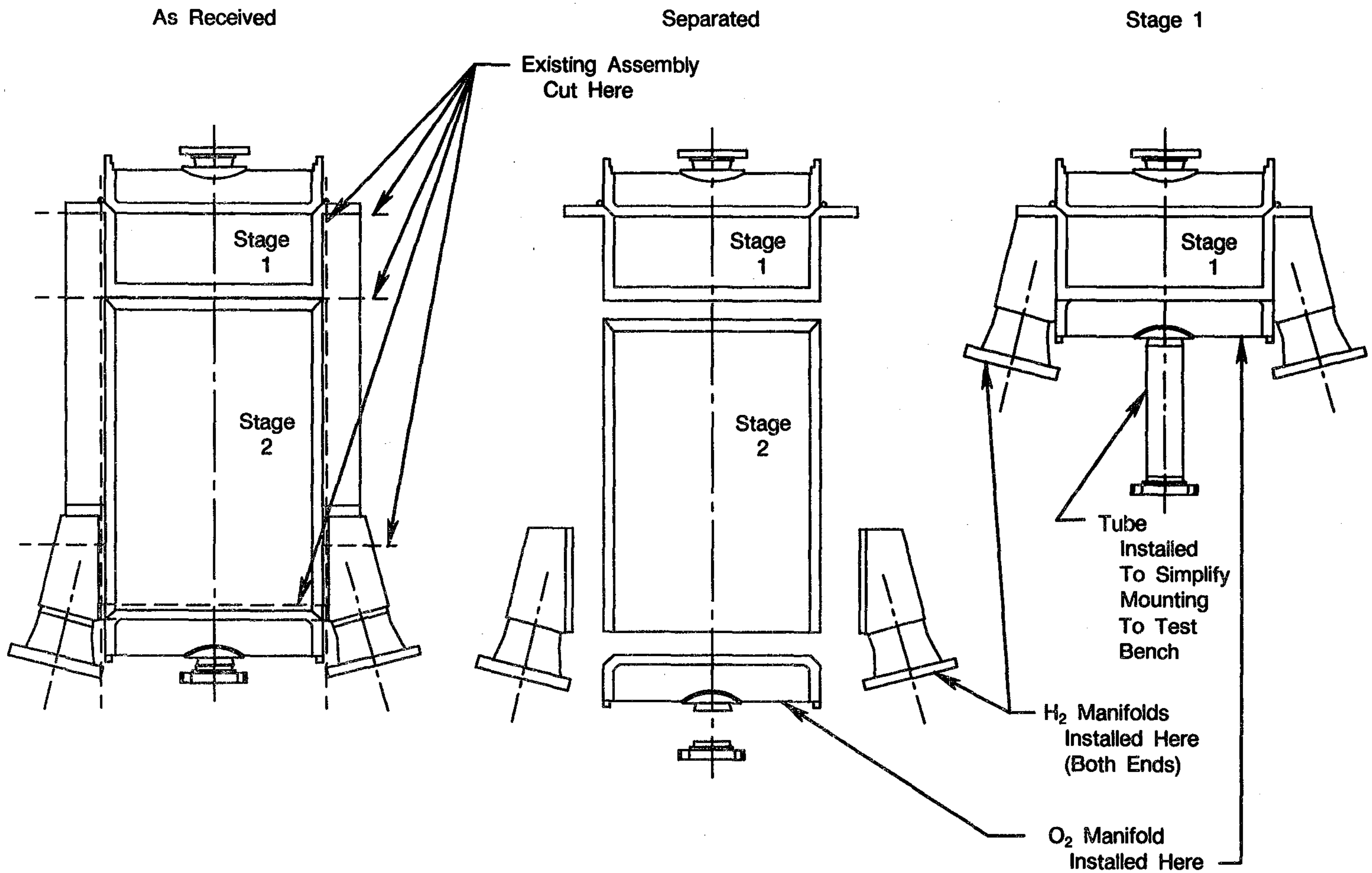

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Figure A-9. Oxidizer Heat Exchanger Stage 1 Rework

Table A1. OHE 1st Stage Leak Check Summary

Date	Leakage at 45 psia O_2 Circuit Insulation Cavity (sccm) GN_2	Leakage at 45 psia H_2 Circuit Insulation Cavity (sccm) GN_2
11/1/84 (prior to running)	1150	400
11/5/84	2850	700
11/6/84	4814	1450

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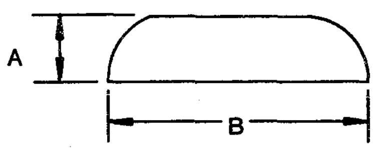
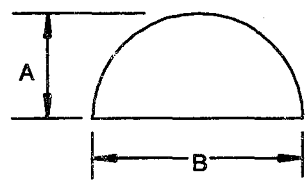
APPENDIX B
OHE FLOW PASSAGE MEASUREMENT

Due to the high pressure losses experienced during engine test of the stage 3 OHE, it was suspected that variations occurred in flow panel dimensions during braze of each OHE stage, causing the flow passage cross sectional area to be less than that specified by the drawing. Therefore, while the stage 1 core flow passages were exposed during the rework process, they were measured for cross sectional height. These are shown in Figure B-1 along with dimensions similarly taken for stage 3. Flow passage surface roughness and passage width were obtained by measuring detail flow panels left over from assembly, and are also presented in Figure B-1.

Both stages showed a reduction in passage height of 0.005 inch. This is probably due to some crushing of the lands which may have occurred during braze. Although the surface roughness of the passages was not specified on the drawings, a roughness of 100 microinches was used in the analytical analysis of the OHE. These changes were incorporated into the OHE performance analysis which was modified after the testing was completed.



Typical O_2 Flow Passage (Stage 1)



Typical H_2 Flow Passage (Stage 1)

Typical O_2 and H_2 Flow Passage (Stage 3).

	Measured		Drawing Specification	
Stage 1	Height Dimension A	Width Dimension B	Height Dimension A	Width Dimension B
O_2 Passages	0.016 in.	0.078 in.	0.021 in.	0.079 in.
H_2 Passages	0.038 in.	0.078 in.	0.043 in.	0.079 in.
Surface Roughness	225 μ in.		None	
Stage 3				
O_2 Passages	0.016 in.	0.078 in.	0.021 in.	0.079 in.
H_2 Passages	0.016 in.	0.078 in.	0.021 in.	0.079 in.
Surface Roughness	225 μ in.		None	

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Figure B-1. Flow Passage Cross Sectional Dimensions

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APPENDIX C
OHE DATA RECORDING

Instrumentation was installed on the rig to provide sufficient accurate data for performance analysis. Instrumentation locations on the test rig are depicted in Figure C-1. An Accurex Model 800 Datalogger was used to calculate GN_2 orifice flows and to record and display data. Rosemount temperature probes were used where possible. Chromel alumel thermocouples were used elsewhere, although several were replaced with copper-constantan thermocouples when some temperature data appeared questionable after the first run. Flowrates were such that sufficient accuracy could be provided by existing stand liquid flowmeters and added gas measurement orifices. O-graph recordings of oxidizer circuit inlet and discharge pressures and flow were taken only during gas-liquid test points to check for possible oscillations due to unstable boiling.

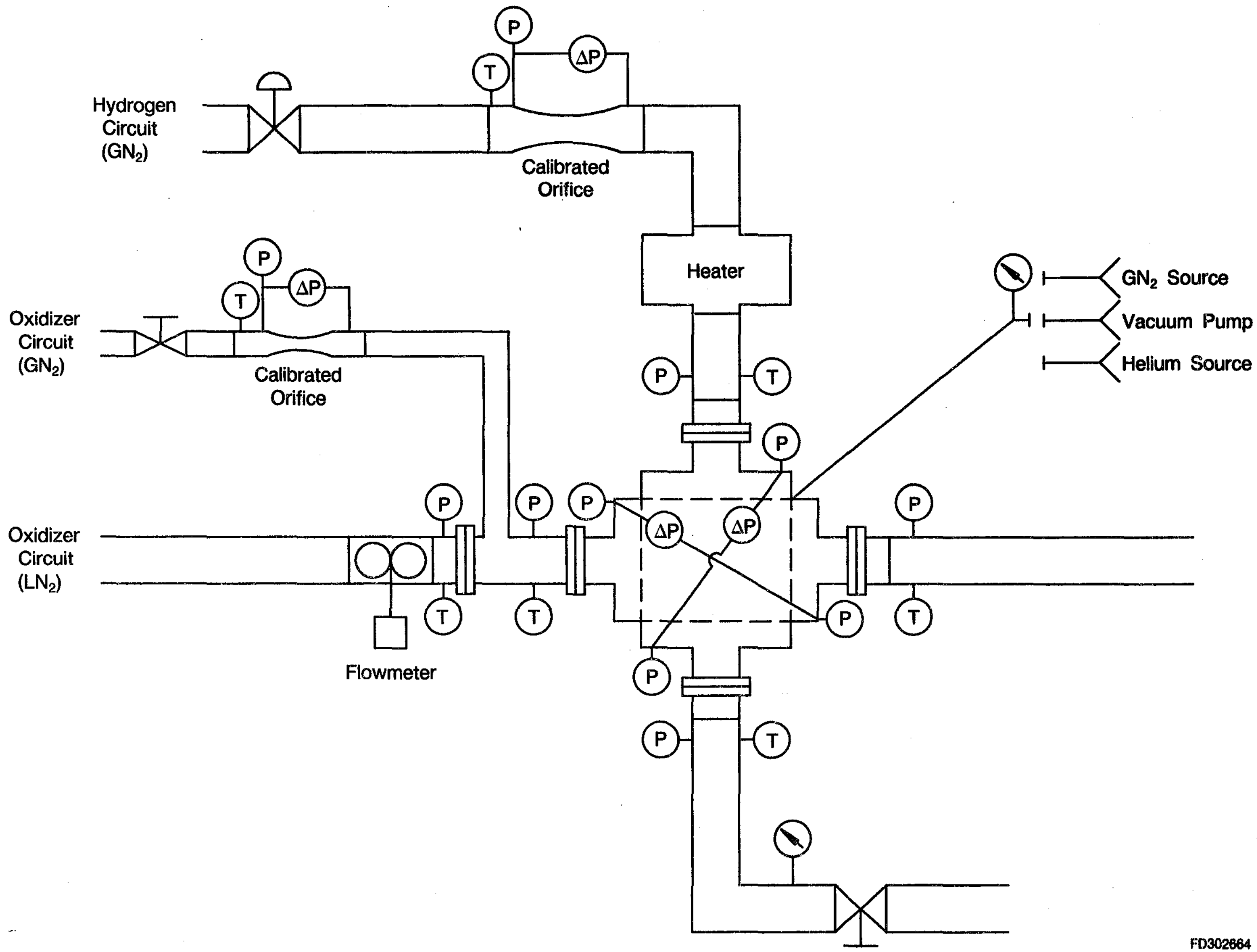

Figure C-1. Oxidizer Heat Exchanger Rig Test Instrumentation Locations

APPENDIX D
RUN SUMMARY

The OHE stage 1 and 3 test points were run as specified in Table D-1. Both pumped idle and tank head idle points were run for each unit, with ambient or heated nitrogen flowing through the OHE hydrogen circuit and liquid nitrogen flowing through the oxygen circuit. In addition, several tests were run with GN_2 flow through both circuits to simplify heat transfer calculations and reduce uncertainties caused by two-phase flow. Flowrates were chosen based on XR201-1 engine run data and were adjusted to compensate for the substitution of nitrogen instead of actual engine fluids. The temperatures were chosen for gas-gas flows to provide sufficient differential temperature for heat transfer calculations. The OHE inlet and discharge pressures were controlled to provide required flowrates and maintain liquid flow if required.

Additions and adjustments to the originally intended test points and test bench configuration were made as required based on preliminary data reviews by the Heat Transfer and Performance Groups. In many instances, inlet pressures were raised to achieve required flows and to assure liquid at the OHE inlet.

Preliminary analysis showed the stage 3 GN_2-GN_2 points run initially (points 13 through 17) as having flow levels too low to provide useful heat transfer data. Those points were therefore rerun at higher flowrates, which required changing a portion of the H_2 circuit supply line to larger ID plumbing to provide the additional flow capability. In addition, an enlarged calibrated orifice was installed in the O_2 circuit before point No. 15 was run to provide additional high flow points. The orifice and increased ID plumbing remained in the stand for the stage 1 tests, which were also run at flowrates higher than originally intended.

A run summary is presented in Table D-1.

Table D1. Run Summary

Test Point	Hydrogen Circuit: Hex Inlet Temperature (°R)	Hydrogen Circuit: GN_2 Flow (lb/sec)	Hydrogen Circuit: Inlet Pressure (psia)	Oxygen Circuit: Hex Inlet Temperature	Oxygen Circuit: LN_2 Flow (lb/sec)	Oxygen Circuit: GN_2 Flow (lb/sec)	Oxygen Circuit: Inlet Pressure (psia)	Insulation Cavity Atmosphere
Stage 3 Gas-Liq								
Pumped Idle 1	632.3	0.329	47.7	150.6	4.292	—	103.8	—
2	599.3	0.706	49.2	156.5	4.588	—	99.1	—
3	577.9	0.586	52.0	154.7	3.381	—	101.8	—
4	567.4	0.697	48.9	154.5	3.556	—	100.5	—
5	629.2	0.317	42.5	154.7	2.623	—	90.4	—
6	658.5	0.685	48.9	154.4	2.536	—	101.3	—
Tank Head Idle 7	526.4	0.167	19.9	155.9	0.955	—	41.9	—
8	516.1	0.332	26.5	155.9	0.955	—	41.7	—
9	514.5	0.168	25.5	156.5	0.812	—	39.4	—
10	513.5	0.265	26.2	156.7	0.856	—	38.7	—
11	512.7	0.265	26.2	157.4	0.669	—	39.7	—
12	508.4	0.325	25.6	157.5	0.702	—	39.7	—
Stage 3 Gas-Gas								
13	719.9	0.014	24.4	525.2	—	0.013	50.2	—
14	789.0	0.046	26.5	515.4	—	0.042	52.4	
15	807.6	0.051	25.4	509.2	—	0.050	50.4	—
16	783.6	0.014	25.7	508.8	—	0.052	49.4	—
17	805.8	0.046	23.8	524.0	—	0.0095	49.4	—
13 Rerun	803.0	0.102	25.4	507.6	—	0.097	49.8	—
14 Rerun	692.5	0.304	23.7	505.0	—	0.308	49.6	—
15 Rerun	639.1	0.533	24.2	507.1	—	0.522	49.8	—
16 Rerun	775.0	0.098	24.4	505.7	—	0.504	49.5	—
17 Rerun	688.1	0.517	24.9	513.3	—	0.093	48.9	—
High H_2-Low O_2 Flow Point	688.1	0.586	49.8	158.6	0.710	—	48.9	—

Table D1. Run Summary (Continued)

Test Point	Hydrogen Circuit: Hex Inlet Temperature (°R)	Hydrogen Circuit: GN_2 Flow (lb/sec)	Hydrogen Circuit: Inlet Pressure (psia)	Oxygen Circuit: Hex Inlet Temperature	Oxygen Circuit: LN_2 Flow (lb/sec)	Oxygen Circuit: GN_2 Flow (lb/sec)	Oxygen Circuit: Inlet Pressure (psia)	Insulation Cavity Atmosphere
Stage 1 Gas Liq								
Pumped Idle 18	634 732	Excursion 0 → Instability	43	155	6.037	—	41	Helium
Tank Head Idle 19	526.6	0.10	20.2	155.1	0.977	—	45.5	Helium
19a	524.9	0.10	20.1	153.1	1.987	—	45.1	
20	518.7	0.20	28.8	155.8	1.306	—	46.2	Helium
20a	524.0	0.20	28.7	153.5	1.976	—	45.6	
21	517.7	0.29	41.1	156.4	1.196	—	47.2	Helium
21a	514.9	0.29	40.9	154.1	2.019	—	45.3	
22	515.1	0.30	42.9	156.3	1.267	—	46.1	Vacuum
23	516.6	0.30	40.8	155.9	1.206	—	44.8	Nitrogen
Stage 1 Gas-Gas								
24	800.9	0.09	20.0	508.8	—	0.11	20.9	Helium
25	642.2	0.30	41.6	504.4	—	0.30	30.7	Helium
27	814.0	0.11	20.3	499.8	—	0.48	45.5	Helium
28	635.9	0.30	41.3	510.9	—	0.10	19.7	Helium
29	637.0	0.30	41.9	506.2	—	0.30	30.9	Vacuum
30	639.8	0.29	41.3	504.9	—	0.30	30.8	Nitrogen
31	805.8	0.11	21.7	488.9	—	0.08	15.8	Helium
32	810.9	0.10	21.2	483.8	—	0.12	17.5	Helium
33	619.8	0.05	20.4	153.1	1.142	—	43.2	Helium
34	556.7	0.05	19.8	152.2	1.119	—	43.5	Vacuum (5 psia)
18 Rerun	641 → 734	Excursion 0 → Instability	45	154	2.744	—	42	Helium

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APPENDIX E
POST-TEST EXAMINATION AND ANALYSIS

A. STAGE 1 EXAMINATION

Due to discrepancies between the predicted and measured heat transfer rates for stage 1, short-circuiting past the insulation was suspected. After testing, the stage 1 was sectioned to examine the insulation cavity and the position of the flow panels. Figures E-1 and E-2 show views of the two circuits. Although there was no apparent wicking of the braze filler into the insulation, many flow panels were touching the header of the other fluid, creating a short circuit around the insulation. This may be partially responsible for the discrepancies.

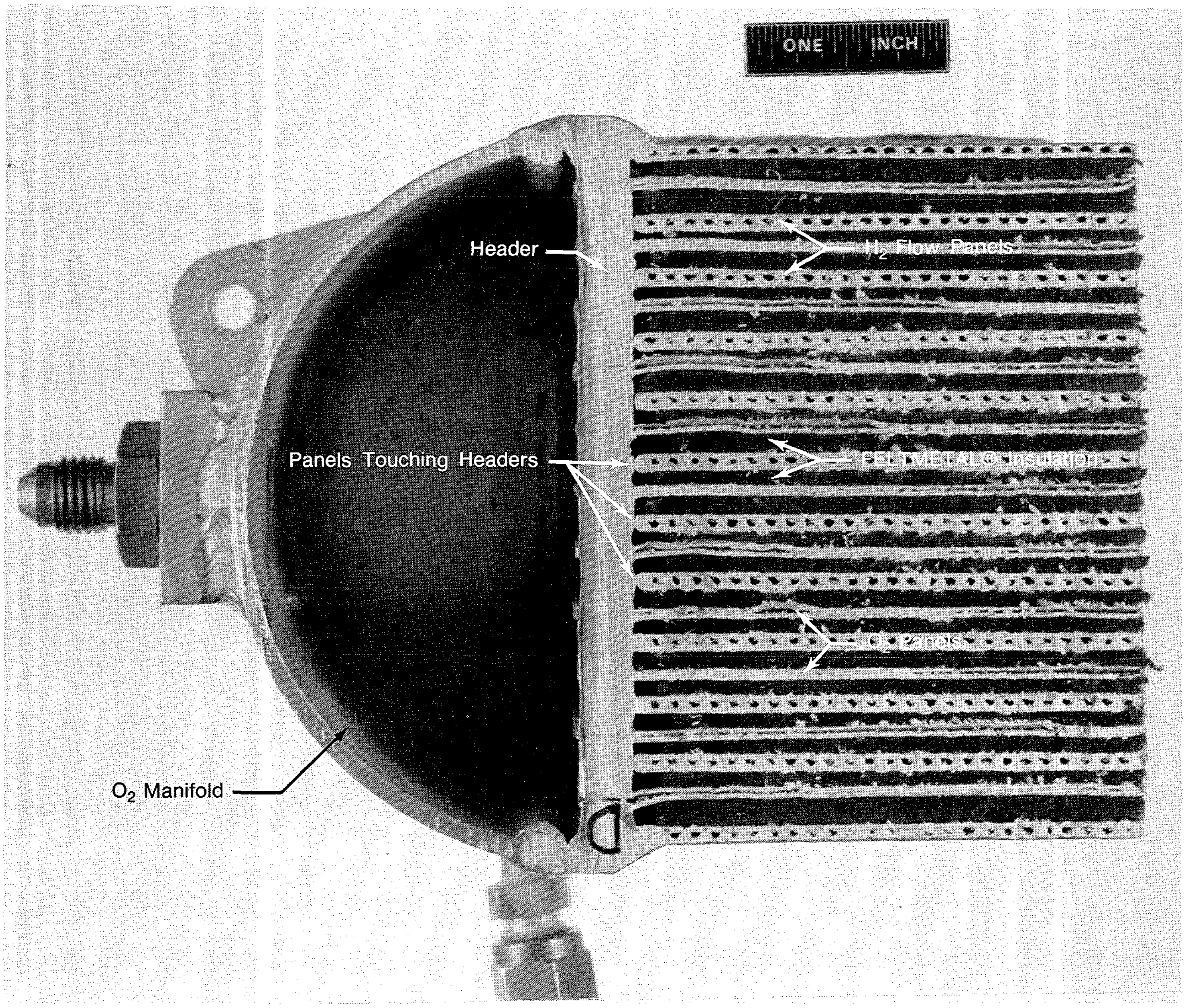

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Figure E-1. Stage 1 Heat Exchanger Section — H_2 Flow Section

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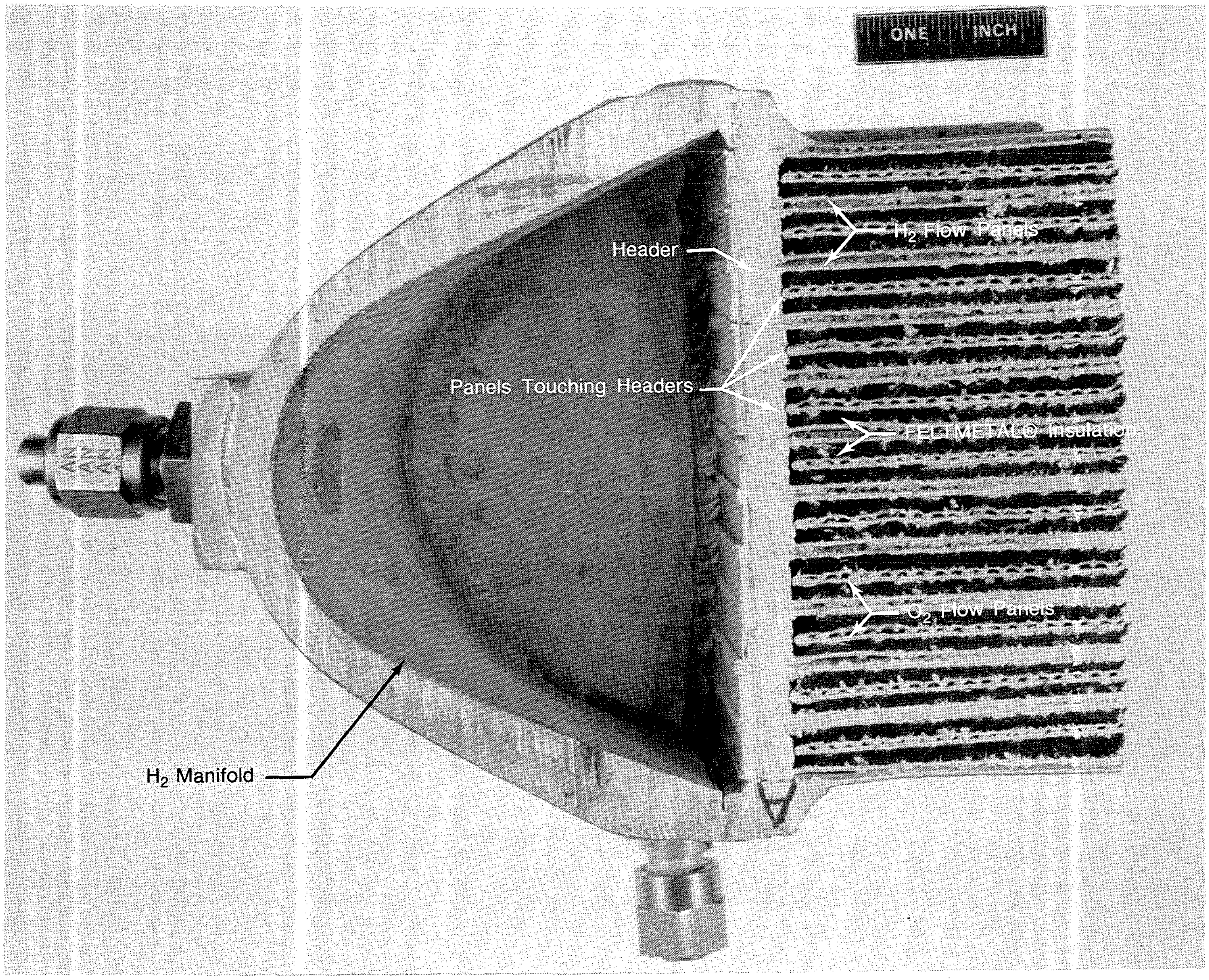

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Figure E-2. Stage 1 Heat Exchanger Section — O_2 Flow Section

B. UTRC/OATL HEAT EXCHANGER PERFORMANCE ANALYSIS

A study of the heat exchanger rig test data was performed by UTRC/OATL using the Crossflow Heat Exchanger Analysis Program (CHEAP) (Reference 3). The results are reported in UTRC Report No. 85R-280251-01, which is included in its entirety in this appendix. The program was developed specifically to analyze stacked-plate crossflow heat exchangers. Modifications were made to the program to reflect actual flow passage geometry, which differed from designed geometry due to manufacturing variations. These differences included a reduction in flow passage cross sectional area and an increase in flow passage surface roughness. Representative points for comparison and analysis were chosen from the rig test data obtained.

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As part of the stage 3 performance analysis, tank head idle and pumped idle data from XR201-1 engine runs were included in the study. The engine test data used in the study was from the same stage 3 unit used in the rig tests. The program was structured such that changes in the thermal conductance of the stage 1 resistance layer could be made to reflect the presence of helium, nitrogen, or vacuum in the insulation.

In the study, references are made to a condition known as "dryout." Dryout or film boiling occurs when the difference between the heat exchanger wall temperature and the saturation temperature of the working fluid ($T_{WALL} - T_{SAT}$) increases beyond a critical level (approximately 30 degrees for O_2 and N_2). At this level, the transfer of heat is severely impeded by a thin layer of gas along the heat exchanger hot wall. Additionally, more extensive correlations beyond the scope of this study would be necessary to accurately predict performance in the dryout regime.

APPENDIX E (CONT'D)
PREDICTED VERSUS MEASURED PERFORMANCE DATA

UNITED TECHNOLOGIES RESEARCH CENTER

Optics and Applied Technology Laboratory

RL10-IIB GOX HEAT EXCHANGER ANALYSIS:
COMPARISON AND EVALUATION OF
PREDICTED VERSUS
EXPERIMENTAL PERFORMANCE RESULTS
85R-280251-01

MAY 17, 1985

Prepared For

ROCKET ENGINE PROGRAM OFFICE
PRATT & WHITNEY AIRCRAFT
GOVERNMENT PRODUCTS DIVISION

Prepared By: Tim Harris
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Approved By: M. E. Meadows
Marcus E. Meadows
Senior Design Engineer

85R-280251-01

RL10-IIB GOX Heat Exchanger Analysis: Comparison and Evaluation of Predicted Versus Experimental Performance Results

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SUMMARY

A study to compare predicted and measured performance data of the RL10-IIB GOX Heat Exchanger using the Crossflow Heat Exchanger Analysis Program (CHEAP) (Reference 1), was performed. Where applicable, modifications to the program were incorporated to improve the accuracy of the existing correlations. For comparison, Stage 1 and Stage 3 oxidizer heat exchanger (OHE) engine and bench test data were supplied. The OHE arrangement consists of three modular stages, each optimized for one mode of operation. This arrangement is shown schematically in Figure 1. Based on comparisons made in this study (before and after program modifications) between predicted and measured performance data, the occurrence of film boiling "dryout" was verified for the Stage 3 OHE engine tests. The accuracy of the program modifications in predicting the occurrence of "dryout" was verified but, if a more accurate quantitative assessment of heat flux and pressure drop is required within the film boiling flow regime, the "1st order" approximations must be replaced with more detailed correlations. The Stage 1 OHE measured performance results indicate that fabrication errors occured, causing deviations from the current heat exchanger design permitting most of the heat to "short circuit" the insulation rendering it ineffective. Modifying CHEAP to predict Stage 1 performance results to predict all hardware features and deviations is not feasible.

The CHEAP Program in its present configuration was specifically developed to analyze stacked-plate (Thermal-Skin[R]) crossflow heat exchangers as shown in Figure 2. The program allows for the addition of insulation between the Thermal-Skin[R] plates. The feasibility of modifying CHEAP to analyze heat exchangers with plate/fin flow panels, instead of Thermal-Skin[R] plates, and plate/fin insulating cavities, instead of the insulation currently being used (combination of SST feltmetal and an evacuating gas), has been studied. Program modifications to include a plate/fin design (heat exchanger and insulating cavity) is feasible for standard (rectangular) crossflow, counterflow, or parallel heat exchanger configurations. However, the program is inadequately structured for modifications to include non-standard plate/fin configurations with non-rectangular geometries and mitered turns (i.e. United Aircraft Products, Inc. oxidizer heat exchanger design).

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RESULTS AND RECOMMENDATIONS

Comparisons between the design and as manufactured and tested passage configurations for the RL10-IIB Gox Heat Exchangers are shown in Table 1. The "as-built" heat exchanger geometry was used for all performance predictions. The comparisons between predicted and measured performance data for the RL10-IIB Stage 1 and Stage 3 oxidizer heat exchangers (OHE) are shown in Tables 2 through 5. Measured performance data were taken from engine and bench tests utilizing Hydrogen (H_2), Oxygen (O_2), and Nitrogen (N_2) as working fluids. From the comparison shown in Table 2 the occurrence of "dryout" (Transition from nucleate to film boiling) was predicted during Stage 3 OHE engine testing. This prediction was made based on the small amount of heat transferred during testing compared to that predicted using liquid, two phase liquid, and gaseous film coefficient correlations. Low film coefficients (low heat fluxes) are associated with "dryout". As shown in Table 3 the heat transfer rate predictions showed excellent agreement with experimental results for Stage 3 OHE nitrogen flow bench tests. Due to the relatively small temperature differential between the wall and saturation temperatures in the O_2 circuit and the prediction accuracy achieved without utilizing required "dryout" correlations, it is believed that "dryout" did not occur in any of the N_2 bench tests.

Using experimental data presented in Reference 7, modifications to the CHEAP program have been made to predict the occurrence of "dryout" and approximate the film coefficient associated with film boiling. With these modifications included, the predicted performance results for the Stage 3 OHE engine tests were regenerated for the H_2/O_2 operation. A comparison between the CHEAP predicted and measured performance results is shown in Table 4. This comparison shows that the predicted heat transfer rates for the pumped idle tests (shown as ΔT error) are in excellent agreement with experimental results (within 5% in three of four engine test cases analyzed). The tank head idle heat transfer rates were not, in general, accurately predicted. This indicates that the film coefficient approximations for film boiling are not valid over a wide range of flowrates and temperature differentials. The program does accurately predict the occurrence of "dryout". However, for the current configuration of the Stage 3 OHE, "dryout", is not a desirable condition because of the limited heat transfer capability; thus it is recommended that the program, in its present configuration, be used as a design tool to indicate that the inlet flow condition will cause "dryout" to occur. A "flag" to indicate the possible occurrence of "dryout" has been included in the program to be displayed with the predicted performance results. The performance results of a sample run which displays this flag is shown in Appendix-1.

A comparison of the Stage 1 OHE N_2 flow bench test predicted versus experimental results is shown in Table 5. An accurate prediction of heat transfer was not possible because an apparent "short circuited" heat flow path was present. The program did not accurately predict heat flux since it assumes (as designed) that all heat flows through the insulation. This conclusion was made after comparing three similar test cases (#28, #29, and #30). If all of the

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heat were transferred through the insulation the heat flux would be proportional to the thermal conductivity of the insulation. In fact, however, all three runs exhibited nearly identical heat fluxes. This "short circuiting" problem is likely to occur in any type of design where the housing and manifold are manufactured from a high thermal conductivity material (aluminum in this case) compared to the insulating material unless the flow panels can be isolated. This problem should be addressed in any of the alternative designs currently being considered.

The CHEAP program in its present configuration was specifically developed to analyze stacked-plate (Thermal-Skin[R]) crossflow heat exchangers as shown in Figure 2. The feasibility of modifying the Stage 3 OHE and Stage 1 OHE prediction programs to analyze a plate/fin heat exchanger which incorporates (for Stage 1) fins between the hydrogen and oxygen flow panels, rather than the insulation currently being used has been studied. Program modifications to include a plate/fin design (heat exchanger and insulating cavity) is feasible for the standard (rectangular) crossflow, counter flow, or parallel heat exchanger configurations. The program is inadequately structured for modifications to include non-standard plate/fin configurations with non-rectangular geometries and mitered turns (i.e. United Aircraft Products, Inc. design).

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DISCUSSION

The prime objective of this analysis has been to compare predicted and measured performance data of the RL10-IIB GOX heat exchanger using the crossflow heat exchanger analysis program (Reference 1) and, if applicable, modify the program to improve the accuracy of existing correlations. Stage 1 and Stage 3 oxidizer heat exchanger (OHE) engine and bench test data have been used to compare predicted versus measured performance results. The "dryout" boiling phenomenon has also been studied and approximations to better predict its occurrence and heat transfer characteristics have been included. Additionally, the feasibility of modifying the Stage 3 and Stage 1 performance prediction program to include a plate/fin heat exchanger analysis which incorporates fins between the hydrogen and oxygen flow panels for the Stage 1 OHE, instead of the existing insulation, was also studied.

GOX Heat Exchanger Design

The RL10-IIB GOX heat exchanger, as defined by Reference 2, consists of three modular stages, each optimized for one mode of operation. The oxygen flows through all three stages in series while the hydrogen flows through Stages 1 and 2 in parallel and then through Stage 3. This arrangement is shown schematically in Fig. 1. In order to control flow stability during tank head idle and pumped idle conditions, insulation has been added between adjacent heat exchanger plates in Stages 1 and 2 to limit the maximum heat flux. This configuration is illustrated in Fig. 2.

Stage 1/Stage 3 OHE Test Configurations

In support of the preliminary design, the performance of the RL10-IIB GOX heat exchanger was evaluated (Ref. 3) utilizing the crossflow heat exchanger analysis program (CHEAP) developed by UTRC. The tested configurations for the Stage 1 and Stage 3 OHE coolant passages (see Ref. 3) deviated from the preliminary design configurations. These deviations are shown in Table 1. The actual passage geometries represent a reduction in flow area for both circuits of the Stage 1 and Stage 3 heat exchangers (Stage 1 OHE: 17%-H_2 circuit and 22%-O_2 circuit, Stage 3 OHE: 22%-H_2 circuit and 22%-O_2 circuit). The blocked passage estimate (Ref. 4) for the Stage 3 OHE represents an insignificant portion of the total flow area (2.7%-H_2 circuit and .7%-O_2 circuit) and thus, its effect was neglected for this analysis. The input data portion of CHEAP was modified to include the actual passage geometry and surface roughness (friction factor) deviations.

Initial Stage 3 OHE Performance Predictions

To verify the predicted performance results for the Stage 3 OHE, engine and bench tests were performed. The working fluids for the engine tests were Oxygen (O_2) and Hydrogen (H_2), and the working fluid for the bench tests was Nitrogen

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(N_2). With the CHEAP program modified to include the actual heat exchanger configuration, predicted performance data were generated using inlet conditions specified in the test data (Ref. 5).

A comparison of the performance results between CHEAP predicted and experimental results for the Stage 3 OHE engine tests is shown in Table 2. From the comparison, because of the significant error in predicted versus actual heat transfer rates [%Error(ΔT)], it was apparent that modifications to the program were required. It was determined that the probable cause for the error was the absence of film boiling ("dryout") correlations in the program (Ref 1). This phenomenon was neglected in the preliminary analysis (Ref. 3) primarily because operating in the film boiling regime is avoided in most cryogenic heat exchanger applications due to the low film coefficients (low heat fluxes) associated with it.

Before an attempt was made to modify the existing program, the CHEAP predicted and experimental performance results for the Stage 3 OHE Nitrogen flow bench tests were compared. This comparison is shown in Table 3. The heat transfer rate predictions (% Error(ΔT)-H_2) showed excellent agreement with experimental data. The predictions are within 10% (most cases below 3%) of the measured data for nine of eleven test cases. The predictions for test cases #13 and #14 are 18.9% and 14.3%, respectively. These predictions are within the accuracy of the heat transfer (film coefficient) correlations utilized. Due to the relatively small temperature differential between the wall and saturation temperatures in the O_2 circuit (driving potential for "dryout") good prediction accuracy was achieved with the existing correlations. It is believed that "dryout" did not occur in any of the N_2 bench tests.

Small errors in pressure measurements and predictions for saturated (two phase) liquids can cause large temperature errors relative to the total temperature difference. For this reason, the O_2 was not used to assess heat transfer prediction accuracy in this analysis. Even though it was not used to assess prediction accuracy, the predicted temperature differential for the O_2 circuit in test #1 was significantly smaller (% Error(ΔT) = 54.2%) than test results and requires explanation. A conservation of energy (heat balance) analysis revealed that for this case the measured data was incorrect (heat flow into the O_2 is about 2 times higher than H_2) and the actual results should correspond to the predicted results.

Also included in Table 4 are the percentage errors (% E (ΔP)) between the predicted and measured pressure drops. It is believed that, for the data provided, the percentage errors are not truly representative. The resolution of the pressure transducers used in the majority of cases was not fine enough to accurately measure values of pressure in the range of interest. With the exception of one case (Test #15-H_2 circuit) the prediction accuracy for pressure drops greater than 1.0 psia (both circuits) is within acceptable values.

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By accurately predicting the heat transfer rate for the Stage 3 OHE Nitrogen flow bench tests, the fundamental correlations utilized by CHEAP are verified. This fact further substantiates the assumption that "dryout" is occurring during the Stage 3 OHE engine tests.

CHEAP Modifications - Film Boiling

Modifying the CHEAP program to predict all possible film boiling conditions utilizing correlations such as those discussed in Reference 6, was beyond the scope of this analysis. To yield approximate results, modifications have been implemented which include experimental film boiling data (Ref. 7). Using this data, the occurrence of "dryout" can be accurately predicted, and an approximate film coefficient (and subsequently heat flux) associated with film boiling can be determined.

The *maximum* temperature differential [ΔT = T (wall) - T (saturation)] associated with the transition from nucleate to film boiling, is the driving potential for "dryout" and occurs at an approximately constant critical heat flux level. Accompanying the boiling transition is a large reduction in film coefficient (heat flux). In Reference 7 plots of heat flux versus ΔT are presented. From this information, the maximum wall minus saturation temperature differential is determined to be approximately 30°F for O_2 and N_2. In addition, the film coefficient as a function of hydraulic diameter for film boiling was found by utilizing the equation shown below.

$$q = h \Delta T \quad \frac{BTU}{hr\ ft^2}$$

Where "q" is heat flux and h represents the film coefficient for film boiling. The film coefficients, given as a function of hydraulic diameter, are shown below.

Hydraulic Dia. (D_H), in.	Film Coefficient(h) $\frac{BTU}{ft^2\ hr\ °F}$
$D_H <$ .004	200.0
.004 < $D_H <$ .008	155.0
.008 < $D_H <$ .020	85.0
.020 < $D_H <$ .040	46.0
.040 < $D_H <$ .400	30.0
.400 < D_H	23.5

Excerpts from the modified program are shown in Appendix 2. Modification #1 is required to display a "flag" notifying that the O_2 is operating in the film boiling regime ("Dryout is occurring"). Modifications #2 and #3 are required to approximate the film coefficient in the film boiling regime. Modifications #2 and #3 are located in the single and two phase sections of the program,

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respectively. Modification #4 allows the O_2 circuit wall temperature to be displayed. Knowing the wall temperature is useful to determine how far the heat exchanger is being operated from the critical heat flux level.

Final Stage 3 OHE Performance Predictions

Utilizing the CHEAP program modified to include film boiling approximations under "dryout" conditions, the performance results were regenerated from the Stage 3 OHE engine tests. A comparison between the CHEAP predicted and measured performance results is shown in Table 4. For three of the four pumped idle engine tests the heat flux (% Error(ΔT)) was accurately predicted within 5%. The exact cause for the large differences in accuracies between test #275 (% Error (ΔT)) and the other cases is unknown but considering the similarities in inlet flow conditions, the accuracy of the measured data is suspect. Being able to accurately predict the heat flux for the pumped idle tests, with the "dryout" approximations being utilized, verifies the assumption that "dryout" occurred during the engine tests and that the constant film coefficient approximations are valid for the pumped idle flow conditions.

Comparing the tank head idle measured and predicted heat fluxes (%Error(ΔT)), shown in Table 4, reveals that the film coefficient approximations for film boiling may not be valid over a wide range of conditions. Correlations, such as those presented in Reference 6, which include the effect of fluid velocity and subcooling on the critical heat flux and film coefficient will be required if an increase in prediction accuracy in this regime is desired. Pressure drop correlations associated with the dryout phenomenon were not included in this analysis. This fact and, as described above, the resolution of the test instrumentation are probable causes for not achieving good correlation with measured pressure drop data. The resolution of the pressure transducers was not fine enough to accurately measure values of pressure drop near zero.

The Stage 3 OHE nitrogen flow bench tests performance results were also regenerated with the modified program. No change in predicted results were noticed because the critical heat flux was not exceeded.

Stage 1 OHE Performance Predictions

To verify the predicted performance results for the Stage 1 OHE, Nitrogen flow bench tests were performed. With the CHEAP program, modified to include the actual heat exchanger configuration and film boiling correlations, predicted performance data were generated using inlet conditions and insulation thermal conductivities, specified in the test data (Ref. 5). Three thermal conductivities were specified corresponding to the gas type used to purge the insulating cavity. Stainless steel feltmetal occupied the remaining space for the three conditions specified. The three gases used were Helium, Vacuum, and Nitrogen corresponding to thermal conductivities of .0526, .001175, and .01125 BTU/hr-ft-°F, respectively.

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A comparison of the performance results between CHEAP predicted and experimental results for the Stage 1 OHE bench tests is shown in Table 5. The predicted heat flux [ΔT (Pred)] is consistently much less than the actual heat flux [ΔT (Meas)]. An explanation for this difference can be found by comparing test cases utilizing different insulations with similar inlet conditions. Test cases #28, #29 and #30 (ref. 5) have similar inlet flow conditions, but have different insulation thermal conductivities. Test case #28 insulation is purged with Helium with a thermal conductivity approximately 45X greater than a Vacuum (Test case #29) and approximately 5X greater than Nitrogen (Test case #30). If all of the heat were conducted through the insulation during testing (as designed), then the heat flux would have been proportional to the thermal conductivity of the insulation. The heat flux [ΔT (Meas)] for test case #28 is only 20% greater than test case #29 and 11% greater than #30. Similarly, the heat flux for test case #30 should have been approximately ten times greater than that measured in test case #30 (based on thermal conductivities) but they were approximately the same.

These results indicate that an additional heat path exists in parallel with the insulation "short circuiting" the heat flow. With aluminum being the flow panel and housing material, having a thermal conductivity of 88.0 BTU/hr-ft-°F, as described in Reference 3, small contact areas would render any of the insulations considered ineffective. Examining the manufacturing technique for the Stage 1 OHE, contact between the hex plate/manifold and hex plate/housing is possible by plate slippage, braze material wicking between gaps, or a combination of slippage and wicking. Hex plate/hex plate contact is also possible from braze material wicking. Another possible explanation for unexpected heat fluxes is insulation contamination with moisture (caused by leakage). Pressure drop comparisons are invalid for Stage 1 OHE tests considering the large discrepancies in predicted versus actual heat flux.

Plate/Fin CHEAP Modification Feasibility

The feasibility of modifying the Stage 3 OHE and Stage 1 OHE prediction programs to analyze a plate/fin heat exchanger which incorporates (for Stage 1) fins between the hydrogen and oxygen flow panels, rather than the insulation currently used has been studied. Modifying the CHEAP program to determine the effective conductance of a plate/fin construction (flow panel or insulating cavity) for standard (rectangular) crossflow, counterflow, or parallel configurations will require a relatively small effort. The effective conductance could be generated from a combination of film coefficient correlations defined for flow across fins and basic conduction through the fins. The program is inadequately structured for modifications to include configurations with non-rectangular geometries with mitered turns and combinations of crossflow, counterflow, and parallel flow schemes such as those described in the United Aircraft Report (Project 4357, United Aircraft Products, Inc.). Critical heat exchanger sections could be analyzed with the program if a rectangular geometry could be assumed.

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Table 1 Stage 1 and Stage 3 OHE Passage Geometry Deviations From Preliminary Design.

	PRELIMINARY DESIGN		ACTUAL	
	STAGE 1	STAGE 3	STAGE 1	STAGE 3
H_2 Passage Ht. in.	.043	.021	.038	.016
O_2 Passage Ht. in.	.021	.021	.016	.016
H_2 Passage Wt. in.	.079	.079	.078	.078
O_2 Passage Wt. in.	.079	.079	.078	.078
Insulation Conductivity (BTU/ft-hr-°R)	.041	N/A	*	N/A
Surface Roughness (μ-in.)	110.0†	100.0†	225.0	225.0
H_2 Blocked Psgs.	N/A	N/A	NONE	120
O_2 Blocked Psgs.	N/A	N/A	NONE	25

* 3 Cases (Ref. Dynatech Test Report No. PRA-102)

1. Insulation in Helium - .0526 BTU/hr-ft-°R
2. Insulation in Nitrogen-.001175 " " "
3. Insulation in Vacuum - .01125 " " "

† Assumed in Original Analysis (Ref. 2).

Table 2 Performance Data Comparison of CHEAP (Unmodified Version) Predicted* and Experimental Results for Stage 3 OHE Engine Tests (Working Fluids – H_2 and O_2)

	OPERATION MODE	TANK HEAD IDLE				PUMPED IDLE			
	RUN NUMBER (EDR TIME)	13.01 (125)	14.01 (78)	15.01 (118)	15.01 (191)	11.01 (275)	13.01 (382)	15.01 (399)	15.01 (573)
H_2	$\dot{w}$ (lbm/sec)	.130	.079	.079	.143	.227	.189	.249	.249
C	Tin (°R)	864.3	944.0	813.5	827.1	606.1	697.2	656.7	648.5
I	ΔT (Measured)	114.8	234.3	89.3	136.7	70.7	148.0	114.6	109.0
R	ΔT (Predicted)	303.3	310.3	261.2	334.8	339.6	416.1	382.9	379.5
C	% Error (ΔT)	164.0	32.4	192.5	144.9	380.3	181.0	234.1	248.2
U									
I	Pin (psia)	17.1	12.2	17.1	18.2	47.5	42.7	56.7	55.0
T	ΔP (Measured)	5.66	4.77	5.84	5.12	3.39	2.75	4.14	3.86
	ΔP (Predicted)	3.29	2.63	3.66	3.05	1.45	1.13	1.56	1.59
	% Error (ΔP)	41.9	44.9	37.3	40.4	57.2	58.9	62.6	58.8
O_2	$\dot{w}$ (lbm/sec)	.588	.313	.570	.809	2.839	2.804	3.555	3.473
C	Tin (°R)	179.5	173.6	178.1	176.3	179.9	176.5	175.1	175.1
I	ΔT (Measured)	1.3	-1.3	-.6	.7	30.4	24.5	28.3	27.2
R	ΔT (Predicted)	541.0	614.7	503.5	453.7	61.9	70.9	83.7	51.0
C	Exit Quality								
U	(Predicted)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
I									
T	Pin (psia)	37.0	28.2	34.8	35.5	99.4	86.5	102.5	99.1
	ΔP (Measured)	1.62	.97	.74	-1.66	3.87	5.30	8.69	8.63
	ΔP (Predicted)	1.76	.62	1.69	2.86	4.32	5.20	6.89	6.48
	% Error (ΔP)	8.6	36.1	128.4	273.5	11.6	7.9	20.7	-24.9

* Dryout Correlation Modifications not Included

TABLE 3 Performance Data Comparison Of CHEAP (Unmodified Version)
Predicted AND Experimental Results For The Stage 3 OHE
Bench Tests (Working Fluid – N_2)

OPERATION MODE		NITROGEN FLOW BENCH TEST CASES										
TEST NUMBER		1	2	3	4	5	7	8	11	13	14	15
H_2 CIRCUIT	$\dot{w}$ (lbm/sec)	.329	.707	.586	.698	.317	.151	.332	.265	.098	.304	.532
	Tin (°R)	632.3	595.5	577.9	567.2	629.2	529.3	516.1	512.7	803.1	694.5	639.1
	ΔT (Measured)	467.8	433.7	394.3	405.7	469.4	345.3	338.0	334.4	175.5	99.7	71.2
	ΔT (Predicted)	455.8	403.8	391.6	377.0	443.2	354.1	337.6	333.1	208.7	100.3	81.4
	% E (ΔT)	2.5	6.9	.68	7.1	5.6	2.5	.12	.09	18.9	.60	14.3
	Pin (psia)	47.7	49.1	52.0	48.8	42.5	19.9	26.5	26.2	24.9	23.7	24.3
	ΔP (Measured)	.022	.70	.29	.75	.14	-0.9	0.0	-.05	.11	.83	3.42
	ΔP (Predicted)	.16	.61	.40	.59	.16	.08	.27	.15	.12	.68	1.42
	% Error (ΔP)	627.2	12.9	38.0	21.3	2.0	—	—	—	9.0	18.1	58.5
O_2 CIRCUIT	$\dot{w}$ (lbm/sec)	4.316	4.582	3.360	3.540	2.620	0.0965	0.952	0.667	0.097	0.308	0.577
	IN. QUALITY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0
	Tin (°R)	145.5	148.0	146.2	146.0	145.9	146.9	147.2	149.2	507.4	505.1	507.1
	ΔT (Measured)	35.6	28.2	37.3	31.7	29.9	11.9	11.4	8.5	170.7	100.2	77.1
	ΔT (Predicted)	16.3	28.4	31.2	31.1	26.9	10.4	10.2	7.4	210.9	98.9	74.9
	EXIT QUAL.	0.0	.021	.025	.047	0.0	.112	.31	.38	1.0	1.0	1.0
	Pin (psia)	103.7	98.4	101.4	100.5	90.4	41.3	41.7	39.7	49.8	49.8	49.8
	ΔP (Measured)	.60	2.0	1.0	1.0	.30	.10	.60	.30	.36	.79	1.86
	ΔP (Predicted)	.72	1.7	1.0	1.26	.52	.24	.53	.34	.11	.42	1.79
	% Error (ΔP)	20.0	15.0	0.0	29.2	73.3	140.0	11.7	13.3	69.4	46.8	3.8

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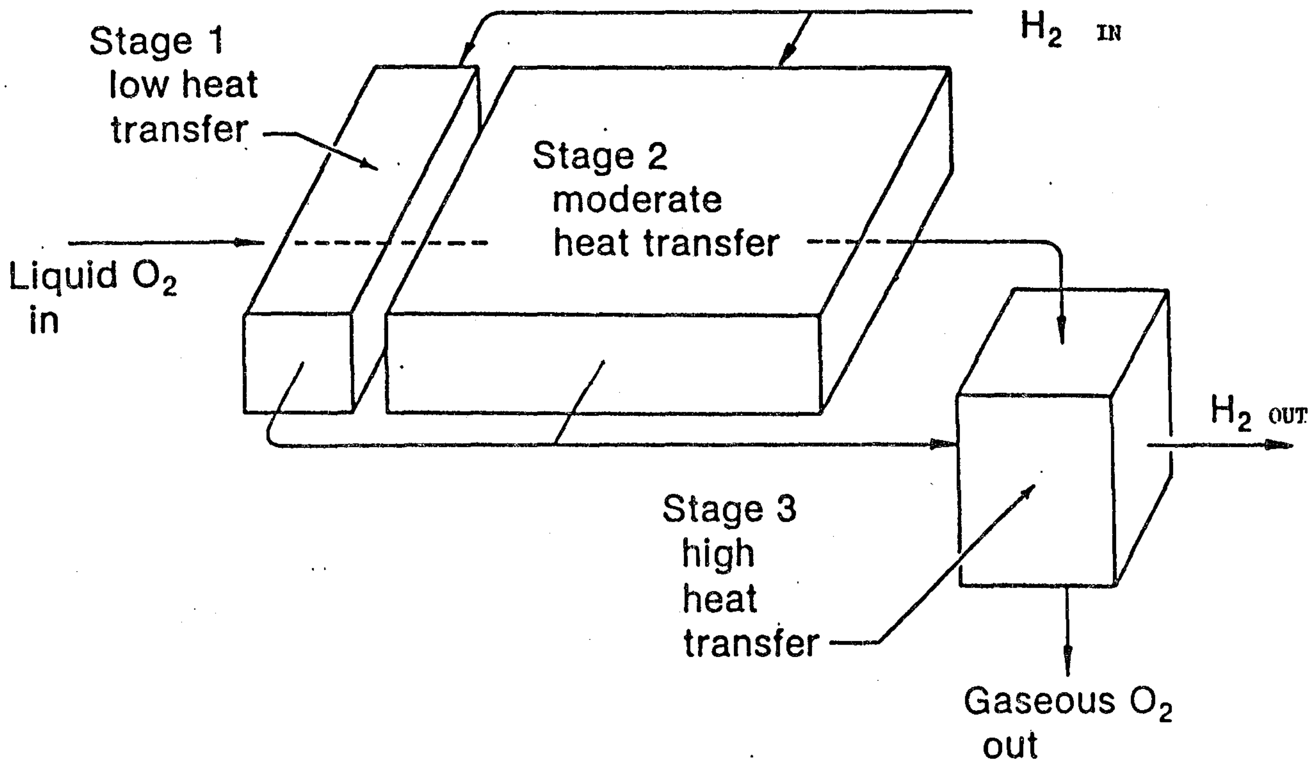
TABLE 4 Performance Data Comparison of CHEAP (Modified Version) Predicted and Experimental Results For OHE Stage 3 Engine Tests (Working Fluids - H_2 and O_2)

	OPERATION MODE	TANK HEAD IDLE				PUMPED IDLE			
	RUN NUMBER (EDR TIME)	13.01 (125)	14.01 (78)	15.01 (118)	13.01 (191)	11.01 (275)	13.01 (382)	15.01 (399)	15.01 (573)
H_2	$\dot{w}$ (lbm/sec)	.130	.079	.079	.143	.227	.189	.249	.249
C	Tin (°R)	864.3	944.0	813.0	827.1	606.1	697.2	656.7	648.5
I	ΔT (Measured)	114.8	234.3	89.3	136.7	70.7	148.0	114.6	109.0
R	ΔT (Predicted)	263.4	277.8	224.4	273.6	106.3	150.3	110.8	112.1
C	% Error (ΔT)	129.4	18.6	151.3	100.1	50.4	1.55	3.32	2.84
U I	Pin (psia)	17.1	12.2	17.1	18.2	47.5	42.7	56.7	55.0
T	ΔP (Measured)	5.66	4.77	5.84	5.12	3.39	2.75	4.14	3.86
	ΔP (Predicted)	3.38	2.71	3.47	3.24	1.74	1.63	2.31	2.02
	% Error (ΔP)	40.3	43.2	40.6	36.7	48.7	40.7	44.2	47.7
O_2	$\dot{w}$ (lbm/sec)	.588	.313	.570	.809	2.839	2.804	3.555	3.473
C	Tin (°R)	179.5	173.6	178.1	176.3	175.9	176.5	175.1	175.1
I	ΔT (Measured)	1.3	-1.3	-.6	.7	30.4	24.5	28.3	27.2
R	ΔT (Predicted)	458.4	602.7	430.3	411.1	28.8	24.1	30.0	29.4
C U	Exit Quality (Predicted)	1.00	1.00	1.00	1.00	.23	.32	.38	.20
I T	Pin (psia)	37.0	28.2	34.3	35.5	99.4	86.5	102.5	99.1
	ΔP (Measured)	1.62	.97	.74	-1.66	3.87	5.30	8.69	8.63
	ΔP (Predicted)	1.40	1.62	.59	1.91	1.15	1.77	1.59	1.55
	% Error (ΔP)	13.5	67.0	20.3	215.1	70.3	66.6	81.7	82.0

Table 5 Performance Data Comparison of CHEAP (Modified Version) Predicted and Experimental Results For the Stage 1 CHE Bench Tests (Working Fluids – N_2)

OPERATION MODE		NITROGEN FLOW BENCH TEST CASES											
TEST NUMBER		19	20	21	22	23	24	25	27	28	29	30	32
	$\dot{\omega}$ (lbm/sec)	.1066	.2029	.3003	.3051	.056	.102	.303	.105	.300	.301	.300	.119
H_2	Tin (°R)	526.6	518.5	517.2	515.0	619.1	801.1	697.8	806.8	645.3	636.8	639.5	811.0
C	ΔT (Measured)	180.5	137.0	100.1	68.9	294.2	121.7	43.7	179.2	24.4	20.4	21.9	141.0
I	ΔT(Predicted)	104.0	59.5	41.7	40.9	207.41	67.86	19.82	81.64	12.01	.38	3.58	20.5
R	% Error (ΔT)	42.4	56.6	58.3	40.6	29.5	53.84	54.6	54.4	50.8	98.1	83.7	85.5
C	Pin (psia)	20.58	28.76	41.34	43.06	20.28	20.21	43.25	20.15	41.76	41.72	41.58	21.49
U	ΔP (Measured)	2.921	8.795	14.56	15.00	.742	5.252	20.04	5.31	19.92	19.99	19.98	5.003
I	ΔP(Predicted)	1.74	4.20	6.35	6.26	.52	2.90	8.76	3.05	8.25	8.29	8.28	3.84
T	% Error (ΔP)	40.4	52.2	56.4	58.3	29.9	44.8	56.3	42.6	58.6	58.5	58.6	23.2
K_t(Insulation) (BTU/hr ft °F)x10^{-3}		52.6	52.6	52.6	52.6	52.6	52.6	52.6	52.6	52.6	1.18	11.3	11.3
Insulation Medium		Helium									Vacuum	Nitrogen	
	$\dot{\omega}$ (lbm/sec)	.994	1.216	.960	1.216	1.083	1.045	.278	.5015	.105	.308	.306	.119
	IN. QUALITY	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
O_2	Tin (°R)	155.1	156.1	156.1	156.1	153.1	510.5	507.3	506.0	513.0	506.1	505.1	483.7
C	ΔT (Measured)	11.0	9.7	10.1	10.7	9.6	111.4	49.0	35.1	66.1	18.1	19.3	118.1
I	ΔT(Predicted)	4.04	3.05	2.91	3.34	5.02	66.63	21.75	17.18	34.63	.37	3.3	20.8
R	EX. QUALITY	.020	.011	.022	.010	.002	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C	Pin (psia)	45.28	45.55	45.18	46.13	43.07	20.29	29.07	43.9	20.16	30.29	30.82	17.49
U	ΔP (Measured)	.179	.217	.359	.722	.425	1.73	9.075	15.99	1.625	10.11	10.03	2.412
I	ΔP(Predicted)	.43	.67	.59	.64	.37	.98	5.2	10.33	.97	5.87	5.71	1.64
T	% Error (ΔP)	140.2	208.8	64.3	11.4	12.9	43.4	42.7	35.4	40.3	41.9	43.1	32.0

GOX HEAT EXCHANGER SCHEMATIC



RL10-IIB Final Baseline Configuration (C.F. Report 18046-3 Figure 65)

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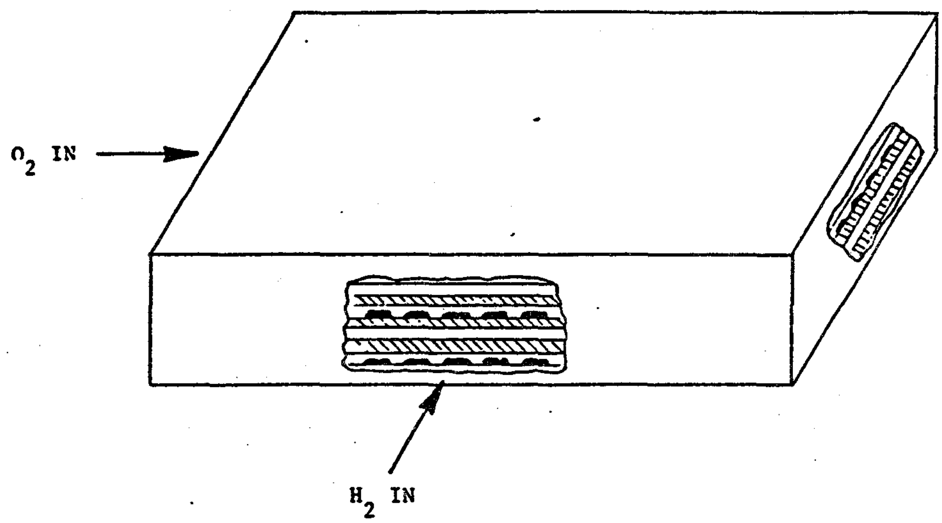
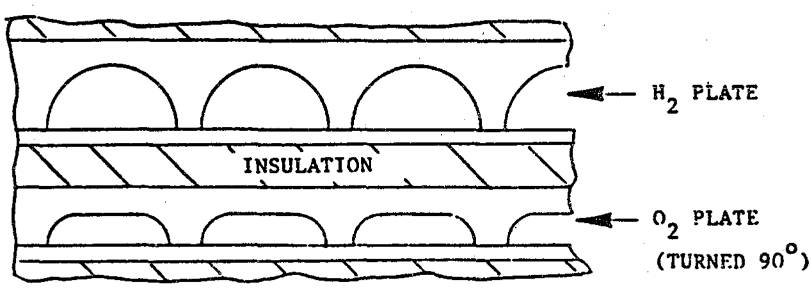
RL10 IIB GASEOUS OXYGEN
HEAT EXCHANGER - TYPICAL STAGE



THERMAL SKIN GEOMETRY BLOW-UP



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APPENDIX 1

DRYOUT OCCURRENCE

TEMPERATURE DISTRIBUTION MAP : COX HEAT EXCHANGER-STAGE 3- PUMPED IDLE (EXPERIMENTAL,...

I	J	TA-IN DEG R	TA-OUT DEG R	TA-MEAN DEG R	TB-IN DEG R	TB-OUT DEG R	TB-MEAN DEG R	QUALITY	TB-WALL DEG R
********* DRYOUT IS OCCURRING **********									
1	1	697.200	678.616	687.908	176.500	187.170	181.835	0.0	642.562
********* DRYOUT IS OCCURRING **********									
1	2	678.616	661.128	669.872	176.500	186.558	181.529	0.0	615.594
********* DRYOUT IS OCCURRING **********									
1	3	661.128	644.548	652.838	176.500	186.051	181.275	0.0	593.287
********* DRYOUT IS OCCURRING **********									
1	4	644.548	628.772	636.660	176.500	185.603	181.052	0.0	573.611
********* DRYOUT IS OCCURRING **********									
1	5	628.772	613.728	621.250	176.500	185.197	180.849	0.0	555.759
********* DRYOUT IS OCCURRING **********									
1	6	613.728	599.357	606.542	176.500	184.823	180.661	0.0	539.324
********* DRYOUT IS OCCURRING **********									
1	7	599.357	585.615	592.486	176.500	184.475	180.488	0.0	524.073
********* DRYOUT IS OCCURRING **********									
1	8	585.615	572.463	579.039	176.500	184.151	180.325	0.0	509.834
********* DRYOUT IS OCCURRING **********									
1	9	572.463	556.809	564.636	176.500	183.803	180.151	0.0	494.640
********* DRYOUT IS OCCURRING **********									
1	10	556.809	541.957	549.383	176.500	183.449	179.975	0.0	479.173
********* DRYOUT IS OCCURRING **********									
2	1	697.200	678.995	688.098	187.170	197.529	192.350	0.0	643.677
********* DRYOUT IS OCCURRING **********									
2	2	678.995	661.842	670.418	186.558	196.340	191.449	0.0	617.193
********* DRYOUT IS OCCURRING **********									
2	3	661.842	645.561	653.701	186.051	195.354	190.702	0.0	595.254
********* DRYOUT IS OCCURRING **********									
2	4	645.561	630.053	637.807	185.603	194.483	190.043	0.0	575.876
********* DRYOUT IS OCCURRING **********									
2	5	630.053	615.251	622.652	185.197	193.691	189.444	0.0	558.274
********* DRYOUT IS OCCURRING **********									
2	6	615.251	601.098	608.175	184.823	192.961	188.892	0.0	542.052
********* DRYOUT IS OCCURRING **********									
2	7	601.098	587.552	594.325	184.475	192.282	188.379	0.0	526.978
********* DRYOUT IS OCCURRING **********									
2	8	587.552	574.576	581.064	184.151	191.648	187.899	0.0	512.898
********* DRYOUT IS OCCURRING **********									
2	9	574.576	559.118	566.847	183.803	190.967	187.385	0.0	497.817
********* DRYOUT IS OCCURRING **********									
2	10	559.118	544.443	551.781	183.449	190.273	186.861	0.0	482.357
********* DRYOUT IS OCCURRING **********									
3	1	697.200	679.365	688.282	197.529	201.107	199.318	0.034	641.491
********* DRYOUT IS OCCURRING **********									
3	2	679.365	662.537	670.951	196.340	201.107	198.723	0.025	616.356
********* DRYOUT IS OCCURRING **********									
3	3	662.537	646.548	654.542	195.354	201.107	198.230	0.018	595.503
********* DRYOUT IS OCCURRING **********									
3	4	646.548	631.303	638.925	194.483	201.107	197.795	0.011	577.060
********* DRYOUT IS OCCURRING **********									
3	5	631.303	616.737	624.020	193.691	201.107	197.399	0.005	560.208
********* DRYOUT IS OCCURRING **********									
3	6	616.737	602.798	609.767	192.961	200.911	196.936	0.0	544.714
********* DRYOUT IS OCCURRING **********									
3	7	602.798	589.443	596.120	192.282	199.910	196.096	0.0	529.814
********* DRYOUT IS OCCURRING **********									

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APPENDIX 2

CHEAP PROGRAM MODIFICATIONS

- MODIFICATION #1 (INSERT AFTER CHP0820)

```
      DTFILM=TWBM-TIN(2,ID,JD)
      IF(DTFILM.LT.30.0)GO TO 2050
      WRITE(KW,2111)
2111  FORMAT('********** DRYOUT IS OCCURRING **********')
```

- MODIFICATION #2 (INSERT AFTER CHP11260)

```
      DT=TWALLB(2,I,J)-TSAT(N)
      IF(DT.LT.30.0)GO TO 341
      IF(CDHYD.LE..004/12.0)HB=200./3600.
      IF(CDHYD.GT..004/12.0.AND.CDHYD.LE..008/12.)HB=155.0/3600.
      IF(CDHYD.GT..008/12.0.AND.CDHYD.LE..020/12.)HB=85.0/3600.
      IF(CDHYD.GT..020/12.0.AND.CDHYD.LE..040/12.)HB=46.0/3600.
      IF(CDHYD.GT..040/12.0.AND.CDHYD.LE..400/12.)HB=30.0/3600.
      IF(CDHYD.GT..400/12.0)HB=23.5/3600.
      HBREAL=HB
```

- MODIFICATION #3 (INSERT AFTER CHP12160)

```
      DT=THALLB(2,I,J) - TSAT(N)
      IF(DT.LT.30.)GO TO 360
      IF(CDHYD.LE..004/12.0)HB=200./3600.
      IF(CDHYD.GT..004/12.0.AND.CDHYD.LE..008/12.)HB=155.0/3600.
      IF(CDHYD.GT..008/12.0.AND.CDHYD.LE..020/12.)HB=85.0/3600.
      IF(CDHYD.GT..020/12.0.AND.CDHYD.LE..040/12.)HB=46.0/3600.
      IF(CDHYD.GT..040/12.0.AND.CDHYD.LE..400/12.)HB=30.0/3600.
      IF(CDHYD.GT..400/12.0)HB=23.5/3600.
```


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APPENDIX 2 (cont'd)

CHEAP PROGRAM MODIFICATIONS

o MODIFICATION #4

```
2110 FORMAT(1H1,/10X,'TEMPERATURE DISTRIBUTION MAP : ',20A4,/,        CHP07950
    X/1X,'    I    J      TA-IN    TA-OUT   TA-MEAN     TB-IN',         CHP07960
    X     '    TB-OUT   TB-MEAN   QUALITY   TB-WALL',                     CHP07970
    X/10X, 6(5X,'DEG R'),16X,'DEG R')                                    CHP07980

     WRITE(KH,2120) ID,JD, TIN(1,ID,JD), TOUT(1,ID,JD),                  CHP08030
    XTMEAN(1,ID,JD),                                                     CHP08040
    XTIN(2,ID,JD), TOUT(2,ID,JD),TMEAN(2,ID,JD),QUAL(ID,JD),TWSH         CHP08050
2120 FORMAT(1X,2I5,8F10.3)                                               CHP08060
```


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