Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION

SVHSER 6534

NASA CR-
141873

LIGHTWEIGHT LONG LIFE HEAT EXCHANGER

FINAL REPORT

by

Earl K. Moore

PREPARED UNDER CONTRACT NAS 9-13552

by

HAMILTON STANDARD

DIVISION OF UNITED AIRCRAFT CORPORATION

WINDSOR LOCKS, CONNECTICUT

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LYNDON B. JOHNSON SPACE CENTER

HOUSTON, TEXAS 77058

APRIL, 1975

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION

ABSTRACT

LIGHTWEIGHT LONG LIFE HEAT EXCHANGER

FINAL REPORT

by

EARL K. MOORE

CONTRACT NAS 9-13552

APRIL, 1975

This report describes the design, fabrication and evaluation of a full scale Shuttle-type condensing heat exchanger constructed of aluminum and utilizing aluminum clad titanium parting sheets. A long term salt spray test of candidate parting sheet specimens is described. The results of an investigation into an alternate method of making composite sheet material are discussed.

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION

SVHSER 6534

LIGHTWEIGHT LONG LIFE HEAT EXCHANGER

FINAL REPORT

by

Earl K. Moore

PREPARED UNDER CONTRACT NAS 9-13552

by

HAMILTON STANDARD

DIVISION OF UNITED AIRCRAFT CORPORATION

WINDSOR LOCKS, CONNECTICUT

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LYNDON B. JOHNSON SPACE CENTER

HOUSTON, TEXAS 77058

APRIL, 1975

FOREWORD

This report has been prepared by the Hamilton Standard Division of the United Aircraft Corporation for the National Aeronautics and Space Administration's Lyndon B. Johnson Space Center in accordance with the requirements of Contract NAS 9-13552, Lightweight, Long Life Heat Exchanger. This report covers all of the work accomplished during the period of the contract, July 1, 1973 to April 30, 1975. The basic objective of the program is to develop the potential of a Lightweight Long Life Heat Exchanger for the Shuttle Environmental Control System.

Personnel responsible for the conduct of this program were Mr. F. H. Greenwood, Program Manager and Messrs. A. E. Francis and L. F. Desjardins, Program Engineers. Appreciation also is expressed to Mr. P. Perkins and Mr. B. S. Blum of the Materials Dept. of Hamilton Standard and Mr. G. Coleman, Manufacturing Engineer and to Messrs. Frank Collier and Nick Lance, Technical Monitors for NASA JSC, whose efforts made possible the successful completion of this program.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION

TABLE OF CONTENTS (CONCLUDED)

LIST OF FIGURES

LIST OF FIGURES (CONT'D)

LIST OF FIGURES (CONT'D)

LIST OF FIGURES (CONT'D)

LIST OF FIGURES (CONCLUDED)

LIST OF TABLES

SUMMARY

A full scale Shuttle-type, condensing, aluminum, heat exchanger was designed, fabricated and tested and demonstrated the performance anticipated. The heat exchanger utilized aluminum clad titanium composite parting sheets, the manufacture of which was refined and firmly established as part of this program. A hydrophilic coating to improve the wetability of the aluminum surfaces was developed and utilized on the full scale heat exchanger. An extensive test program including performance mapping, vibration, thermal shock and mission life was completed to demonstrate the thermal characteristics and structural capabilities of the heat exchanger.

An alternate, lower cost method of composite sheet fabrication was attempted but proved unsuccessful. Consequently, the developed vacuum diffusion bonding process remains the only viable method at this time, for fabrication of the composite sheets.

An eighteen month salt spray test of laminate coupons confirmed that the titanium core of the laminate was protected from corrosion by the sacrificial action of the aluminum surface laminate.

The development and evaluation completed by this program has demonstrated the potential of saving at least 40 percent of the weight of an equivalent stainless steel condensing heat exchanger.

Calculations and data pertaining to this program were made in U.S. customary units and then converted to SI units.

INTRODUCTION

Recognizing the need for long-life equipment on future space applications such as the Space Shuttle and Space Station, Hamilton Standard embarked on an IR&D program in 1971 to develop a lightweight, long-life heat exchanger. The overall result of this program was the development of an aluminum/titanium "Leak Barrier" construction. The program indicated that a heat exchanger using this construction is capable of meeting a life of 25,000 hours at a weight that is less than 60% of an equivalent stainless steel heat exchanger. Highlights of our work to date include:

- An analysis demonstrating that the aluminum/titanium construction offers a weight that is 59% of that of an equivalent stainless steel heat exchanger for the Shuttle cabin heat exchanger.

- Demonstration of the aluminum/titanium construction's capability to meet the 25,000 hour life requirement based on accelerated life testing.

- Successful fabrication of scale model aluminum/titanium laminates and cores.

- Tentative confirmation of the compatibility of aluminum in an otherwise stainless steel water circuit.

As a result of the success of the IR&D program, the NASA initiated contract NAS 9-13552 to evaluate the potential of a Lightweight Long Life Heat Exchanger for the Shuttle ECS. The program encompassed the fabrication of laminates, the design, fabrication of a full scale Shuttle type condensing heat exchanger and the performance and life testing of a successfully fabricated unit. A condensing heat exchanger was chosen since the wet air side presents the most corrosive environment of the types of heat exchangers used.

The program included an extensive test program to demonstrate both the structural and thermal capabilities of the lightweight design and included performance mapping, life testing, vibration and thermal cycling.

CONCLUSIONS

As a result of this program, the following conclusions have been made:

- Full scale aluminum heat exchanger fabrication utilizing composite aluminum-titanium-aluminum laminates is feasible.

- A full scale heat exchanger utilizing composite laminates presents no performance penalties.

- A full scale heat exchanger utilizing composite laminates will weigh less than 60 percent of the weight of a comparably performing stainless steel heat exchanger.

- Roll cladding may still be a viable alternate laminate fabrication procedure, but more development would be required.

- Aluminum successfully protects thin titanium from pitting attack in a corrosive environment.

RECOMMENDATIONS

Based upon the conclusions reached as a result of this program, the following recommendations are made:

- Design, fabricate and evaluate the performance of a prototype Shuttle heat exchanger which will be completely interchangeable with the existing Shuttle unit but will save at least forty percent of its weight.

- A test program should be performed to demonstrate conclusively, the compatability of an aluminum heat exchanger in a stainless steel water system.

- The development of an alternate laminate fabrication method, to be applicable to future generation Lightweight Long Life Heat Exchangers, should be continued.

- All other Shuttle EC/LSS heat exchangers should be analyzed for potential weight savings and additional applications based on weight, cost and schedule should be recommended.

DISCUSSION

The discussion of this program is divided into several major task areas. These are Review of Technical Approach, Fabrication of Laminates, Design of the Full Scale Heat Exchanger, Fabrication of the Heat Exchanger, and Test of the Heat Exchanger. Each major task corresponds to a major element of the program work breakdown structure.

REVIEW OF TECHNICAL APPROACH

An IR&D program completed by Hamilton Standard prior to the start of this program had a) selected the materials to be used; b) defined a concept to allow the use of a lightweight material; c) chosen a heat exchanger configuration; d) selected a method of laminated sheet fabrication; e) brazed sample heat exchanger cores to demonstrate the practicability of brazing the laminated sheet; f) evaluated the thermal aspects of the laminate; g) completed compatibility tests of aluminum in stainless steel water circuits; h) evaluated effluent generation; and i) initiated salt spray life tests of candidate coupons. All of this effort had been completed prior to award of this contract, and the initial program activity was concerned with a review of this effort with the NASA, so as to achieve complete mutual understanding and approval of the selected heat exchanger approach. This review was held at the NASA JSC on August 29, 1973 and is summarized below.

Material Evaluation

The primary objective of this program was to develop a heat exchanger concept with a useful life of 25,000 hours and a weight that is 60 percent of that of an equivalent stainless steel heat exchanger.

An evaluation of various materials indicated that only an aluminum construction was feasible for meeting the required weight target. However, corrosion can be expected if it is utilized in a condensing heat exchanger application such as the Space Shuttle cabin heat exchanger, or in other applications where exposure to potential electrolytes such as water or glycol solutions is expected. To maintain the weight and fabrication advantages of aluminum in these applications, an aluminum/titanium laminated parting sheet construction was selected. Such a construction does not prevent corrosion in aluminum, but does eliminate the primary consequence, i.e., leakage through parting sheets from one circuit to the other. Using the more noble (less corrosive) titanium between two aluminum sheets offers a "leak barrier" preventing pitting from proceeding through the parting sheet. Aluminum was selected for the rest of the heat exchanger (fins, end plates and headers) as minor corrosion can be tolerated in fins and the thickness of the end plates and headers precludes through pitting during the 25,000 hour life requirement.

Durability

In analyzing long life, service experience with aluminum heat exchangers indicated that four primary wearout failure modes had to be examined; namely, structural, thermal degradation, wear, and corrosion. Perhaps the most demanding structural consideration is that of thermal cycling when the temperature changes exceed 196 K (350°F). Since all the Shuttle heat exchanger applications are well within this temperature range limitation, thermal cycling was not considered a problem. It was considered that other structural considerations such as pressure and temperature limits, vibration, impact and shock could be handled by designing and testing for such.

Thermal degradation resulting from contamination (surface coating) is another mode of failure and results in a decrease in heat transfer. However, in the Shuttle condensing heat exchanger there is little likelihood of a significant contamination buildup on the primary and secondary surfaces. Wear is likewise not considered a problem since the Shuttle fluids do not normally travel at a velocity sufficiently high to cause erosion.

Lastly, corrosion is a potential failure mode for the heat exchanger material. In analyzing the corrosion potential, the heat exchanger applications in the Space Shuttle were investigated. There are four basic heat exchangers on this vehicle within the water and Freon-21 loops -- gas-to-liquid condensing heat exchangers, liquid-to-liquid heat exchangers, equipment-to-liquid cold plates and liquid-to-phase change heat sinks (flash evaporators and ammonia boilers). Of these, the cabin condensing heat exchanger operates in the most severe environment because of the formation of an oxygen concentration cell. The oxygenated water promotes the formation of electrolytic cells which can result in pitting in the heat exchanger. The other applications involving the use of potential electrolytes also are expected to cause corrosion in aluminum although not as severe as the condensing application, because of the absence of air.

Field experience shows that pitting in heat exchanger parting sheets has been the most frequent cause of failure. Analysis supports this in that the parting sheets are the thinnest members and have numerous junctures which are the focal point for pitting. This pitting in parting sheets is particularly harmful over long periods since it can lead to leakage from one circuit to the other. Zero-g operation compounds this problem in that water droplets formed tend to stay in crevices and joints. Surface coating to promote wetting in the form of a film rather than droplets minimizes the problem.

One of the best materials for corrosion resistance over a long duration exposure to condensate water is stainless steel. Aluminum, on the other hand, is susceptible to corrosion when exposed to condensed water for long periods. This fact is based on fourteen years' experience with aircraft aluminum Freon system evaporators which operate with Freon on one side and moisture laden air on the other side. Communications with Delta Airlines indicated these evaporators average approximately 2,000 hours before leakage occurs. Single pass air circuits coated with epoxy ester increase this life to 4,000 hours. TWA experiences 5,000 to 7,000 hour lives with similarly coated evaporators in the Boeing 707 and Convair 880 aircraft.

Weight

A heat exchanger weight analysis necessitated an investigation into both the heat exchanger configuration and material weights. Figure 1 presents various potential heat exchanger configurations examined. Where fluid conductances are matched, the plate fin construction provides the maximum heat transfer for minimum weight. A tube and fin configuration requires the use of prohibitively small tubes 0.250-0.508 mm (0.010 in.-0.020 in. diameter) and the provision for separate redundant circuits adds extra weight. An "egg crate" design presents no significant advantages over a plate and fin construction since it does not provide additional surface for the same bulk. Perforated plates, pin fins, dimpled parting sheets and screen separators are interesting possibilities where pressure drop is not a critical factor, and distribution and through-conductivity are paramount. Since pressure drop is critical on the air side of the Shuttle cabin heat exchanger (and in one or more circuits of most heat exchangers), the plate fin with its versatility is the most practical lightweight baseline configuration and the one that was selected for this program.

Table I presents a listing of potential materials for the heat exchanger application along with the conductivity per unit weight for each. Conductivity per unit weight is a measure of the relative weight of a material in a heat exchanger application where the heat exchanger is conductivity limited as in the case of redundant passages. The higher the conductivity per unit weight for a given material, the lighter the potential heat exchanger weight. Included in this table is the specific strength of each material, which also must be considered when analyzing weight for a heat exchanger application.

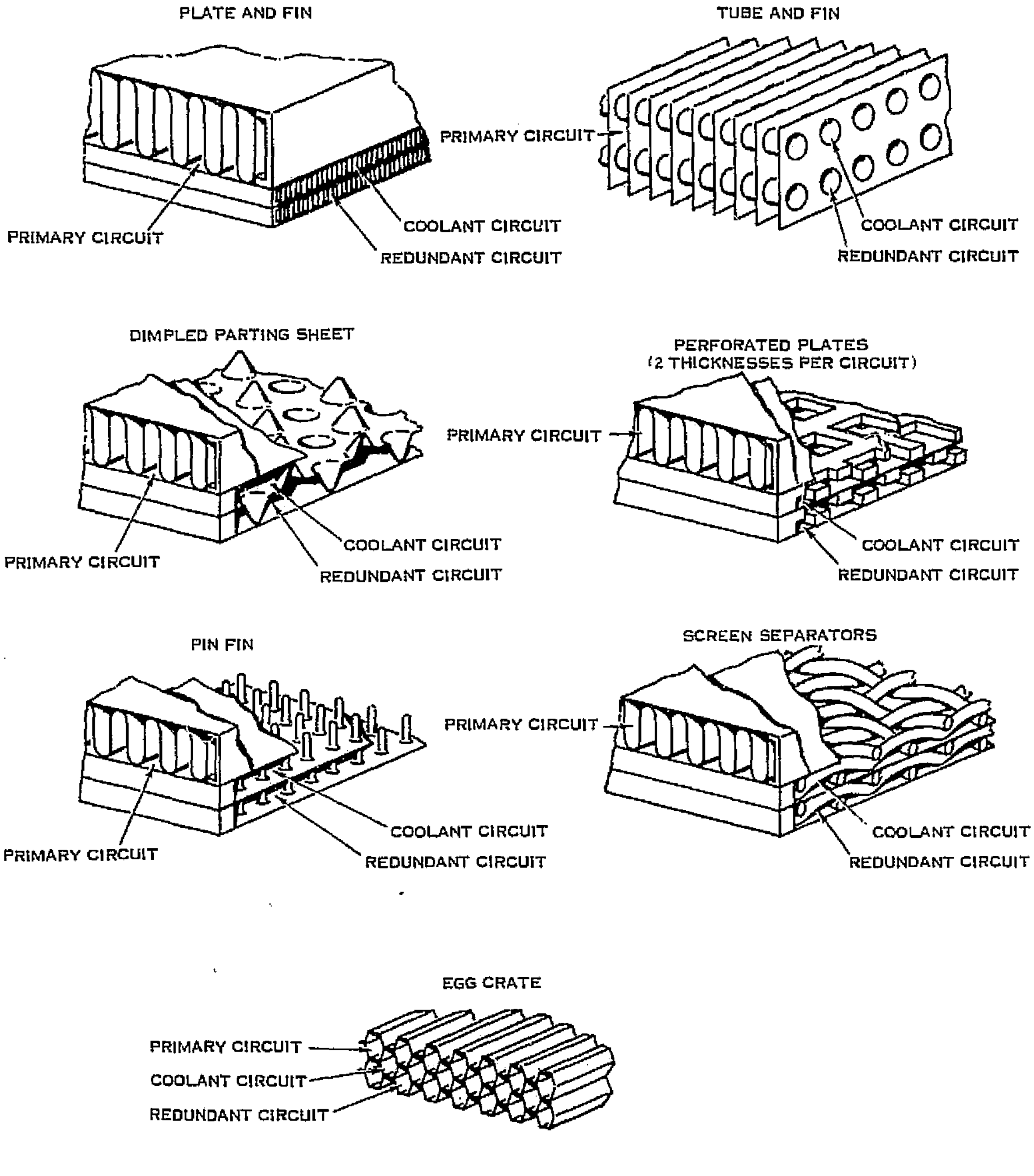


FIGURE 1 HEAT EXCHANGER CONFIGURATION

TABLE I COMPARISON OF VARIOUS MATERIALS

Material	Conductivity Per Unit Weight		Specific Strength	
	$\frac{W/m\text{-}K}{kg/m^3}$	$\left(\frac{Btu/Hr\text{-}Ft\text{-}^\circ F}{lbs/ft^3}\right)$	$\frac{kN}{kg/m^3}$	$\left(\frac{lbs/in^2}{lbs/ft^3}\right)$
Pure Aluminum	0.0843	(0.78)	10.2	(23.7)
Beryllium	0.0838	(0.775)	122.6	(285.0)
Aluminum Alloy	0.0648	(0.60)	15.6	(35.0)
Copper	0.0431	(0.399)	7.7	(18.0)
Silver	0.0399	(0.369)	5.2	(12.0)
Nickel	0.0101	(0.093)	11.6	(27.0)
Titanium	0.0045	(0.0418)	91.2	(212.0)
Stainless Steel	0.0021	(0.0193)	34.4	(80.0)

As indicated by this table, pure aluminum offers the lightest potential for heat exchanger applications; however, it has low inherent strength and therefore is not amenable to this use. The next best material from a weight standpoint is beryllium; however, it is not attractive from a manufacturability standpoint -- it requires the development of brazing and welding processes. In addition, beryllium's brittleness impedes fin forming. Lockalloy, a combination of aluminum and beryllium, would appear to be a good alternative, but it is not weldable and offers poor corrosion resistance.

Elimination of materials offering a weight advantage over an aluminum alloy construction indicates that such an alloy is the lightest material practically adaptable to heat exchanger fabrication. The heavier candidates (copper, silver, nickel and titanium) do offer a weight advantage over stainless steel. Of these heavier materials, plain copper, silver, and nickel do not have sufficient strength to provide for a lightweight heat exchanger construction. They therefore were eliminated from further consideration as a material for the entire heat exchanger construction, but were considered as possibilities in combination with a stronger material such as stainless.

Since the conductivity per unit weight criterion presented in Table II is only an approximation of the heat exchanger weight for various materials, the Shuttle cabin heat exchanger was sized for a stainless steel, an aluminum alloy, a titanium and a stainless steel with copper fins or nickel fins construction to accurately define the weight of each. The copper/stainless and nickel/stainless constructions with stainless used for structural integrity and the copper or nickel for thermal conductivity, provided a weight advantage over an all stainless construction.

The results of this sizing are shown in Table

TABLE II HEAT EXCHANGER MATERIAL WEIGHT COMPARISON

Material	% of Stainless Steel Weight
Stainless Steel	100
Aluminum Alloy	61
Titanium	88
Stainless Steel with Copper Fins	83
Stainless Steel with Nickel Fins	98

From this table it can be seen that only an aluminum alloy construction approached the required weight target, namely 60 percent of stainless steel weight.

Material Selection

From the preceding material evaluation, it can be seen that only an aluminum construction met the weight target; however, by itself it would not meet the corrosion resistance requirements. Since the weight of stainless steel or stainless steel combinations could not be sufficiently reduced to meet the target, the best approach was to increase the corrosion resistance of aluminum or eliminate the consequences of corrosion.

The employment of a coating could have been used to improve the corrosive resistance of aluminum. Epoxy ester was considered, but discarded because of its limited life (approximately 7,000 hours), potential for clogging headers where multi-passes are used, and conflict with wetting requirements.

Increasing the thickness of parting sheets (separation of circuits) would have served to increase the life expectancy of aluminum, although pitting still would have occurred. This approach was eliminated, however, as it would have reduced the weight advantage of aluminum.

Another method of allowing for corrosion, but preventing leakage between circuits, is to fabricate laminated parting sheets with aluminum on the exterior covering a center layer of a more noble material such as stainless steel, nickel, titanium, or Inconel. The more noble center material of the parting sheets would serve as a leak barrier. Thus, any pits or voids developing in the outer aluminum surfaces would not progress through the more noble center material, but would remain in the outer material. Experience showed that such voids or pits are both small and limited and therefore would not affect the structure or thermal performance.

Thus the "leak barrier" construction shown in figure 2 was evolved. This approach replaced the conventional parting sheets with an impenetrable, laminated layer. This offered the fabrication and weight advantages associated with aluminum as most of the heat exchanger could be constructed of aluminum. Weight calculations on an aluminum heat exchanger with aluminum/titanium laminated parting sheets provided a weight of 59 percent of an equivalent stainless steel heat exchanger weight.

Fabrication of Laminates

The laminates selected for investigation consisted of aluminum outer layers surrounding either stainless steel, nickel, Inconel, or titanium centerstrates. Potential fabrication methods considered included rolling, plating, dipping, flame spraying and diffusion bonding. Plating was eliminated because of probable high porosity, high cost and difficulty in maintaining dimensional stability. Flame spraying and dipping were eliminated due to the probable high porosity, non-uniformity of thickness and tendency to distort. The quality of adhesion and surface roughness were also of concern with dipping and spraying. Thus, the only feasible methods remaining were rolling and diffusion bonding.

Samples of 0.10 mm (0.004 in. thick) aluminum sheet 10.16 cm x 10.16 cm (4 in. x 4 in. square) were bonded to each side of 0.051 to 0.076 mm (0.002 to 0.003 in.) sheets of AISI 347 stainless, titanium, and Inconel by diffusion bonding. Subsequent to bonding, the sheets were exposed to

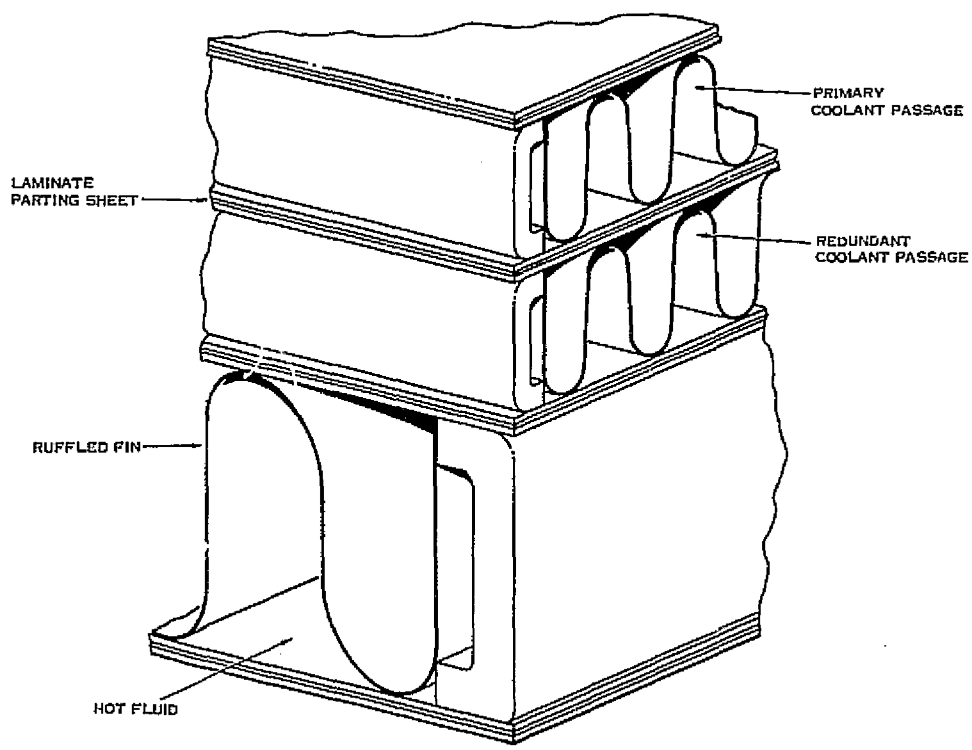


FIGURE 2 LEAK BARRIER CONSTRUCTION

braze temperatures of 877 K (1120°F) for half an hour. Visual examination, manual flexure and tear tests indicated that the aluminum would tear before failure of the bond for the Inconel and the titanium laminates. The stainless steel laminate bond, however, could be broken by 12 or more 180 degree flexures, and microscopic examination revealed a formation of intermetallic (brittle compound of aluminum and stainless steel) lamination. Table III summarizes these test results.

TABLE III EVALUATION OF LAMINATE FABRICATION TECHNIQUES

Method	Core Material	Results
Roll Cladding	AISI 347 SS	Severe tearing, distortion
Roll Cladding	201 Nickel	Tearing, distortion
Diffusion Bonding	AISI 347 SS	Delaminates at intermetallic
Diffusion Bonding	Inconel 625	Good flexure and tear; hard intermetallic boundary
Diffusion Bonding	A70 Titanium	Good flexure and tear; no intermetallic boundary

Diffusion bonding of laminates of 0.10 mm (0.004 in.) aluminum on each side of 0.06 mm (0.003 in.) titanium centerstrate also was successfully performed in sheet sizes up to 11.43 cm x 19.05 cm (4 1/2 in. x 7 1/2 in.) and subsequently used in the fabrication of a quarter scale typical Shuttle condensing heat exchanger core.

Since diffusion bonding of aluminum and stainless steel was unsuccessful, rolling was attempted with 0.102 mm (0.004 in.) aluminum on each side of a stainless steel core. It proved unsuccessful due to tearing of the inner stainless steel layer during the final rolling process to get the total 0.254 mm (0.010 in.) thickness. Subsequent attempts at rolling with nickel as the centerstrate and allowing intermediate annealing between rollings was somewhat better and produced only occasional tears in the centerstrate. However, it was impossible to obtain completely flat sheets in the roll process, so no further rolling efforts were pursued and diffusion bonding became the primary laminate fabrication mode and only titanium and Inconel laminates were successfully fabricated.

Inspection techniques to insure the integrity of the centerstrate and the quality of lamination had included micros selected randomly and examined, tear tests to insure that the aluminum and not the bond fractures first, x-rays and ultrasonic scans. X-rays were quite successful in identifying voids in the centerstrate, however they were of no help in determining the quality of the lamination in diffusion bonded specimens. For detection of improper lamination, ultrasonic scanning proved the best method of inspection showing virtually all unlaminated areas, however, it sometimes also provided false indications of defects. Therefore, further development of this inspection technique was needed.

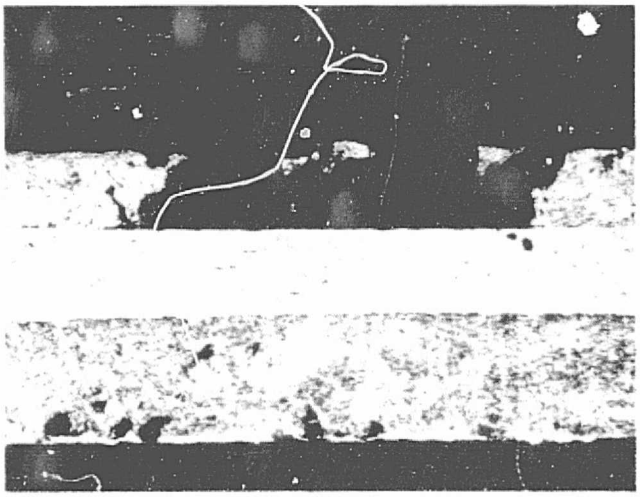
Corrosion Resistance

The primary purpose of the parting sheet in a plate fin heat exchanger is to separate the operating fluids while transferring heat between the fluids. Any penetrations through the parting sheets results in leakage from one fluid circuit to another and such leakage is particularly critical in space applications because of the closed environments and limited supply of fluids.

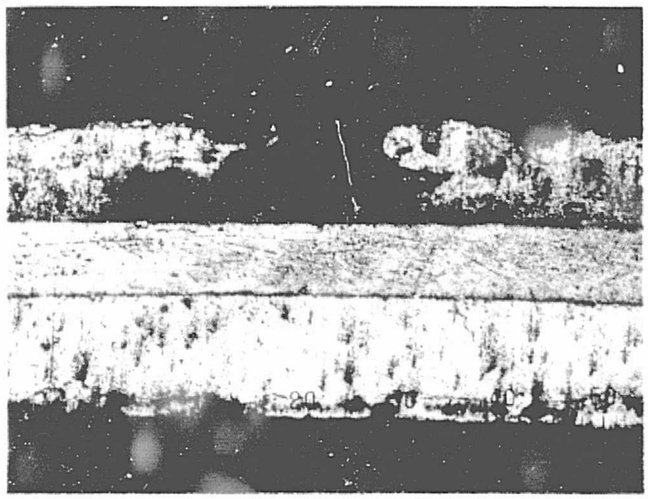
Because of its criticality, corrosion testing was started immediately after fabrication of laminated parting sheets by diffusion bonding. Strips (approximately 1.27 cm x 10.16 cm) (0.5 in. x 4 in.) of titanium, Inconel and stainless steel laminates were placed in a salt spray chamber at 314 K (105°F) on September 21, 1971. These samples had no surface coating such as alodine, epoxy or ceramic. After two weeks exposure to the salt spray (accelerated corrosion environment) micro examination showed that pitting had initiated and progressed through the aluminum layer but was stopped by the more noble center layer. The samples not destroyed in this micro examination were returned to the salt spray test.

After five weeks, micro examinations were again conducted and again the effectiveness of an inner layer of more noble material was demonstrated. Figure 3 displays the effectiveness of the noble center layer in stopping corrosion. Examination of the samples after six months displayed pits in the aluminum outer layer, but none penetrated the center layer except where a poorly bonded stainless steel centerstrate became separated from the aluminum and thus had no protection. In this case, two holes had penetrated the 0.051 mm (0.002 in.) thick center layer of stainless steel, indicating very clearly that stainless steel alone cannot be relied on to prevent pitting under the adverse circumstances of a salt spray test.

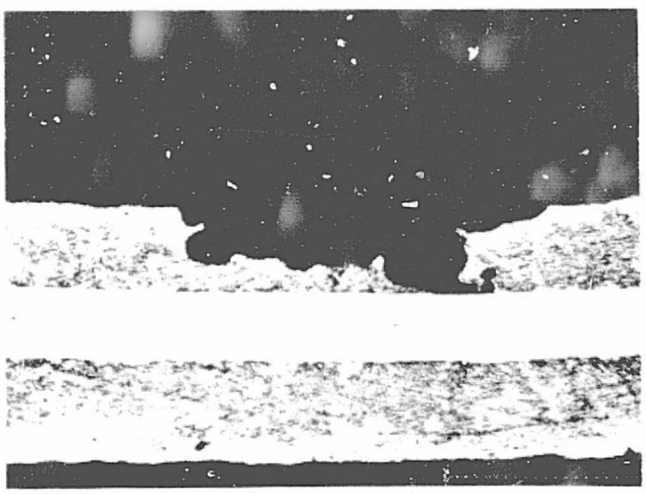
Upon availability of greater quantities of laminates, additional corrosion testing was initiated. Three 1.27 cm x 5.1 cm (0.5 in. x 2 in.) samples each of plain No. 3003 aluminum and diffusion bonded titanium and Inconel



DIFFUSION BONDED ALUMINUM/ STAINLESS STEEL/ ALUMINUM EXPOSED TO SALT SPRAY FOR 5 WEEKS (125X)



DIFFUSION BONDED ALUMINUM/ TITANIUM/ ALUMINUM EXPOSED TO SALT SPRAY FOR TWO WEEKS (150X)



DIFFUSION BONDED ALUMINUM/ TITANIUM/ALUMINUM EXPOSED TO SALT SPRAY FOR FIVE WEEKS (125X)

FIGURE 3 SALT SPRAY TEST SAMPLES

ORIGINAL PAGE IS
OF POOR QUALITY

laminates were prepared in bare, alodine, wetting ceramic, and epoxy coatings. The ceramic coating was a potassium silicate used in conjunction with alodine to provide a wetting surface applicable to a condenser design. The epoxy coating employed was one used in many single pass aircraft applications to provide greater resistance to erosion and penetration. The cut edges of each specimen were coated with stopoff lacquer to expose only the working surfaces and thus simulate the parting sheet applications. These specimens were examined at two weeks, one month, and two month intervals thereafter. Table IV contains a detailed description of the various specimens at intervals during the 12 months exposure.

The most significant result of this series of tests was the fact that the laminates again showed their effectiveness in precluding corrosion from penetrating through the sheets. Some other noteworthy results of this test series were:

- The alodined and ceramic coated specimens displayed the worst pitting with complete penetration of plain aluminum specimens and penetration through the outer aluminum layer of the laminates in some locations.

- Continued exposure between the eighth and twelfth months showed no significant increase in the size of pits, but did reveal an increase in the number of pits.

- The epoxy coated samples showed no corrosion damage.

Although the epoxy coated samples appeared to offer the best corrosion resistance, it was considered that the complete coating possible on a flat plate test sample could not be duplicated in an actual core. This is so because the coating must be applied after brazing and the crevices created by fins preclude a completely effective coating. In addition, the epoxy is undesirable in a condensing application and cannot be used in a multi-pass heat exchanger because it will clog the header. Since it is hydrophobic, the water has a tendency to form bubbles rather than dispense water into a thin film.

While it is difficult to quantify an accelerated test such as salt spray exposure to real time, the exposure duration was in excess of 8,500 hours which should be at least three times more severe than a normal condensing application; therefore it was concluded that the laminates would give protection for at least the 25,000 hour objective.

TABLE IV SALT SPRAY TEST OF PARTING SHEET MATERIAL FOR HEAT EXCHANGER

Sample	I.D.	Exposure Time	Results						
Alum-Bare	A-B-1	Start 11/19/71	12/3 light pitting	1/19/72 medium pitting	3/20 medium pitting	5/22 medium pitting	7/21 heavy pitting	9/22 heavy pitting	11/22/72 heavy pitting
"	A-B-2	"	"	"	"	"	"	"	"
"	A-B-3	"	"	"	"	"	"	pit thru wall*	"
Alum-Alodine	A-A-1	"	12/3 no corrosion	1/19/72 light staining	medium pits	Same as 3/20	pits thru wall	pit thru wall	pit thru wall
"	A-A-2	"	"	"	pit thru wall*	hole -2	"	"	"
"	A-A-3	"	"	"	"	hole	"	"	"
Alum-Epoxy	A-E-1	"	"	"	light stain	light stain	No corrosion	No corrosion	No corrosion
"	A-E-2	"	"	"	"	"	"	"	"
"	A-E-3	"	"	"	"	"	"	"	"
Alum-Ceramic	A-C-1	12/13/71		1/19/72 heavy pitting	*3 pits thru wall	several holes	heavy pits thru wall	pits thru wall	pits thru wall
"	A-C-2	"		"	*2 pits thru wall	"	"	"	"
"	A-C-3	"		"	*3 pits thru wall	"	"	"	"

TABLE IV SALT SPRAY TEST OF PARTING SHEET MATERIAL FOR HEAT EXCHANGER (CONTINUED)

Sample	I.D.	Exposure Time	Results						
Al/Ti/Al-Bare	T-B-1	11/19/71	12/3 light pitting	1/19/72 medium pitting	medium pits	heavy ** pits	thru** clad	pit ** thru clad	heavy pits**
"	T-B-2	"	"	"	1 heavy pit	"	"	"	"
"	T-B-3	"	"	"	pit to centerstrate 1 other pit**	Thru Al clad	"	"	"
Al/Ti/Al-Alodine	T-A-1	11/19/71	12/3 No corrosion	1/19/72 light pitting	heavy pits**	pits** thru Al clad	heavy** pits thru clad	pits** thru clad heavy corrosion	heavy pits**
"	T-A-2	"	"	"	"	"	"	"	"
"	T-A-3	"	"	"	heavy pits to center-strate **	"	"	"	"
Al/Ti/Al-Epoxy	T-E-1	Start 11/19/71	12/3 no corr.	1/19/72 light staining	3/20 light staining	5/22 light staining	7/21 light staining	9/22 light stains no corr.	11/22/72 no corr. blisters
"	T-E-2	"	"	"	"	"	"	"	"
	T-E-3	"	"	"	"	"	"	"	"
Al-Ti/Al-Ceramic	T-C-1	12/13		heavy pitting	heavy pit** thru clad**	same as 3/20	heavy corr.** thru clad	thru clad** heavy corr.	heavy pits**
"	T-C-2	"		"	"	"	"	"	"
"	T-C-3	"		"	"	"	"	"	"

TABLE IV SALT SPRAY TEST OF PARTING SHEET MATERIAL FOR HEAT EXCHANGER (CONCLUDED)

Sample	I.D.	Exposure Time	Results						
Al/Inco/Al-Bare	I-B-1	Start 11/19/71	12/3 light pitting	1/19/73 med pits small blisters	medium pits	medium pits	medium** pits	heavy** pits	heavy** pits
"	I-B-2	"	"	med. pits	"	"	"	"	"
"	I-B-3	"	"	"	"	"	"	"	"
Al/Inco/Al-Alodine	I-A-1	"	no corr.	light stains	heavy pits	heavy pits	heavy pits** thru clad	heavy pits**	heavy pits**
"	I-A-2	"	"	"	"	"		"	"
"	I-A-3	"	"	"	"	"		"	"
Al/Inco/Al-Epoxy	I-E-1	"	"	"	light stains	light stains	no corr.	no corr.	no corr.
"	I-E-2	"	"	"	"	"	"	"	"
"	I-E-3	"	"	"	"	"	"	"	"
Al/Inco/Al-Ceramic	I-C-1	Start 12/13		heavy pitting	heavy pits**	pits** thru Al clad	thru clad**	heavy pits**	heavy pits**
"	I-C-2	"		"	thru clad**	"	"	"	"
"	I-C-3	"		"	"	"	"	"	"

*Pits completely through sheet

**Pits only through clad

Effluent Generation

Because exposure of dissimilar metals is inherent in pitting and corrosion of a laminated parting sheet, tests were conducted to determine the rate of effluent generation for corroding parting sheets. Early salt spray corrosion tests indicated that three 0.1016 cm (0.040 in.) diameter pits per square inch were formed after five weeks in salt spray. Assuming that twice this number of pits will be formed in ten years of normal fluid exposure, pit density was set at approximately 1 per cm^2 (6 per in^2) for effluent generation.

Because of the difficulty of producing similar simulated pits in each specimen, it was decided to drill through holes which would expose an area of the centerstrate (cathode) equal to a 0.1016 cm (0.040 in.) diameter pit. For a 0.057 mm (0.002 in.) thick centerstrate, a pit could be simulated by a 0.0051 cm (0.020 in.) diameter hole. Therefore, six 0.0508 cm (0.020 in.) diameter holes were drilled in each 1.27 cm x 5.05 cm (0.5 in. x 2 in.) specimen.

The specimen edges were coated with stopoff lacquer as in the corrosion tests and prepared in bare, alodine, ceramic and epoxy coated conditions. Six specimens of each in plain aluminum alloy, titanium laminate and Inconel laminate were prepared for each coating condition noted above.

Samples were immersed in 150 milliliters of water in accordance with SVP 114[1]. Non-volatile residue measurements of the water were made at the start of the test and at 2, 4, 8, 16, 32 and 64 week intervals in order to obtain a gradation in the effluent generation. Table V presents the results of the effluent test.

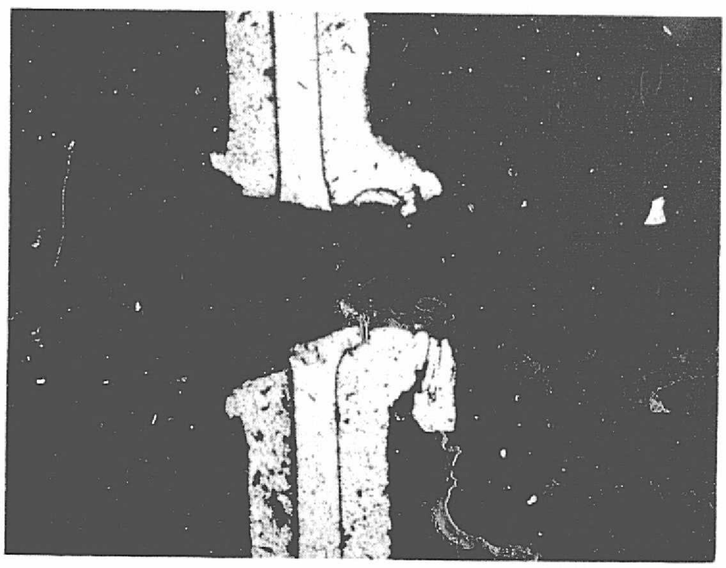
As can be seen from this table, there was no clear cut pattern of growth indicating effluent generation. Therefore, the effluent generation either was very small and thus insignificant in relation to background levels, or effluent generation took place in the first two weeks and then leveled off. The former theory tends to be supported by the fact that the laminates were not significantly different from the plain aluminum alloy. Further, micro examination of the holes in the aluminum and the titanium laminate showed no significant corrosion, as shown in figure 4 . Thus it was concluded that corrosion after pitting to the titanium surface of the centerstrate would not produce significant effluent.

Another potential location for effluent is the laminated parting sheet edges. To determine the effect of this laminated parting sheet edge exposure, three core specimens (plain aluminum, titanium laminate and rolled nickel laminate parting sheets) were immersed in a 1000 cc (61 in^3) of

---

(1) SVP 114 - Hamilton Standard Procedure - "Test Fluid Control (High Purity Water and Isopropyl Alcohol)"

CROSS SECTION OF HOLE–DRILLED THROUGH ALUMINUM ALLOY EFFLUENT SPECIMEN AFTER IMMERSION IN WATER FOR 64 WEEKS (78X)



CROSS SECTION OF HOLE DRILLED THROUGH TITANIUM LAMINATE EFFLUENT SPECIMEN AFTER IMMERSION IN WATER FOR 64 WEEKS (78X)

FIGURE 4 RESULTS OF HOLE EXAMINATION

TABLE V NON-VOLATILE EFFLUENTS FROM PARTING SHEET SPECIMEN

Configuration	Weeks Of Immersion					
	2	4	8	16	32	64
Aluminum Alloy Bare	1.9 mg	3.3 mg	1.8 mg	0.5 mg	1.7 mg	2.0 mg
Titanium Laminate Bare	0.4 mg	0.8 mg	1.9 mg	0.9 mg	0.8 mg	1.8 mg
Inconel Laminate Bare	3.4 mg	3.3 mg	1.3 mg	1.3 mg	1.9 mg	1.6 mg
Aluminum Alloy Alodined	1.2 mg	2.7 mg	2.3 mg	0.9 mg	1.6 mg	1.4 mg
Titanium Laminate Alodined	0.9 mg	2.3 mg	1.3 mg	0.6 mg	1.6 mg	1.3 mg
Inconel Laminate Alodined	6.4 mg	5.0 mg	2.3 mg	0.6 mg	0.8 mg	0.6 mg
Aluminum Alloy - Epoxy	1.7 mg	1.0 mg	1.8 mg	0.5 mg	1.8 mg	1.2 mg
Titanium Laminate - Epoxy	1.1 mg	0.3 mg	1.5 mg	1.3 mg	1.1 mg	1.6 mg
Inconel Laminate - Epoxy	0.7 mg	2.7 mg	2.1 mg	1.4 mg	1.9 mg	2.5 mg
Aluminum Alloy - Ceramic	2.4 mg	16.7 mg	0.8 mg	2.5 mg	1.9 mg	1.0 mg
Titanium Laminate - Ceramic	2.5 mg	0.6 mg	1.8 mg	7.5 mg	2.0 mg	3.0 mg
Inconel Laminate - Ceramic	0.6 mg	5.0 mg	1.6 mg	5.0 mg	2.0 mg	3.0 mg

NOTES: All reading are non-volatile residue from 30 mg water sample.

Control samples before varied from 1.5-4.0 mg/30 ml.

Specimen for each time interval were in separate containers.

distilled, demineralized water. The specimens were alodined with rough cut edges coated with stopoff lacquer to prevent exposure of non-representative edges. The plain aluminum and titanium laminate specimens contained 71.1 linear cm (28 in.) of sheet edges exposed to water. The rolled nickel had 60.96 linear cm (24 in.) exposed. Table VI presents the results of this test.

TABLE VI EDGE EXPOSURE EFFLUENTS

Sample All Alodined	Weeks of Immersion			
	4	8	32	64
Aluminum	1.1 mg	2.6 mg	11.0 mg	8.2 mg
Titanium Laminate	1.1 mg	3.7 mg	6.0 mg	13.6 mg
Nickel Laminate	0.6 mg	2.6 mg	2.0 mg	7.9 mg

Note: All readings are non-volatile residue from 30 ml water sample.

This table indicates that the effluent was negligible and comparable in laminates to conventional aluminum.

Core Fabrication and Structural Integrity

The primary fabrication and structural questions associated with the use of a laminated parting sheet in an aluminum plate fin heat exchanger were possible delamination of the parting sheet, the effect of the laminate parting sheet on brazed joints and closure bars, and the ability to weld across exposed edges of the dissimilar metal. Differential material expansion was not considered significant as the parting sheet and heat exchanger remained intact through the 866 K (1100°F) plus temperature excursion experienced during the braze cycle.

The structural criteria established for the lamination bond and brazed joints was that they must be at least as strong as the fins when subjected to a load normal to the parting sheet. This represents an abnormaly severe loading of the parting sheet and subjects the fins and brazed joints to simulated pressure loads. Thus, any laminated heat exchanger which is equal to or better than aluminum alloy in tensile tests was considered acceptable.

Brazing Operation

Table VII presents a summary of information available at the start of this program, relating to the core brazing with plain aluminum, titanium laminates and Inconel laminates. Figure 5 shows a typical brazed core.

From the tensile test results it was concluded that the titanium laminates exhibit a structural capability equal to the conventional aluminum parting sheets. However, tensile test results of the Inconel laminate revealed gross delaminations of the parting sheet and over-melting of fins as shown in figure 6 . The delaminations were attributed to the formation of a hard intermetallic between Inconel and aluminum. Figure 7 shows a photomicrograph of the Inconel laminate revealing the intermetallic region. Also shown is a photomicrograph of the titanium laminate indicating no such intermetallic formation. Microhardness testing of both laminates clearly indicated that an intermetallic, which was harder than either the aluminum or Inconel, was formed in the Inconel sample. Microhardness testing on the titanium laminate showed only the titanium and aluminum hardness, no intermetallic.

Because of the excess of alloying in the Inconel core as indicated by the extreme over-melting of the fins, the Inconel core was rebrazed with less braze alloy. Delaminations and the formation of an intermetallic occurred again and therefore the Inconel laminate was dropped from further consideration.

In order to duplicate Shuttle hardware more accurately, titanium aluminum laminate parting sheets were fabricated of 0.102 mm (0.004 in.) aluminum, 0.076 mm (0.003 in.) titanium, and 0.102 mm (0.004 in.) aluminum in a size of 11.43 cm x 19.05 cm (4.5 in. x 7.5 in.). This size was dictated by the limit of the experimental presses available. The 0.076 mm (0.003 in.) titanium also was more readily available than the 0.050 mm (0.002 in.) used later in the program. A heat exchanger core was then brazed. It was four layers high and consisted of a primary water circuit and a redundant water circuit of three passes of serrated fins 0.193 cm high, 0.127 mm thick, and 7 fins per cm (0.076 in. high, 0.005 in. thick, and 18 fins per in.). The air side was a single pass with fins 1.08 cm high, 0.0767 mm thick, and 4.72 fins per cm (0.003 in. thick, 0.426 in. high and 12 fins per in.) in a ruffle configuration. Figure 8 shows a photograph of a cross section cut through the heat exchanger core. Tensile pull test of samples from this core were conducted and revealed pull strengths of approximately 3.59 MN/m^2 (520 psi) for two samples. Figure 9 displays one such sample. Fracture occurred only in the fins indicating both an excellent brazed joint and the absence of any delamination of the parting sheets.

TABLE VII CORE BRAZING

Material	Dimensional Description						Tensile Strength	
	Overall		Fins		Parting Sheets			
Plain Aluminum Parting Sheets	10.16 cm x 10.16 cm x 10.16 cm	4 in. x 4 in. x 4 in.	<u>Liquid Circuit</u> 5 layers 0.196 cm high, 13.8 fins per cm, 0.076 mm thick <u>Air Circuit</u> 6 layers, 1085 cm high, 11 fins per cm, 0.23 mm thick	<u>Liquid Circuit</u> 5 layers 0.077 in. high, 35 fins/in., 0.003 in. thick <u>Air Circuit</u> 6 layers, 0.427 in. high, 28 fins/in., 0.009 in. thick	0.4 6 mm	0.016 in.	Section 1 - $8.618\ MN/m^2$ Section 2 - $10.239\ MN/m^2$	Section 1 - 1250 psi Section 2 - 1485 psi
Titanium Laminate Parting Sheets	10.16 cm x 10.16 cm x 10.16 cm	4 in. x 4 in. x 4 in.	<u>Liquid Circuit</u> 5 layers 0.196 cm high, 13.8 fins per cm, 0.23 mm thick <u>Air Circuit</u> 6 layers, 1.085 cm high, 11 fins per cm, 0.23 mm thick	<u>Liquid Circuit</u> 5 layers 0.077 in. high, 35 fins/in., 0.003 in. thick <u>Air Circuit</u> 6 layers, 0.427 in. high, 28 fins/in., 0.009 in. thick	0.051 mm to 0.076 mm titanium surrounded by 0.102 mm thick aluminum	0.002 to 0.003 in. titanium surrounded by 0.004 in. thick aluminum	Section 1 - $9.308\ MN/m^2$ Section 2 - $10.49\ MN/m^2$	Section 1 - 1350 psi Section 2 - 1522 psi
Inconel Laminate Parting Sheets	10.16 cm x 10.16 cm x 10.16 cm	4 in. x 4 in. x 4 in.	<u>Liquid Circuit</u> 5 layers, 0.196 cm high, 11 fins per cm, 0.23 mm thick <u>Air Circuit</u> 6 layers, 1.085 cm high, 11 fins per cm, 0.23 mm thick	<u>Liquid Circuit</u> 5 layers 0.077 in. high, 35 fins/in., 0.003 in. thick <u>Air Circuit</u> 6 layers, 0.427 in. high, 28 fins/in., 0.009 in. thick	0.051 mm to 0.076 mm Inconel surrounded by 0.102 mm thick aluminum	0.002 to 0.003 in. Inconel surrounded by 0.004 in. thick aluminum	Delaminated at $1.213\ MN/m^2$	Delaminated at 176 psi

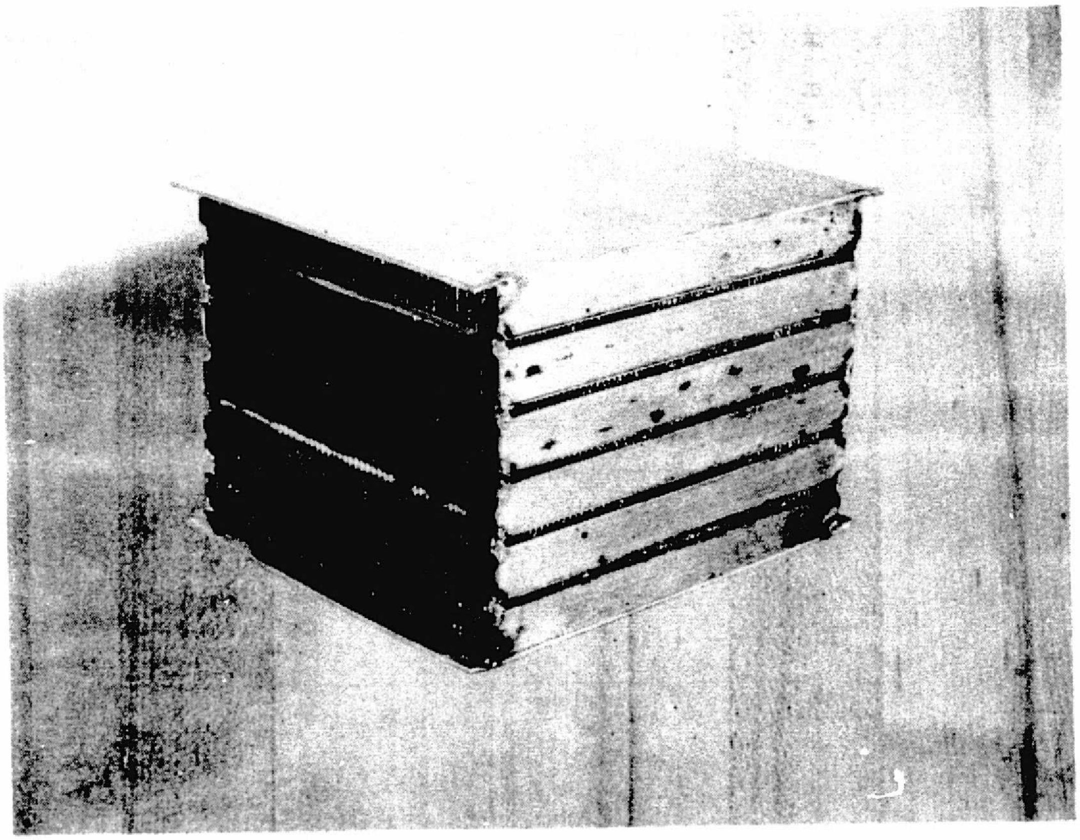


FIGURE 5 TYPICAL BRAZED CORE MODULE TO EVALUATE FABRICATION & STRUCTURE

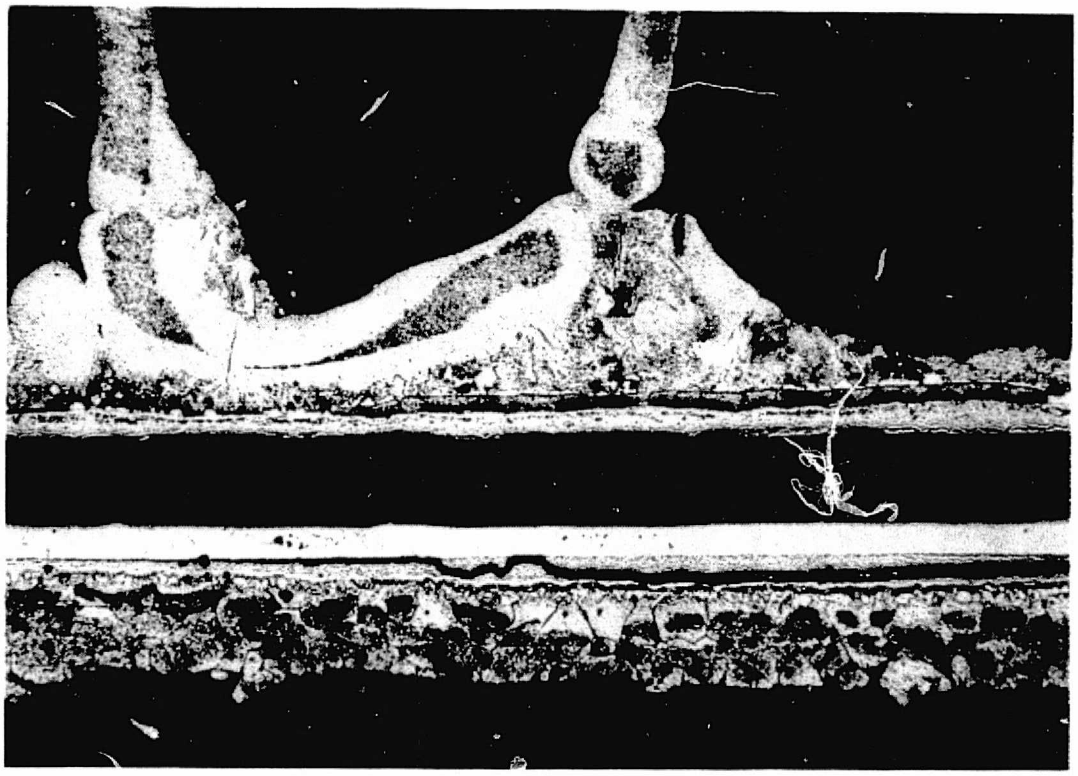
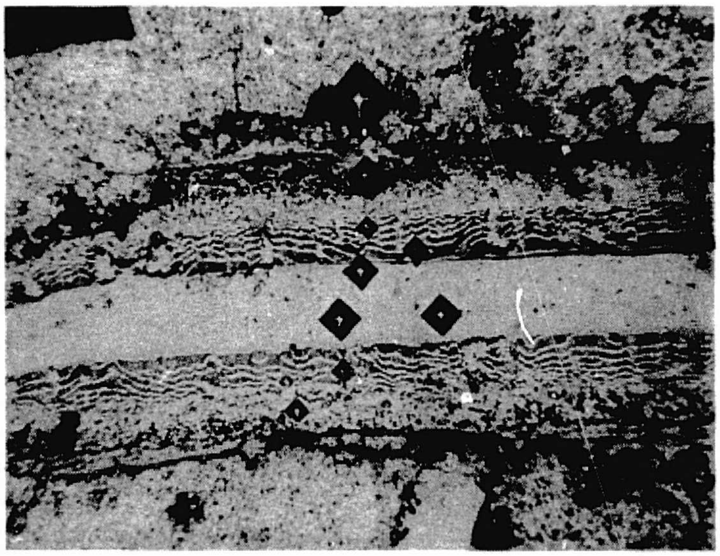
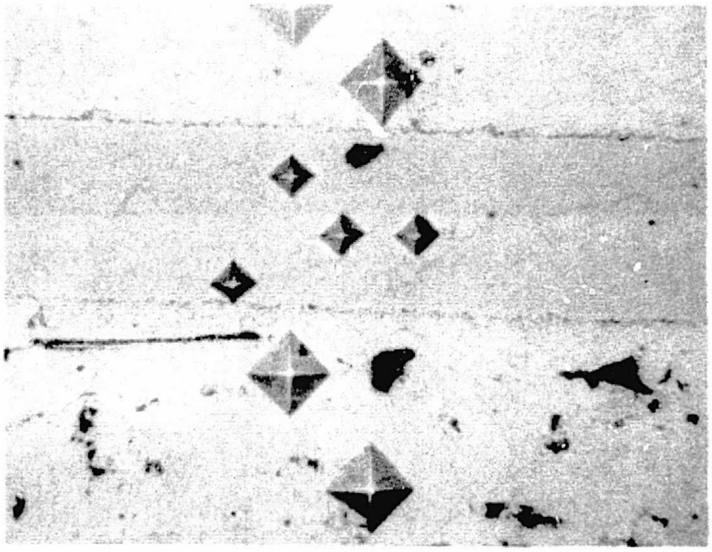


FIGURE 6 PHOTOMICROGRAPH OF INCONEL DELAMINATION AND FIN OVERMELTING – 50X



PHOTOMICROGRAPH OF BRAZED INCONEL LAIMINATE SHOWING CROSS SECTION HARDNESS TEST POINTS — (300X).



PHOTOMICROGRAPH OF BRAZED TITANIUM LAMINATE SHOWING CROSS SECTION HARDNESS TEST POINTS (300X).

FIGURE 7 CROSS SECTION OF LAMINATES

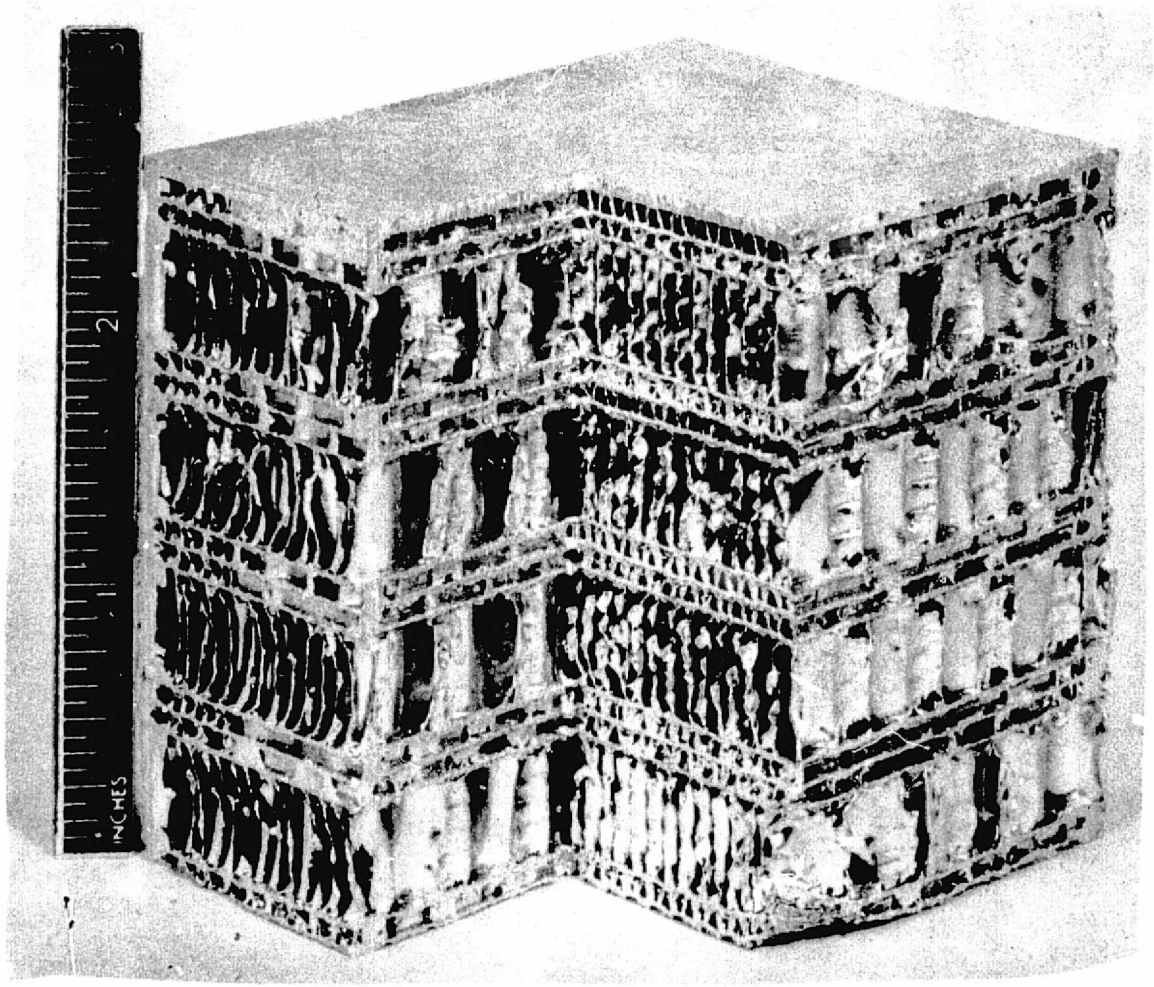


FIGURE 8 CROSS SECTION OF 1/4 SCALE TYPICAL SHUTTLE CONDENSING
HEAT EXCHANGER WITH LAMINATED PARTING SHEET
(NOTE FIN EDGES ARE ROUGH CUT DURING SECTIONING)

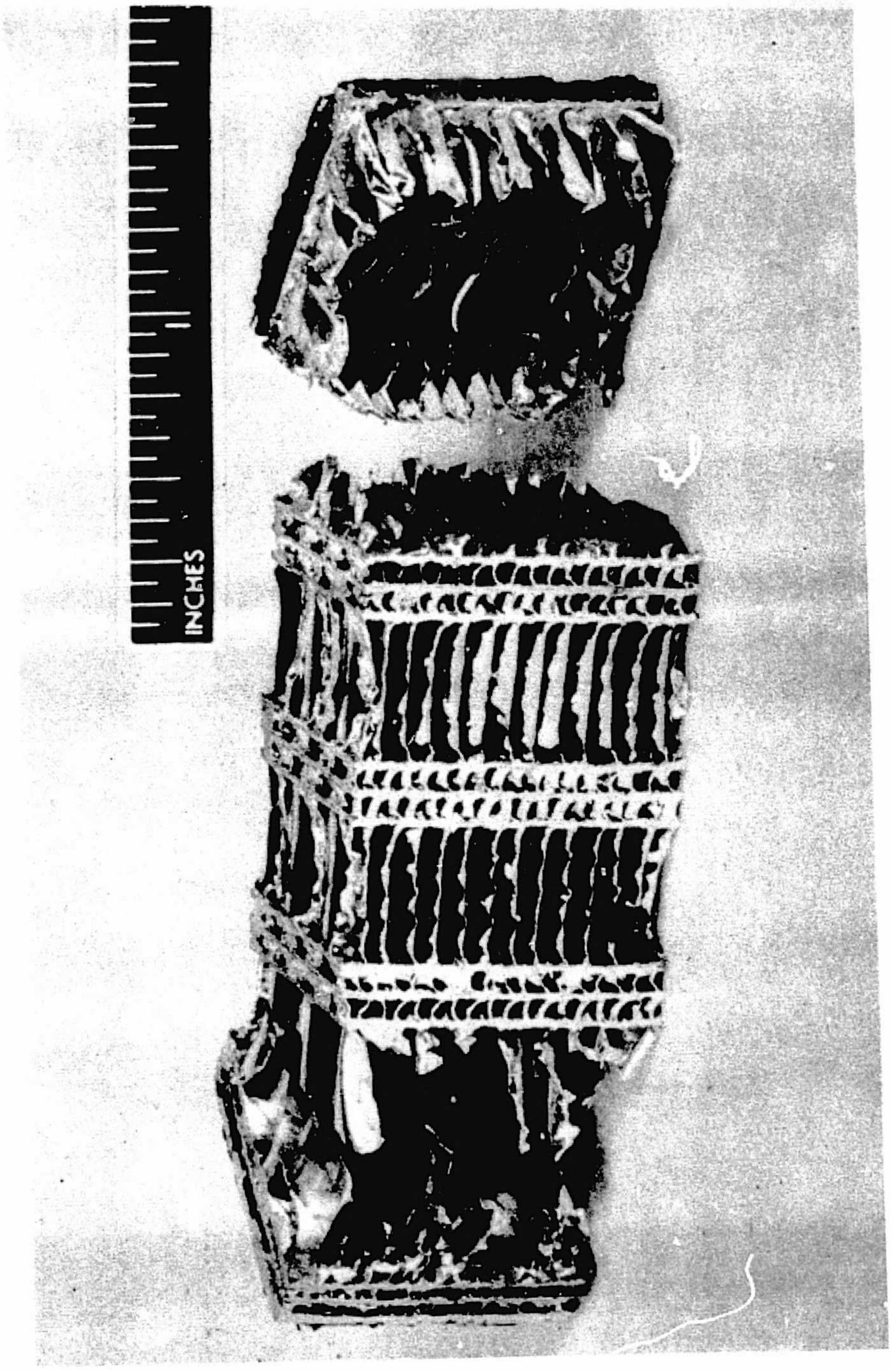


FIGURE 9 TENSILE TEST SPECIMEN OF 1/4 SCALE TYPICAL SHUTTLE CONDENSING HEAT EXCHANGER WITH LAMINATED PARTING SHEETS

End Welding

End welding of the titanium laminate was accomplished during the core fabrication to verify the ability to join the laminate to an aluminum end plate. Subsequent leakage tests of the joint revealed no bubbles with the core pressurized to 0.239 MN/m^2 (20 psig) air and immersed in water. Subsequent sectioning revealed an excellent weld joint across the laminated parting sheet as shown in figure 10.

Stainless Steel-Aluminum Compatibility

To confirm the durability of aluminum alloy heat exchangers in an otherwise stainless steel water circuit, four test circuits were set up as illustrated in figure 11. These circuits contained a proportion of stainless steel to aluminum alloy surface area similar to that expected in the Shuttle Orbiter water coolant loop. Mating flanges, ducts and housings also were similar to those anticipated in the Shuttle. To obtain representative areas, the stainless steel housing contained an AISI 347 stainless steel heat exchanger core, and the aluminum housing contained a portion of the quarter scale Shuttle condensing heat exchanger which had been alodined. The heat exchangers were operated 30 percent of the time and inoperative the remaining 70 percent to simulate anticipated Shuttle operation.

Two of the circuits were at normal room temperature, 294 to 305 K (70 to 90°F) while inoperative and at approximately 322 K (120°F) when simulating operating conditions. The other two circuits were operated at temperatures 27.8 to 33.3 K (50 and 60°F) above the first two in order to obtain a corrosion acceleration factor of 8 to 1. This corrosion acceleration was intended to obtain the equivalent of a ten year service life in 15 months. In order to demonstrate the validity of this temperature acceleration, one high temperature unit was retired at the equivalent of 15 months (57 days) for comparison with a normal temperature unit after 15 months.

Figure 12 is a view of the heat exchanger housing and core sections. The housing on the left is stainless steel and that on the right is aluminum alloy. Examination of the units after test exposure of 57 days at high temperature revealed no evidence of corrosion.

The high temperature aluminum core that was retired after 57 days was sectioned and the parting sheet surfaces examined under a microscope at up to 80X. No evidence of corrosion was found. Photomicrographs of the cross section showed no sign of corrosion and revealed that the three layer "leak barrier" parting sheet was intact and exhibited good structural bond as shown in figure 13.

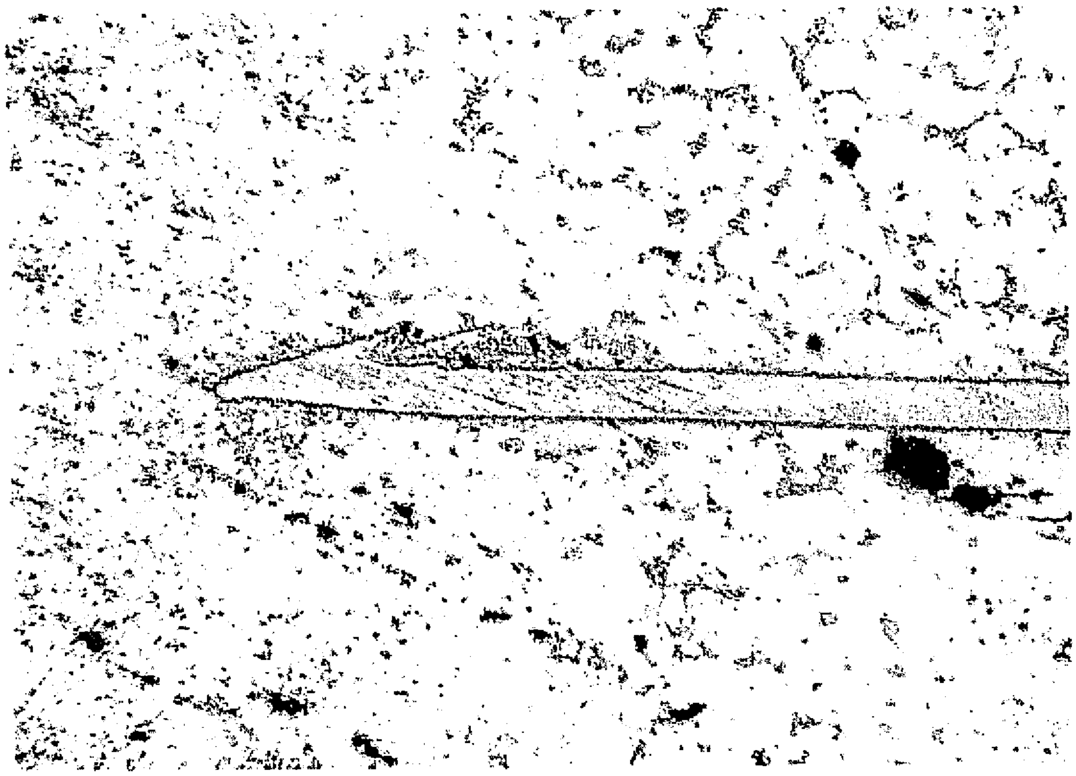


FIGURE 10 PHOTOMICROGRAPH SHOWING WELD AROUND EDGE OF TITANIUM LAMINATE CENTERSTRATE – 50X

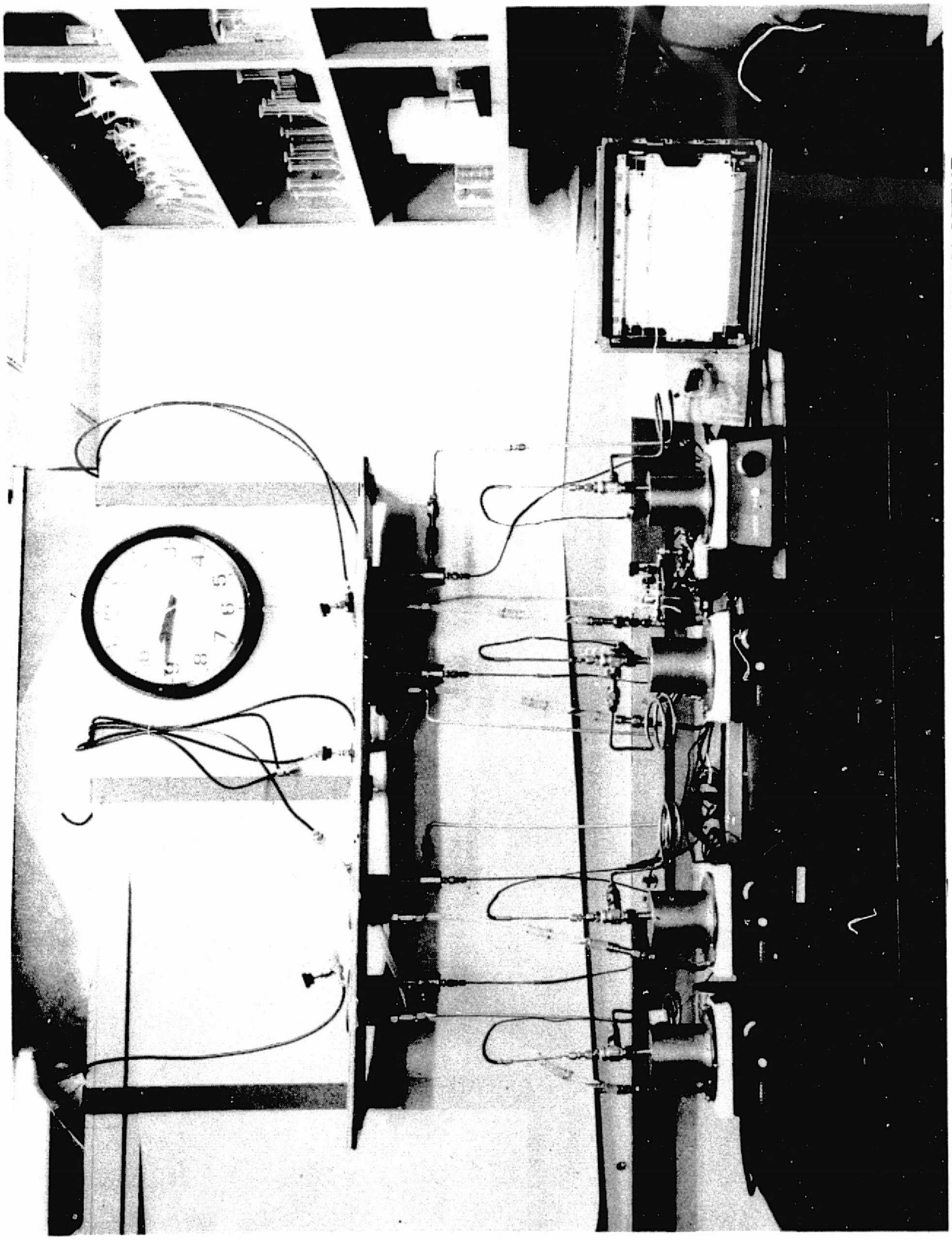


FIGURE 11 STAINLESS STEEL/ALUMINUM COMPATIBILITY TEST SETUP

SS 10465-4

ORIGINAL PAGE IS
OF POOR QUALITY

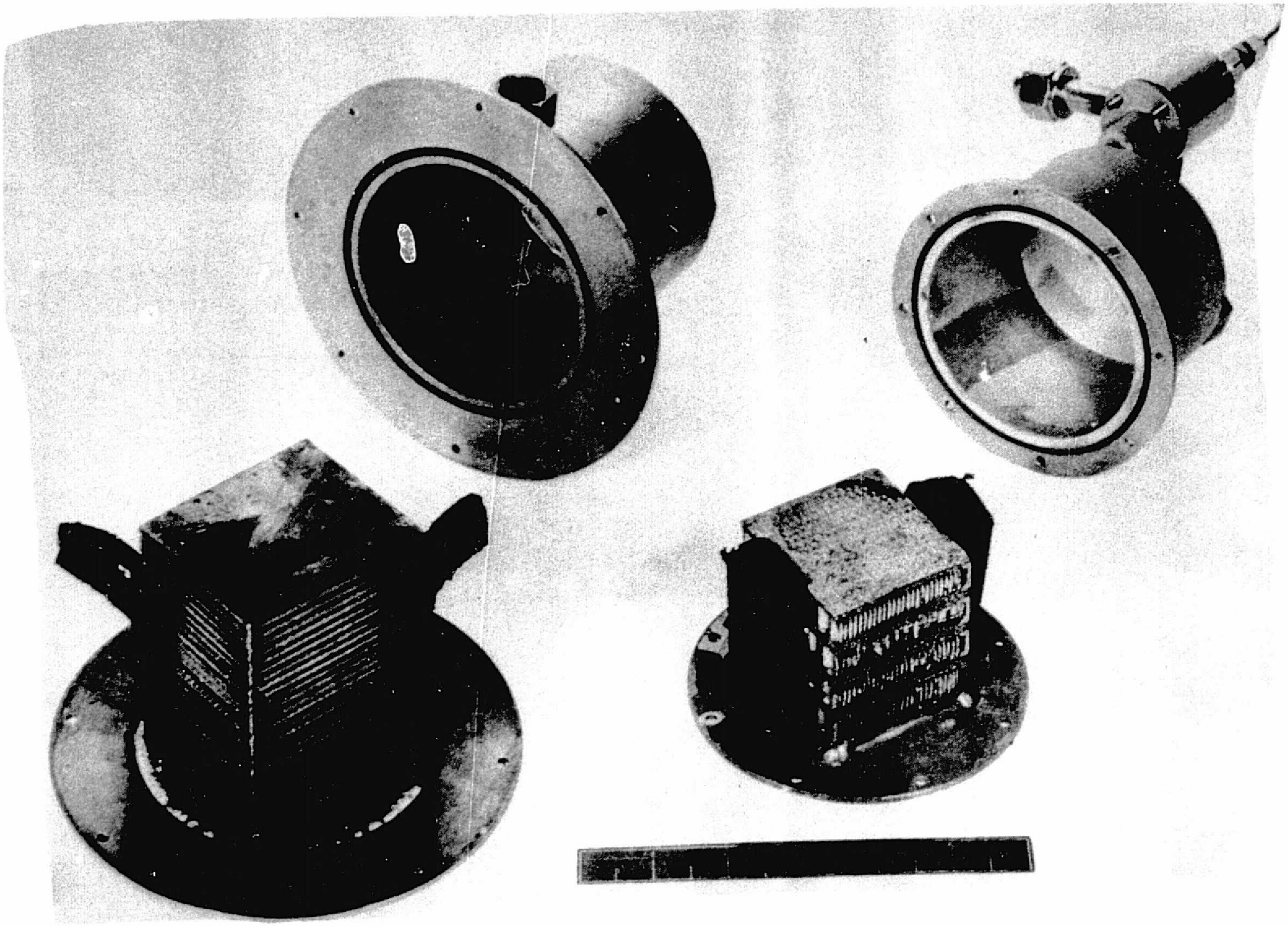
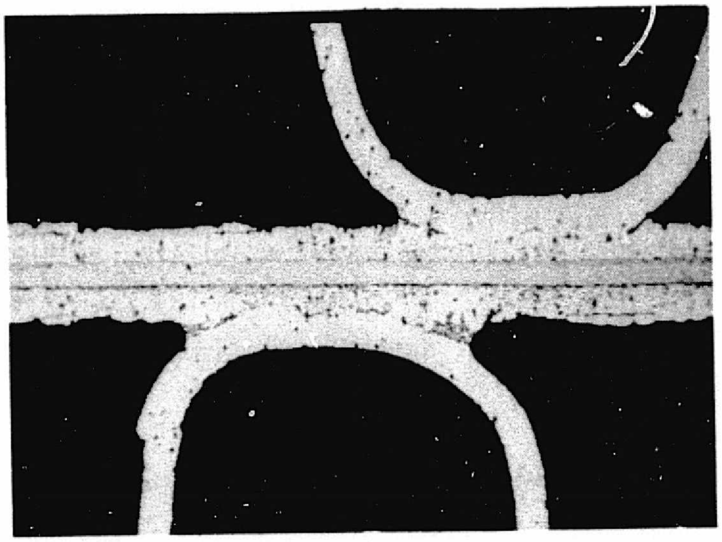
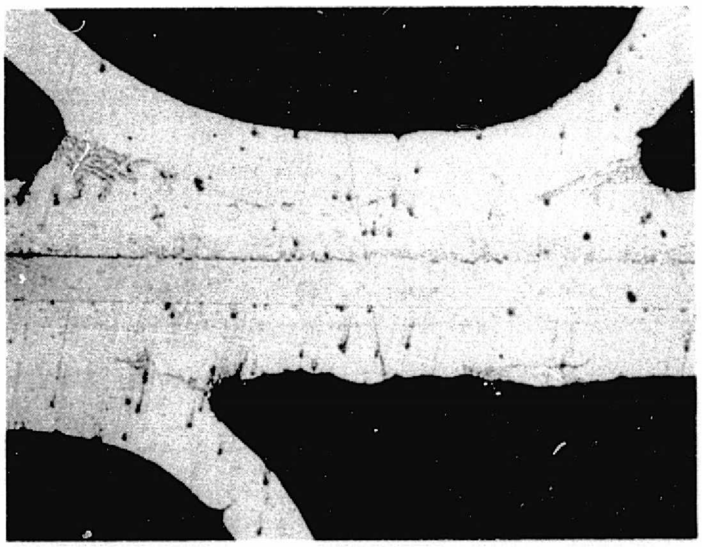


FIGURE 12 HEAT EXCHANGER HOUSING AND CORE SECTIONS



CROSS–SECTION OF ALUMINUM CORE AT PARTING SHEET
NOTE SOUND BRAZE JOINT BETWEEN FIN AND
PARTING SHEET, AND GOOD DIFFUSION BOND
JOINT BETWEEN ALUMINUM AND TITANIUM CENTERSTRATE
OF PARTING SHEET. MAGN. 38X



SAME AS ABOVE EXCEPT MAGN. 78X

FIGURE 13 LEAK BARRIER STRUCTURAL BOND

After 57 days, the loop water was still clear and had a pH of 7.8. Its electrical specific conductivity was up to 27,000 micromhos per cm as compared to 2,750 micromhos per cm before test exposure, thus indicating a progressively increasing ionic content which yields the basis for corrosive action. The non-volatile residue in the water was 8 milligrams from a 30 milliliter sample as compared to 3 milligrams per 30 milliliter before test.

The results of the 15 months of testing are summarized below. As a result of the visual examination and the before-and-after measurements these conclusions were reached.

- Self-protective oxide coatings are formed to inhibit corrosion.
- Increased temperatures probably promote more rapid formation of oxide coating.
- No pitting attack was discernable.
- Lack of corrosion after 57 days or 15 months precluded calculation of an acceleration rate.
- Ten year life is probable in a neutral water, stainless steel circuit.

In addition, water from each loop was analyzed before and after the test for pH, conductivity and non-volatile residues. The results are shown in Table VIII.

TABLE VIII LOOP WATER ANALYSES

	Temp.	Retired at	pH	Specific Conductivity μMHOS/cm	NVR mg/30 ml
Orig. H_2O Value	-	-	7.0	2,750	3.0
Unit No. 1	High	57 days	7.8	27,000	8.0
Unit No. 2	High	15 months	7.3	35,000	8.7
Unit No. 3	Normal	15 months	7.8	47,000	5.6
Unit No. 4	Normal	15 months	7.5	54,000	3.8

Thermal Capability

Since the cross sectional thermal resistance of thin parting sheets is so small, it is usually neglected in heat exchanger calculations. However, there was concern that the interfaces and the laminates could add significant resistance. Based on this supposition, an effort was made to compare the resistance with that of plain aluminum, recognizing that the measurement of thermal conductivity in very thin plates is subject to large errors due to the inability to generate significant temperature differences.

Twelve basic samples were selected with measured conductivities tabulated in Table IX. Two samples of each material were tested with an alodine coating and two each were coated with a wear resistant epoxy and a ceramic (potassium silicate) wetting coating. The test apparatus selected utilized a comparative method with a reference metal of known conductance on each side of the specimen. Thermocouples inserted in each reference material displayed a temperature gradient allowing for extrapolation across the specimen obviating the need for sample surface temperature measurement. A heated guard around the periphery of the sample minimized heat leaks to the outside and molten indium between the sample and reference material minimized interface effects.

Absolute conductivities were grossly in error (approximately 1 percent of book values), however, the consistency between similar samples indicated that the error though quite large was repeatable. Thus there were no significant differences between the various laminates, with and without coatings, to indicate high thermal resistance between the layers of the laminate.

Based on these results, the use of an analytically determined conductivity was warranted. Calculated conductivities for the various parting sheet combinations were:

• 0.41 mm (0.016 in.) thick aluminum alloy #3003	173 watts/m-K (100 Btu/hour-foot-°F)
• 0.102 mm (0.004 in.) thick #3003 aluminum on each side of 0.051 mm (0.002 in.) titanium centerstrate	62.35 watts/m-K (36 Btu/hour-foot-°F)
• 0.102 mm (0.004 in.) thick #3003 aluminum on each side of a 0.051 mm (0.002 in.) pure nickel centerstrate	126.44 watts/m-K (73 Btu/hour-foot-°F)

TABLE IX APPARENT THERMAL CONDUCTIVITIES OF ALODINED AND COATED METAL LAMINATES

		Thickness		Thermal Conductivity	
		(mm)	(in.)	watts / mm- K	Btu / Hr-ft-°F
A1	Aluminum Alloy #3003 Alodined	0.25	0.0098	1.31	0.76
A2	Aluminum Alloy #3003 Alodined	0.25	0.0098	1.25	0.72
AE	Aluminum Alloy #3003 Alodined and Epoxy Coated	0.25	0.0098	1.36	0.79
T1	Aluminum Alloy #3003 on Titanium-Alodined	0.27	0.0106	0.97	0.56
T2	Aluminum Alloy #3003 on Titanium-Alodined	0.26	0.0102	0.93	0.54
TC	Aluminum Alloy #3003 on Titanium-Alodined and Ceramic Coated	0.30	0.0118	0.52	0.30
I1	Aluminum Alloy #3003 on Inconel-Alodined	0.25	0.0098	0.88	0.51
I2	Aluminum Alloy #3003 on Inconel-Alodined	0.24	0.0094	0.91	0.53
I3	Aluminum Alloy #3003 on Inconel-Alodined and Coated with Epoxy	0.24	0.0094	0.93	0.54
S1	Aluminum Alloy #3003 on Stainless Steel-Alodined	0.26	0.0102	0.60	0.35
S2	Aluminum Alloy #3003 on Stainless Steel-Alodined	0.26	0.0102	0.65	0.38
SC	Aluminum Alloy #3003 on Stainless Steel-Alodined and Ceramic Coated	0.30	0.0118	0.84	0.48

In order to determine the overall thermal effect of the indicated reductions in conductivity resulting from the use of laminates, the reduction in effectiveness associated with the various parting sheets was calculated for two typical Shuttle heat exchangers - the interface heat exchanger and the condensing heat exchanger.

The results shown in figure 14 indicated that the maximum effect on performance was an almost negligible 0.3 percent. The temperature differential across the parting sheets is perhaps a more familiar indication of the insignificant effect of the reduction in the thermal conductivity resulting from the use of laminates. Figure 15 displays the temperature differential across the parting sheet as a function of heat load for various conductivities. From this curve it can be seen that for the highest heat loads of the interface heat exchanger and the lowest conductivity laminate, the temperature difference across the parting sheet would be only 0.0156 K (0.028°F). This is insignificant to the heat exchanger application.

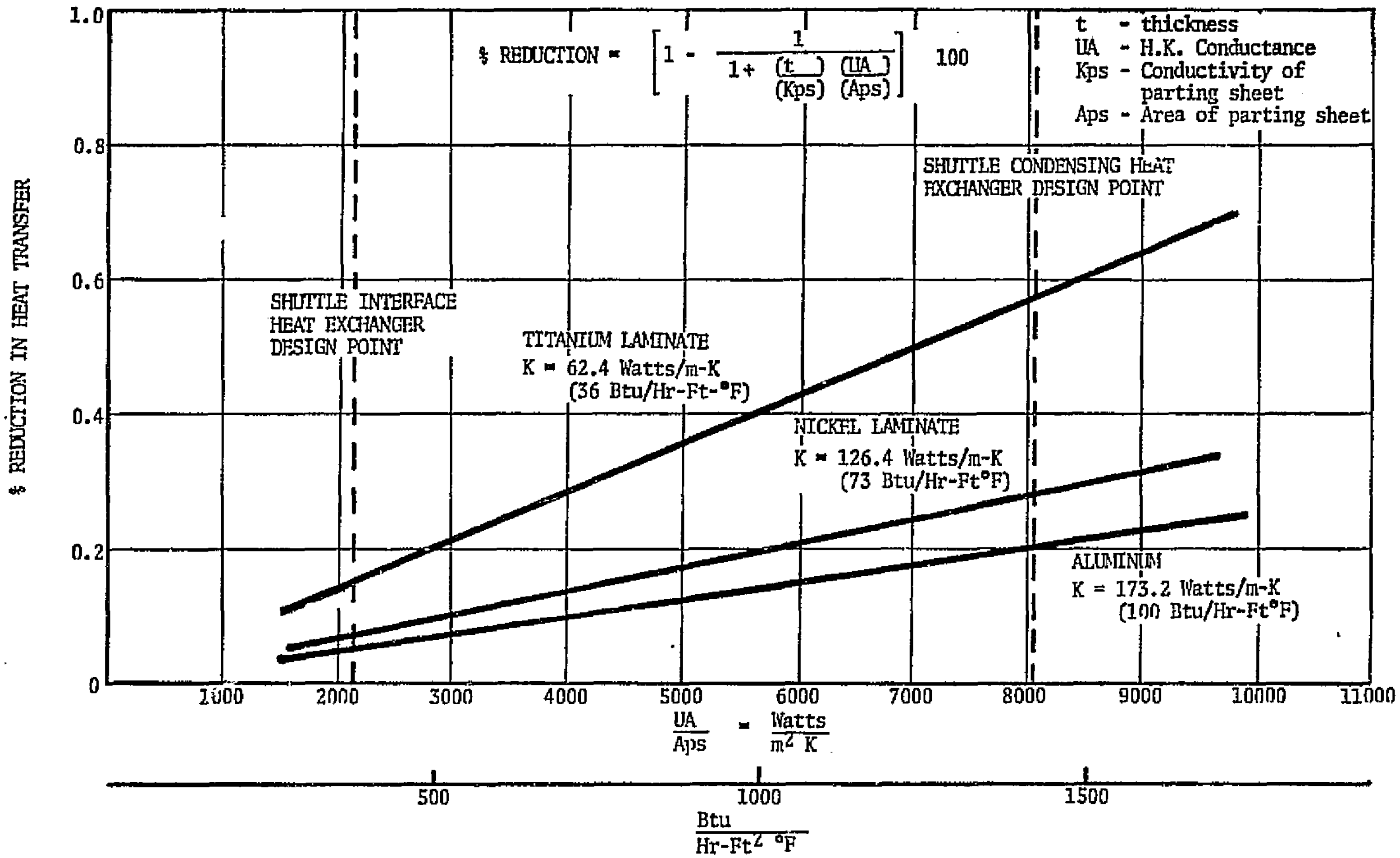


FIGURE 14 PERCENT REDUCTION IN HEAT EXCHANGER PARTING SHEET HEAT TRANSFER

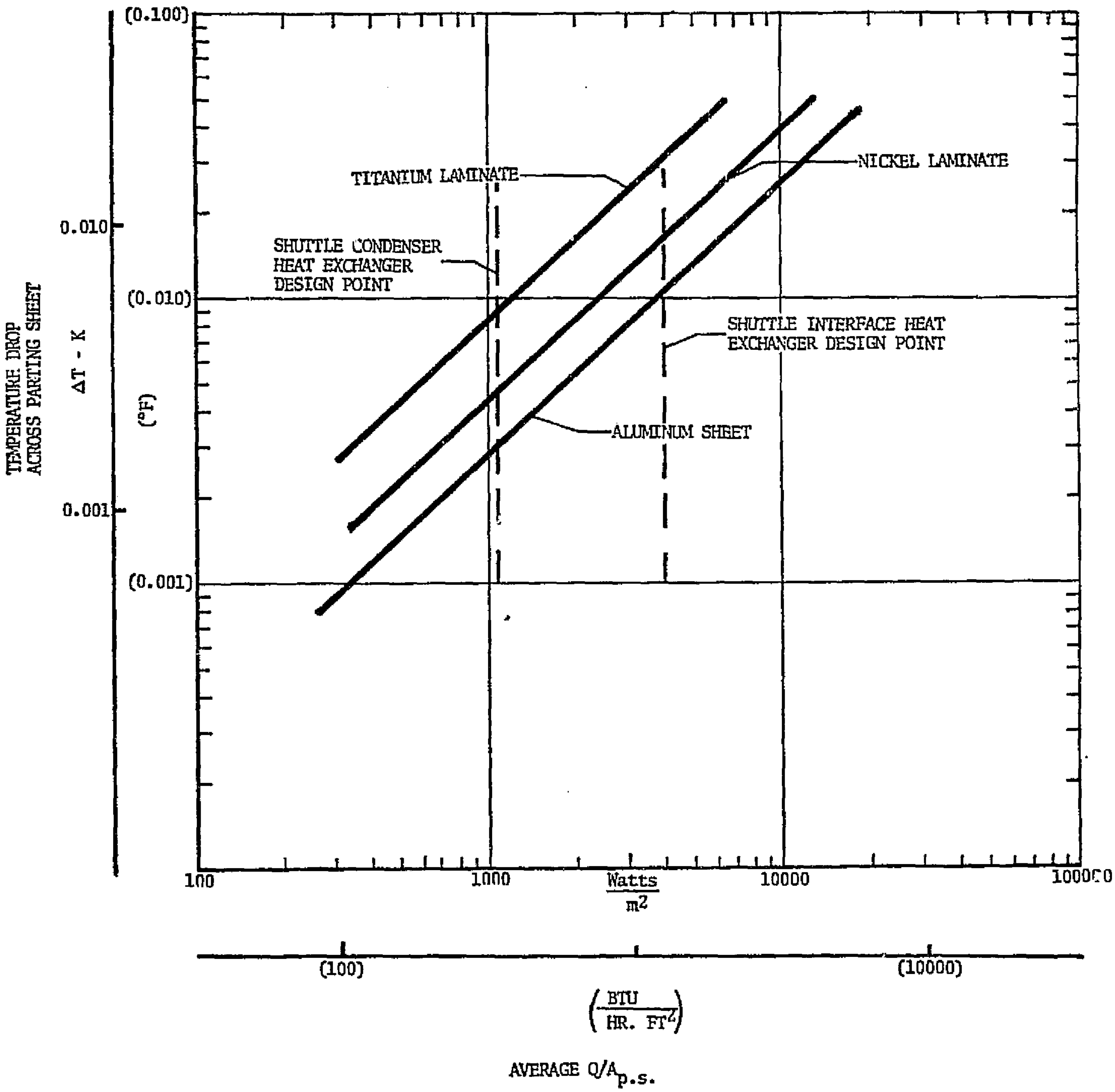


FIGURE 15 TEMPERATURE DROP ACROSS PARTING SHEETS

FABRICATION OF LAMINATES

The laminates for the heat exchangers fabricated for this program were produced by the vacuum diffusion process. However, due to the cost of the laminates, an alternate process was attempted. Both are reported below. The results of an eighteen month IR&D salt spray program are also presented.

Vacuum Diffusion Process

While the basic process of vacuum diffusion bonding had been established during prior IR&D programs, the use of a different facility to accommodate the plate size required, dictated that a pilot run be made and the plates inspected prior to attempting production quantities.

The process basically consists of placing the aluminum/titanium/aluminum sandwich in a press, under pressure and in a vacuum for a specified length of time and then cooling while still under pressure. The laminates are prevented from sticking or bonding to one another by stainless steel separator sheets which have been coated with graphite. Cleanliness is mandatory throughout the operation.

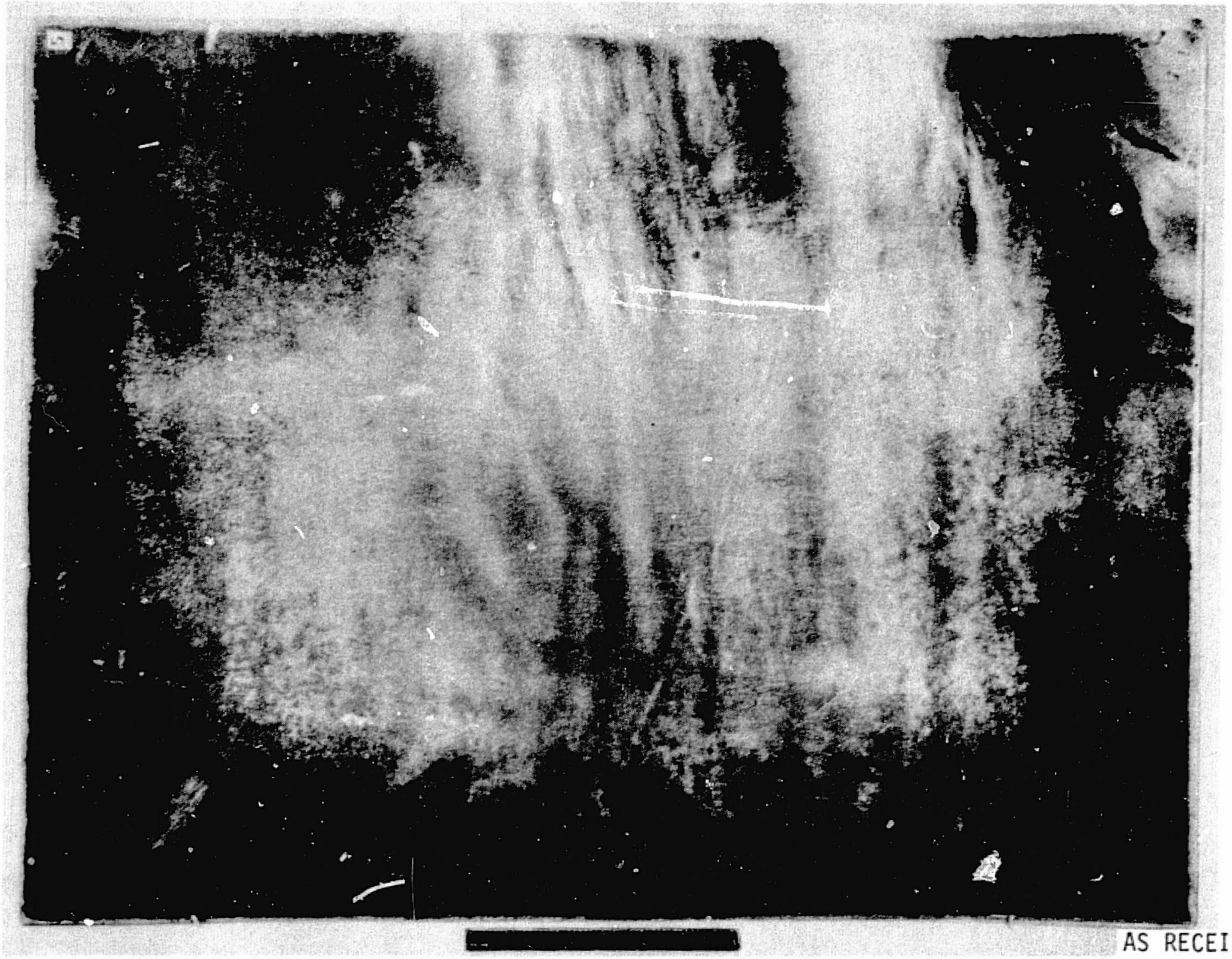
The first run was a pilot lot of ten plates and revealed difficulties; the plates were weakly bonded to the separator sheets and graphite diffusion into the aluminum had occurred. Figures 16 thru 18 show typical plates before and after cleaning. A second pilot lot of eight plates, utilizing process changes including reduced pressure, increased amount of graphite, a lower peak temperature and less time at temperature, resulted in acceptable plates with ultrasonic inspection indicating complete bonding. Destructive examination of one plate revealed no delamination in flexure tests. Based on the good results from this pilot lot, two production runs of seventy and eighty plates each were made with similar good results. Figures 19 and 20 show typical plates before and after cleaning from one of the production runs.

The summary of the four runs shows that of one hundred sixty-eight sheets bonded, one hundred twenty good sheets remained for use. Of the total, twenty four were destructively examined, eleven sheets had defects as indicated by ultrasonic tests, and thirteen had surface defects.

One problem, not fully resolved, is that ultrasonic scanning produces false indications of defects. While this is a "fail safe" process, some sheets have been unnecessarily rejected, reducing the yield. From the destructive examination performed, true faults have been faithfully detected, allowing high confidence in plates selected for use.

BEFORE CLEANING

FIGURE 16 LIGHTWEIGHT LONG LIFE HEAT EXCHANGER
PILOT RUN #1, PLATE 3

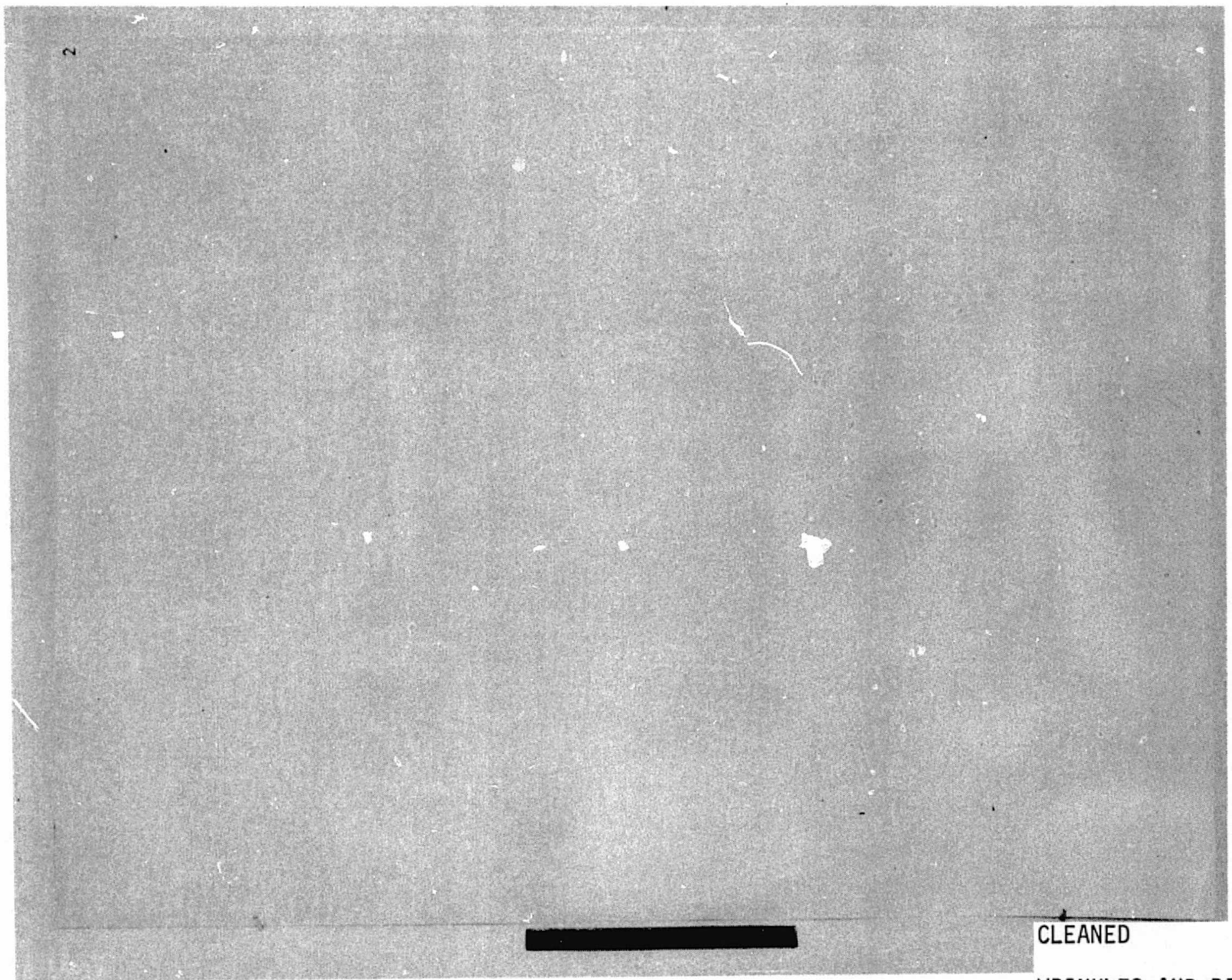


AS RECEIVED

FIGURE 17 LIGHTWEIGHT LONG LIFE HEAT EXCHANGER
PILOT RUN #1, PLATE 5

LOWER LEFT SHOWS
CARBON REMOVAL BY
ERASURE

BEFORE CLEANING



CLEANED

WRINKLES AND DIMPLING
CAUSED BY SEPARATING
THE PLATES STUCK TOGEATHER
IN THE STACK

FIGURE 18 LIGHTWEIGHT LONG LIFE HEAT EXCHANGER
PILOT RUN #1, PLATE 2

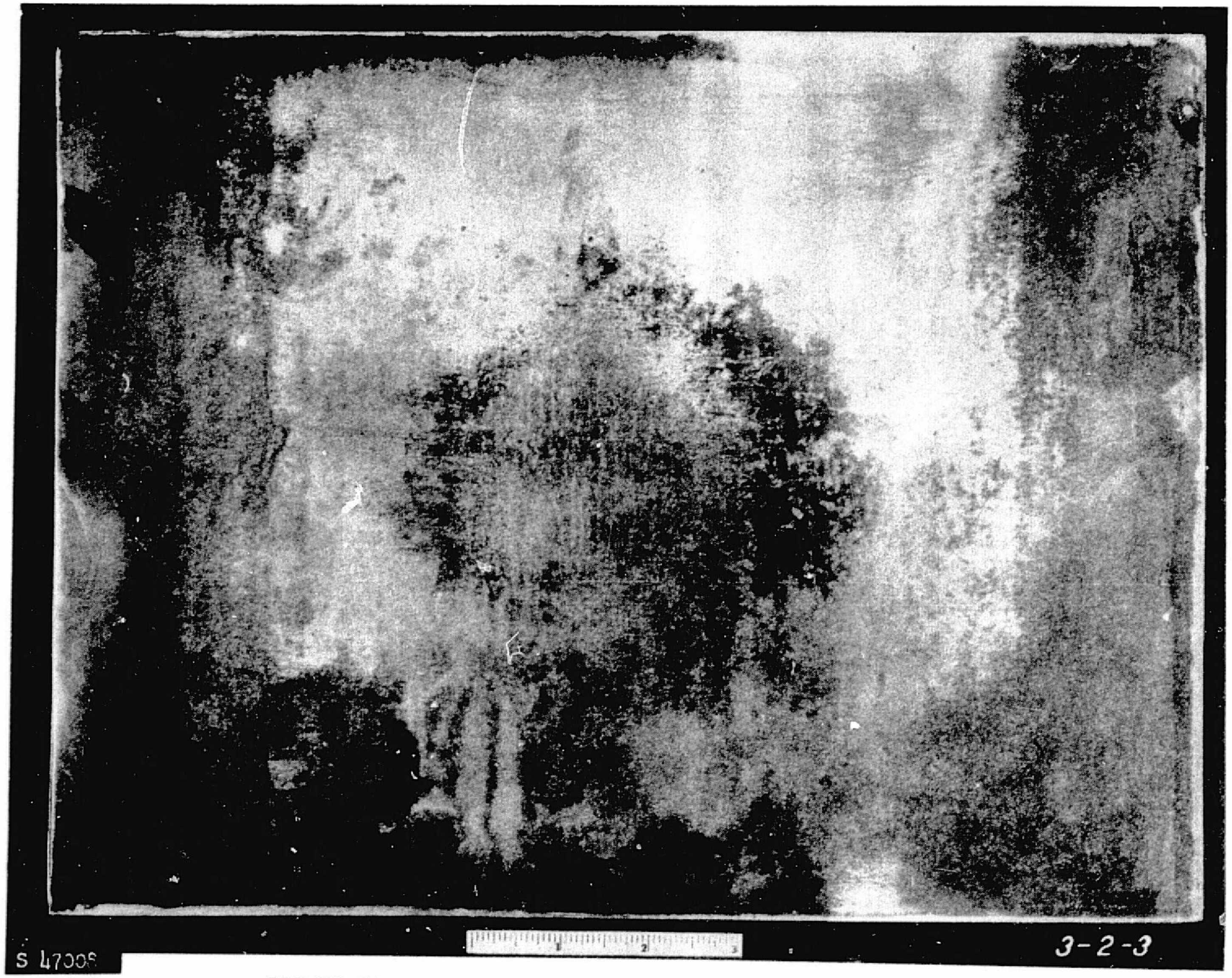


FIGURE 19 LIGHTWEIGHT LONG LIFE HEAT EXCHANGER
BONDING (PRODUCTION) RUN #3, AS RECEIVED

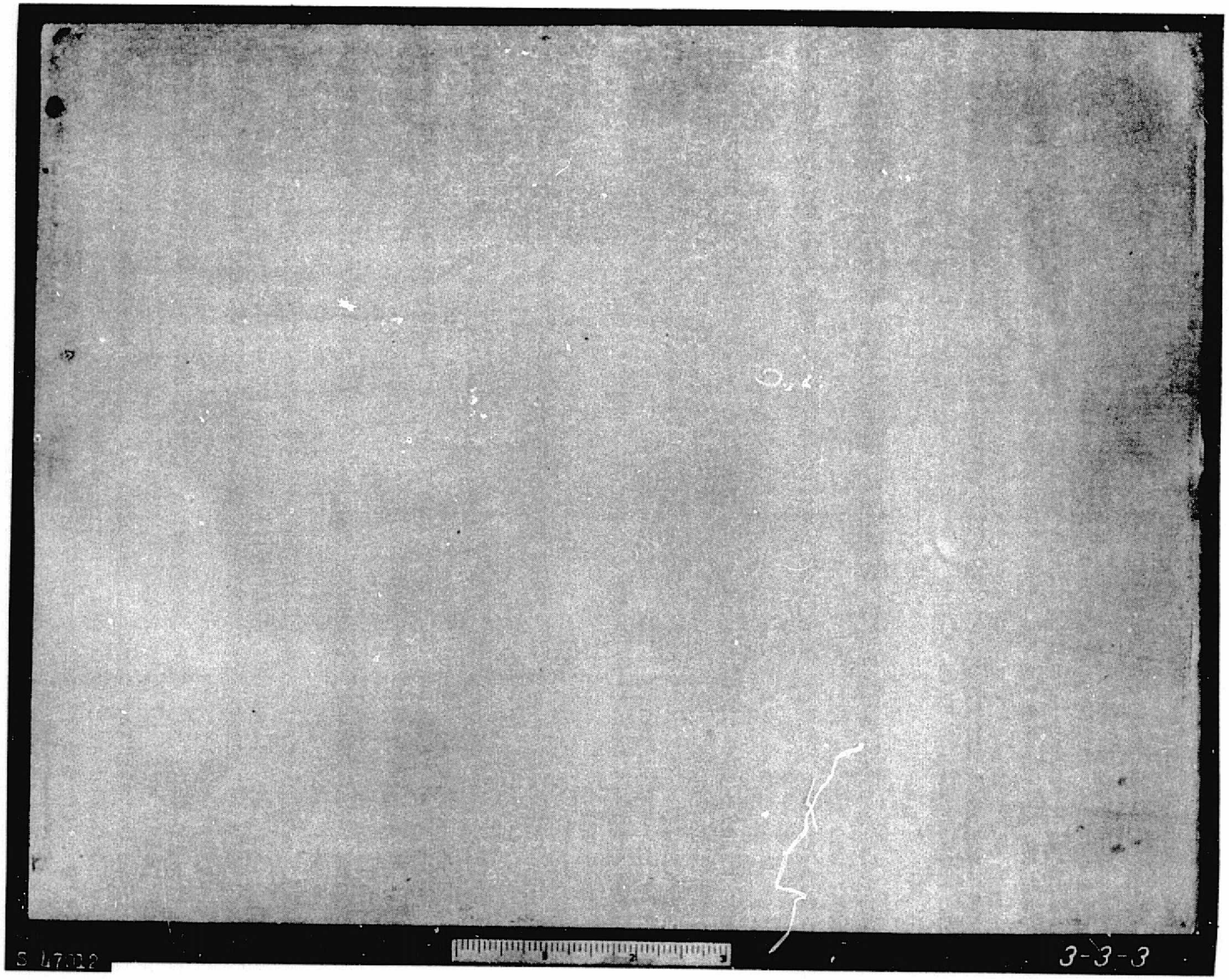


FIGURE 20 LIGHTWEIGHT LONG LIFE HEAT EXCHANGER BONDING (PRODUCTION) RUN #3, AFTER CLEANING

ORIGINAL PAGE IS OF POOR QUALITY

Roll Cladding

The results of the vacuum diffusion program indicated a low yield, approximately seventy percent, and high cost per sheet. The NASA, therefore, agreed that an alternate method be investigated. Accordingly, a best effort contract was arranged with Clad Metals, Inc., of Canonsburg, Pennsylvania to attempt laminate fabrication by roll cladding, a proprietary process which achieves bonding by rolling the sandwiched materials at pressure and temperature.

Five trials were made with none producing acceptable results. Although some improvement was made over the first trial, where the laminate stuck to the pressure plate, all plates had surface irregularities, bubbles and sporadic bonding.

No further trials are planned, due to facility work load and overexpenditure of funds by the vendor, although Clad Metals has expressed the opinion that further work might produce acceptable laminates. Since no further work with Clad Metals is anticipated, the vacuum diffusion method currently is the only viable process for the fabrication of laminates.

Salt Spray Test

The salt spray test of laminates, initiated as an IR&D effort prior to the start of this NASA program, was continued to an eighteen months duration. The results are summarized below.

Three parting sheet materials were exposed to salt spray for eighteen months. Six test panels each of (1) AA 3003 aluminum, 0.20 mm (0.008 in.) thick; (2) AISI 347 stainless steel, 0.20 mm (0.008 in.) thick; and (3) 0.10 mm (0.004 in.) AA 3003 aluminum diffusion bonded to both sides of 0.076 mm (0.003 in.) A70 titanium were removed from salt spray and examined for corrosive attack every two months. All observations, in summary form, are shown in figure 21. All specimens were coated at the top surrounding the suspension point with plater's red lacquer to prevent extraneous corrosive attack and to retain the panel. Figures 22 to 27 were extracted from SVME 669[1] and are included here for a comparison of the deterioration at eight months with the 18 month photos in figures 28 to 32.

All aluminum panels were heavily attacked by the salt environment and three of the six had through pits in the center of the panel (see figure 27). Figure 28, a higher magnification of test panel A2, shows an edge pit on

[1] SVME 669 - Memo, P. Perkins to L. Desjardins, dated Oct. 10, 1973, "Eighth Month Salt Spray Examination - Heat Exchanger Parting Sheet Materials".

		MONTH OF TEST								
		2	4	6	8	10	12	14	16	18
Specimen		4/3/73	6/1/73	7/27/73	10/2/73	12/4/73	2/15/74	4/17/74	6/19/74	8/19/74
Aluminum	A1	Very Light Pitting and Surf. Attack	Blotchy Pitting Light Surf. Attack	Blotchy Pitting Light Surf. Attack	Light Pitting Light Surf. Attack	Light Pitting Light Surf. Attack	Light Pitting Med. Surf. Attack	Light Pitting Med. Surf. Attack	Medium Pitting Heavy Surf. Attack	Med-Heavy Pitting Heavy Surf. Attack
	A2	Very Light Pitting and Surf. Attack	Blotchy Pitting Med. Surf. Attack	Blotchy Pitting Med. Surf. Attack	Light Pitting Med. Surf. Attack	Light Pitting Med. Surf. Attack	Light Pitting Med. Surf. Attack	Light Pitting Hvy Surf. Attack	Medium Pitting Hvy Surf. Attack	2 Pits Thru Ctr & 1 Edge Hvy Surf. Attack
	A3	Very Light Pitting and Surf. Attack	Blotchy Pitting Med. Surf. Attack	Blotchy Pitting Med. Surf. Attack	Light Pitting Med. Surf. Attack	Med. Pitting Med. Surf. Attack	Med. Pitting Med. Surf. Attack	Med. Pitting Med. Surf. Attack	1 Pit Thru & 1 Edge Hvy Surf. Attack	2 Pits Thru Ctr & 1 Edge Hvy Surf. Attack
	A4	Very Light Pitting	Blotchy Pitting Med. Surf. Attack	Blotchy Pitting Med. Surf. Attack	Light Pitting Med. Surf. Attack	Med. Pitting Med. Surf. Attack	Med. Pitting Med. Surf. Attack	Med. Pitting Hvy Surf. Attack	Med-Hvy Pitting Hvy Surf. Attack	Unlacquered Portion Lost
	A5	Very Light Pitting	Light Pitting Med.-Hi Surf. Attack	Blotchy Pitting Med. Surf. Attack	Lt. Pit 1 Edge Thru Med. Surf. Attack	M. Pit 1 Edge Thru Med. Surf. Attack	M. Pit 1 Edge Thru Med. Surf. Attack	H. Pit 1 Edge Thru Hvy Surf. Attack	H. Pit 1 Edge Thru Hvy Surf. Attack	1 Pit Thru Ctr & 1 Lg Edge Heavy Surf. Attack
	A6	Medium Surface Corrosion	Lt-Med Pitting Med. Surf. Attack	Edge Pit Through Med. Surf. Attack	Edge Pit Through Hvy Surf. Attack	1 Edge Pit Thru Hvy Surf. Attack	1 Edge Pit Thru Hvy Surf. Attack	M. Pit 1 Edge Thru Hvy Surf. Attack	M. Pit 1 Edge Thru Hvy Surf. Attack	1 Large Edge Pit Heavy Surf. Attack
Stainless Steel	S1	No Corrosion	No Corrosion Rust Stain Top	Hvy Rust Stain Shallow Surf. Crater	Heavy Rust Stain Shallow Crater	Heavy Rust Stain Shallow Crater	Heavy Rust Stain Shallow Crater	Heavy Rust Stain Shallow Crater	Heavy Rust Stain A Med. Crater	Heavy Rust Stain A Medium Crater
	S2	No Corrosion	No Corrosion Rust Stain Top	No Corrosion Rust Stain	Heavy Rust Stain Shallow Crater	Heavy Rust Stain Shallow Crater	Heavy Rust Stain Shallow Crater	Heavy Rust Stain Shallow Crater	Heavy Rust Stain Shallow Crater	Heavy Rust Stain Shallow Crater
	S3	No Corrosion	No Corrosion	Heavy Rust Stain Shallow Surf. Crater	Heavy Rust Stain Shallow Surf. Crater	Heavy Rust Stain Sm. Surf. Crater	Heavy Rust Stain Sm. Surf. Crater	Heavy Rust Stain Sm. Surf. Crater	Heavy Rust Stain Sm. Surf. Crater	Heavy Rust Stain Small Surf. Crater
	S4	No Corrosion	1 Sm. Pit	Rust Stain Shallow Surf. Crater	Light Rust Stain Shallow Surf. Crater	Light Rust Stain Sm. Surf. Craters	Light Rust Stain Sm. Surf. Craters	Light Rust Stain Sm. Surf. Craters	Heavy Rust Stain Sm. Surf. Craters	Heavy Rust Stain Small Surf. Craters
	S5	No Corrosion	No Corrosion Rust Stain Top	No Corrosion Rust Stain Top	No Corrosion Heavy Rust Stain	No Corrosion Heavy Rust Stain	No Corrosion Heavy Rust Stain	No Corrosion Heavy Rust Stain	No Corrosion Heavy Rust Stain	No Corrosion Heavy Rust Stain
	S6	No Corrosion	No Corrosion Rust Stain Top	Heavy Rust Stain No Corrosion	Heavy Rust Stain No Corrosion	Heavy Rust Stain Small Craters	Heavy Rust Stain Small Craters	Heavy Rust Stain Small Craters	Heavy Rust Stain Small Craters	Heavy Rust Stain Small Surf. Crater
Titanium Laminate	T1	Lt-Med. Pitting	Light Pitting & Surf. Attack	Light Pits to Ti Med Hy Surf. Attack	Light Pits to Ti Hvy Surf. Attack	Light Pits to Ti Hvy Surf. Attack	Med Pits to Ti Hvy Surf. Attack	$<$5% Ti Exposed Hvy Surf. Attack	~ 5% Ti Exposed Hvy Surf. Attack	~ 5% Ti Exposed Hvy Surf. Attack
	T2	Light Pitting	1 Pit to Ti	Lt Pitting to Ti Med-Hy Surf. Attack	Lt Pitting to Ti Hvy Surf. Attack	Hvy Pitting to Ti Hvy Surf. Attack	Hvy Pitting to Ti Hvy Surf. Attack	~20% Ti Exposed Heavy Surf. Attack	~ 75% Ti Exposed Hvy Surf. Attack	~ 90% Ti Exposed Heavy Surf. Attack
	T3	Lt-Med Pitting (1 Lg Pit to Center)	Several Pits to Ti Hvy Surf. Attack	Med Pitting to Ti Med-Hy Surf. Attack	Med Pitting to Ti Hvy Surf. Attack	Hvy Pitting to Ti Hvy Surf. Attack	Heavy Pitting to Ti Hvy Surf. Attack	~ 5% Ti Exposed Hvy Surf. Attack	~ 40% Ti Exposed Hvy Surf. Attack	~ 60% Ti Exposed Heavy Surf. Attack
	T4	Med. Pitting	4 Pits to Ti Med-Hy Surf. Attack	Med Pitting to Ti Med-Hy Surf. Attack	Hvy Pitting to Ti Hvy Surf. Attack	Hvy Pitting to Ti Hvy Surf. Attack	Heavy Pitting to Ti Hvy Surf. Attack	~ 10% Ti Exposed Hvy Surf. Attack	~ 60% Ti Exposed Hvy Surf. Attack	~ 90% Ti Exposed Heavy Surf. Attack
	T5	Med-High Pitting Over Lg. Area	Several Pits to Ti Hvy Surf. Attack	Hvy Pits to Ti Hvy Surf. Attack	Heavy Pitting to Ti Hvy Surf. Attack	50% Ti Exposed Hvy Surf. Attack	$>$ 50% Ti Exposed Hvy Surf. Attack	$>$ 50% Ti Exposed Hvy Surf. Attack	~ 80% Ti Exposed Hvy Surf. Attack	~ 90% Ti Exposed Heavy Surf. Attack
	T6	Lt-Med Pitting	Med. Pitting Med-Hy Surf. Attack	Lt Pitting to Ti Med-Hy Surf. Attack	Lt Pitting to Ti Hvy Surf. Attack	Med Pitting to Ti Hvy Surf. Attack	Hvy Pitting to Ti Hvy Surf. Attack	$<$ 5% Ti Exposed Hvy Surf. Attack	~ 40% Ti Exposed Hvy Surf. Attack	~ 60% Ti Exposed Hvy Surf. Attack

NOTE: TEST STARTED IN FEBURARY, 1973

FIGURE 21 SALT SPRAY VISUAL EXAMINATION

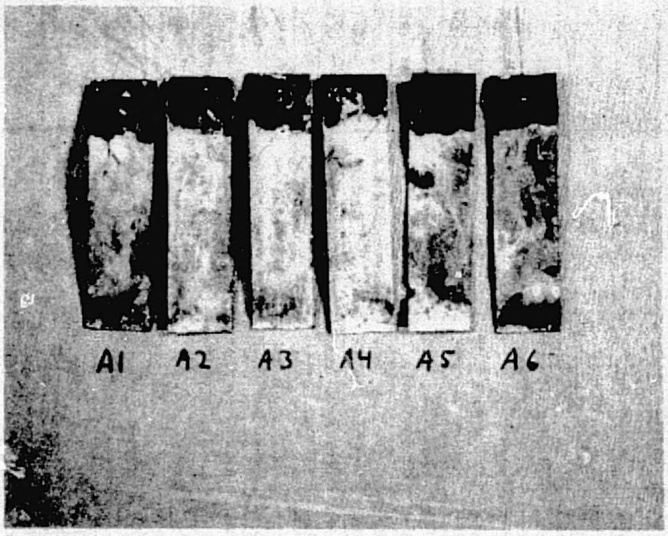


Fig. 22 Aluminum Panels After 8 Months of Salt Spray Exposure

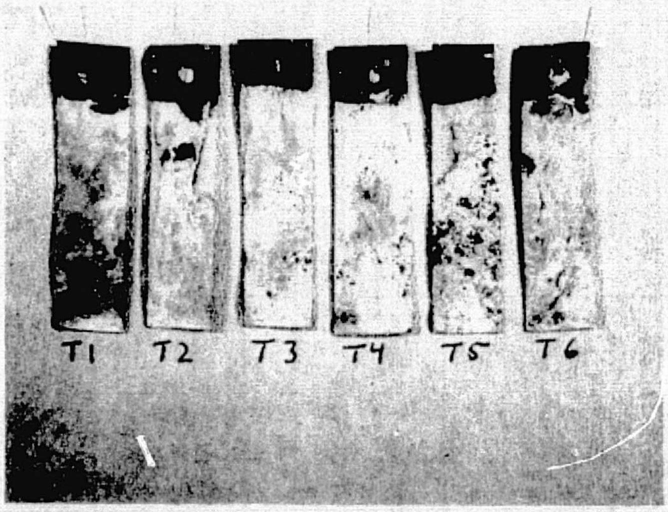


Fig. 23 Aluminum-Titanium Laminate Panels After 8 Months of Salt Spray Exposure

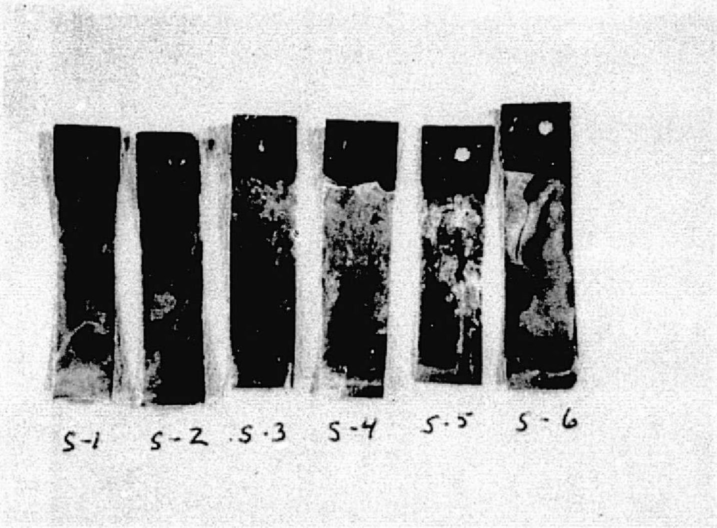


Fig. 24 Stainless Steel Panels After 8 Months of Salt Spray Exposure

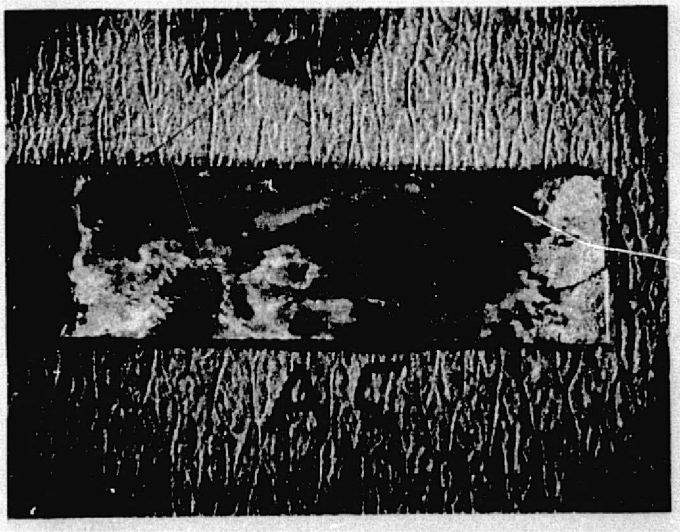


Fig. 25 Aluminum Panel, Showing Through Pitting (Lower Right)

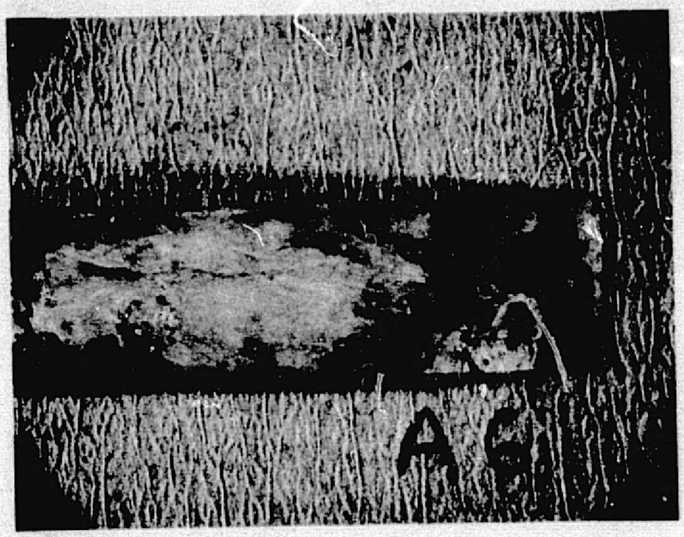


Fig. 26 Aluminum Panel, Showing Through Pitting (Lower Right)

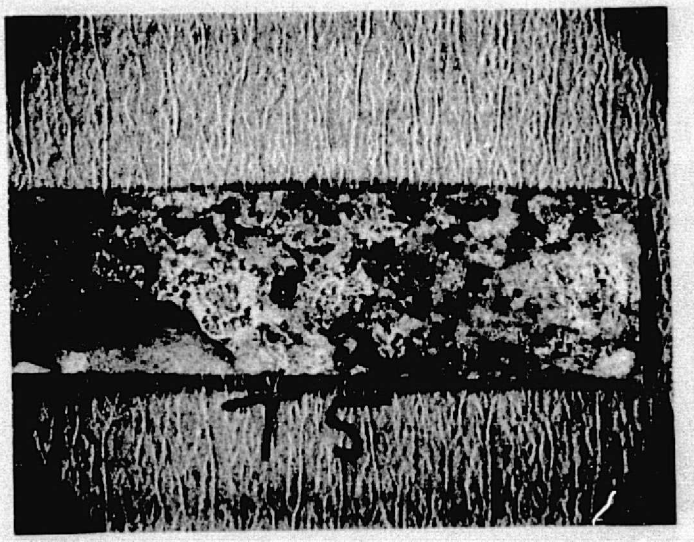
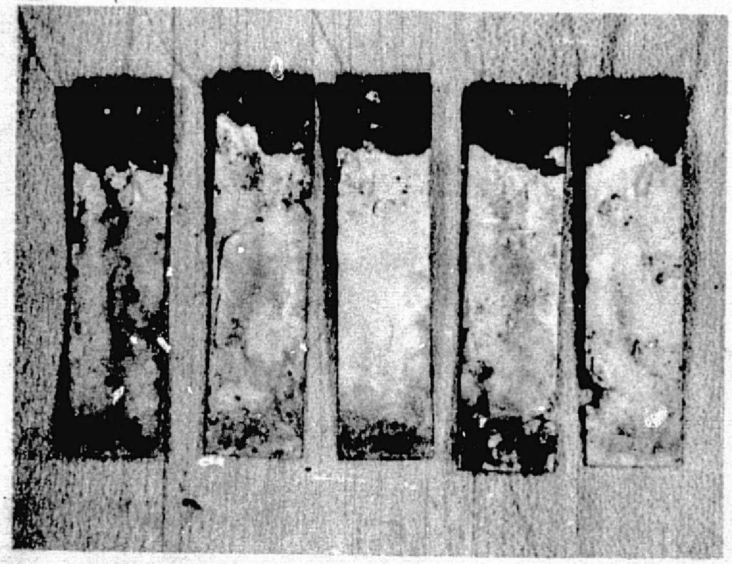


Fig. 27 Aluminum-Titanium Laminate, Showing Extensive Surface Corrosion Exposing Titanium Centerstrate



A1 A2 A3 A5 A6

FIG. 28 - ALUMINUM PANELS AFTER 18 MONTHS SALT SPRAY 1.2X

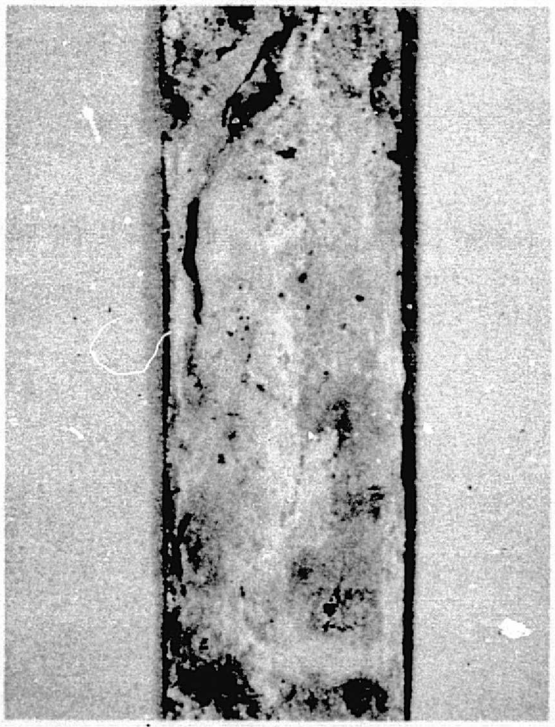
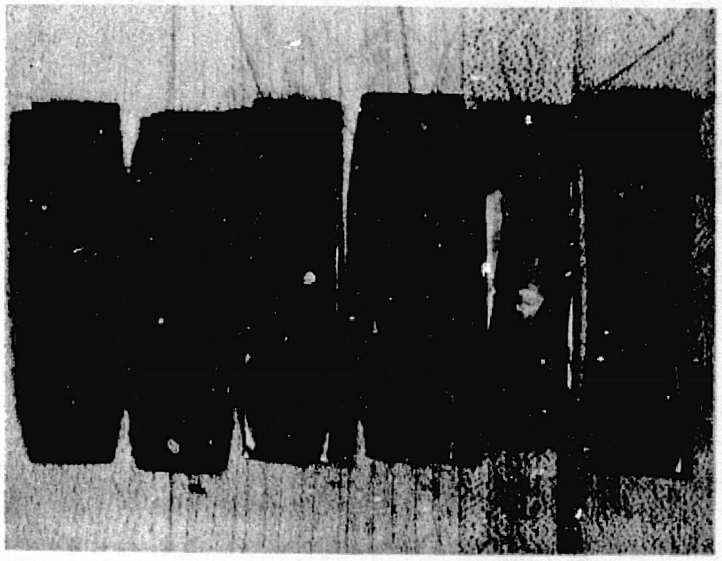
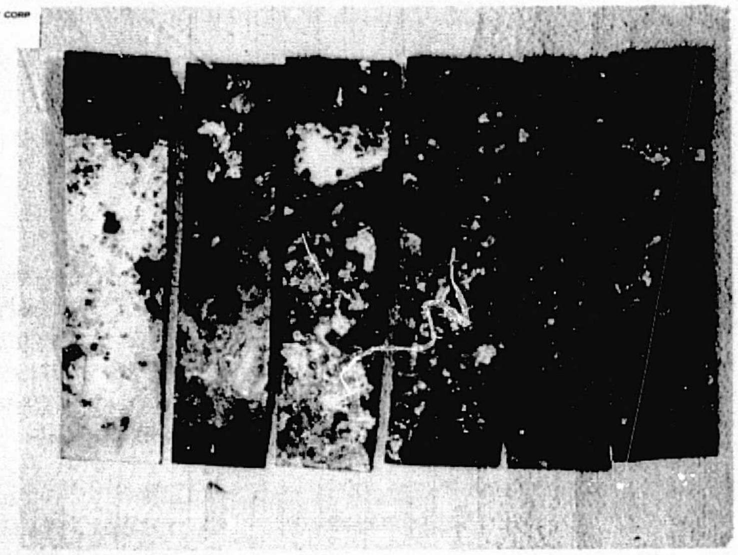


FIG 29 - ALUMINUM PANEL, A2, AFTER 18 MONTHS SALT SPRAY 2.7X



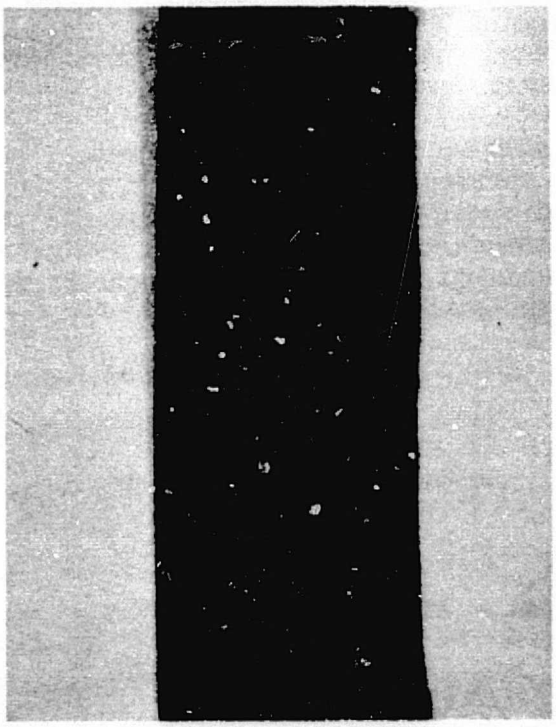
S1 S6

FIG 30 - STAINLESS STEEL PANELS AFTER 18 MONTHS SALT SPRAY 1.2X



T1 T6

FIG. 31 - ALUMINUM/TITANIUM LAMINATED PANELS AFTER 18 MONTHS SALT SPRAY 1.2X



ORIGINAL PAGE IS OF POOR QUALITY

FIG. 32 - ALUMINUM/TITANIUM LAMINATED PANEL, T5 (WHITE AREAS AL CORROSION PRODUCTS) 2.7X

the upper side of the panel and two through center pits in the lower right of the panel. Severe crevice corrosion was present beneath the plater's lacquer at the top of all aluminum panels. Most of specimen A4 was lost during testing due to the separation of the panel from the lacquered section, which resulted from the crevice corrosion cell formed under the lacquer.

The stainless steel specimens were only superficially attacked (see figure 30). All test pieces were covered with a rust stain emanating from the lacquer/metal crevice. No pitting attack was evident on the exposed panel except for some very shallow craters. However, some small pits were found beneath the lacquer accounting for the rust stain noted.

In contrast to the aluminum panels, the aluminum/titanium laminate panels did not show any through pits. However, the aluminum layers in these laminate specimens were more severely attacked than the plain aluminum specimens. The advanced stage of attack shown in figure 31 and magnified in figure 32 results from the galvanic corrosion potential of aluminum in contact with titanium. Most test panels retained little metallic aluminum after 18 months. Metallographic inspection of T5 after mounting and polishing indicated that some minor corrosive attack had begun on the exposed titanium center stratum.

While the 18 month salt spray exposure is extremely severe, it cannot be directly related to service life. However, in this case a comparison between the proposed aluminum/titanium laminate and the two common parting sheet materials, aluminum and stainless steel indicates that the aluminum/titanium laminate resisted through pitting much better than aluminum and equally as well as the stainless steel.

DESIGN OF FULL SCALE HEAT EXCHANGER

The design of the heat exchanger was accomplished in three steps, analytical sizing, design layout and detail drawings.

Analytical Sizing

Based upon the design requirements listed in Table X, eight configurations were analyzed to allow selection of the configuration for the final design.

Four cases (1-4) were studied to evaluate the effect of varying the air side fin height for a stainless steel design with the passages arranged:

air
primary coolant
air
redundant coolant
air
etc.

Figure 33 shows that a fin height of approximately 2.54 mm (0.10 in.) results in lowest mass.

Case five was then analyzed for comparison with case three (the lightest configuration of the first four), to evaluate an alternate passage arrangement:

air
primary coolant
redundant coolant
air
primary coolant
redundant coolant
air
etc.

TABLE X HEAT EXCHANGER DESIGN REQUIREMENTS

Parameter	Specification		Design Point	
	S.I. Units	U.S. Units	S.I. Units	U.S. Units
Outlet Total Pressure	101.4 $\pm$ 0.14 kN/m^2	14.7 $\pm$ 0.2 psia	101.4	14.7
PPO_2	21.37 $\pm$ 0.07 kN/m^2	3.1 $\pm$ 0.1 psia	21.37	3.1
Gas Flow	399.16 kg/hr	880 lbs/hr	399.16	880.0
Gas Inlet Pressure	295-309 K	71-97°F	309	97.0
Gas Outlet Pressure	280-283 K	45-50°F	283	50.0
Inlet Dew Point	277-289 K	39-61°F	289	61.0
H_2O Inlet Temperature	277.4 K	40°F	277.4	40.0
H_2O Flow	272.16 kg/hr	600 lbs/hr	272.16	600.0
H_2O Inlet Pressure	413.69 kN/m^2	60 psia	413.69	60.0
Maximum Air Side Δ P	96.3 N/m^2	0.5 in H_2O	96.3	0.387

The result indicates a small weight advantage for case five where the two coolant passages are adjacent to one another.

Three cases were then analyzed (6-8) to evaluate the effect of varying the air side fin height for an aluminum heat exchanger whose primary and redundant coolant passages are adjacent to one another. Figure 34 shows the lowest mass is achieved with a fin height of 3.15 mm (0.080 in.) or greater.

Experience has shown that the greatest practicable fin height in aluminum is 8.26 mm (0.325 in.). Therefore, the final design utilized two layers of 8.26 mm (0.325 in.) fins to achieve a total practicable fin height of 1.652 cm (0.650 in.). A further manufacturing consideration included increasing cold side fin height from 1.25 mm (0.050 in.) to 1.83 mm (0.072 in.). These two changes in fin height resulted in a core with more hot and cold side layers as well as different hot and cold side lengths. As a result, and including maximum tolerances, instead of the nominal dimensions used in the preliminary cases, the final maximum heat exchanger mass was 90.52 N (20.35 lbs) or 50.2 percent of the lightest stainless steel configuration (case 3). The calculated effectiveness of the aluminum heat exchanger, 0.8331 is almost identical to the effectiveness of the stainless steel heat exchanger, 0.8325. The nine cases analyzed are summarized in Table XI.

Design Layout

In addition to the thermal design discussed in the previous section, other design considerations were as follows:

Life	25,000 hours
Proof Pressure	
Water Side	718 kN/m^2 (90 psig)
Air Side	34.47 kN/m^2 (5 psid)
Leakage	No bubbles at proof pressure
Vibration	See figure 35
Air Side Δ P	124.2 N/m^2 (0.50 in. H_2O)

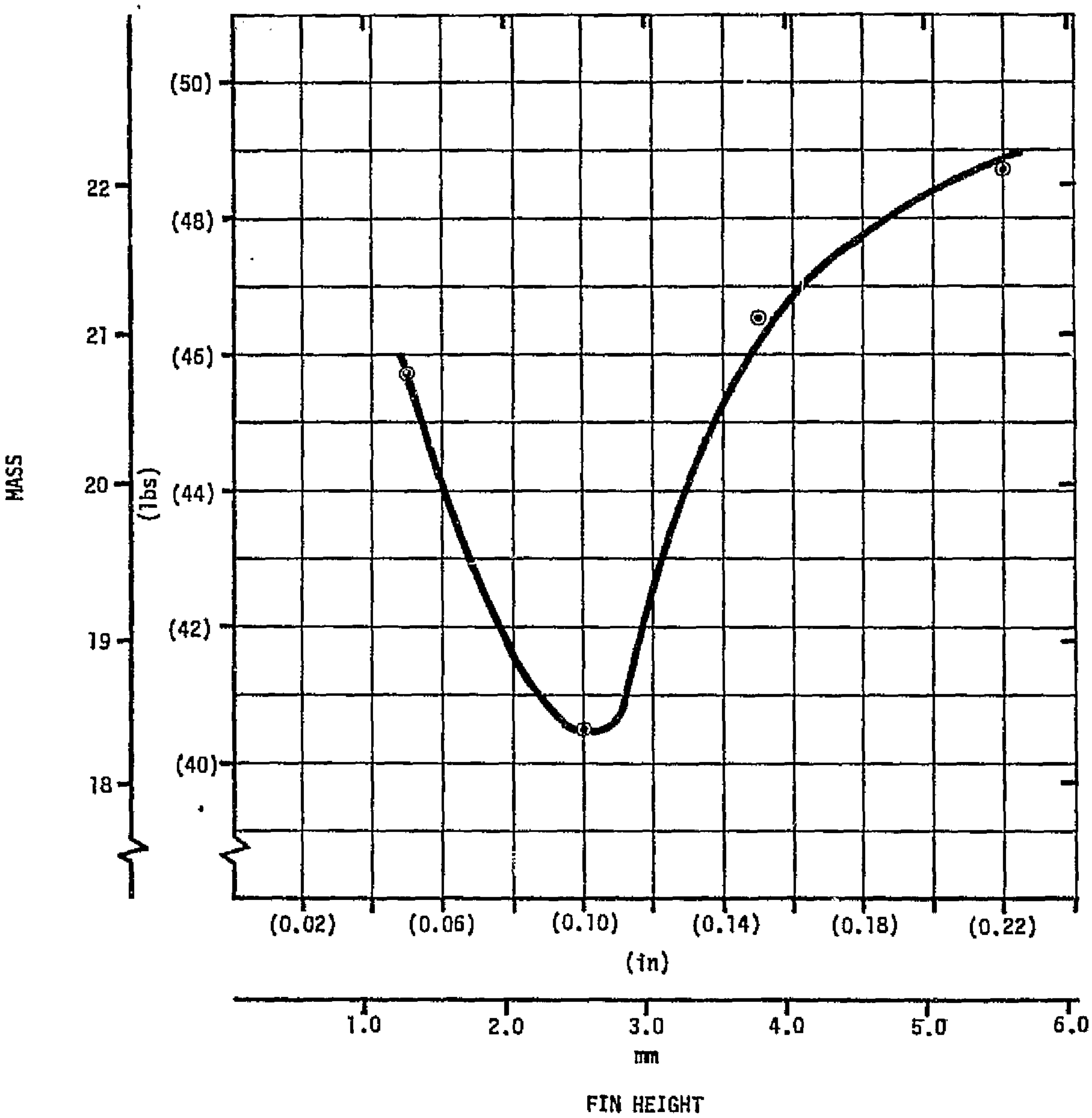


FIGURE 33 MASS vs. AIRSIDE FIN HEIGHT FOR STAINLESS STEEL HEAT EXCHANGER

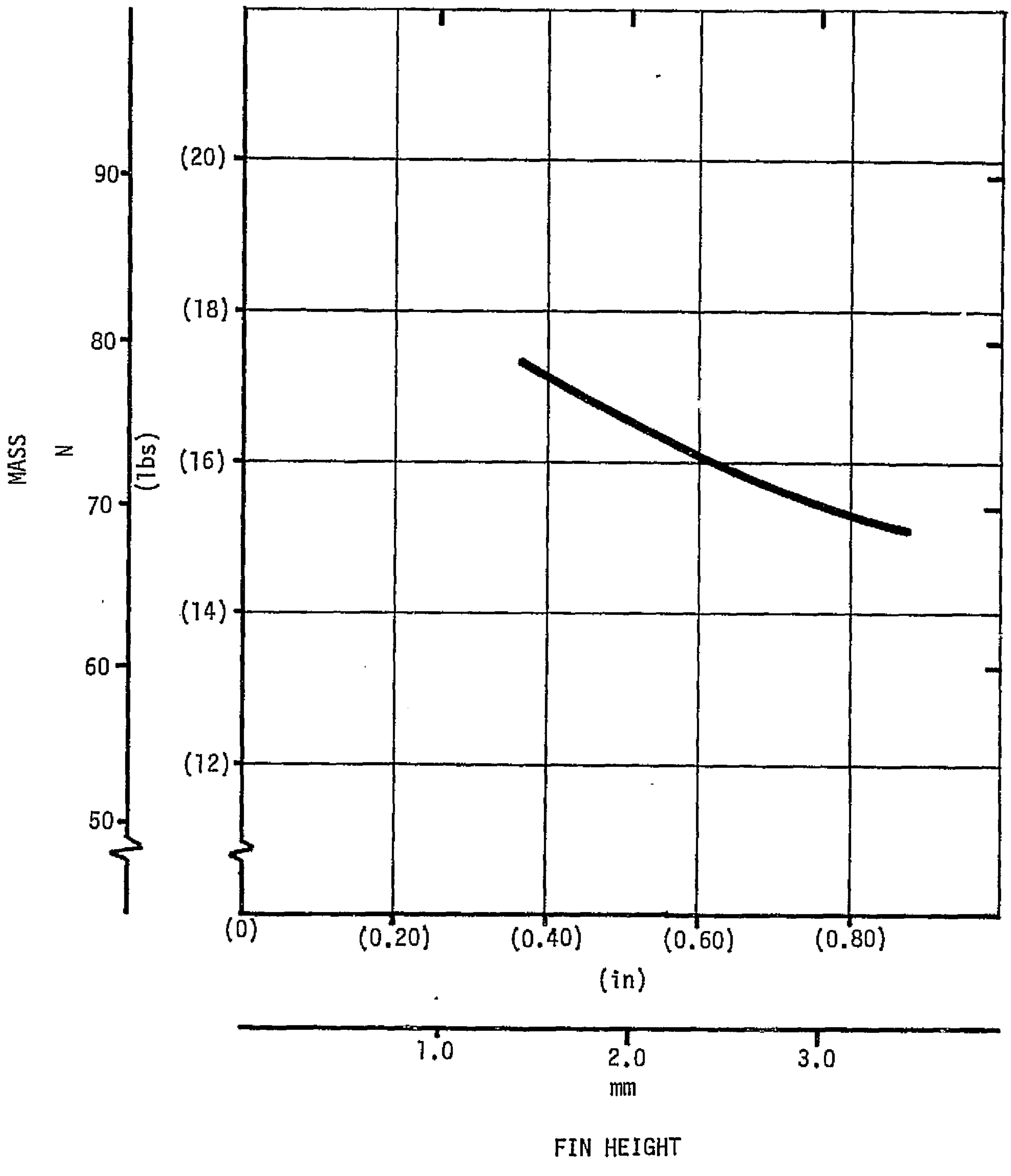


FIGURE 34 MASS vs. AIRSIDE FIN HEIGHT FOR ALUMINUM HEAT EXCHANGER

TABLE XI DESCRIPTION OF ANALYTICAL CASES - S.I. AND STANDARD UNITS

Material	1 CRES	2 CRES	3 CRES	4 CRES	5 CRES	6 Al	7 Al	8 Al	9 Al
Hot Flow Length cm (in.)	37.08 (14.6)	13.97 (5.5)	21.34 (8.4)	28.19 (11.1)	22.48 (8.85)	25.91 (10.2)	23.28 (9.4)	22.35 (8.8)	25.15 (9.9)
Cold Flow Length cm (in.)	25.40 (10.0)	23.88 (9.4)	25.02 (9.85)	24.64 (9.7)	25.02 (9.85)	21.84 (8.6)	21.34 (8.4)	20.32 (8.0)	21.84 (8.6)
No. Hot Fin Layers	34	124	62	46	32	9	12	17	11
No. Cold Fin Layers	35	125	63	47	66	20	26	36	24
Hot Fin (Ruffled)									
Fin Height mm (in.)	5.59 (0.220)	1.27 (0.050)	2.54 (0.100)	3.81 (0.150)	5.08 (0.200)	20.32 (0.800)	15.24 (0.600)	11.18 (0.440)	16.56 (0.652)
Fin Density cm (in.)	5.51 14	5.51 14	5.51 14	5.51 14	5.51 14	5.51 14	5.51 14	5.51 14	5.51 14
Fin Thickness mm (in.)	0.051 (0.002)	0.051 (0.002)	0.051 (0.002)	0.051 (0.002)	0.051 (0.002)	0.127 (0.005)	0.127 (0.005)	0.127 (0.005)	0.127 (0.005)
Cold Find (Ruffled)									
Fin Height mm (in.)	1.27 (0.050)	1.27 (0.050)	1.27 (0.050)	1.27 (0.050)	1.27 (0.050)	1.27 (0.050)	1.27 (0.050)	1.27 (0.050)	1.83 (0.072)
Fin Density cm (in.)	4.72 12	4.72 12	4.72 12	4.72 12	4.72 12	4.72 12	4.72 12	4.72 12	4.72 12
Fin Thickness mm (in.)	0.051 (0.002)	0.051 (0.002)	0.051 (0.002)	0.051 (0.002)	0.051 (0.002)	0.127 (0.005)	0.127 (0.005)	0.127 (0.005)	0.127 (0.005)
No. Passes Hot	1	1	1	1	1	1	1	1	1
No. Passes Cold	6	6	6	6	6	6	6	6	6
Weight kg (lbs)	22.09 (48.71)	20.73 (45.71)	18.37 (40.51)	21.12 (46.57)	17.43 (38.43)	6.94 (15.31)	7.34 (16.19)	7.30 (16.91)	9.23 (20.35)

These requirements were achieved as shown below:

Life	Use of laminated parting sheets achieves objective
Proof	Minimum safety factor is 1.27
Leakage	All brazed as welded construction - no mechanical joints
Vibration	Lowest safety factor is 1.38 (Ref. fig. 35)
Air Side Δ P	Calculated to be 97 N/m^2 (0.39 in. H_2O) or a margin of 22 percent over specification

Figure 36 shows the design layout.

Detail Drawings

Following completion of the layout, figure 36, the final manufacturing drawing was made. The Hamilton Standard drafting system allows the use of a single drawing to define all parts of a brazed and/or welded assembly. Figure 37 shows the manufacturing drawing completely defining the lightweight long life heat exchanger.

Quality Assurance

The design of the unit was such that known quality problems were eliminated. For example, the possibility of trapped brazing flux was avoided by the use of fluxless brazing. The possibility of poorly laminated parting sheets was reduced by the use of 100 percent ultrasonic inspection along with destructive sampling. In addition, the design of the unit was such that cleanliness of all parts could be attained and maintained throughout the assembly and braze process. The unit also is capable of being cleaned, as an assembly, by the use of appropriate flushing procedures.

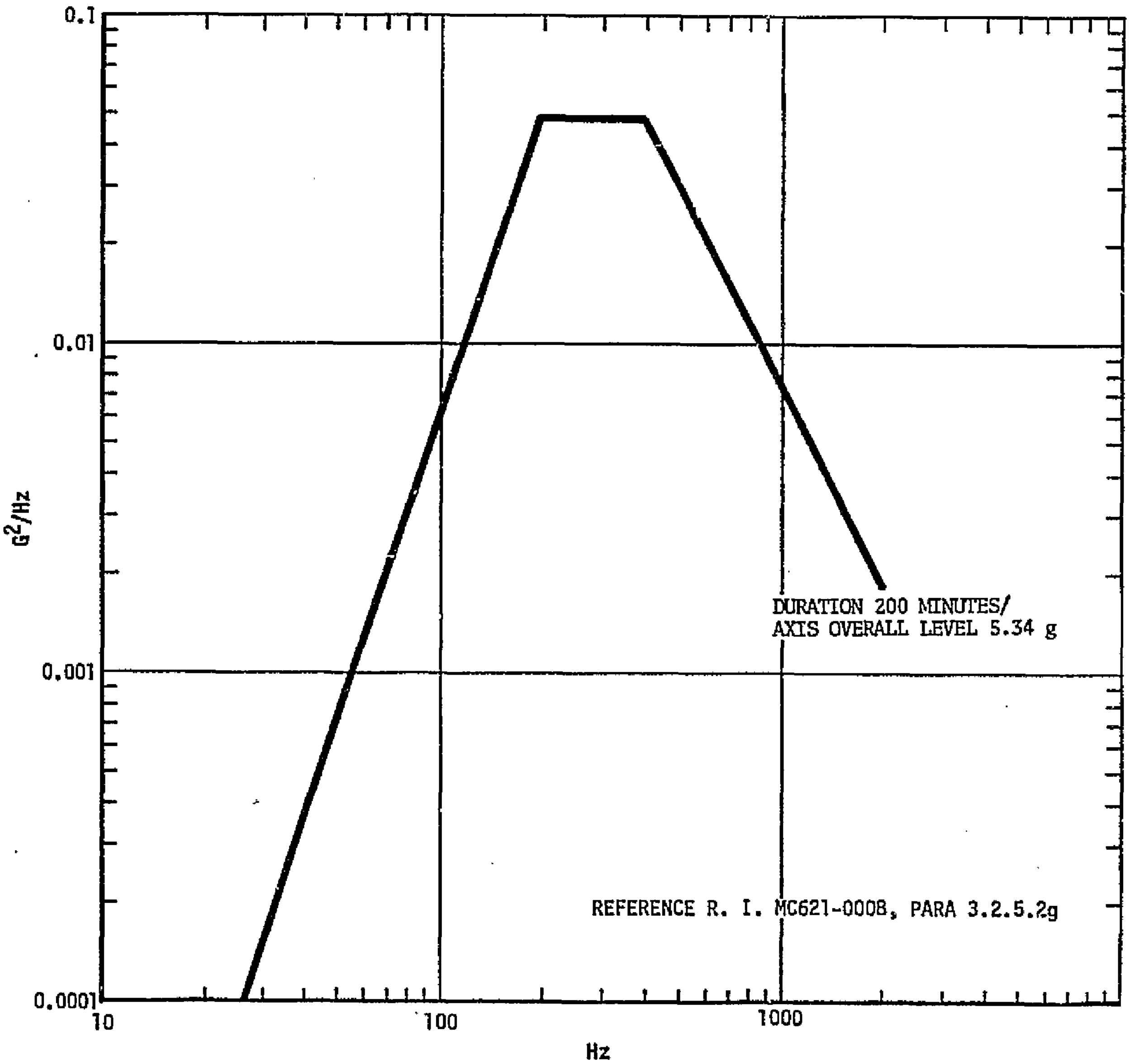
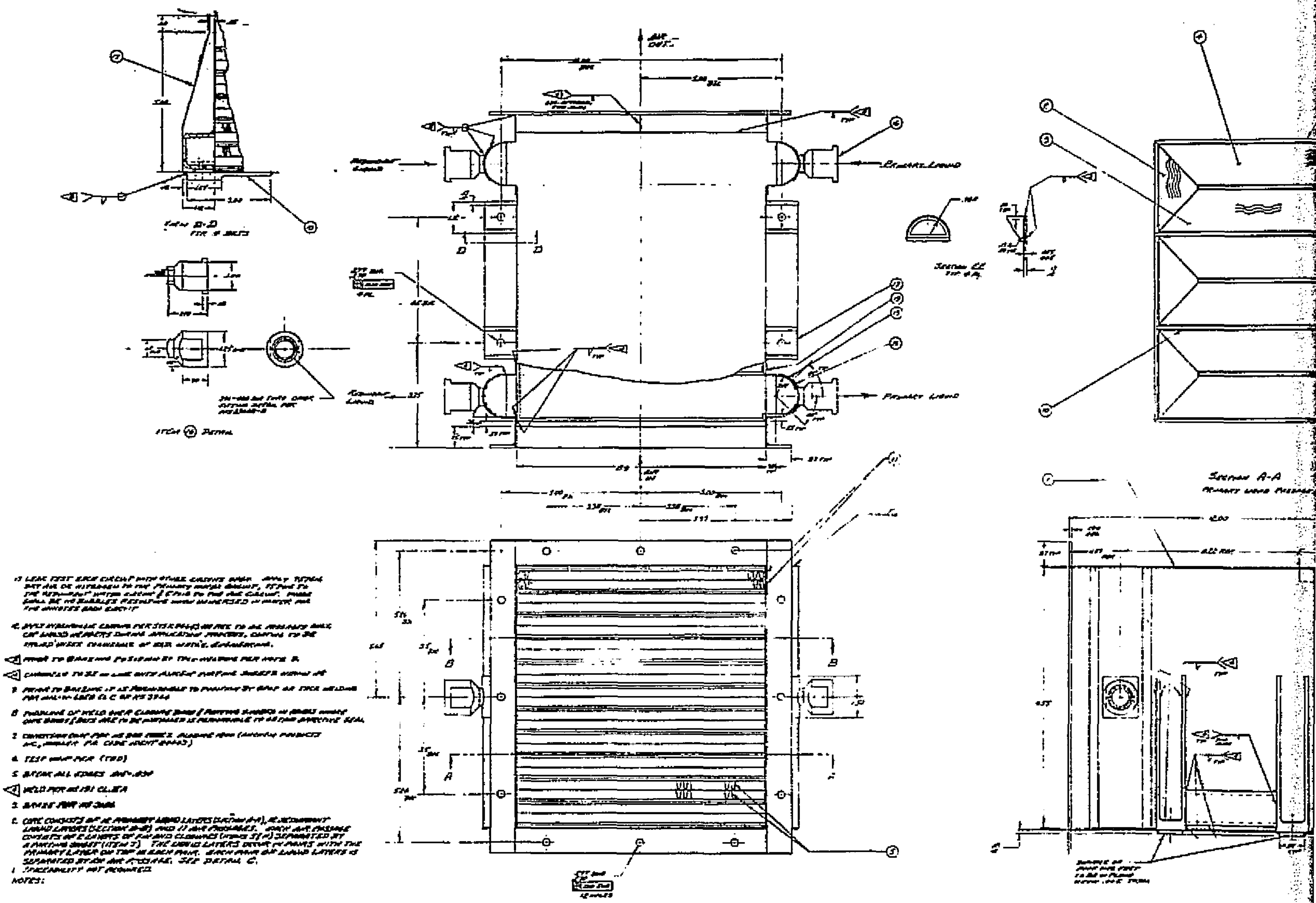
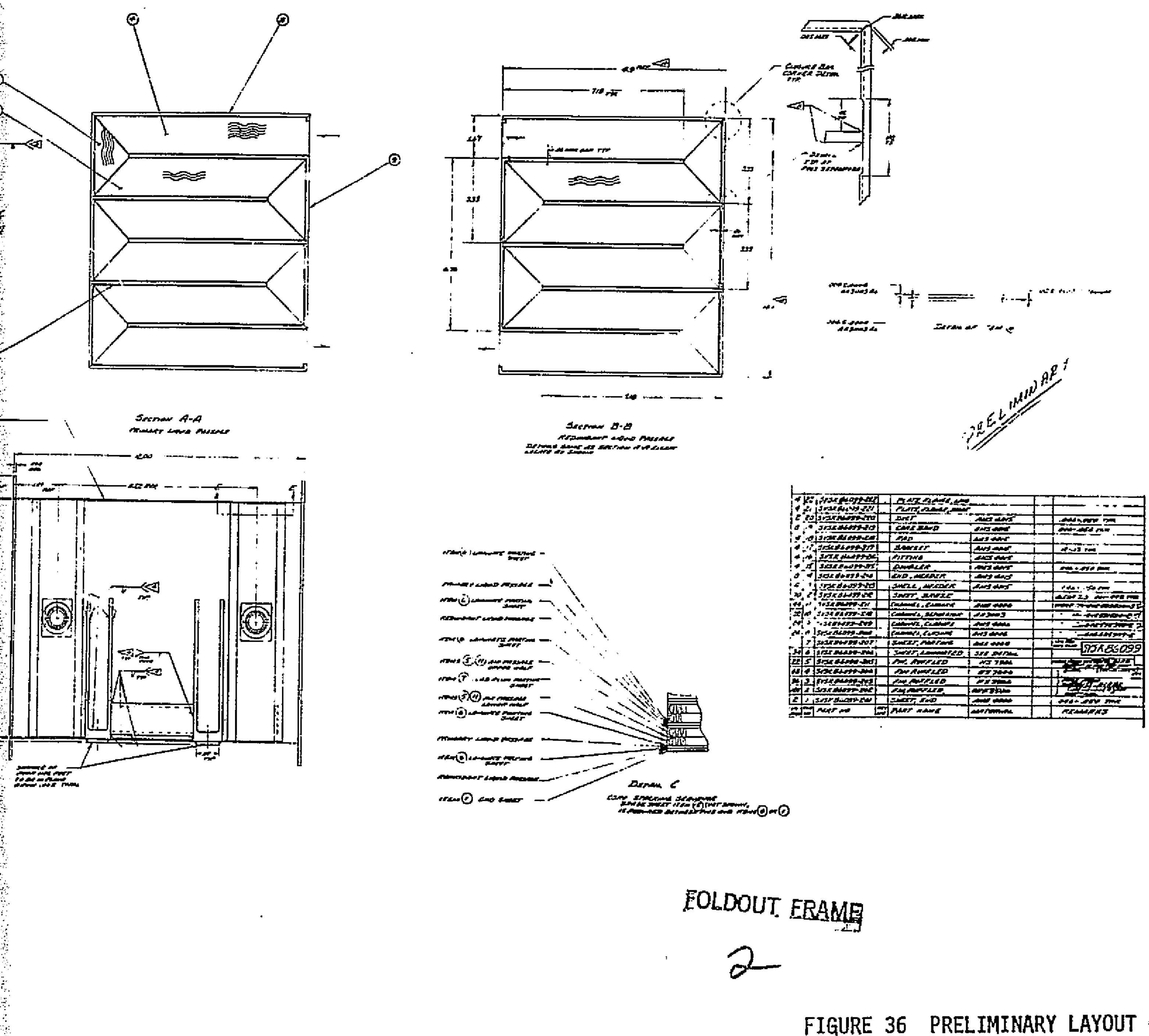


FIGURE 35 LIGHTWEIGHT LONG LIFE HEAT EXCHANGER VIBRATION SPRECTUM



ORIGINAL PAGE IS
OF POOR QUALITY

FOLDOUT FRAME



FOLDOUT FRAME

2

FIGURE 36 PRELIMINARY LAYOUT OF LIGHTWEIGHT LONG LIFE HEAT EXCHANGER

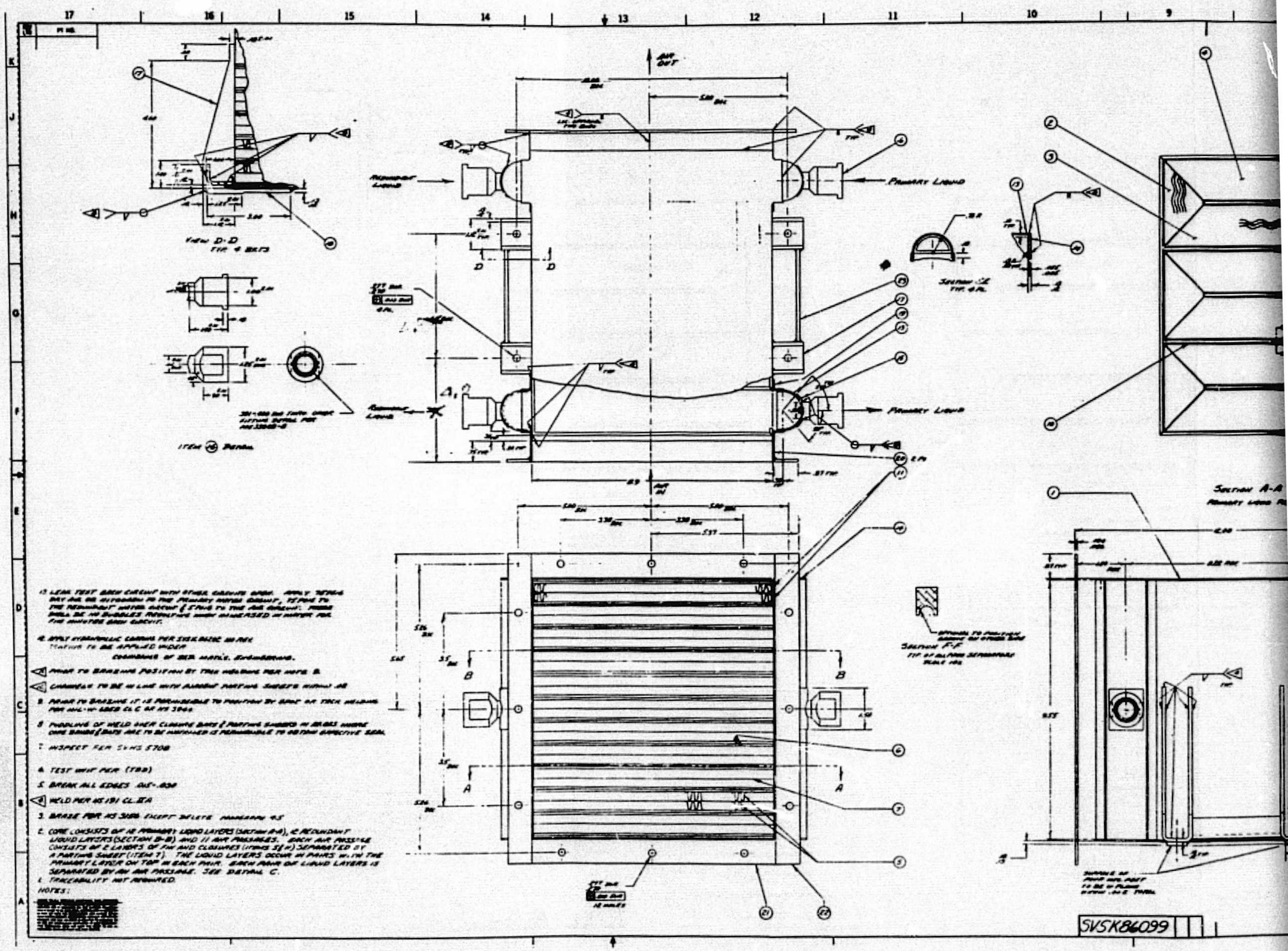
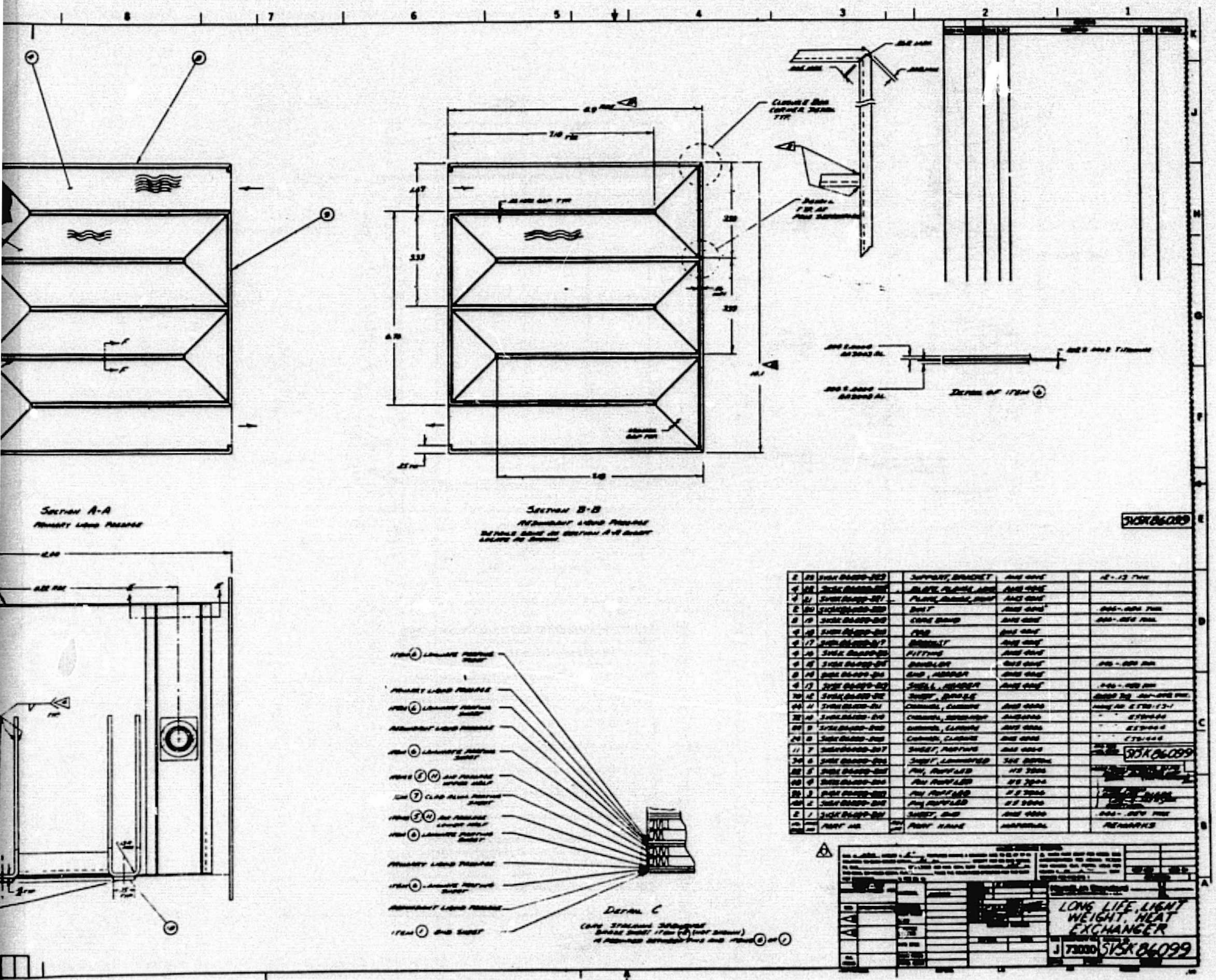


FIGURE 37 MANUFACTURING DRAWING

FOLDOUT FRAME

1



FOLDOUT FRAME

2

Reliability

As a completely brazed and welded unit with no moving parts, the only realistic failure mode is through corrosion of the parting sheets. The use of the laminated titanium sheets precludes this mode of failure. All other parts are tolerant of corrosion because of their thickness.

Safety

The unit was designed with safety margins which have been demonstrated, during previous flight programs, to provide adequate safety margins.

FABRICATION OF HEAT EXCHANGER

The original program plan anticipated the fabrication of a heat exchanger after having certified the brazing process through the successful fabrication of two cores. However, difficulties in the fabrication of the two cores resulted in a more extensive program to solve brazing difficulties and resulted in the ultimate manufacture of two heat exchangers; the first suitable for performance evaluation only and the second suitable for both performance and structural testing.

The fabrication program can be divided into the following four phases.

Initial Phase.- Braze two full size cores with laminate parting sheets.

Corrective Action Phase.- Braze three one-half scale (one-eighth volume) core modules.

Demonstration Phase.- Braze one full scale, all aluminum core.

Final Phase.- Braze final heat exchanger core, using laminate parting sheets.

Initial Phase - First Core

In the initial phase of the program, the first core was stacked and brazed, and in accordance with normal fabrication practices, a test module was brazed with the core. The details of the module were cleaned after the core itself already had been stacked, but using the same cleaning procedures. The sample was stacked and brazed in the same fixture as the core itself and, therefore, reasonably could be expected to resemble the full scale core. All details came from the same lots of material as were used for the actual core. The sample consisted of the following components, in the order in which they were stacked:

1. AMS 4064 braze sheet
2. Liquid pass fins and bars
3. 713 braze foil
4. Composite parting sheet
5. 713 braze foil
6. Liquid pass fins and bars
7. 713 braze foil
8. Composite parting sheet
9. 713 braze foil
10. Air fins and bars
11. AMS 4064 braze sheet.

Visual Examination of the Sample

Both the sample and core were clean and bright after brazing. The test sample was not leak checked since that would have involved welding core bands and was considered unnecessary for metallurgical examination purposes.

The sample was slightly crushed at one liquid face. Some liquid pass closure bars were not properly aligned. The misalignment is believed to have occurred as a result of sliding during brazing rather than during set-up, and was judged to be correctable by more elaborate tooling and set-up procedures, and/or by slowing down the heating rate during the braze cycle. On the core itself, a liquid bar had "popped" out of the plane of the core face and had to be sealed by welding.

Tensile and Tear Tests of the Sample

Seven tensile specimens approximately 6.45 cm^2 (1 $in.^2$) were extracted from the test sample, adhesive bonded to test grips, and tensile tested in the no-flow direction with the following results:

Specimen Location	Fracture Stress kN/m^2	(psi)	Fracture Location
Liquid internal hardware fin intersection	2813	(408)	Liquid pass, 100% fin fract.
Liquid internal hardware fin intersection	2772	(402)	Liquid pass, 100% fin fract.
Liquid internal hardware fin intersection	3103	(450)	Liquid pass, 100% fin fract.
Across flow sep. bar	2841	(412)	Air fin at composite sheet braze; 1 fin unbrazed; braze coverage approx. 80%.
Mid heat exchanger area between separator bars	3185	(462)	Liquid pass 100% fin fract. and partial air side fin fracture; air side braze 60% coverage.

Specimen Location	Fracture Stress kN/m^2	(psi)	Fracture Location
Mid heat exchanger area between separator bars	2903	(421)	Mainly liquid pass with 100% fin fracture plus random braze cover on air side.
Mid heat exchanger area between separator bars	2510	(364)	Liquid pass, 100% fin fract.

Tensile data provides an indication of the magnitude of pressure the core can survive providing there are no unbrazed areas. The air side fractures were against the composite parting sheet adjacent to the liquid pass. Evidence indicated the less-than-optimum braze in that area was probably due to a non-uniform fin height rather than brazeability of the composite sheet.

Tear tests confirmed that the sample, as a whole, met internal braze requirements. It was not possible to rip the parting sheets off either the closure bars or pass separator bars, thus indicating sound braze in those areas.

No tear or tensile test specimen showed any evidence of lack of bond between the aluminum parting sheet surface and its titanium substrate.

Metallography

Nine metallographic cross-sections were extracted, mounted and polished, representing various areas of the sample. In general, liquid fin joints were wider than five times the fin thickness, with joints on the composite sheets having slightly more rounded fillets than joints to the conventional braze sheet. Air fin joints were generally three to four times the air fin thickness, with occasional joints lower to nonexistent. The width of the air fin and liquid fin joints appears to be related to the original fin shape.

All pass separator and closure bars examined were 90 to 100 percent brazed, although fillets were generally not well rounded.

There were general areas where a portion of the braze foil, instead of laying on the parting sheet, formed a bridge between the fin and the sheet.

This did not appear to affect the fin joint itself. The same effect had been observed in conventional production cores at end sheets and therefore was not peculiar to these composite sheets.

An intermetallic compound, probably TiAl or Ti_3 Al or $TiAl_3$ exists between the aluminum and titanium, approximately 0.00254 to 0.00762 mm (1×10^{-4} to 3×10^{-4} inches) thick. There was no evidence of any separations between the aluminum and the compound, or the compound and the titanium, and no microcracking was observed.

In summary, the test sample metallurgically indicated a good core braze, well within Hamilton Standard's braze requirements. No adverse effects were attributable to the use of the composite Ti/Al parting sheet.

The core itself had three observable faults. Along the air passage direction, the core appeared slightly pinched at the passage ends, a condition which is not unusual in conventional cores and which can be corrected by adjustment of loading during braze. In addition and apparently as a result of this loading, water circuit closure bars popped out in places and some air circuit crushing occurred. Finally, there were visible incompletely brazed areas.

None of these faults, however, appeared to be sufficiently significant to warrant discarding the core. Figure 38 shows both the ends of the air passages and oblique views of the water circuit outlets. Closure bar and incomplete braze faults were repaired by welding, a normal procedure. Core bands were added around the water circuit openings to facilitate attachment of fixtures. The unit then was subjected to core proof and leakage testing.

During this process, the core is pressurized to proof levels and submerged in water to locate pressure leaks. Several repair welding cycles are usually required on new cores to achieve pressure integrity.

After the fifth repair cycle it was evident that further leakages were being created by this cycle, in a self-defeating manner. At this point, repair welds had built up to an unacceptable degree.

The core then was examined to establish the exact nature of the problem. Figure 39 is a photomicrograph of a typical leakage area, occurring over a large percentage of the brazed joints and shows the separation of previously brazed joints. It was reasoned that this braze joint cracking was caused either by residual stresses, resulting from expansion differences between the aluminum and the composite parting sheets, or by weld induced stresses.

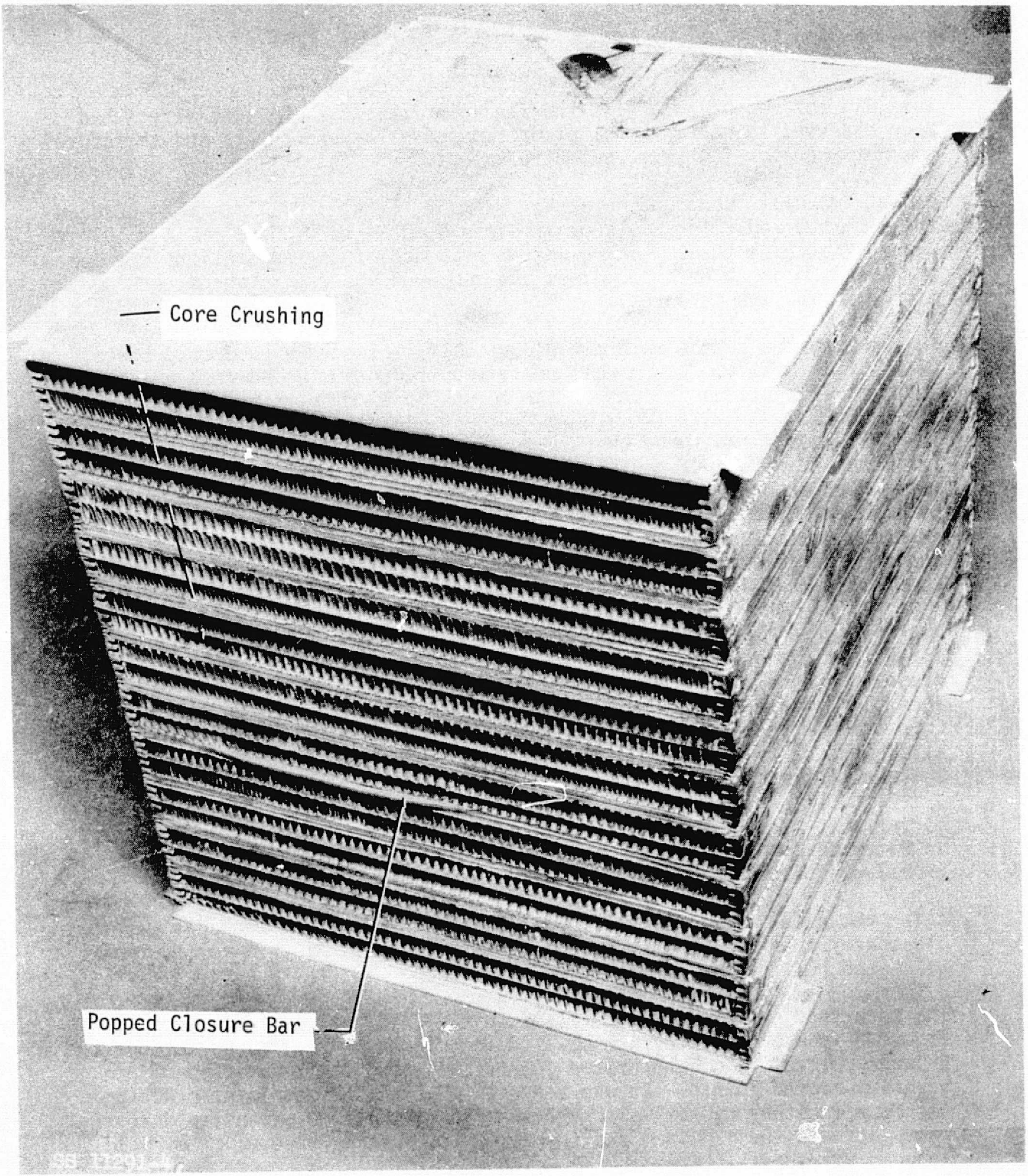


FIGURE 38 FIRST LLL-HX CORE INNEDIATELY AFTER BRAZE

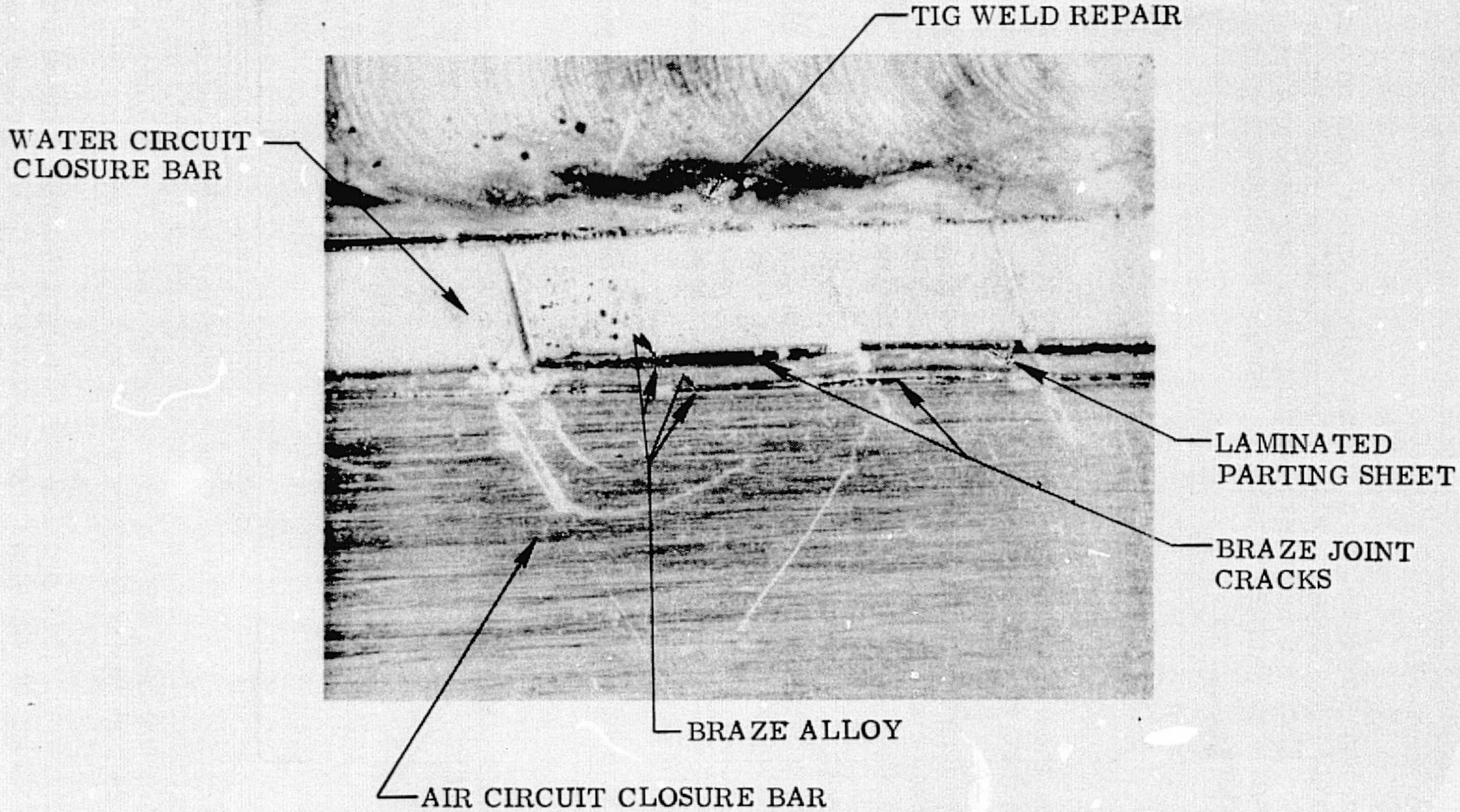


FIGURE 39 CORE NO. 1 - TYPICAL LEAKAGE POINTS AFTER FIFTH REPAIR CYCLE

The core then was subjected to a stress relief cycle with no further observable cracking. Repair welds were quite large relative to the joint being sealed. Electron beam seal welding then was used successfully to seal joints with no further cracking, thereby demonstrating an alternative repair procedure.

Initial Phase - Second Core

A second core then was assembled and brazed. Several process changes were made in an effort to improve the braze results:

- Tack welding of the closure bars to parting sheets during lay-up, a known cause of leakages, was reduced further. Such welds are frequently used in lieu of elaborate fixturing.
- Braze foil, on either side of the laminate parting sheets, was allowed to protrude beyond the stack. This was done to provide additional braze alloy at the closure bar/parting sheet interface.
- The braze cycle was modified to allow time for the material to creep, thereby providing for stress relief.
- Electron beam welding instead of TIG welding was stipulated for repairs.

Figure 38 shows a water circuit closure bar "popped" out of the stack face of the first core. This fault occurred on the second core to a larger degree. To correct the core, the bars were pushed back into place or replaced and welded closed. The electron beam weld process was used for this repair.

This fault was the result of eliminating tack welds as described above. The difference in thermal expansion between the AA3003 closure bar and the laminated parting sheets placed the closure bar in compression at elevated temperature. Deletion of a restraining tack weld increased the closure bar compression length to the full 22.86 cm (9 inch) width of the core. This closure bar, with a cross-section of 2.8 x 1.9 mm (0.110 x 0.075 inch), failed in buckling as a column.

Corrective action for this problem was straightforward. Based on the absence of buckling on subscale cores previously fabricated or on the first lightweight core, the cores subsequently made were tack welded along the bars at approximately 7.62 cm (3 inch) centers.

Core bands were added to the second, S/N 2, core and the core was stress relieved. This core then was subjected to pressure leakage checks and repair welds using electron beam techniques. However, repair problems, similar to those on the first core, were encountered and work was stopped.

Corrective Action Phase

In the second phase of the fabrication, a series of corrective actions was implemented. As a first step two parallel lines of investigation were pursued. The first was a review for process anomolies from manufacturing records; and the second, an attempt at characterization of the weld repair problem.

The review for process anomolies included records from both lightweight long life heat exchanger cores, the braze of quarter scale modules from the original IR&D effort, and a comparison with successful production run processes on other programs. The following facts were established as a result of this investigation:

- There were no dimensional discrepancies in the detail parts of the lightweight long life heat exchanger cores.
- The laminated sheets were degreased, but not chemically cleaned as are all the other parts. Some improvement in cleanliness of all parts appeared to be warranted.
- A different, and less sophisticated, braze cycle was used on the IR&D cores. However, all braze cycles which were used have been successfully applied in production hardware.
- The use of braze foil as used in the lightweight long life heat exchanger, has been discontinued on production applications in favor of parting sheets clad with braze alloy, as a cost reduction.

In characterizing the weld repair problem, the leakages on the two lightweight long life heat exchanger cores were located and evaluated by "mapping". This mapping did not reveal any distinction between leaks at the aluminum (air circuit) parting sheets, or the composite parting sheets. Further attempts to repair weld, resulted in chasing leaks to between 0.64 to 1.27 cm (1/4 to 1/2 inch) beyond the end of the weld. External leakage from the water circuits was finally stopped only by completely welding all joints of the solid faces of the heat exchanger. Leakages from the water to the air circuit in approximately three locations were attributed to weld bridging over the parting sheet.

The second step in the recovery plan included a reduction of the test scope on the two existing cores. The necessity of demonstrating corrective action on the braze process before brazing the third and final laminate core, was established. A similar demonstration requirement for leak repair welding also was deemed necessary.

Test scope reduction was necessitated by the fact that external leakage integrity of the core was attained only by complete joint welding of the solid faces of the heat exchanger. Since this is not representative of the intended design, little would be gained by subjecting such a unit to proof pressure or vibration environment tests. However, since the leakage problem and resulting rework affect the outside skin only, heat transfer performance would be representative.

Accordingly, the water to air leaks of core S/N 1 were sealed using an epoxy filler. These leaks occurred at the outside edges of the air passages in three locations and were successfully sealed. This core then was completed by welding on the headers; the mounting feet were omitted as an economy measure. The air side was alodined and hydrophilic coated and the unit was performance tested per the Master Test Plan, included herein as appendix A .

To implement two other aspects of the planned corrective action, core S/N 2 was cut in half. Cutting was done parallel to the parting sheets, thus providing two half-cores, each of which maintained leakage integrity. One half-core was to be used for development of weld repair techniques. Unfortunately, the extent of the welding already performed on the core precluded its use in developing weld repair techniques. Actually, the standard repair techniques proved to be adequate once good braze procedures were established.

The second half-core of core S/N 2 was destructively examined (figures 40 & 41 along with the test sample from core S/N 1 (figure 41) and samples of the original IR&D core (figures 42 & 43). The purpose of this examination was to evaluate the leaks and braze quality specifically at the external closure bars. The following facts were established by this examination:

- Comparing figure 40 with figure 42 showed that the internal brazing of S/N 2 core was essentially as described for the test sample from core S/N 1. One small non-laminated plate area was located. Excessive gaps were noted between core parts.

- There was no evidence of any joint cracking. However, lack of braze was discovered, as characterized by wetting of only one surface. This appeared typical, under such close examination, of both lightweight long life heat exchanger cores and the original IR&D cores (figures 40 thru 43).

FIGURE 40 a

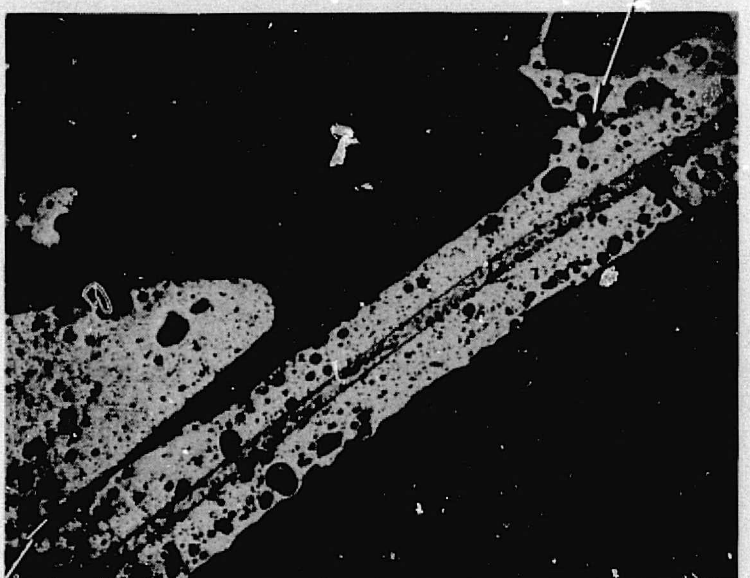


FIGURE 40 b

FIGURE 40 LLL-HX CORE S/N 2

ORIGINAL PAGE IS
OF POOR QUALITY

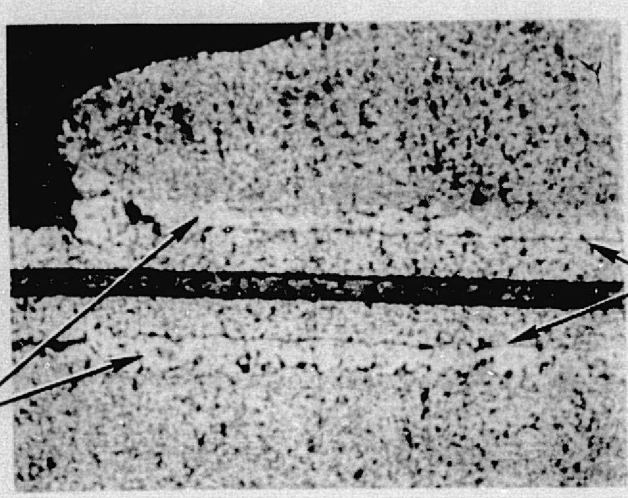


FIGURE 41 a

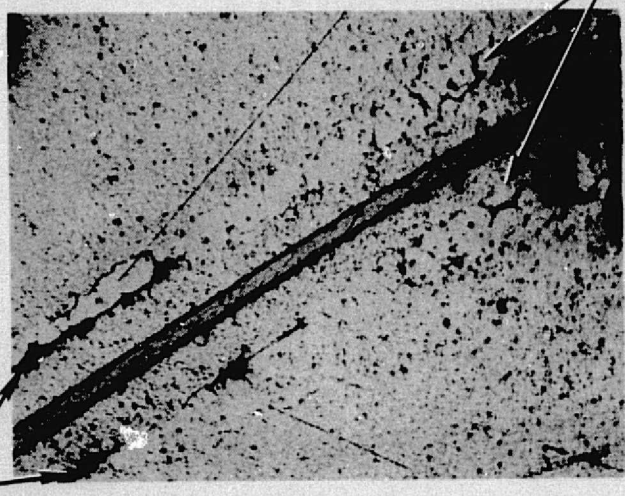


FIGURE 41 b

FIGURE 41 LLL-HX CORE S/N 2

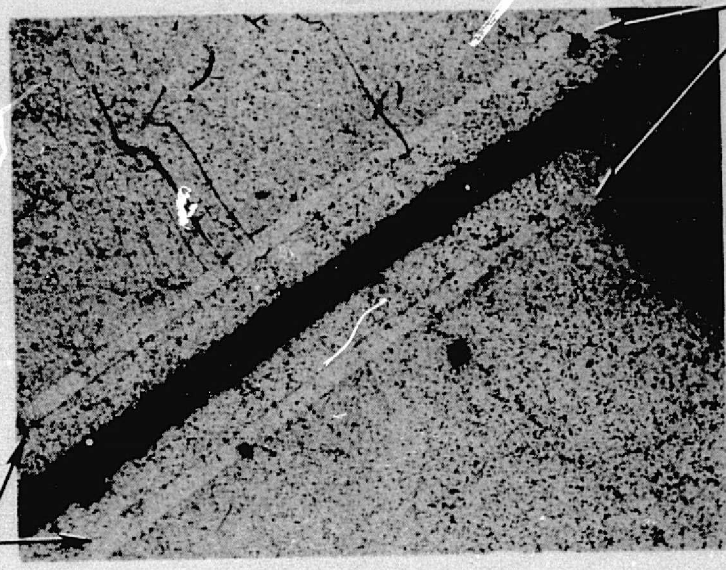


FIGURE 42 a

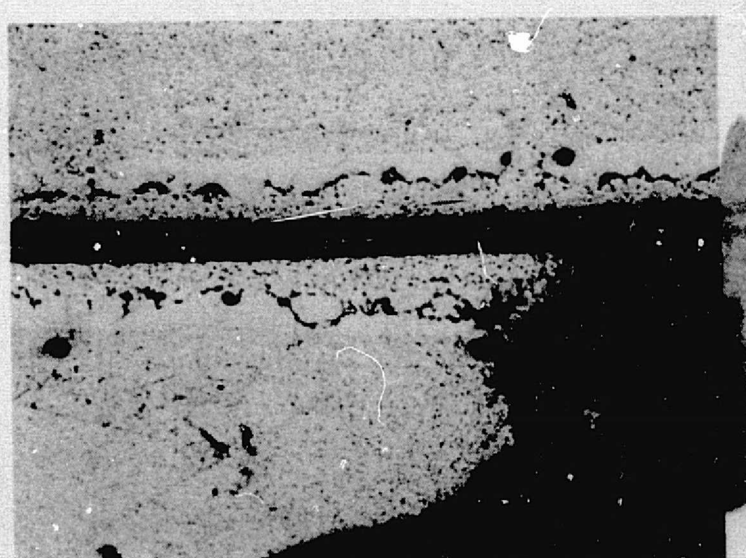


FIGURE 42 b

JOINT COMPLETELY BRAZED

ORIGINAL PAGE IS OF POOR QUALITY

FIGURE 42 LLL-HX CORE S/N 1 TEST SAMPLE

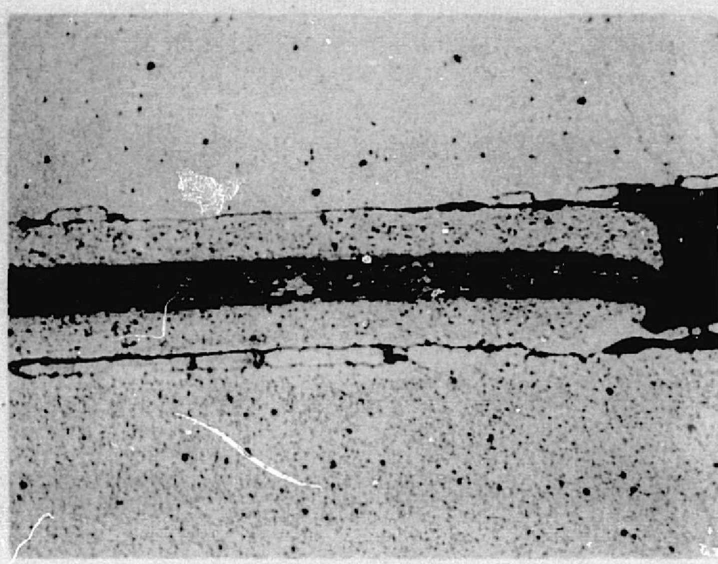


FIGURE 43 a

NO WETTING ON PARTING SHEET

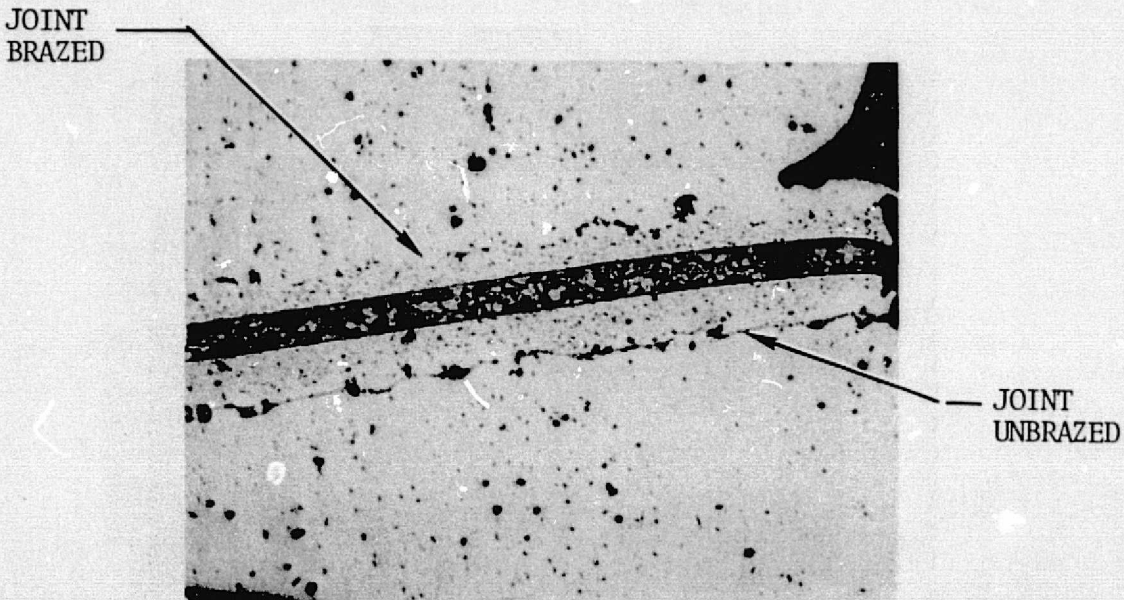
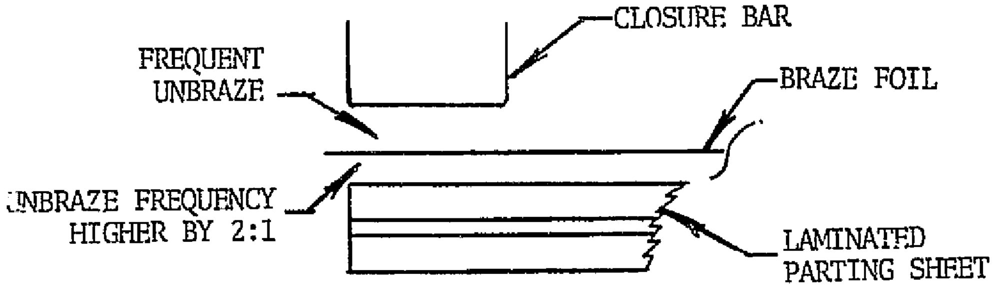


FIGURE 43 b

FIGURE 43 IR&D CORE

- Lack of braze was noted at the aluminum, air circuit, parting sheet to a small degree.

- Lack of braze at the parting sheets predominated, with unbrazed areas between the parting sheet and the foil occurring in a 2 to 1 ratio to unbraze between the foil and the closure bars (figures 40a-41a).



The impact of the presence of braze foil was obvious, increasing the incidence of unbrazed joint areas. This is analogous to braze difficulties encountered at end sheets, where the foil is used, on production heat exchangers. The remaining unbraze was a function of braze process control and also has occurred on production runs. In production, these leaks are repaired using TIG welding methods.

From this analysis, the leakage problem was identified as one of braze quality. It was further established that presence of the laminated parting sheet does not contribute to the problem to any visible degree.

Corrective action to the braze process was defined, which did not involve design changes to the heat exchanger. These process changes were included on three small scale core modules. The modules were half the core height and a fourth of the sectional area parallel to the parting sheets. Successful braze and repair of these modules was made a prerequisite to brazing of the third, and final, full-scale laminate core.

Accordingly, a drawing of a one half scale, one eighth volume, core utilizing scrap laminates, was prepared. This design was representative in all respects of the full size unit with the exception of volume, flow path length and coolant flow passes. Since no changes to the full size design were recommended, specifications for the module were taken from that drawing, SVSK 87355. A reduced copy of the module drawing is given as figure 44.

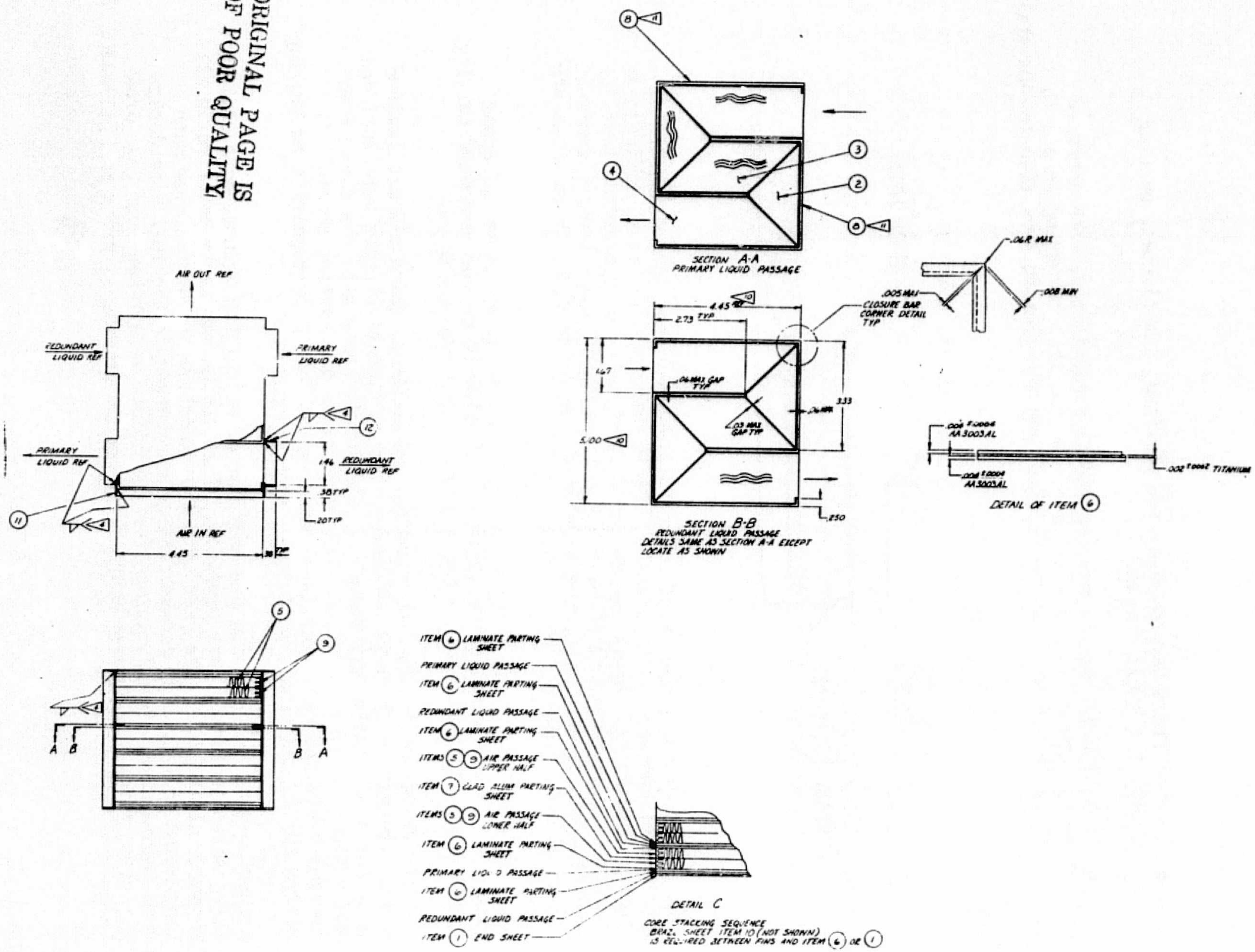


FIGURE 44 LIGHTWEIGHT LONG LIFE HEAT EXCHANGER TEST MODULE

Many of the details were made from extra details for the third full size core, by cutting down as required. The remainder of the parts were fabricated from stocked materials. Process sheets for the detail parts were reviewed and process sheets for core fabrication - the processes of cleaning, stacking and brazing - also were reviewed prior to braze.

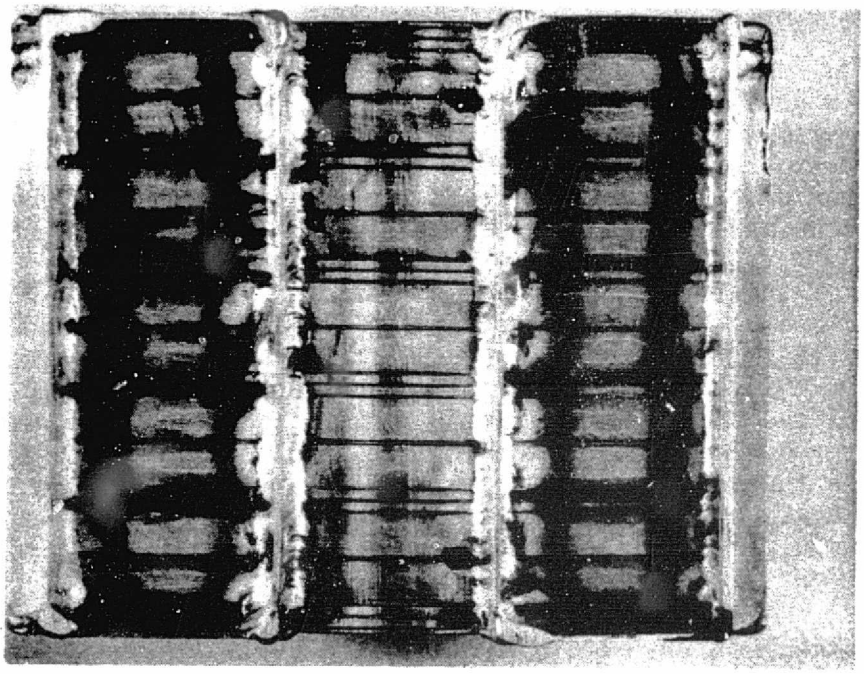
The first of the trial core modules, fabricated per SVSK 87355, was stacked, brazed and evaluated for leakage, and showed three leaks attributable to unbrazed areas. These three areas were the result of foil (braze alloy) wrinkles or chips which mechanically prevented a proper braze gap. During stack-up of the module several foil wrinkles had been found and eliminated; however, three were deliberately retained and located by marking before braze. The three areas found unbrazed were at these three locations, verifying again that during stack-up extreme care must be taken to eliminate all foil wrinkles or chips to help insure a good braze.

The leakage areas found during the proof pressure test at 718 kN/m^2 (90 psig) are shown on figures 45 and 46, marked in black. It can be seen that the majority of the leaks were adjacent to core band welds. The module was sectioned and the welds microscopically examined in the areas where leakage was indicated. It was found that insufficient weld penetration existed to completely entrap the parting sheet and adjacent closure bars. The result was weld bridging of the joint, allowing a leak path along the joint across the flow passages and out from under the weld ends. The leaks encountered were external type leaks, correctable by better weld penetration.

Metallurgical examination of the internal braze joints showed excellent braze joints; typical sections are illustrated in figure 47. These joints are of the quality desired in the heat exchanger.

The second module then was stacked and brazed. A slightly different set-up and braze process was utilized, in an attempt to reduce the time and manpower required for core brazing. The quality of the resultant braze joints was marginally acceptable. Joints were adequate in that weld was achieved as in a normal production application with the module holding pressure at the proof level. However, the incidence of leakage after braze was high. Figure 48 indicates the leakage areas, and the joints showed unbrazed areas similar to those found on the full size core, S/N 2. Typical joints are shown in figures 49 and 50. As a result of the experience with module 2, the process change was rejected for future use.

The procedure for welding of the core bands to the core was modified on this module by first laying down a base layer of weld material in contrast to the first core where no base layer was used. The purpose of this material was to seal the parting sheet/closure bar joints, thereby providing a solid base to which the core band was welded. This technique appeared effectively to eliminate weld bridging as a cause of leakage.



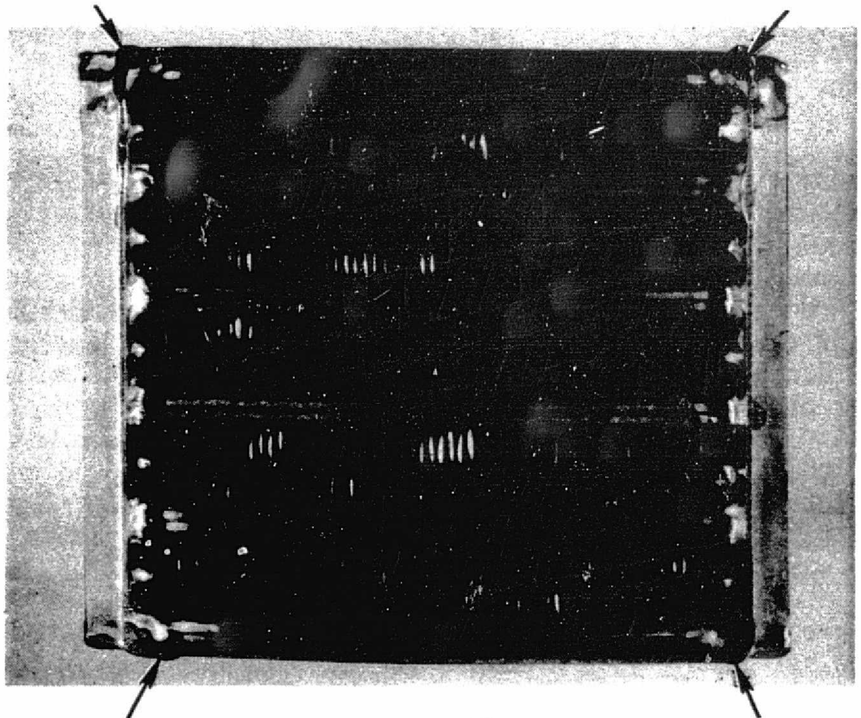
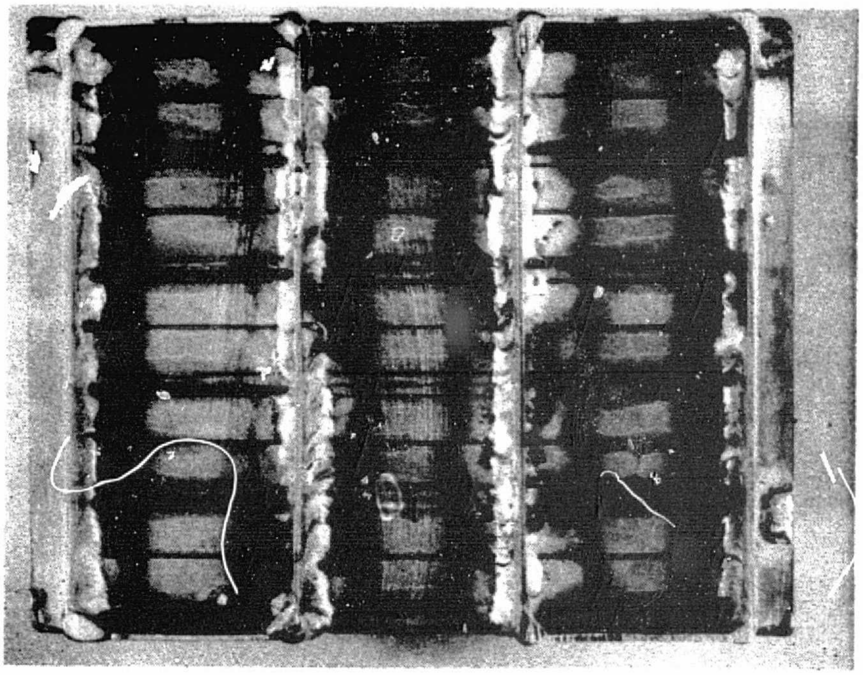


FIGURE 45

PRIMARY LEAKAGE AREAS MODULE #1



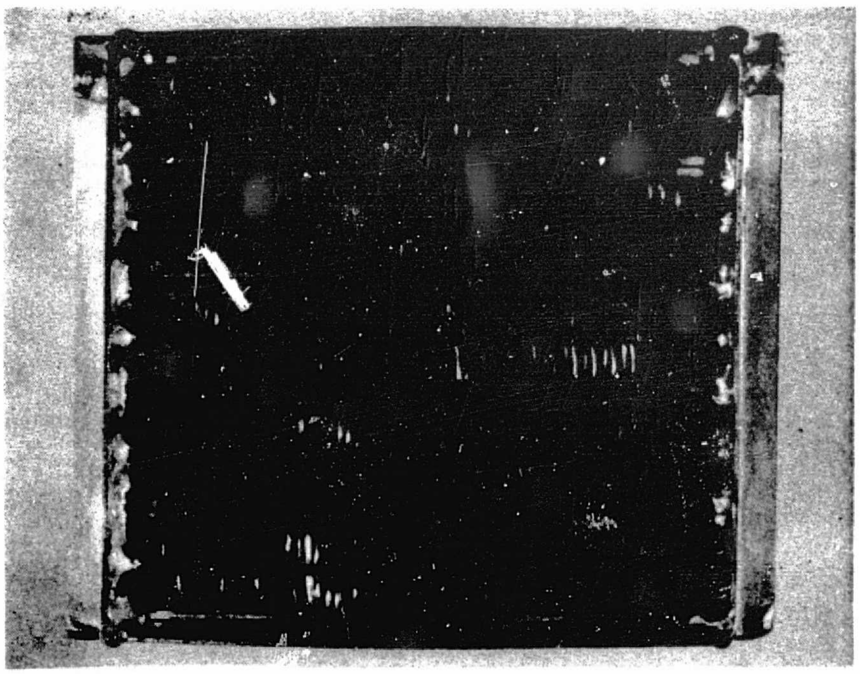
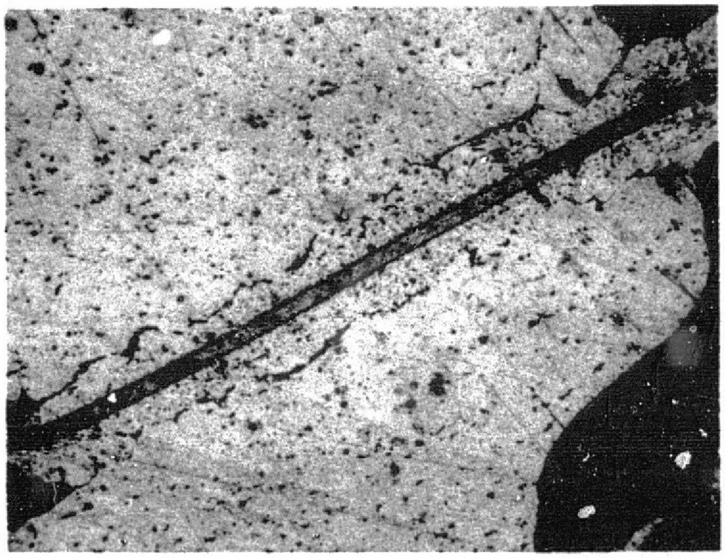


FIGURE 46

PRIMARY LEAKAGE AREAS MODULE #1, OPPOSITE FACES TO FIGURE 46



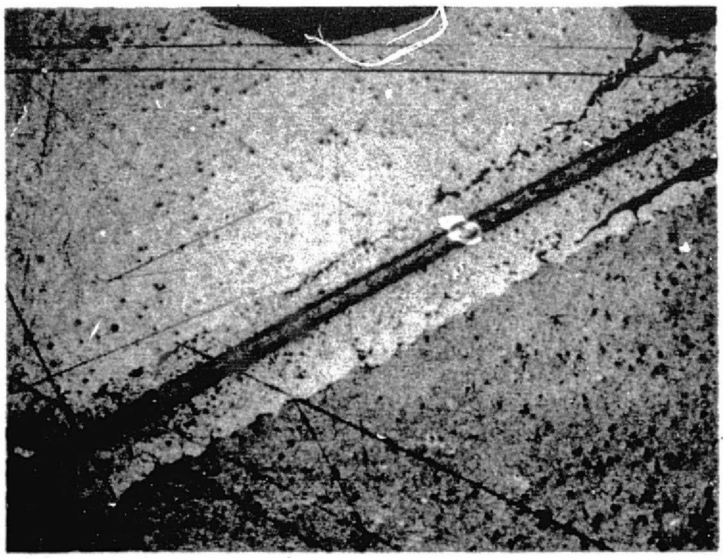


FIGURE 47

TYPICAL BRAZE JOINTS MODULE #1

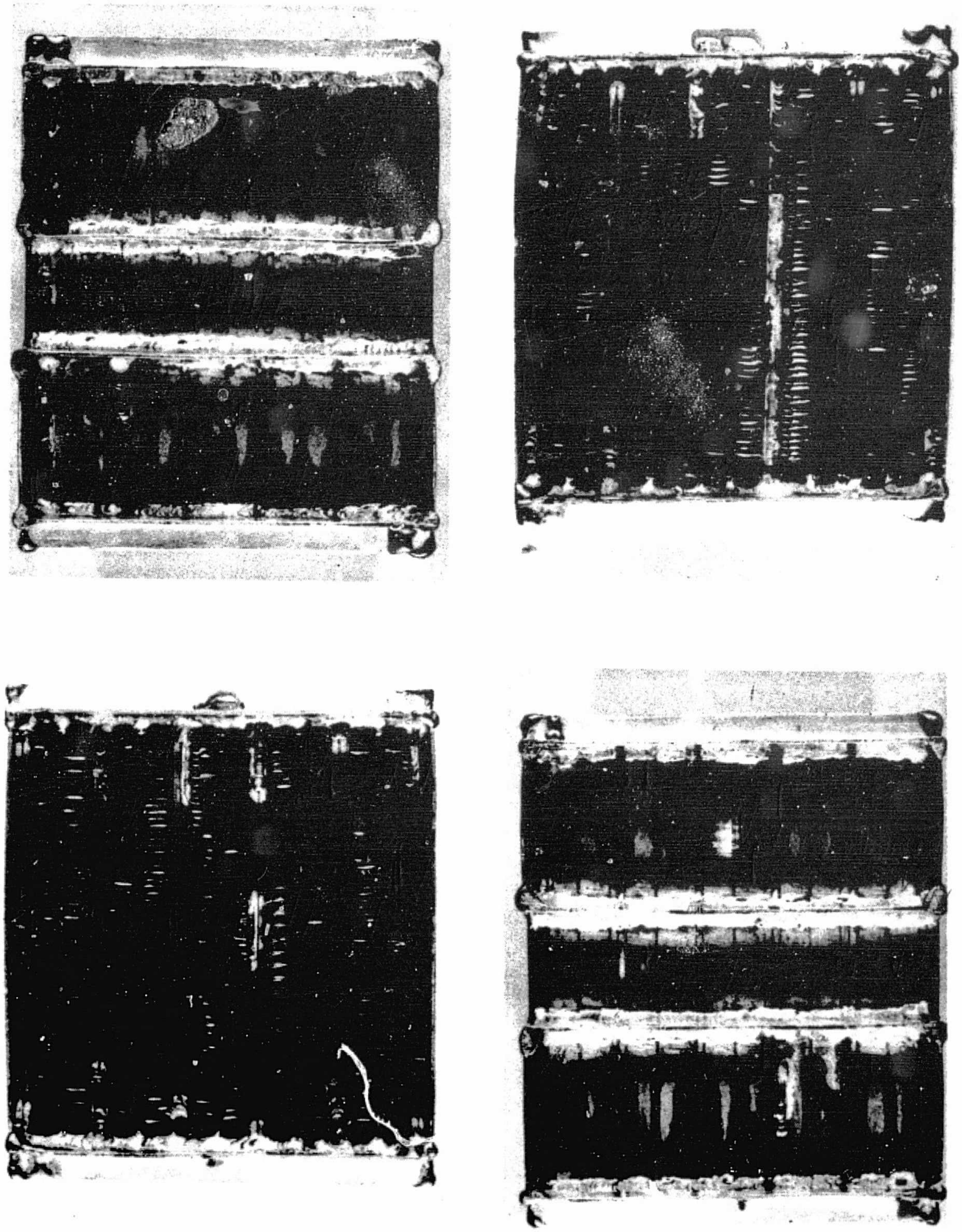


FIGURE 48

MODULE #2 - LEAK TIGHT EXCEPT UNDER CORE BANDS ON FACE C

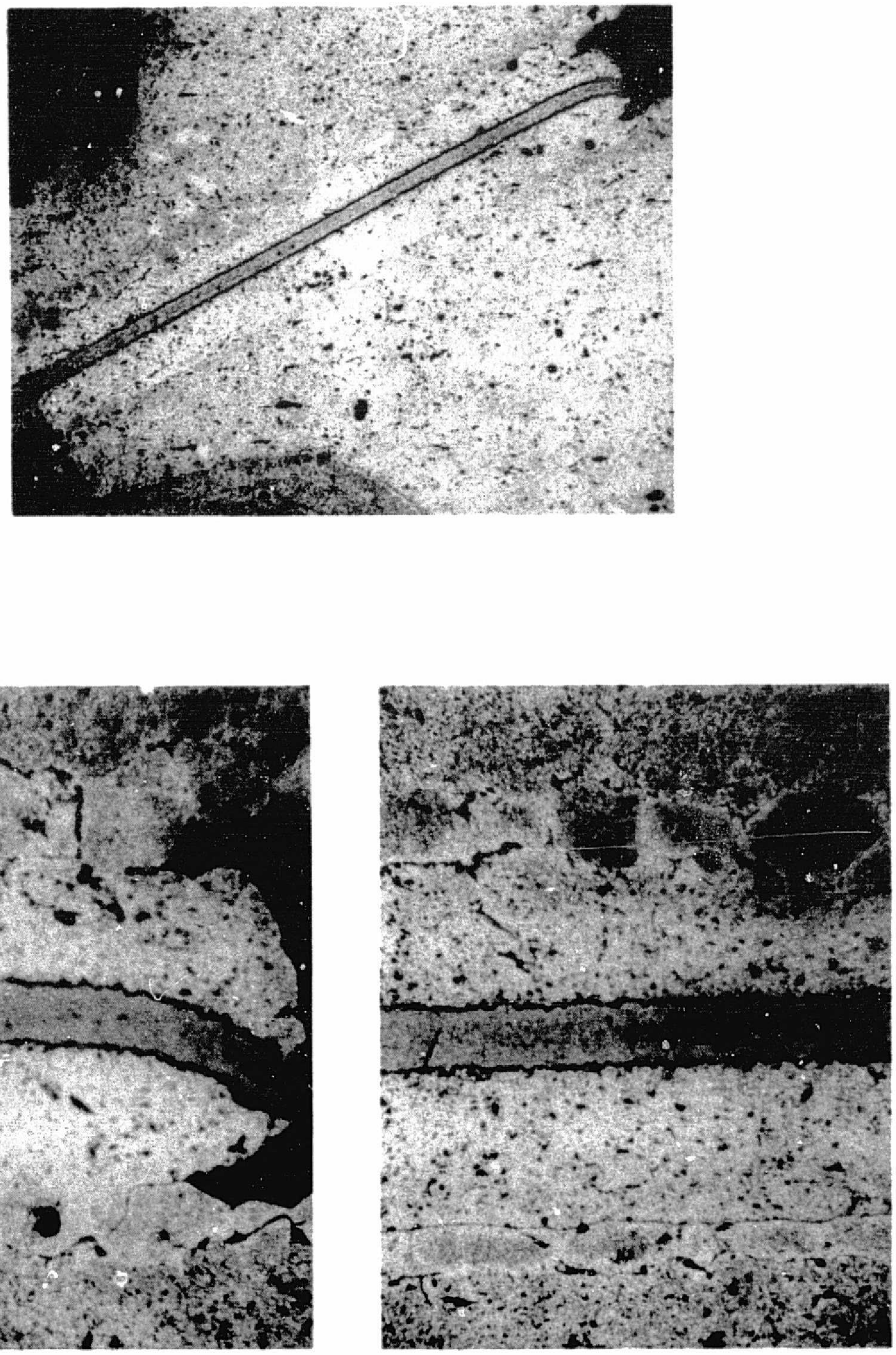


FIGURE 49 MODULE #2 EXAMPLES OF LACK OF WETTING AFTER BRAZE

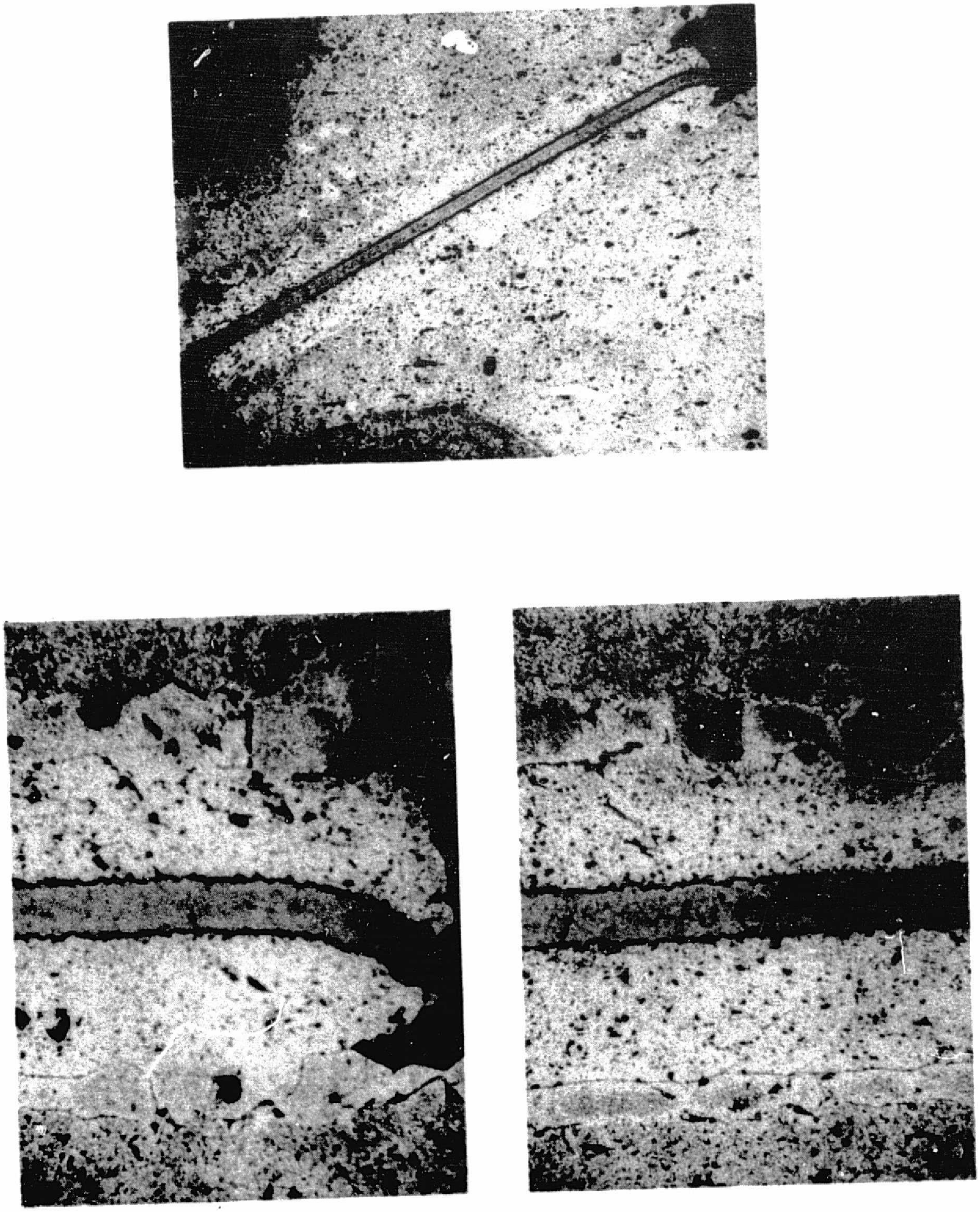


FIGURE 50

MODUEL #2, EXAMPLE OF POOR BRAZE ALONG FULL LENGTH OF A JOINT EXCEPT FOR SMALL AREA NEAR END

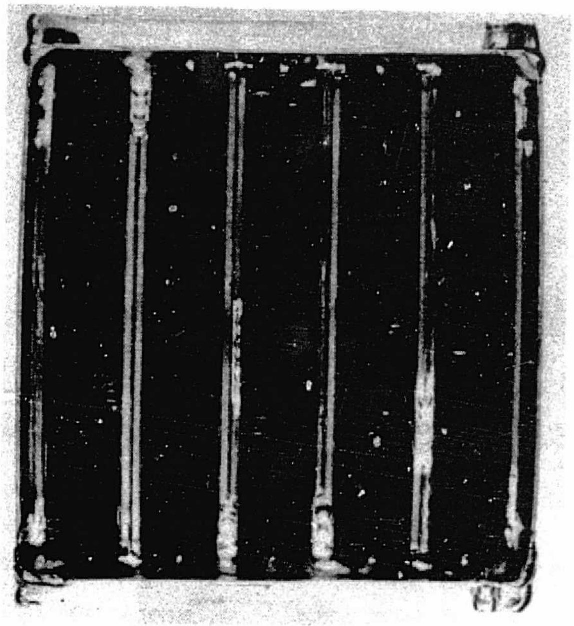
Stack-up and braze of the third module then was completed. The braze process utilized was identical to that used for module 1 and the core bands were attached using the method utilized on module 2. The unit was pressurized to proof levels and met the specification, although some leakage was encountered.

The metallurgical evaluation of the third core module indicated that excellent internal brazing of the core was accomplished. The core had passed the 620.5 kN/m^2 (90 psig) proof pressure test. Although some leakage had been encountered the investigation revealed that the leakage was all external, originating from under the weld where the core bands were attached. Figure 51 shows four faces of the core. Faces A and C indicate leakage locations by the small black dots. Further investigation revealed poor filleting at the end of the #12 parting sheet (air bar). This lack of filleting occurs with other heat exchangers being produced for various aircraft programs and is generally weld repaired. The core band weld should have penetrated sufficiently to eliminate the leakage; when it did not, it was decided to investigate the core rather than do additional weld repair. Figure 52 shows the end of a typical air bar and the lack of filleting at the end of the bar is easily seen.

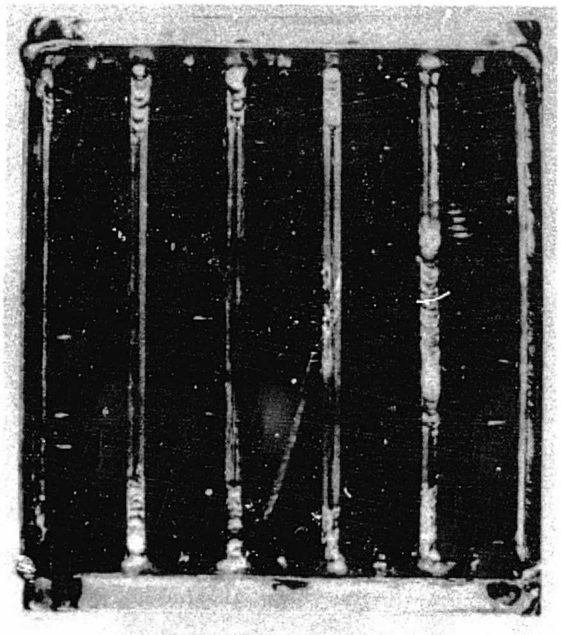
Evaluation of all the results obtained from the core module brazing led to the conclusion that sufficient information was available to give a high degree of confidence in the ability to braze a full scale laminate core. However, in order to gain additional confidence that there would be no scale up problems, it was decided to build a full size, all-aluminum core as a braze cycle verification unit. The changes that had led to successful modules 1 and 3 were:

- Gas flow circulation in the retort was revised.
- More stringent cleanliness requirements were implemented.
- The closure bars were reversed to provide better retention of the closure bars to prevent "popping".
- A static load was substituted for the bellows load, as a more accurate loading method in the brazing fixture.
- The stack-up and braze were monitored 100 percent to insure cleanliness of parts and integrity of the stack-up.

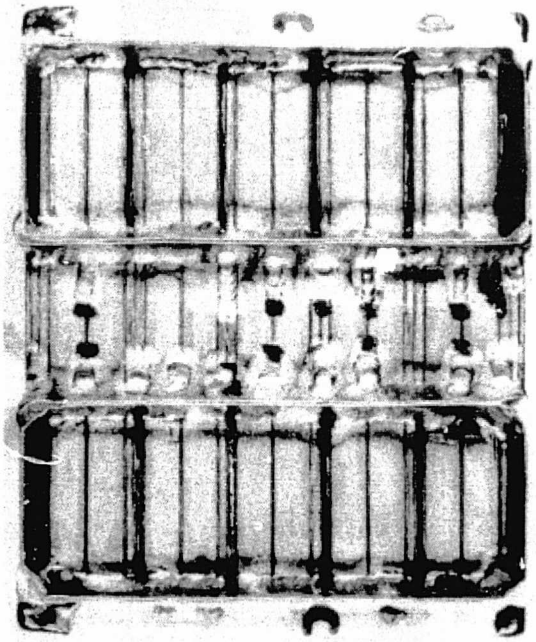
The results of the module braze program, along with core samples from module 3, were presented to the NASA at a program review meeting held at NASA JSC on June 13, 1974. In addition, Hamilton Standard's plan to build the full scale aluminum core was presented. NASA concurred that the braze verification of the scale-up was a sound approach.



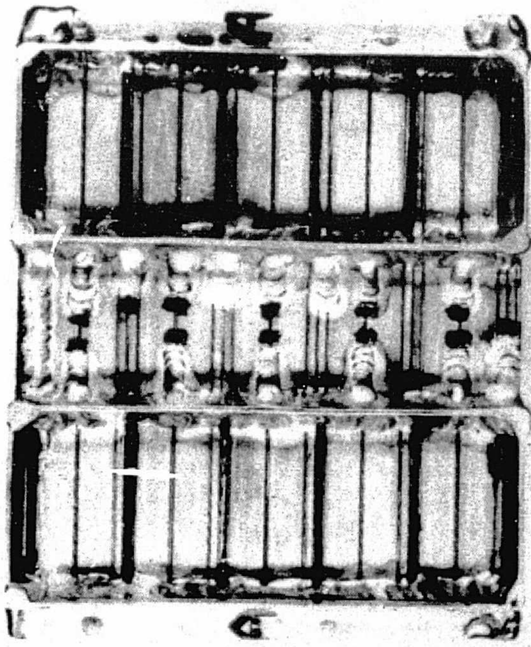
FACE D



FACE B



FACE C



FACE A

FIGURE 51 MODULE #3 LEAKAGE AREAS (INDICATED BY DARKENED AREAS ON FACES A AND C)

ORIGINAL PAGE IS
OF POOR QUALITY

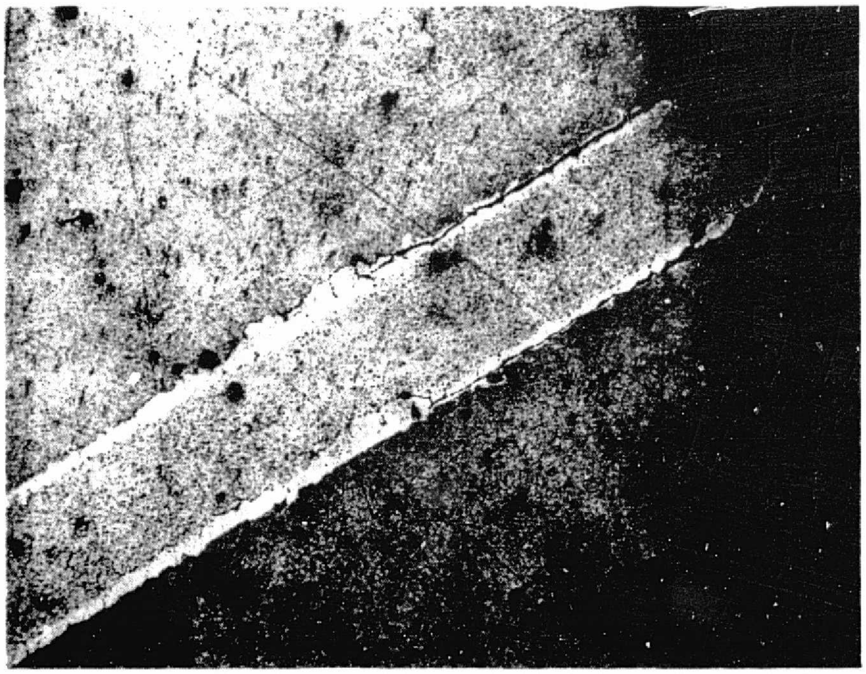


FIGURE 52 MODULE #3, TYPICAL AIR BAR, ILLUSTRATING LACK OF FILLETING AT END

Demonstration Phase

After fabrication of detail parts, the full-size, all-aluminum core was brazed. Appearance was good with no slippage of closure bars or other portions.

Examination of the all-aluminum test core revealed a total of 38 leaks. All but two were corrected by approximately 162.6 cm (64 inches) of weld. This compares with 124.5 cm (49 inches) allowable on conventional cores and was considered acceptable. The two remaining leaks were internal and were not considered repairable by ordinary means. Test pressure was 65.5 kN/m^2 (95 psig), or well in excess of proof testing.

The heat exchanger next was subjected to destructive examination to determine cause of the leaks and quality of the braze. It was determined that one leak occurred at the point of spot welding of a pass separator to the parting sheet while the second appeared to be the result of corrective weld penetration. This required that in the future each spot weld be examined before use and that greater care be exercised in corrective welding. Pull tests of representative core sections displayed a range of 1.123-2.992 kN/m^2 (163-434 psi). The lower values were from marginal braze on the air fins while the higher values represented fracture of the water fins. While these levels are acceptable the anomoly of why some air fins had marginal braze could not be answered. One specimen in particular was confusing in that a straight line diagonally across the fracture surface separated the marginal from the high strength braze. No good procedure could be defined to trace the anomoly; however, it was emphasized that cleanliness would have to be the best possible in the next assembly.

Final Phase

With the cautions noted above it was decided to proceed on the core for S/N 3.

Therefore, the core of the final heat exchanger was brazed, core bands welded in place and a number of leaks were repaired. Photo, figure 53 , shows the leak tight core prior to installation of brackets, flanges and headers. Final leak testing utilized air at 620.5 kN/m^2 (75 psig) with the unit immersed in water. Leaks resulting in bubbles as small as approximately 0.127 mm (0.005 inch) were detected and corrected.

Following closure of leaks, the headers, flanges and mounting feet were added and the air passages were coated with a hydrophilic coating. Figures 54 and 55 show the completed heat exchanger.

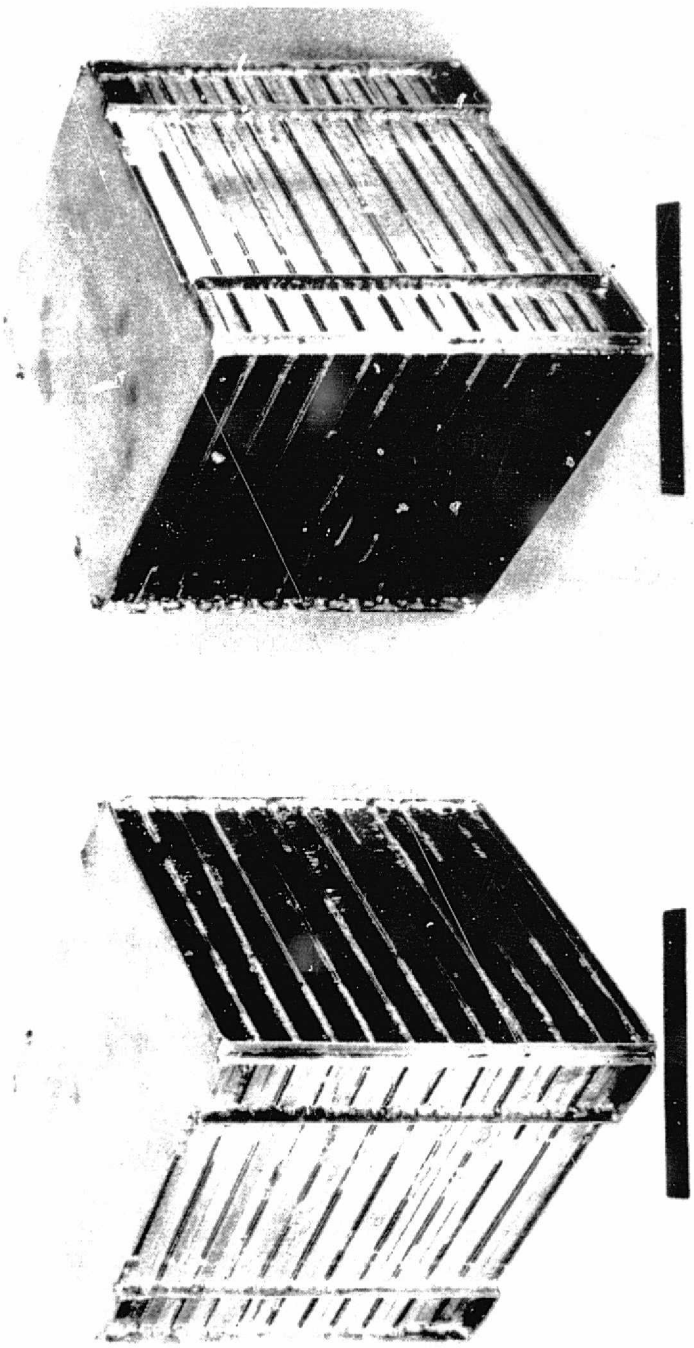


FIGURE 53 FINAL HEAT EXCHANGER CORE

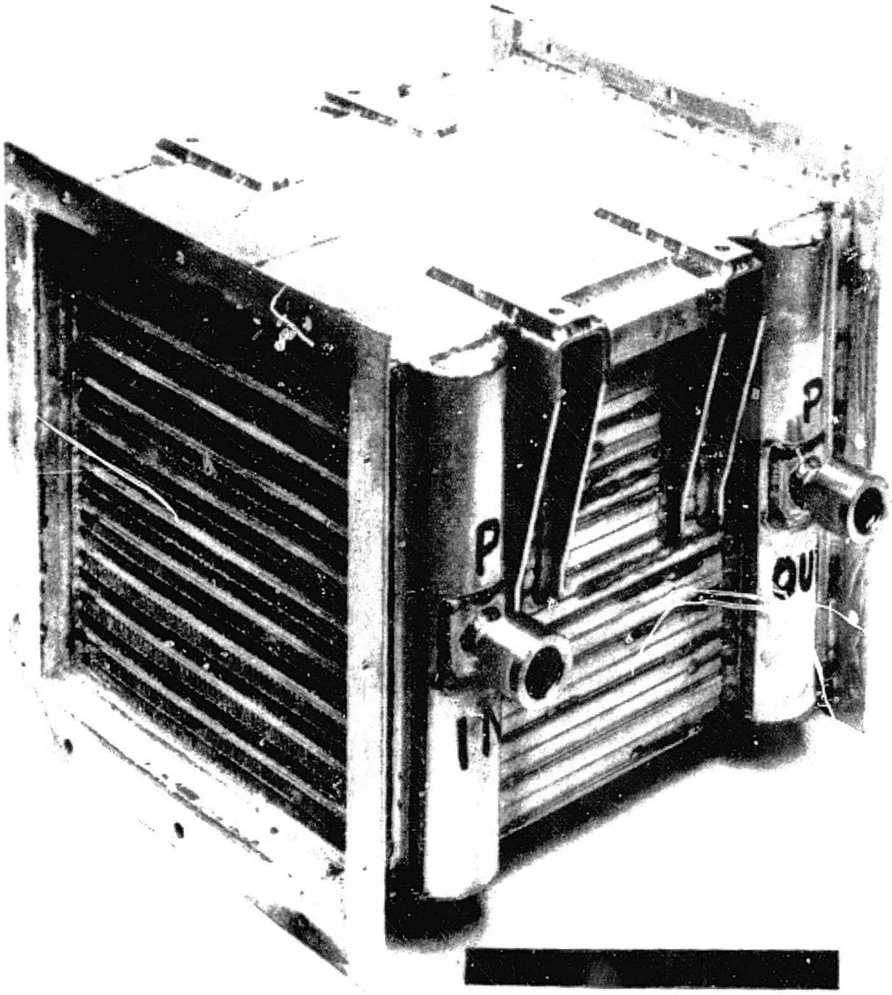


FIGURE 54 HEAT EXCHANGER BEFORE TEST

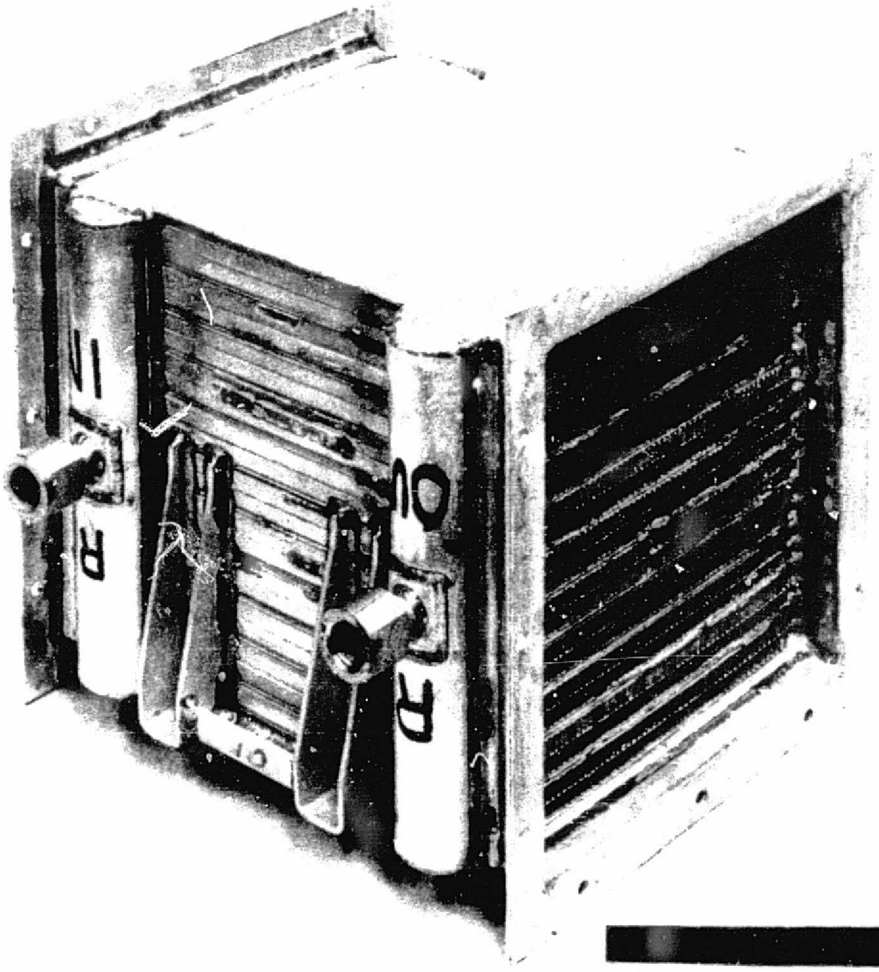


FIGURE 55 HEAT EXCHANGER BEFORE TEST

LIGHTWEIGHT LONG LIFE HEAT EXCHANGER TEST

As a result of the fabrication sequence described in the previous section two cores were available for testing. The first, S/N 1, was suitable only for performance testing due to its structural limitations and was used for an early assessment of the item's performance. The second, S/N 3, was suitable for all tests. S/N 1, therefore was subjected only to performance tests; the use of eopxy sealer to stop core leaks precluded performing valid weight and leakage tests. This discussion of the heat exchanger tests, therefore, pertains only to S/N 3 except that the performance of S/N 1 is discussed in the section on performance.

From the results of all testing a number of conclusions may be made:

- Thermal performance tests were successfully completed on lightweight long life heat exchanger S/N 3. The unit meets the thermal performance and pressure drop conditions for which it was designed. Based on a correlation with these data, accurate analytical prediction of the unit's thermal performance is established.
- No degradation in unit performance occurred over a period of 100 simulated mission cycles.
- Thermal performance differences between S/N 1 and S/N 3 are within the range of data accuracy and the performance can be considered essentially equivalent.
- Based on analytical predictions, the current lightweight long life heat exchanger configuration will meet the thermal performance requirements of Shuttle Condensing Heat Exchanger Specification SVHS 6442, Revision A. The air side pressure drop at these high flow rates is excessive, however, and for this reason a redesign of the unit is recommended to ensure a Shuttle compatible product.
- The heat exchanger can withstand the structural and thermal shock requirements of the Shuttle applcation.

The completed S/N heat exchanger was subjected to a test program whose intent was to verify its performance and to determine any performance degradation under repeated simulated Shuttle missions. The test program also was intended to demonstrate the structural integrity of the design.

A test plan, whose intent was as above, was prepared and approved by the NASA. The first part of the plan subjected the item to the full range of operating conditions for humidity, temperature, flows and heat loads to verify the thermal design of the unit. The remaining portion of the plan subjected the item to structural loads, a one hundred cycle simulated mission test, and to thermal cycling and shock, all designed to demonstrate the items structural and life capability. Repetitive leakage and base-point tests were used throughout the program to monitor structural integrity and performance.

The Master Test Plan appears in Appendix A.

The test facility, Space Systems Department test rig No. 61, was prepared and set-up for the lightweight long life heat exchanger. The inlet adapter, heat exchanger mount and general set-up are shown in figures 56-59. Other set-ups also used are shown as pertinent.

Test Program and Results

The test program was run during the period, November 20, 1974 to January 10, 1974, using rigs 61 and 66 in the Space System Department laboratory. All test requirements are per the Master Test Plan and the tests were performed as indicated in Table XII.

TABLE XII SUMMARY OF TESTS

Test No.	Title	Completion Date
1	Weight	11/20/74
2	Visual Examination	11/20/74
3	Leakage	11/21/74
4	Proof Pressure	11/21/74
5	Performance	11/27/74
6	Leakage	11/27/74
7	Vibration	12/3/74
8	Leakage	12/4/74
9	Proof Pressure	12/4/74
10	Leakage	12/4/74
11	Performance Base Point	12/4/74
12	Simulated Shuttle Mission	1/7/75
13	Performance Base Point	1/7/75
14	Leakage	1/8/75
15	Thermal Cycling and Shock	1/8/75
16	Performance Base Point	1/9/75
17	Leakage	1/10/75
18	Visual Examination	1/10/75

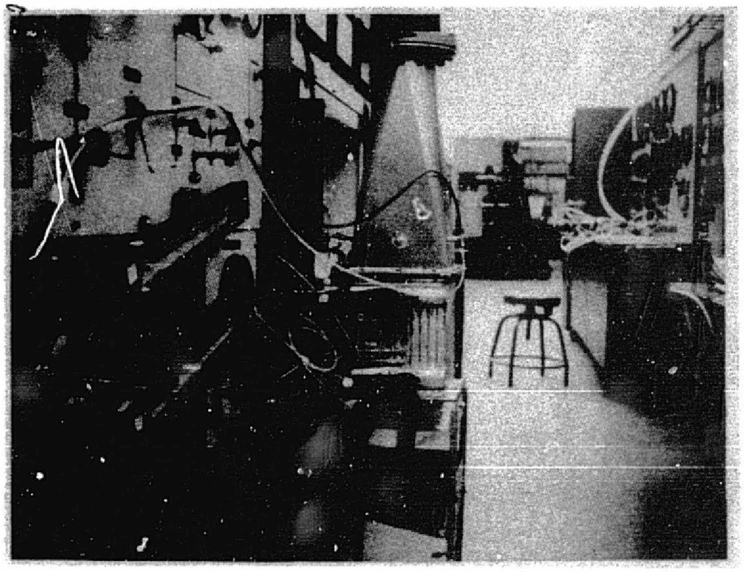


FIGURE 56 HEAT EXCHANGER TEST SETUP

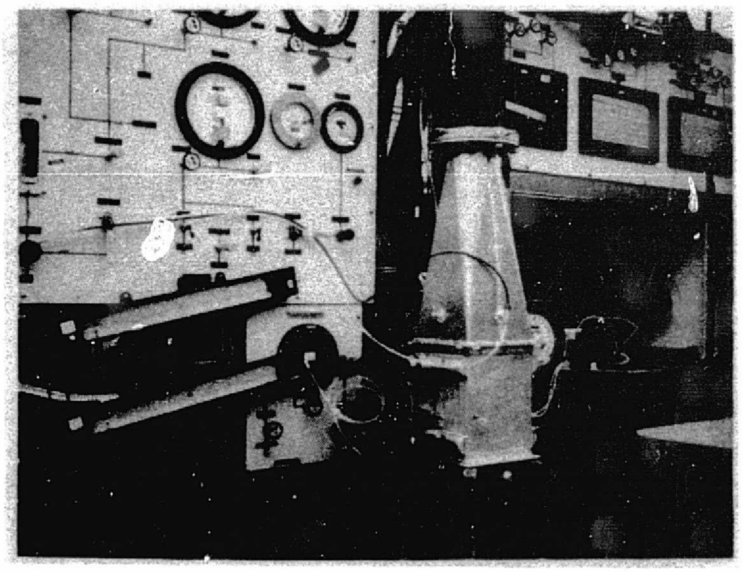


FIGURE 57 HEAT EXCHANGER TEST SETUP

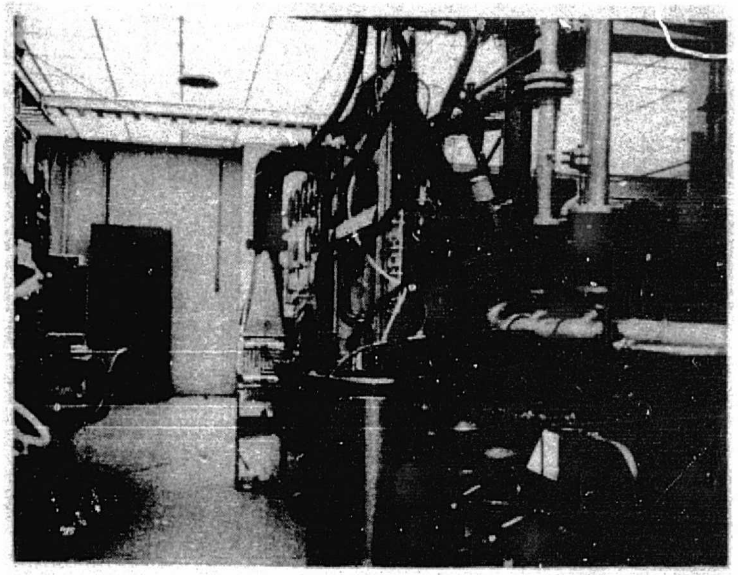


FIGURE 58 HEAT EXCHANGER TEST SETUP

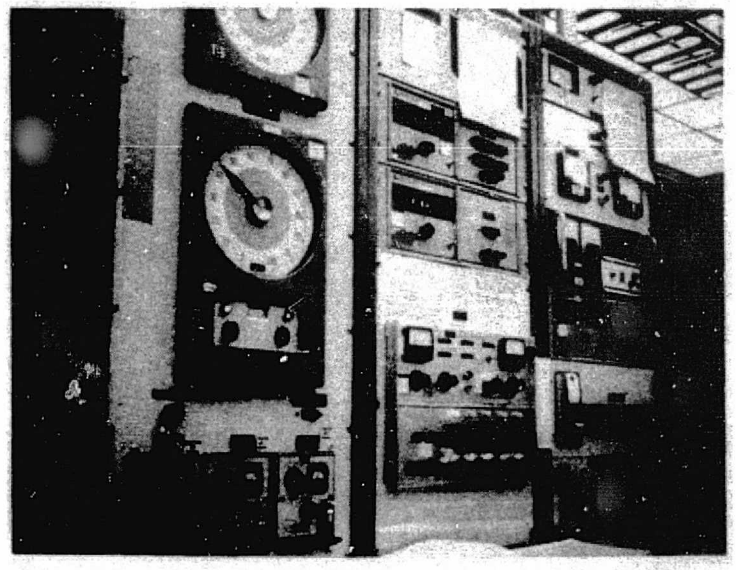


FIGURE 59 HEAT EXCHANGER TEST SETUP

Weight and Visual Examination (Tests 1 and 2)

Photographs of the test item were taken to record its physical condition, see figures 60-65. The unit was weighed on a beam balance scale, Fairbanks Morse and Co., Model 5901 Beam Balance, both before and after the hydrophilic coating was applied. Total weight, including coating was 67.56 N (15 lbs. 3 oz.). The hydrophilic coating accounted for 4.45 N (1.0 lb).

Leakage and Proof Pressure (Tests 3 and 4)

For simplicity, leakage testing was performed coincident with proof testing, at proof pressure using laboratory air as a pressurant and "snoop" as a leak detector. Figures 65 and 67 show the set-ups for the coolant and air side passages respectively. Minor leakage was experienced during air side testing at the mounting flange and closure plate joints.

Leakage at approximately 1.5×10^{-7} grams per second (2×10^{-5} lbs per min.) was indicated for both primary and redundant coolant passages. The NASA agreed that the leakage was sufficiently low as to be negligible and that testing should continue.

Performance (Test 5), Performance Base Point (Test 11), Simulated Shuttle Mission (Test 12), and Performance Base Point (Test 13)

Performance testing of the third lightweight long life heat exchanger, S/N 3, was performed and the data reduced according to the Master Test Plan. The analysis of performance data of S/N 3, shown in Table XIII, a comparison with heat exchanger S/N 1 and an evaluation of prelife and post life performance base point data are discussed below.

In its original concept, the unit was designed to meet the specification requirements shown in Table XIV. These requirements were derived from early Shuttle Orbiter and Representative Shuttle Environmental Control System definition. The unit design point represents a set of conditions that fall within the specification range but which do not represent any particular Shuttle mission phase. All heat exchanger sizing and weight tradeoff was accomplished utilizing this design point as the baseline while the test series defined in the Master Test Plan was designed to provide the maximum return of information over the complete range of specification environment. Confirmation of the design point performance is established by analytical extrapolation.

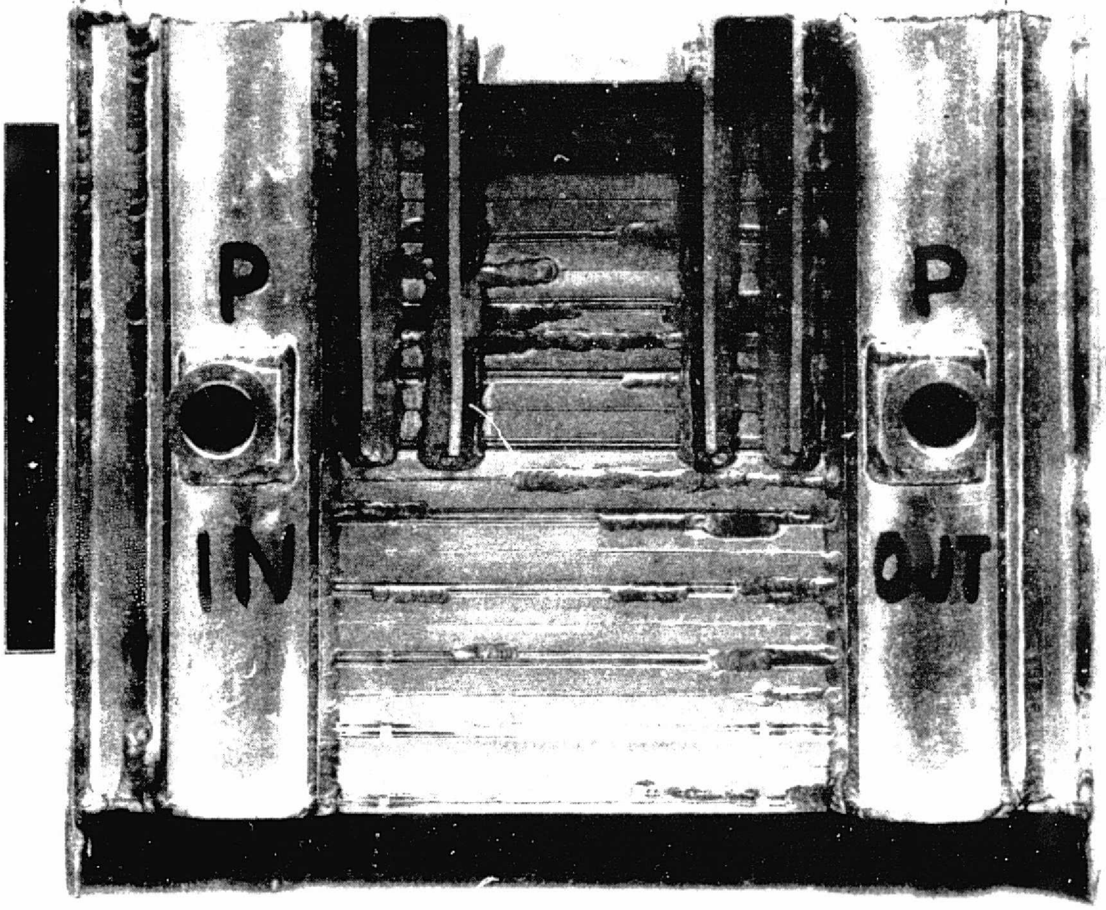


FIGURE 60 HEAT EXCHANGER BEFORE TEST

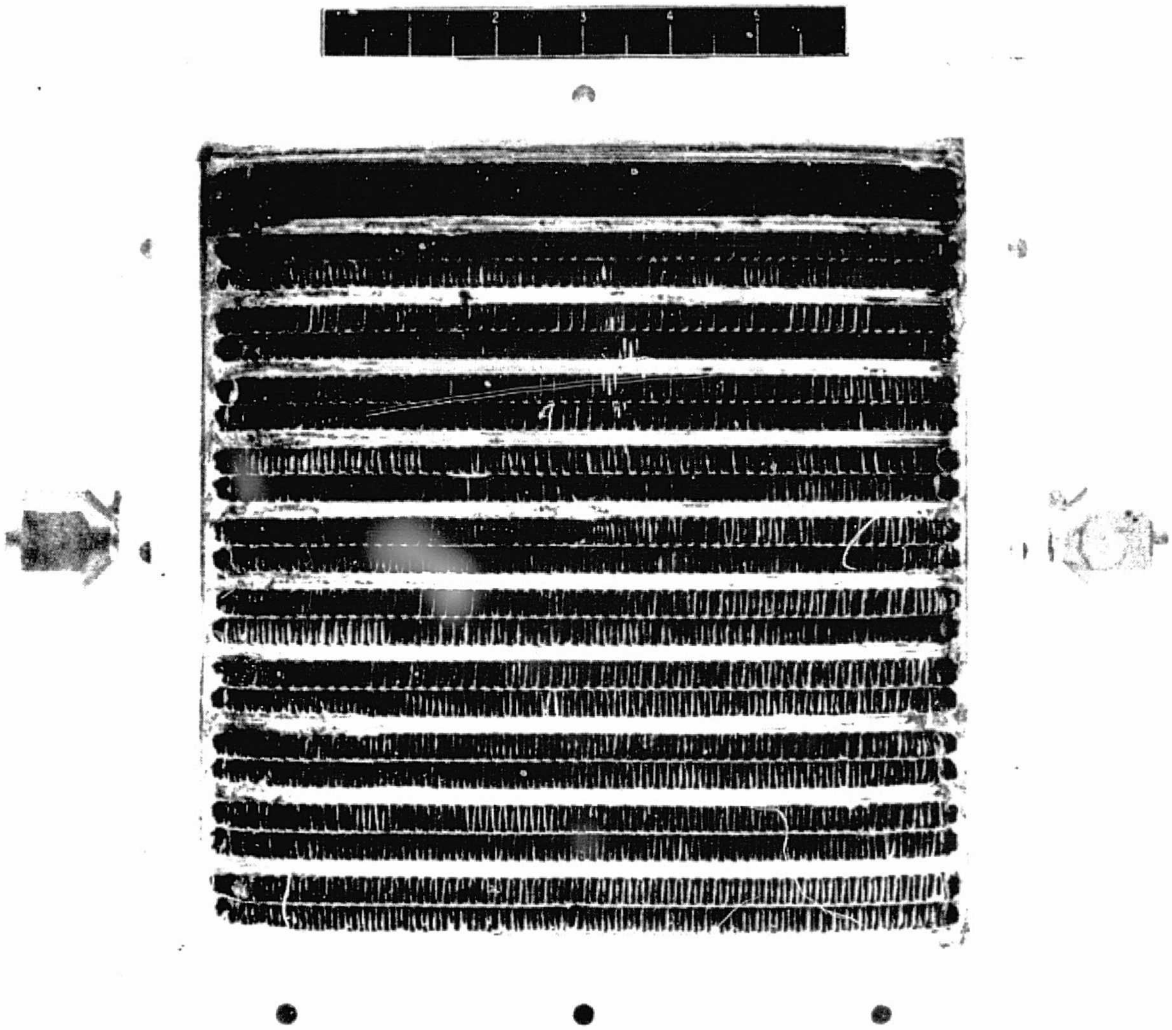


FIGURE 61 HEAT EXCHANGER BEFORE TEST

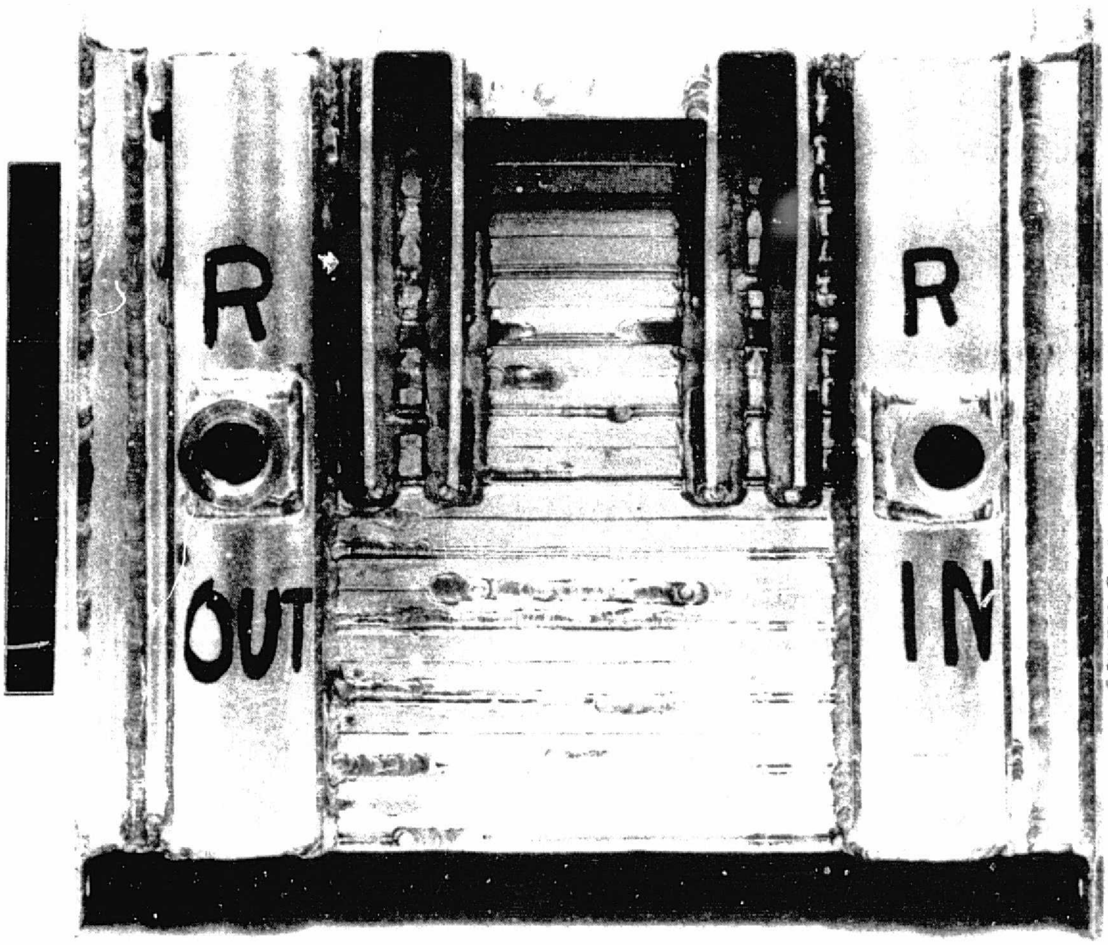


FIGURE 62 HEAT EXCHANGER BEFORE TEST

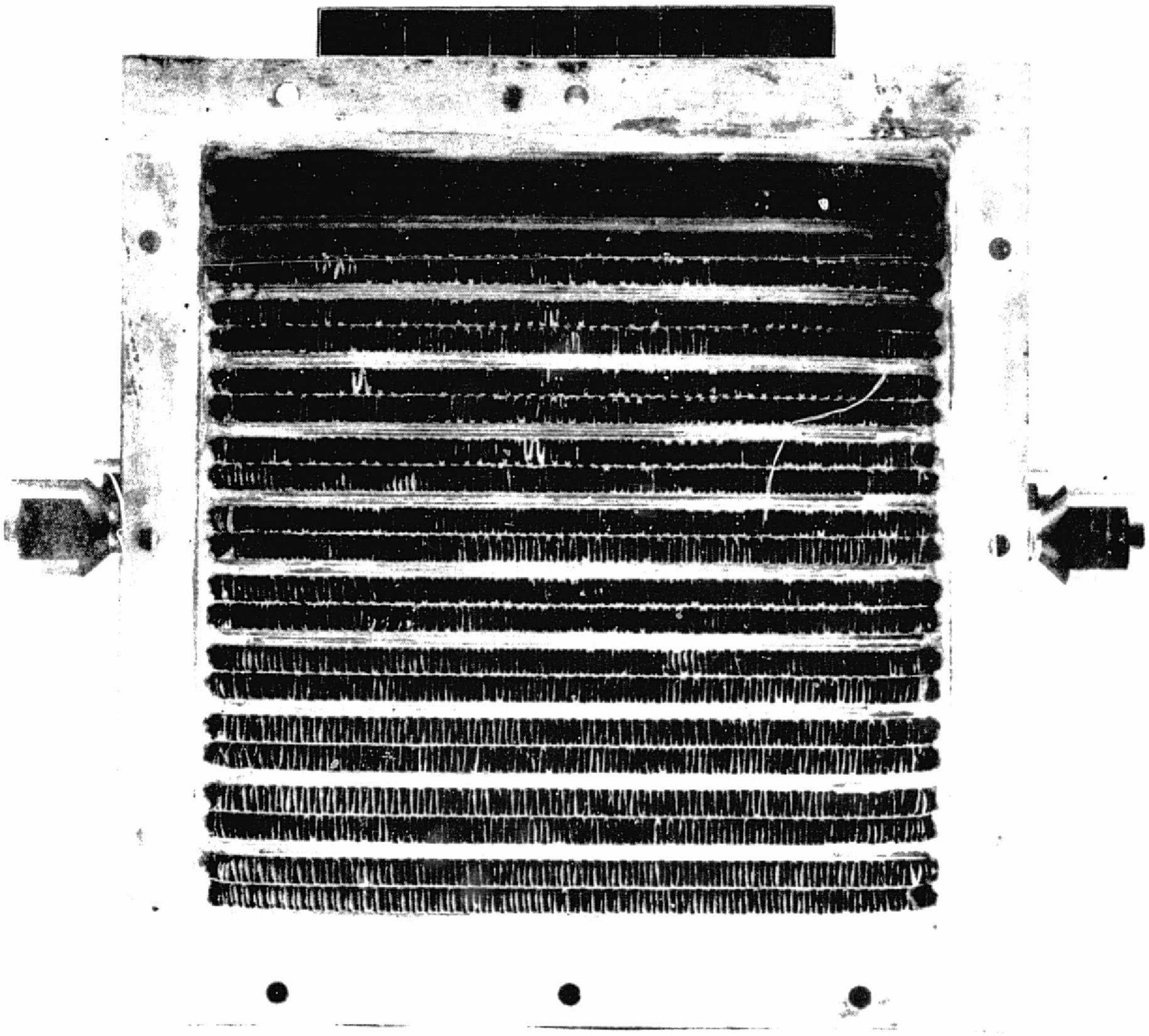


FIGURE 63 HEAT EXCHANGER BEFORE TEST

TABLE XIII PERFORMANCE DATA - LIGHTWEIGHT LONG LIFE HEAT EXCHANGER S/N 3

Log No.	Run No.	m Air		T_{air} in		T_{DP} in		T_{air} out		T_{DP} out		m H_2O		T_{H_2O} in		T_{H_2O} out		Qs		QL		Q_{Total} (Air)		Q_{H_2O}		Heat Bal.	E Air %
		kg/hr	#/Hr	K	°F	K	°F	K	°F	K	°F	Kg/Hr	#/Hr	K	°F	K	°F	Watts	BTU/Hr	Watts	BTU/Hr	Watts	BTU/Hr	Watts	BTU/Hr		
10538	1	397.3	876	309.88	98.1	274.83	35	280.94	46.7	274.83	35	272.2	600	279.33	43.1	291.04	64.2	3201	10,915	0	0	3201	10,915	3713	12,660	13.8	93.6
11550	2	598.7	1320	309.66	97.7	274.83	35	283.22	50.1	274.83	35	272.2	600	280.10	44.5	295.54	72.3	4384	14,949	0	0	4384	14,949	4945	16,680	10.37	87.97
11555	3	201.4	444	388.60	95.8	269.26	25	280.72	45.6	269.27	25	272.2	600	279.05	42.6	284.87	53.1	1581	5,393	0	0	1581	5,393	1795	6,120	11.6	94.55
10538	4	389.2	858	293.93	69.4	274.83	35	278.16	42.8	274.83	35	272.2	600	278.27	41.2	283.82	51.2	1606	5,477	0	0	1600	5,477	1742	5,940	7.6	93.67
10538	5	396.9	875	301.66	83.3	274.83	35	280.60	45.4	274.83	35	272.2	600	278.77	42.1	287.82	58.4	2367	8,071	0	0	2367	8,071	2851	9,720	[illegible]	92.47
11555	6	396.9	875	309.88	98.1	279.83	44	281.94	47.8	279.83	44	272.2	600	278.75	43.2	290.15	62.6	3147	10,730	0	0	3147	10,730	3432	11,700	8.3	91.99
10537	7	396.9	875	309.85	98.4	285.94	55	282.22	48.3	281.49	47	272.2	600	228.94	42.4	243.09	66.1	3120	10,641	704	2401	3825	13,042	4153	14,160	7.9	89.28
10537	8	396.9	875	309.77	97.9	290.66	63.5	283.94	51.4	282.33	49.5	272.2	600	279.49	43.4	293.74	69.6	2881	9,824	1469	5007	4350	14,831	4663	15,900	6.7	84.59
10535	9	386.9	875	301.82	83.6	285.38	63.	283.38	50.4	283.66	50.	272.2	600	281.33	43.1	290.98	64.1	2070	7,056	1256	4282	3325	11,338	3871	13,200	14.	81.73
11555	10	396.9	875	295.66	72.5	307.60	64.	282.38	48.6	283.16	50	272.2	600	279.38	43.2	288.93	60.4	1507	5,137	1394	4754	2901	9,891	3097	10,560	6.3	82.25
10535	11	396.9	875	294.32	70.1	289.94	62.2	282.05	48.0	282.33	48.5	272.2	600	279.05	42.6	288.65	59.9	1369	4,666	1252	4270	2621	8,936	2921	9,960	10.3	79.64
10535	12	396.9	875	293.94	69.4	286.49	56.0	280.99	46.1	281.22	46.5	272.2	600	278.75	42.6	286.43	55.9	1448	4,938	705	2404	2153	7,342	2288	7,800	5.9	86.57
11551	13	396.9	875	293.99	69.5	280.10	44.5	280.10	44.5	280.10	44.5	272.2	600	278.75	42.6	284.50	52.5	1559	5,315	0	0	1559	5,315	1742	5,940	[illegible]	91.94

SYMBOLS

M - Quantity of Flow

T - Temperature

DP - Dew Point

Qs - Sensible Heat Load

Ql - Latent Heat Load

Qt - Total Heat Load - Air Side

QH_2O - Total Heat Load - Water Side

E - Effectivity

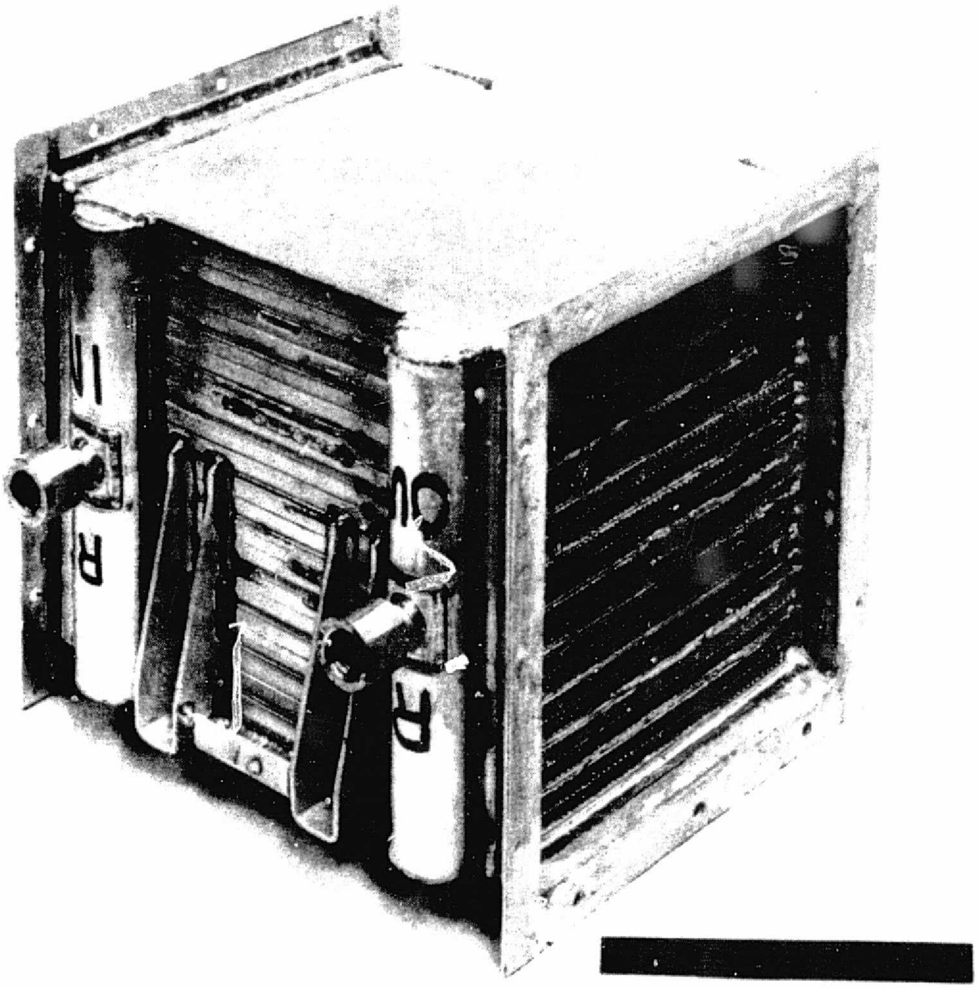


FIGURE 64 HEAT EXCHANGER BEFORE TEST

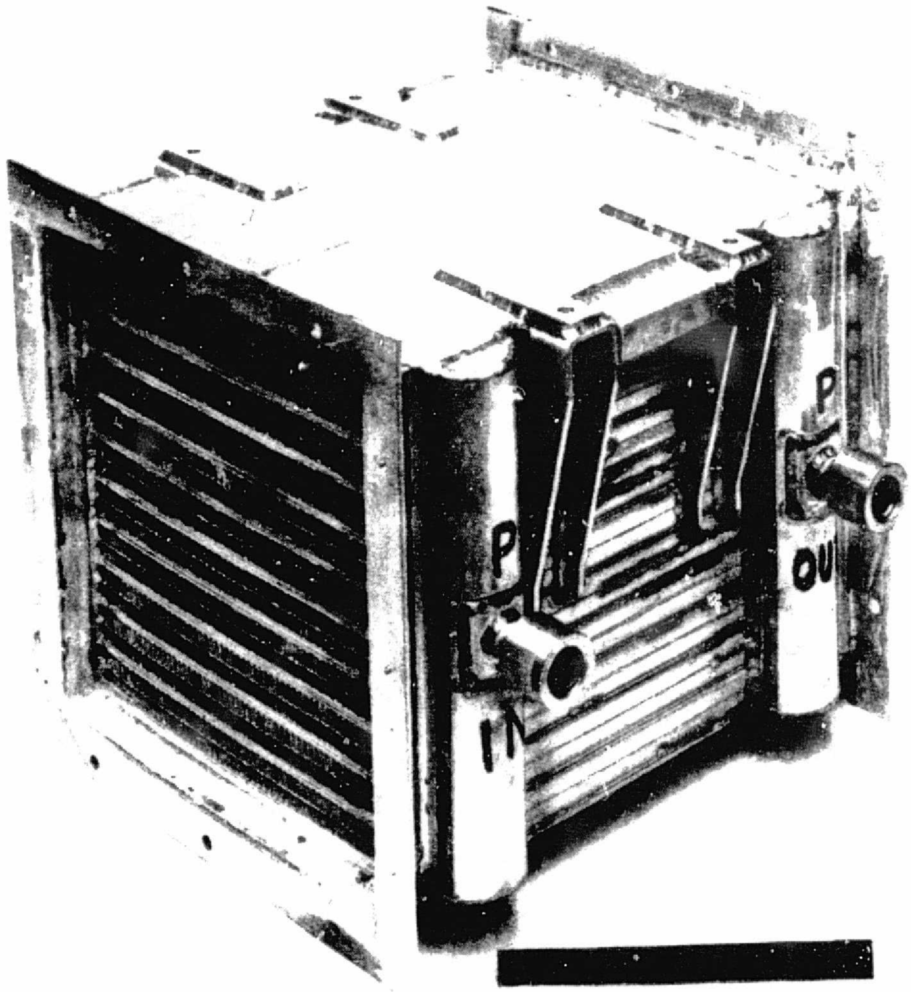
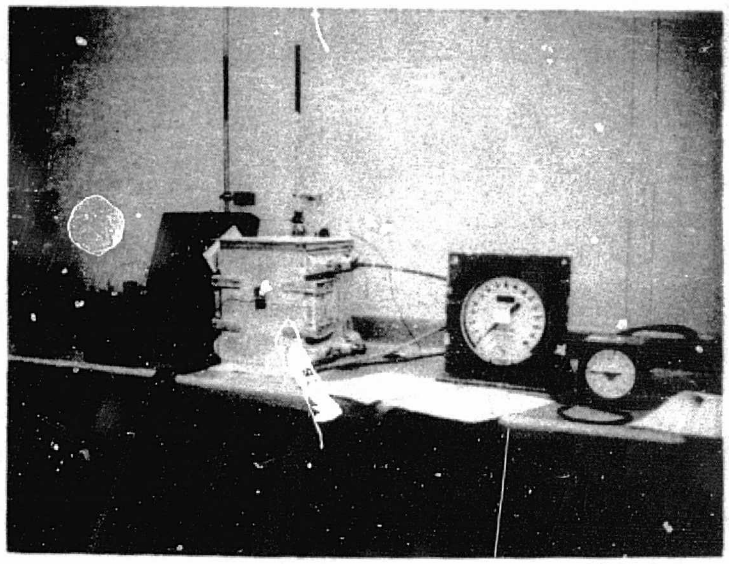


FIGURE 65 HEAT EXCHANGER BEFORE TEST



3732

FIGURE 66 COOLANT SIDE PROOF AND LEAKAGE SETUP

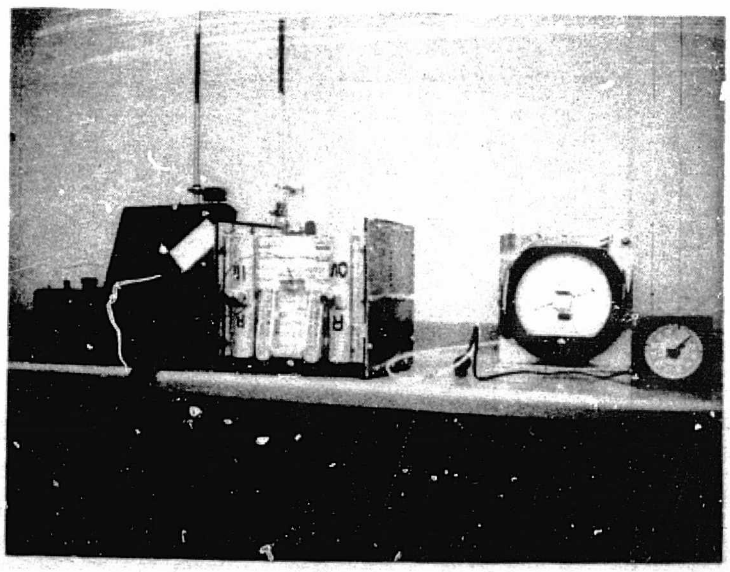


FIGURE 67 AIR SIDE PROOF AND LEAKAGE SETUP

TABLE XIV HEAT EXCHANGER DESIGN REQUIREMENTS

Parameter	Specification		Design Point	
	S.I. Units	U.S. Units	S.I. Units	U.S. Units
Outlet Total Pressure	10.14 ± 0.14 KN/m^2	14.7 ± 0.2 psia	10.14	14.7
PPO_2	21.37 ± 0.07 N/m^2	3.1 ± 0.1 psia	21.37	3.1
Gas Flow	399.16 kg/hr	880 lbs/hr	399.16	880.0
Gas Inlet Pressure	295-309 K	71-97°F	309	97.0
Gas Outlet Pressure	280-283 K	45-50°F	283	50.0
Inlet Dew Point	277-289 K	39-61°F	289	61.0
H_2O Inlet Temperature	277.4 K	40°F	277.4	40.0
H_2O Flow	272.16 kg/hr	600 lbs/hr	272.16	600.0
H_2O Inlet Pressure	413.69 KN/m^2	60 psia	413.69	60.0
Maximum Air Side Δ P	96.3 N/m^2	0.5 in H_2O	96.3	0.387

To maintain a systematic approach, the data from each test was reduced according to analytical procedures outlined in the Master Test Plan. In addition, the performance of the heat exchanger was evaluated on the basis of its effectiveness value, ϵ , which is defined as:

$$\epsilon = \frac{T_{Air\ In} - T_{Air\ Out}}{T_{Air\ In} - T_{Water\ In}}$$

The heat exchanger effectiveness is a nondimensional grouping which possesses readily visualized physical significance since it compares actual attained heat transfer to maximum theoretical values.

A preliminary review of all performance test data indicated that the heat balances were within 15 percent. Although slight variances between inlet and outlet dew pointer readings were observed during non-condensing rungs, this critical instrumentation generally could be relied on to give accurate readings in the condensing mode.

Figure 68 presents non-condensing heat exchanger effectiveness as a function of total air flow. Although the data from S/N 3 appear improved over S/N 1, the difference is well within the error limits of test accuracy. At the relatively high effectiveness levels achieved by these units, a total variation of 274 K (2°F) in either air outlet temperature or water inlet temperature would be reflected as a 4 percentage point variation in effectiveness.

Figure 69 presents a plot of heat exchanger effectiveness versus percent latent heat load for an air flow of 1940 kg/hr (880 lbs/hr) for S/N 3. The decrease in effectiveness as latent load is increased is normal and results primarily from air flow maldistribution caused by water droplets collecting on the airway fin surface. This effect is minimized through the use of hydrophilic coatings and will be further reduced when operation with the functional water collection device, the slurper, is achieved.

The original design point of the heat exchanger is included on the graph for reference. This point shows that the unit's heat transfer capabilities have a slight margin over the requirements for which it was designed. Two points at approximately 32 percent and 47 percent latent heat load determined the unit's operation using the redundant coolant loop. The points verify repeatable and successful operation of the unit in either mode of operation.

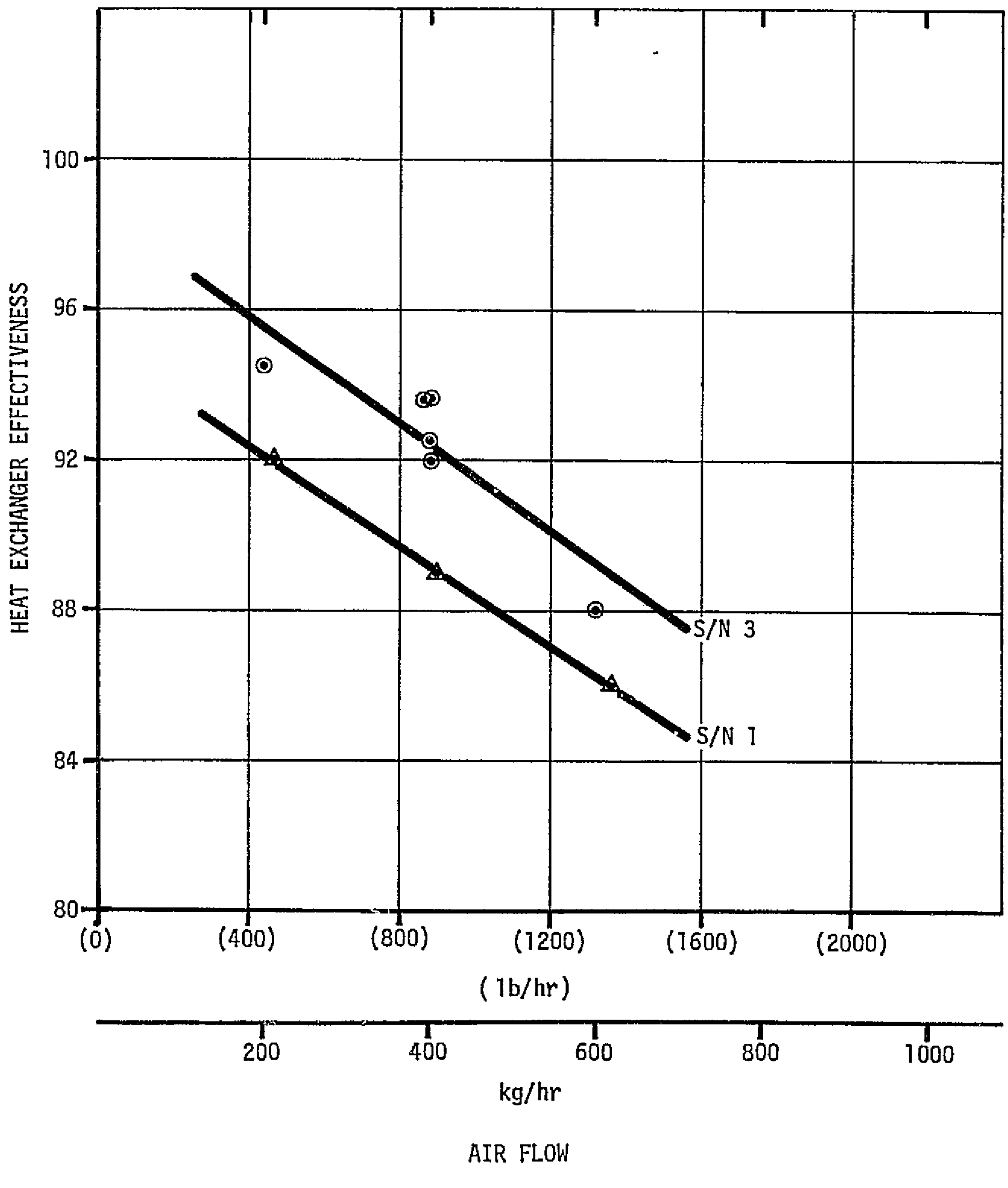


FIGURE 68 LIGHTWEIGHT LONG LIFE HEAT EXCHANGER EFFECTIVENESS vs. AIRFLOW (NON-CONDENSING MODE)

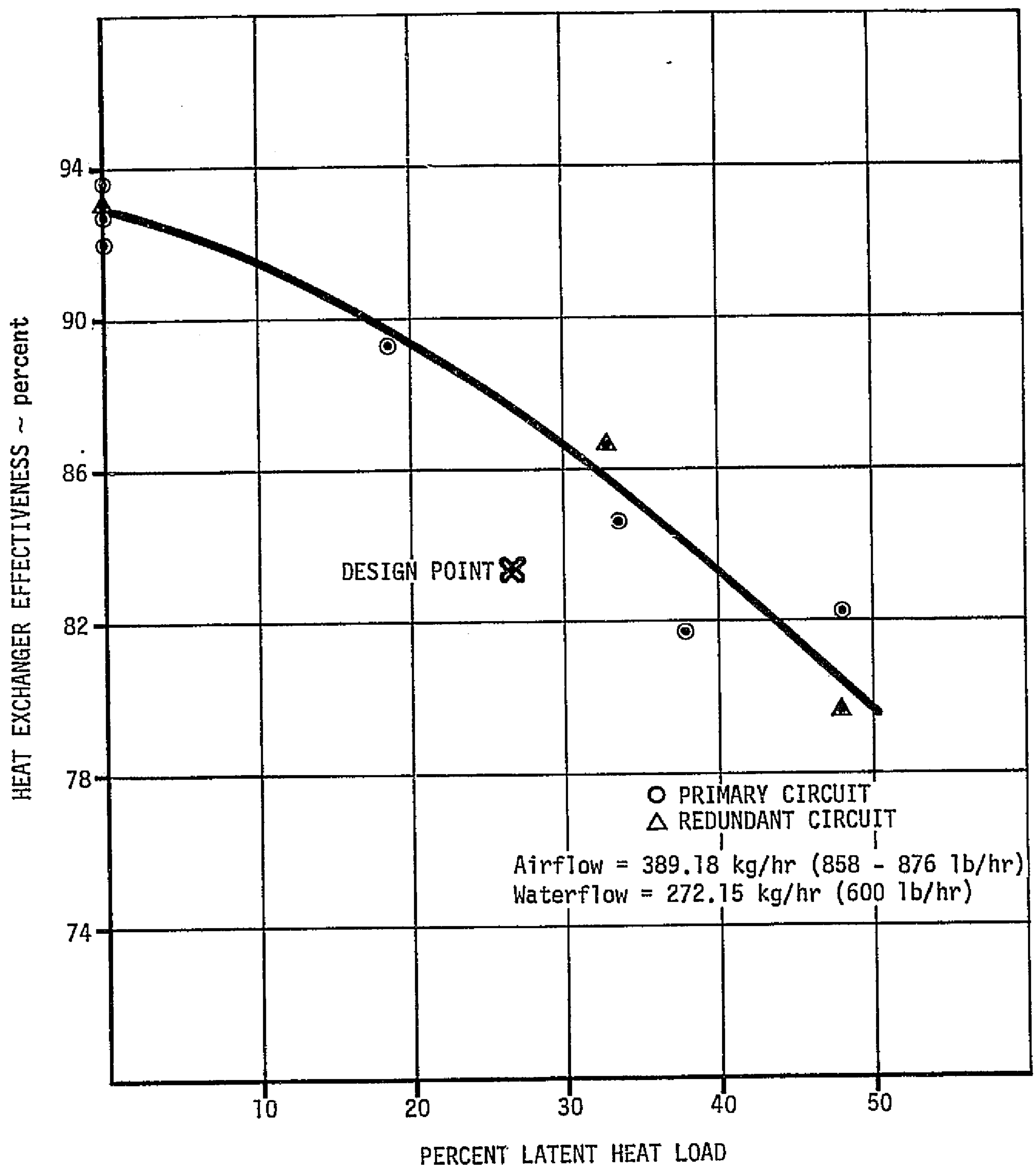


FIGURE 69 HEAT EXCHANGER EFFECTIVENESS vs. LATENT LOAD FOR LIGHTWEIGHT LONG LIFE HEAT EXCHANGER S/N 3

Figure 70 is a plot of S/N 3 heat exchanger air side dry pressure drop versus flow rate. The design point is again included for reference and shows that the unit operates within its design limitations. As the heat exchanger switched to the condensing mode, the air side pressure drop increased over the dry value as shown in figure 71. The equivalent data for S/N 1 is included for comparison. The recorded water side pressure drop for S/N 3 at a flow rate of 272 kg/hr (600 lbs/hr) is 4.43 kN/m^2 (0.63 psi). This value is obtained by substracting the test rig tare pressure drop of 3.62 kN/m^2 (0.525 psi) from the value recorded in the log. Since the operating conditions of Run Number 8 in the Master Test Plan are closest to the original design performance requirements, this run was designated as the base point for the endurance tests. However, after the test was begun, a discussion with the NASA resulted in changing the air flow to 635 kg/hr (1400 lbs/hr) to be more representative of current Shuttle requirements.

Base point performance tests both before and after the 100 cycle simulated Shuttle mission indicated no degradation in heat exchanger performance during the life cycle test. Pre-mission base point data indicated a unit effectiveness of 85.8 percent while the post-mission base point effectiveness was 85.7 percent. Data generated from this unit, S/N 3, was compared with data from the first lightweight heat exchanger, S/N 1, figure 72. Although the test requirements were identical for both units, some tolerance in test parameters, such as fluid flow rate and fluid inlet temperatures were allowed. At some test points, these tolerances were sufficiently large to result in approximately 10 percent difference in total heat loading from one heat exchanger to another at the same test point. Whenever this variation occurs, it does not allow for a direct comparison from one unit to another. Allowing for variations in heat loads, the units appear to be nearly identical in heat transfer capability. The heat loads for units for S/N's 1 and 3 were within 5 percent of each other for test condition 10 and this test condition shows a unit to unit difference in effectiveness of only 0.65 percent.

The unit to unit measurement of air side pressure drop did not show similar values. The first unit has a dry air side pressure drop of 89.58 N/m^2 (0.36 in. H_2O) at 408.2 kg/hr (900 lbs/hr) while the second unit has a corresponding pressure loss of 79.63 N/m^2 (0.32 in. H_2O) at the same flow rate. The 12.5 percent higher pressure drop experienced in the first unit is believed to be traceable to epoxy sealant pluggage in the air passage and is not a function of design, as the third unit demonstrates.

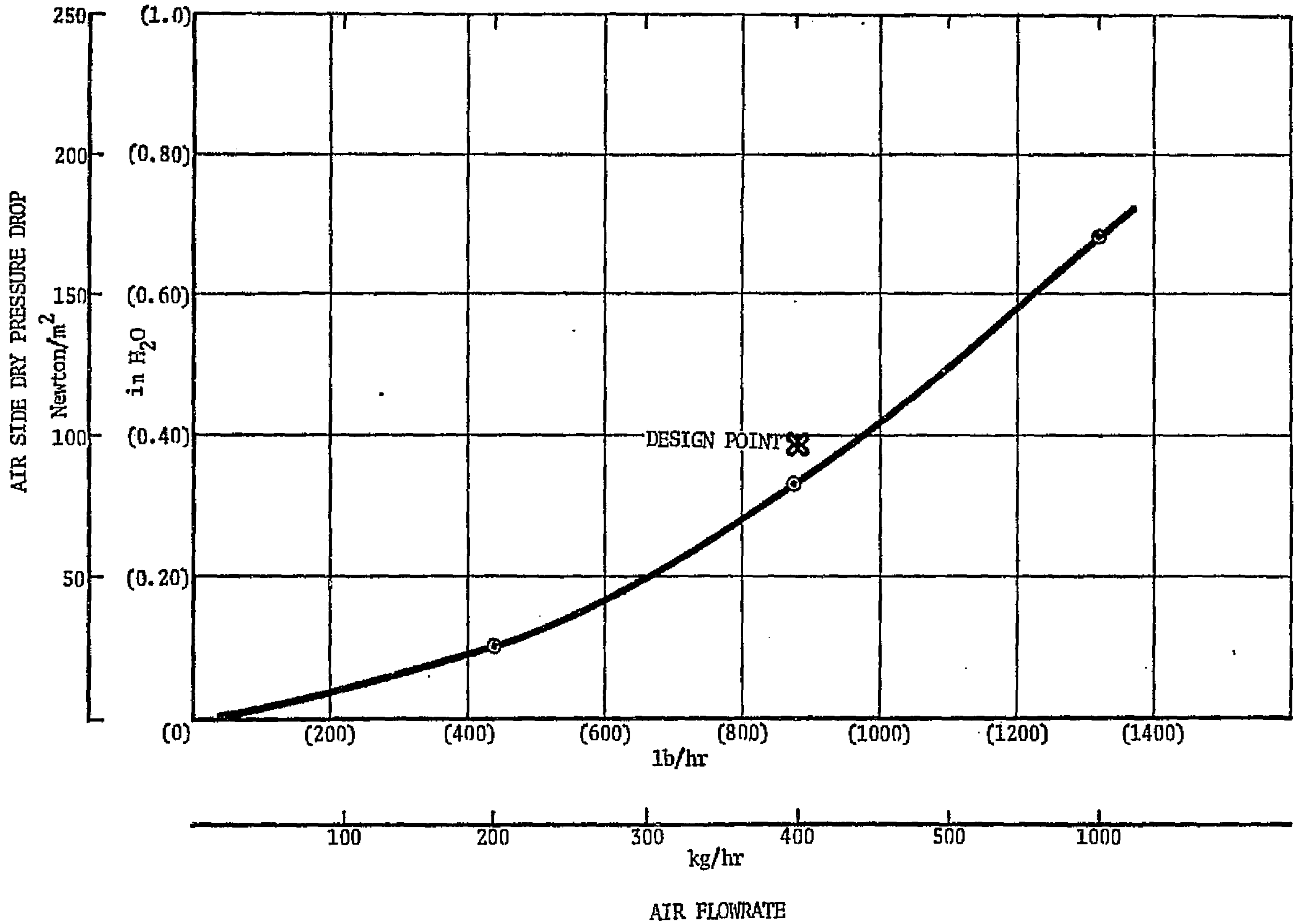


FIGURE 70 LIGHTWEIGHT LONG LIFE HEAT EXCHANGER S/N 3 AIR SIDE PRESSURE DROP (DRY)

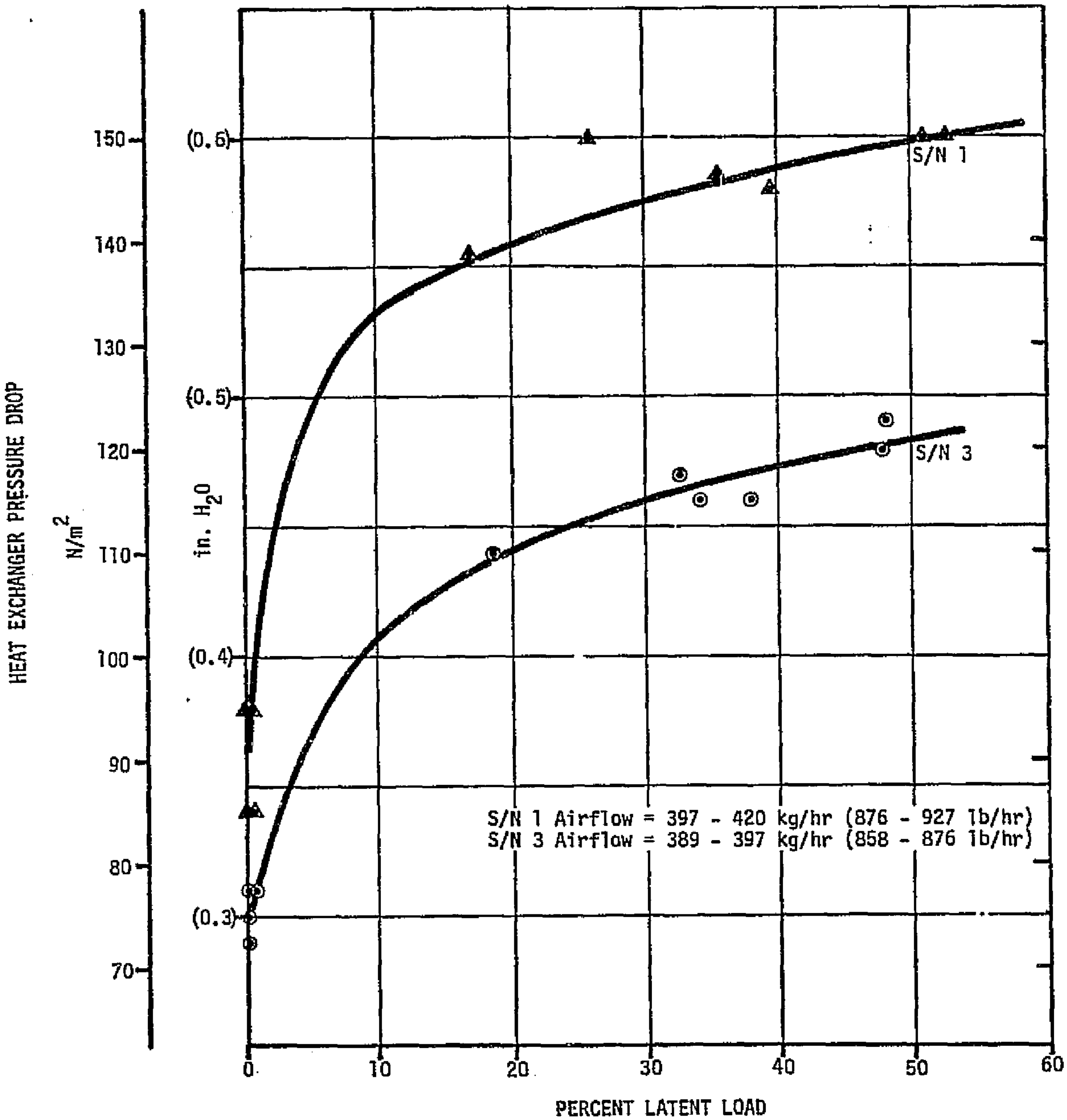


FIGURE 71 LIGHTWEIGHT LONG LIFE HEAT EXCHANGER PRESSURE DROP vs. LATENT LOAD

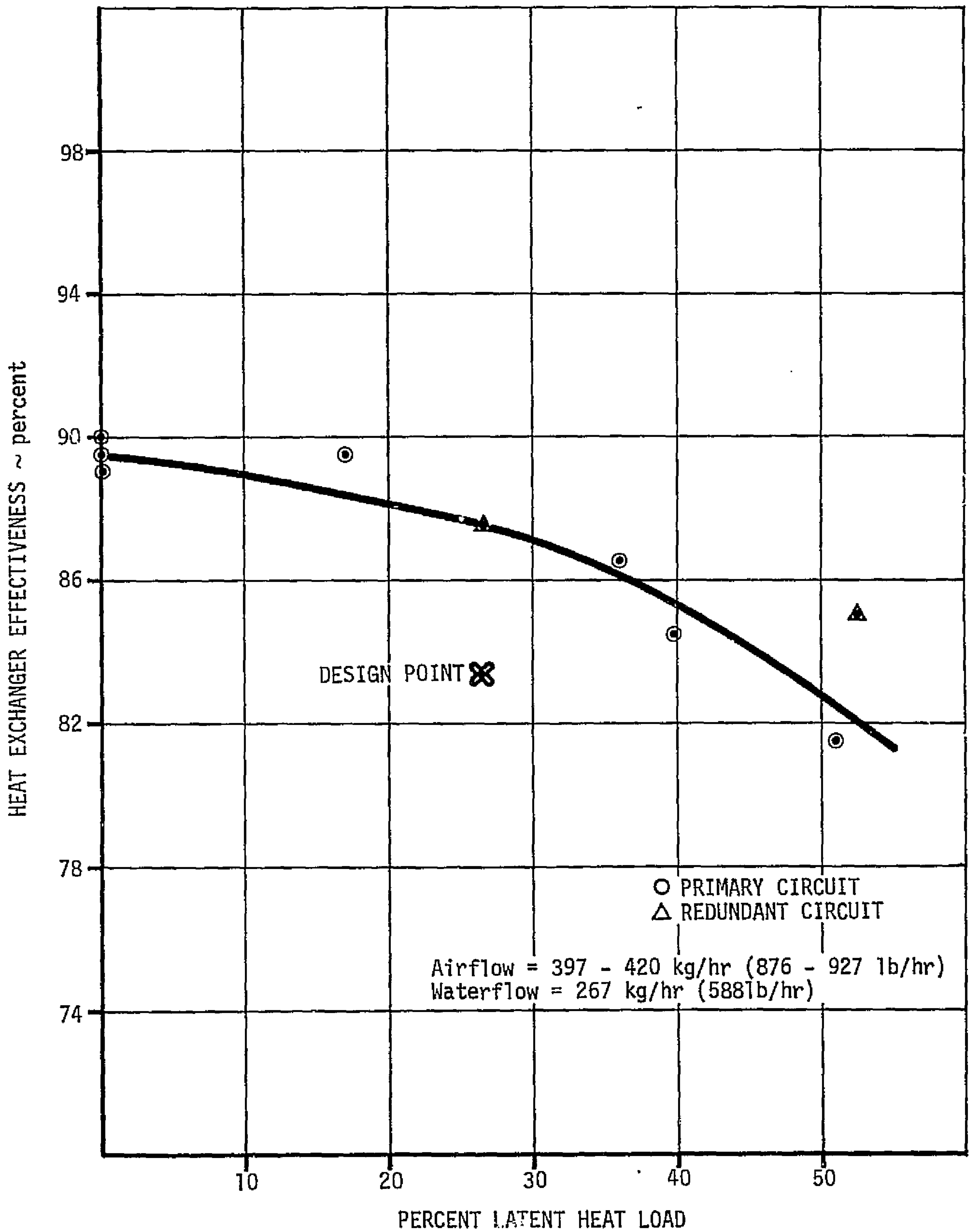


FIGURE 72 HEAT EXCHANGER EFFECTIVENESS vs. LATENT LOAD LIGHTWEIGHT LONG LIFE HEAT EXCHANGER S/N 1

Finally, the flow input requirements of Shuttle condensing heat exchanger Specification SVHS 6442, Revision A, shown in Table XV, were analytically input into Hamilton Standard Condensing Heat Exchanger Computer Program P280, along with the aluminum heat exchanger geometry, to determine if the unit could meet the Shuttle performance requirements. The heat exchanger was capable of meeting the thermal performance but indicated an air side pressure drop that exceeded the limits. It is recommended that a new configuration be generated that will meet all Shuttle requirements.

Leakage (Test 6)

Leakage testing after performance tests again showed leakage at the air flange but no water side leakage was detected.

Vibration (Test 7), Leakage (Test 8 & 10) and Proof (Test 9)

The unit was subjected to the random vibration level of figure 73 (overall level, 5.34 g) for two minutes, each axis. Subsequent visual examination revealed no damage. The leakage and proof tests immediately following the vibration test were completed without change from the pre-vibration tests and confirmed that no damage had occurred.

Simulated Shuttle Mission (Test 12)

The unit was subjected to 100 cycles of simulated mission performance. During each cycle, both condensing and non-condensing conditions were used, each sufficiently long to provide stabilized performance over a 15-minute period. The cycles were completed without incident except that after 30 cycles the air flow was increased from 397 kg/hr (875 lbs/hr) to 635 kg/hr (1400 lbs/hr).

Leakage (Test 14)

The leakage test following life testing revealed no change from previous tests, i.e., no air or water leakage but leakage at one of the mounting flanges.

TABLE XV SHUTTLE PERFORMANCE CHARACTERISTICS

	AIR				COOLANT				CONDENSATE			
	Condition A		Condition B		Condition A		Condition B		Condition A		Condition B	
Inlet Temp K (°F)	302.76 (min)	85.3 (min)	313.16 (min)	104.0 (min)	282.56 (min)	49.0 (min)	279.56 (min)	43.5 (min)	302.76 (min)	85.3 (min)	313.16	104
Inlet Pressure kN/m^2 (psia)	102 (max)	14.8 (max)	102 (max)	14.8 (max)	137/168	19.9/24.3	137/168	19.9/24.3	102	14.8	102	14.8
Inlet Dew Point K (°F)	286.26 (min)	55.5 (min)	287.36 (min)	57.6 (min)	-	-	-	-	-	-	-	-
Flow Rate kg/sec (lb/hr)	10.67 (min)	1411 (min)	10.33 (min)	1366 (min)	7.75 (max)	1025 (max)	7.63 (max)	1009 (max)	.0090 (min)	1.19 (min)	.0249 (min)	3.29 (min)
Q Watts (Btu/hr) (Ref.)	3,244 (Sens.)	11,070 (Sens.)	5,229 (Sens.)	17,842 (Sens.)		12,338		21,351				
	372 (Latent)	1,268 (Lat.)	1,028 (Latent)	3,509 (lat.)								
ΔP kN/m^2 (in. H_2O)	0.149 dry (max)	0.6 dry (max.)	0.149	0.6 dry (max)	8.96	1.4	15.86	1.3	0.573	2.3	0.573	2.3
	0.199 wet (max)	0.8 wet (max)	0.199 wet (max)	0.8 wet (max)								
Outlet Temp K (°F)	284.76 (max)	52.9 (max)	283.26 (max)	50.1 (max)	289.26 (Ref.)	61.0 (Ref.)	291.16 (Ref.)	64.4 (Ref.)	284.76 (Ref.)	52.9 (REF.)	283.26 (Ref.)	50.1 (Ref.)
Outlet Dew Point K (°F)	284.76 (max)	52.9 (max)	283.26 (max)	50.1 (max)		-		-		-		

Air In T =	296.96 to 313.16 K	(75	TO	104°F)
H_2O In T =	275.86 to 283.26 K	(37	to	50.1°F)
Inlet Dew Point =	276.96 to 289.26 K	(39	to	61°F
Total Heat Transfer =	1.21 to 6.26 watts	(4,130	to	21,351 Btu/hr)
Sensible Heat Transfer =	0.73 to 5.23 watts	(2,500	to	17,842 Btu/hr)
Latent Heat Transfer =	0.29 to 1.03 watts	(1,000	to	3,509 Btu/hr)
Air Flow =	204 to 693 kg/hr	(450	to	1,528 lbs/hr)
Water Flow =	209 to 465 kg/hr	(460	to	1,025 lbs/hr)
Air Inlet Pressure =	100.6 to 103 kN/m^2	(14.6	to	15.0 psia)
Water Inlet Pressure =	137 kN/m^2 to 620 kN/m^2	(19.9 psia	to	90 psia)
Condensate Air Flow =	20.4 to 22.7 kg/hr	(45	to	50.0 lb/hr)
Condensate Flow -	0.136 to 1.8 kg/hr	(0.3	to	4.0 lb/hr)
Maximum Touch Temp. =	318.16 K			(113°F)

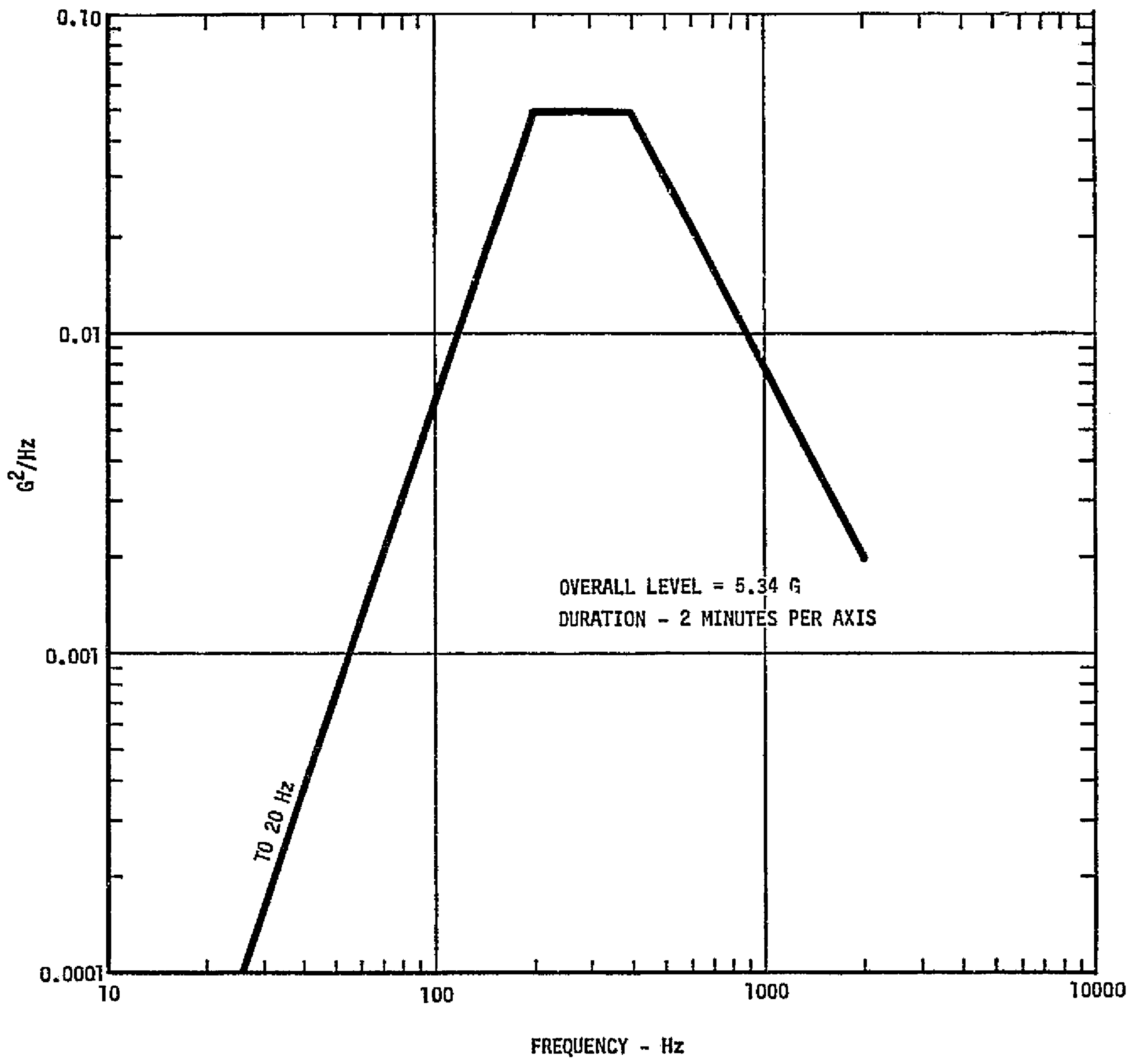


FIGURE 73 SHUTTLE RANDOM VIBRATION LEVEL

Thermal Cycling and Shock (Test 15), Performance Base Point (Test 16) and Leakage (Test 17)

The three cycles of thermal cycling were completed without incident and the subsequent performance base point and leakage tests confirmed that no changes to the heat exchanger had occurred. Heat exchanger effectiveness was 79.6 percent.

Each cycle of thermal shock consisted of heating the unit for two hours with air flow at 333 K(140°F) and with water flow shut off to stabilize the unit at high temperature. Then the water flow was turned on at minimum rig temperature and the air flow temperature was lowered as rapidly as possible. This condition was maintained for one hour, then the high temperature conditions were again established.

Visual Examination (Test 18)

Photographs again were used to record the physical condition of the heat exchanger, figures 74-79. The hydrophilic coating was checked for wettability and appearance. Wettability was excellent and the coating appeared unchanged. Final weight of the heat exchanger was 80.07 N (18.0 lbs).

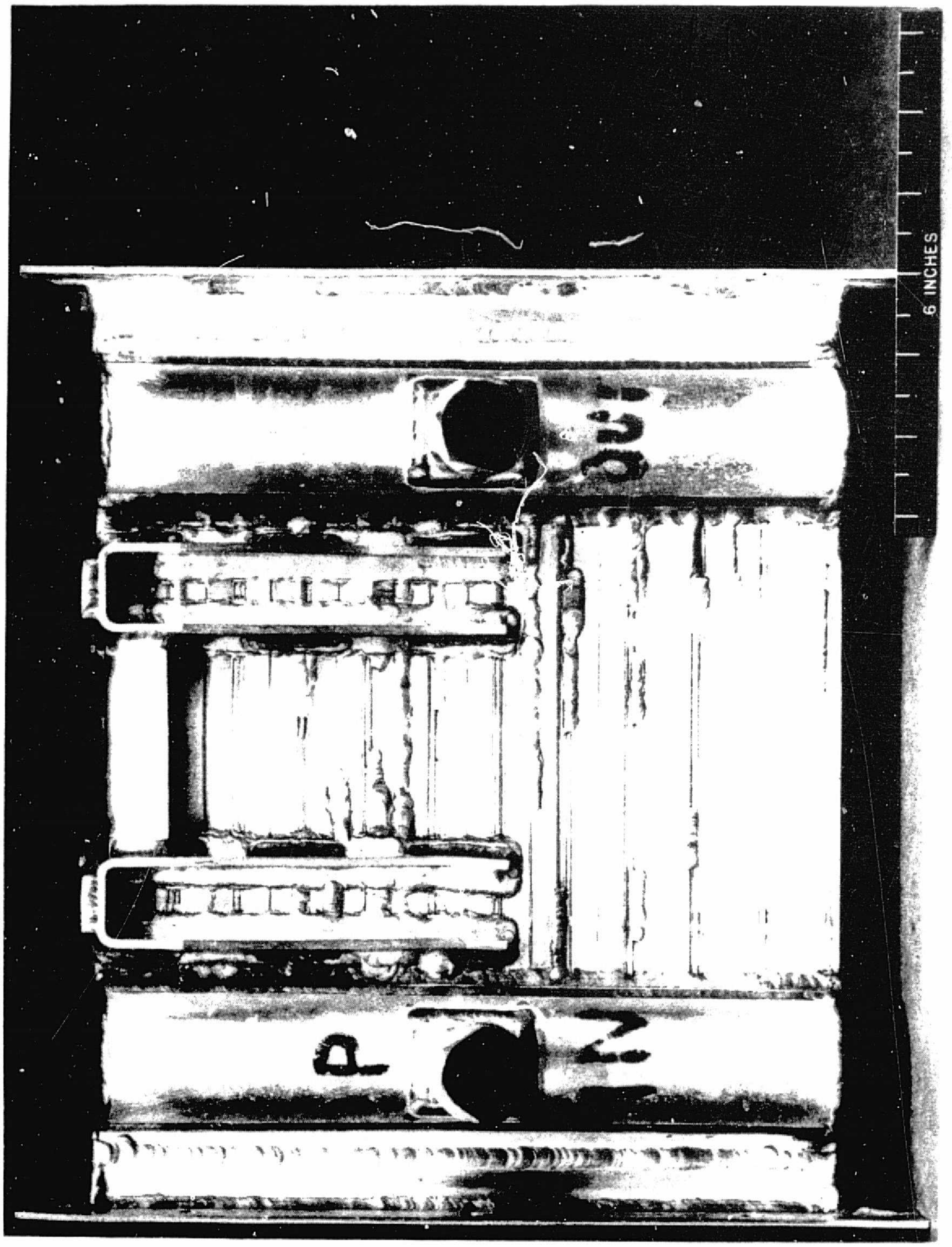


FIGURE 74 HEAT EXCHANGER AFTER TEST

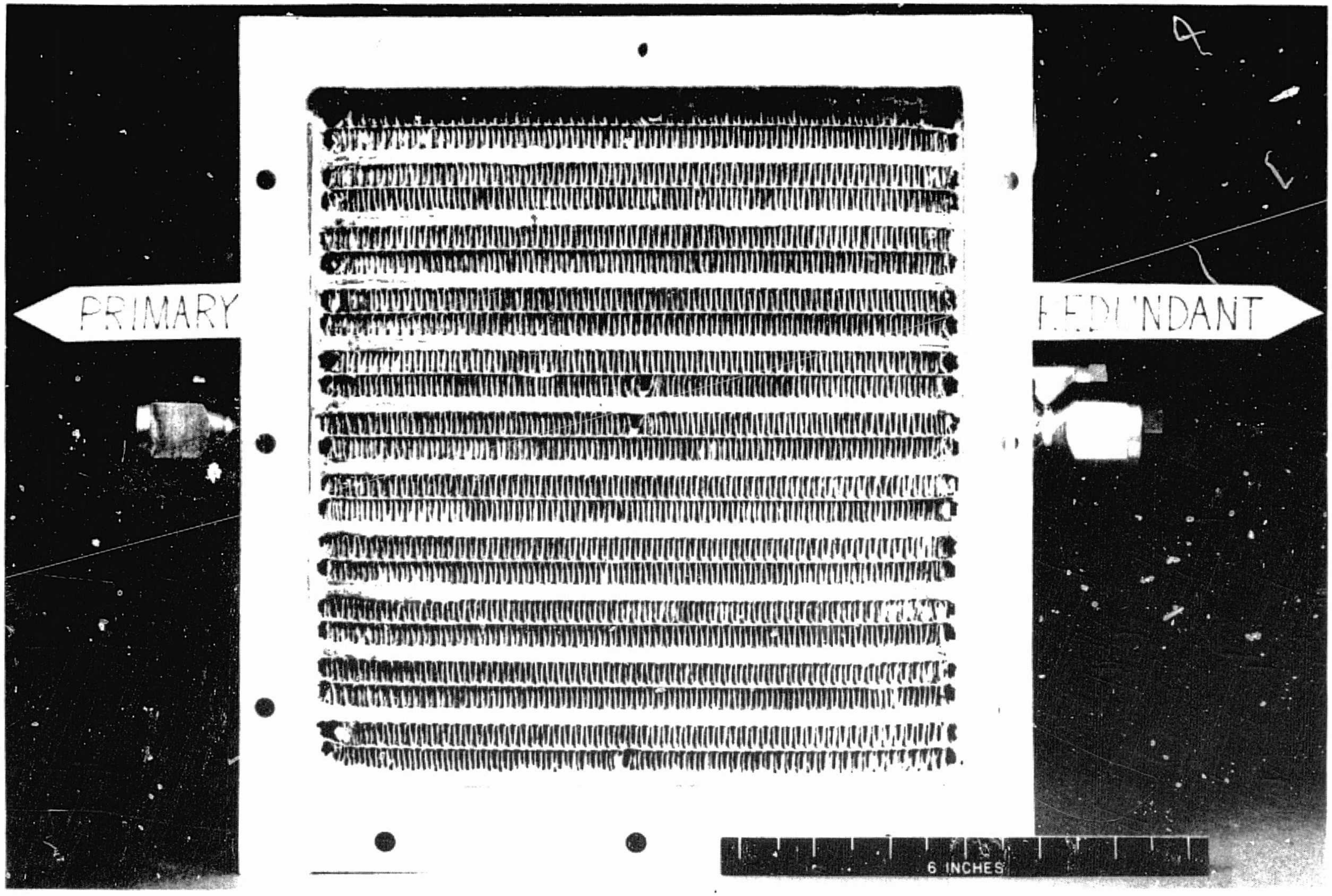


FIGURE 75 HEAT EXCHANGER AFTER TEST

ORIGINAL PAGE IS
OF POOR QUALITY

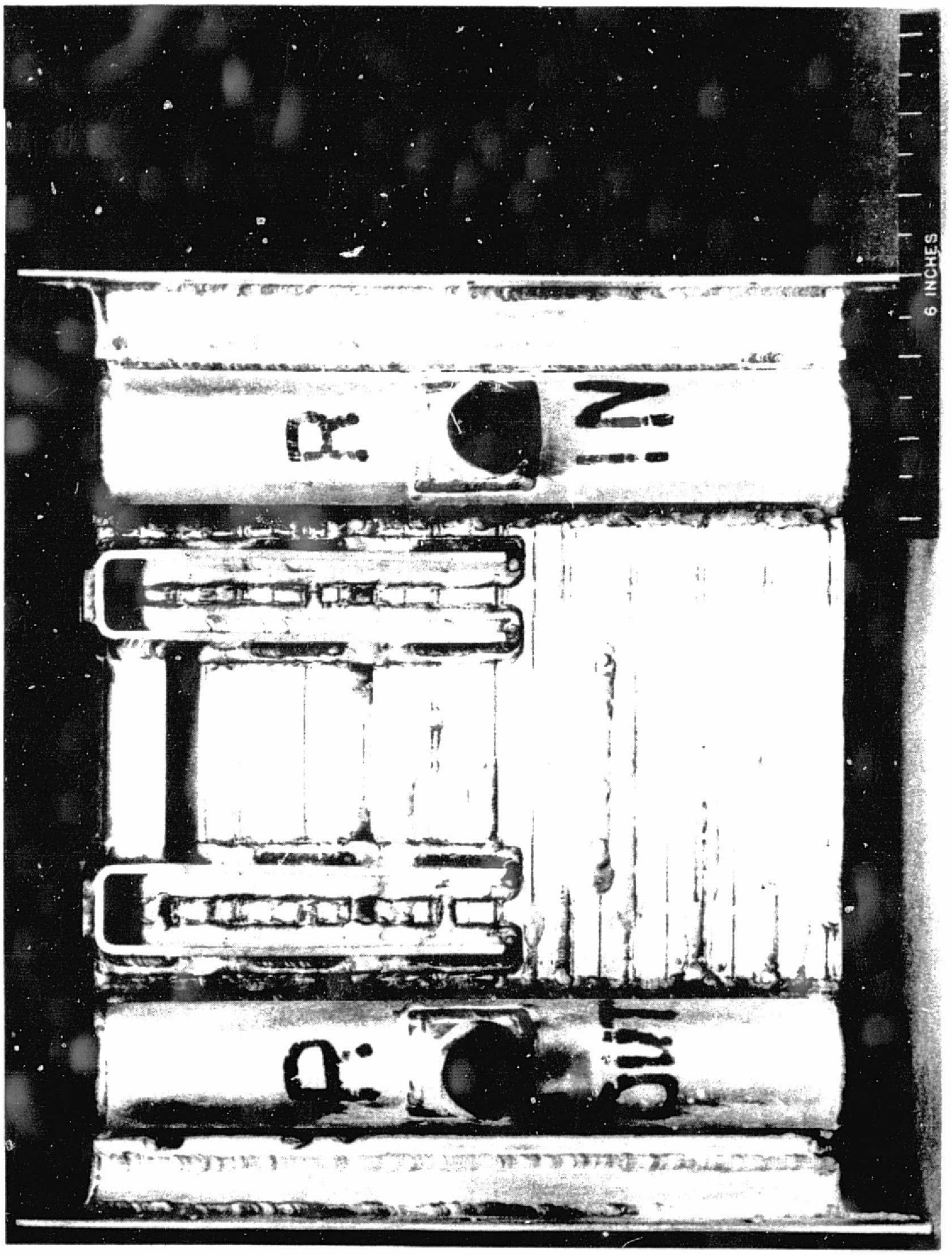


FIGURE 76 HEAT EXCHANGER AFTER TEST

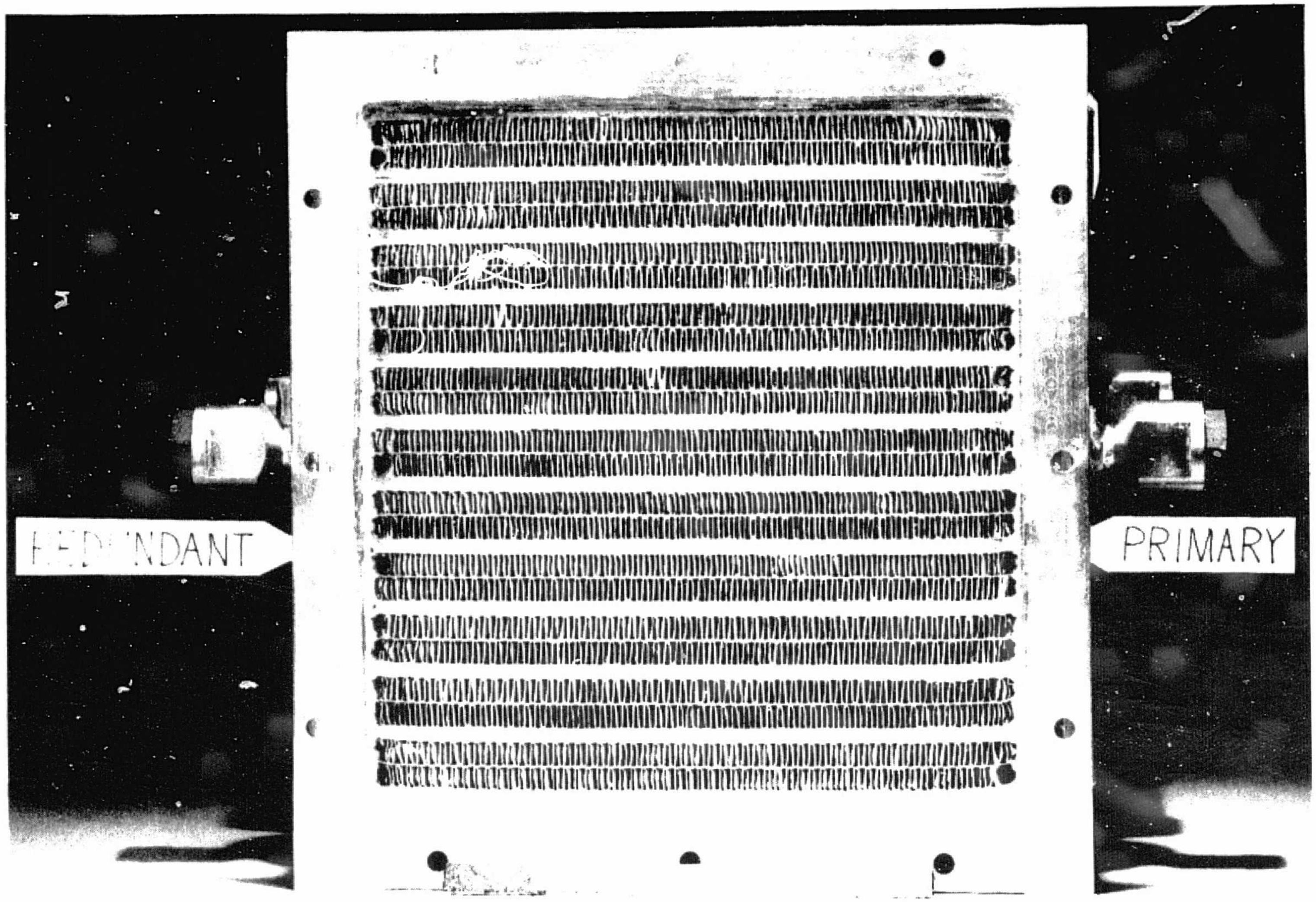


FIGURE 77   HEAT EXCHANGER AFTER TEST

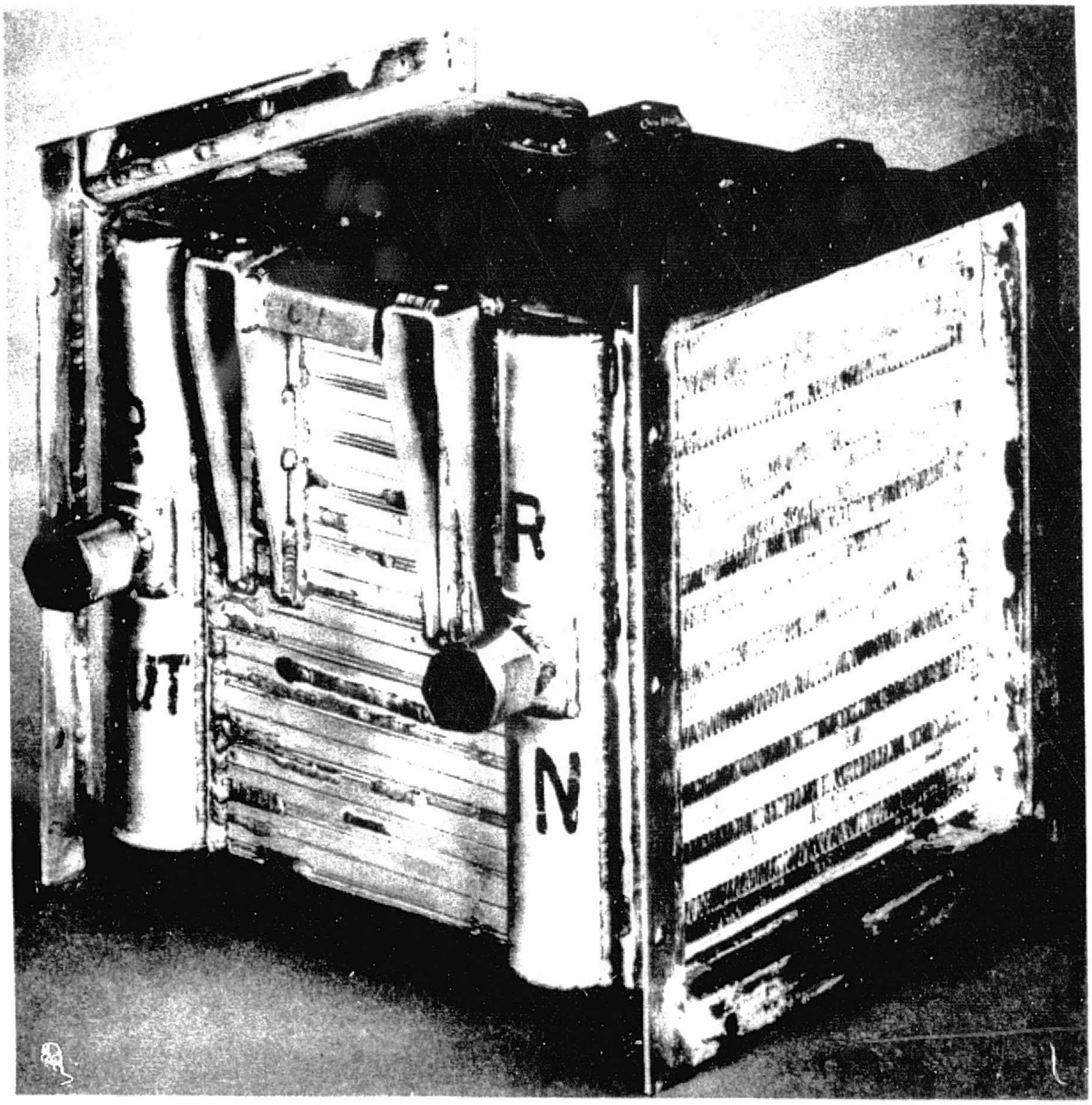


FIGURE 78 HEAT EXCHANGER AFTER TEST

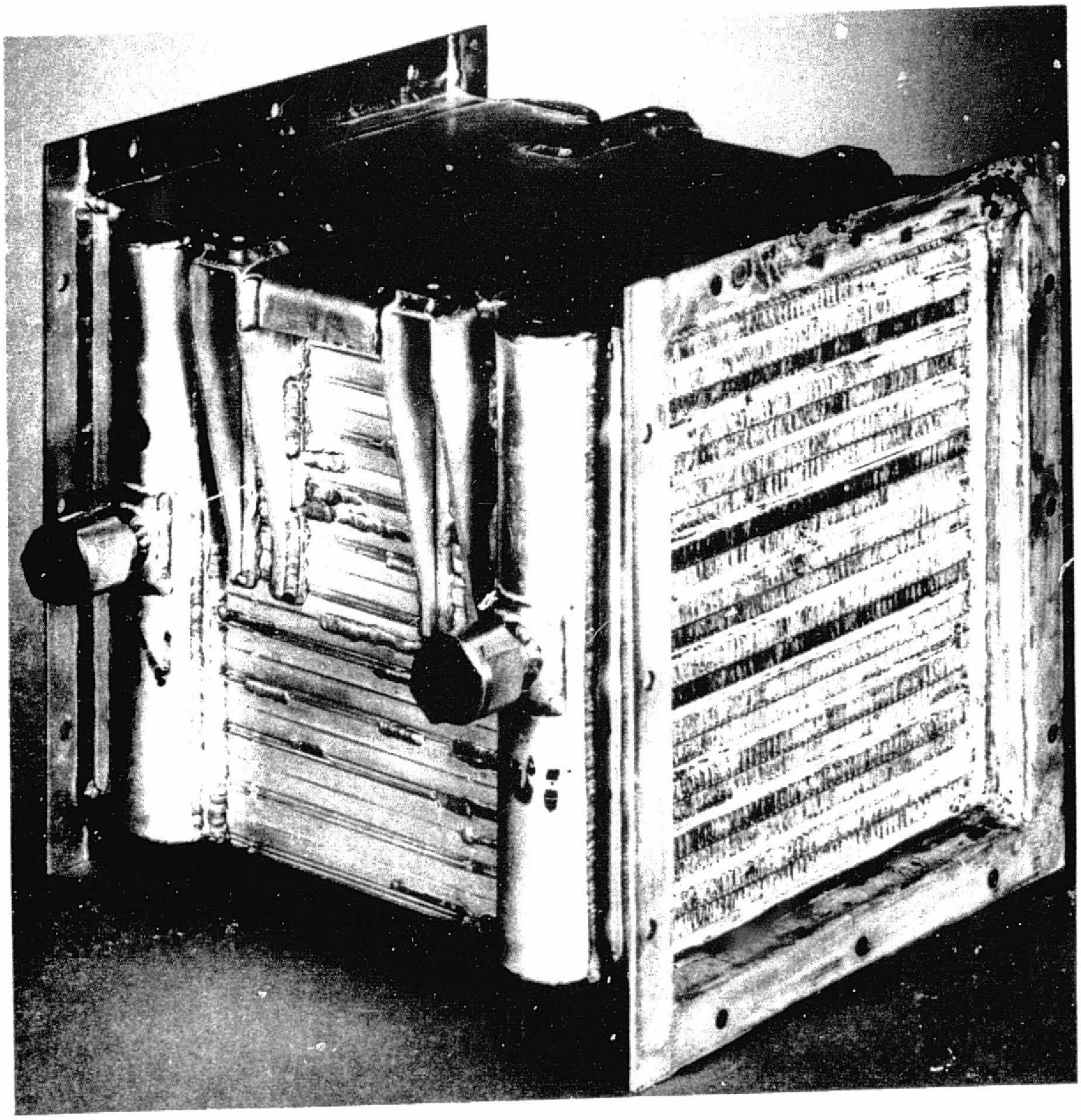


FIGURE 79 HEAT EXCHANGER AFTER TEST

APPENDIX A

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION

ECS-730022-L-012
Rev. A Sept. 19, 1974
Rev. B Nov. 26, 1974

LIGHTWEIGHT LONG LIFE HEAT EXCHANGER

MASTER TEST PLAN

PREPARED UNDER CONTRACT NAS 9-13552

BY

HAMILTON STANDARD

DIVISION OF UNITED AIRCRAFT CORPORATION

WINDSOR LOCKS, CONNECTICUT

FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LYNDON B. JOHNSON SPACE CENTER

HOUSTON, TEXAS

NOVEMBER, 1973

Prepared by: A. E. Francis
A. E. Francis
Program Engineer

Approved by: Fred H. Greenwood
F. H. Greenwood
Program Manager

1.0 SCOPE

This test plan defines design evaluation testing of a Lightweight Long Life Heat Exchanger (LLL HX) being conducted for the National Aeronautics and Space Administration Lyndon B. Johnson Space Center, NASA Contract 9-13552.

2.0 APPLICABLE DOCUMENTS

2.1 Government

No.	Title	Para. Ref.
MIL-P-27407	Propellant, He Pressurizing	4.3.4.3.f

3.0 GENERAL

3.1 Item Description

The Lightweight Long Life Heat Exchanger (LLL HX), Hamilton Standard Part Number SVSK 86099, is designed to the requirements, as of the writing of this test plan, for the Shuttle Condensing Cabin heat exchanger application. The design conditions are as follows:

Q Sensible	=	11,049 BTU/HR.
Q Latent	=	2,400 BTU/HR.
Outlet Total Pressure	=	14.7 ± 0.2
PPO_2	=	3.1 ± 0.1 Psia
Gas Flow	=	880 lbs./Hr.
Gas Inlet Temperature	=	71-97° F
Gas Outlet Temperature	=	45-50° F
Inlet Dew Point	=	39-61° F
H_2O Inlet Temperature	=	40°F
H_2O Inlet Pressure	=	60 Psia
H_2O Flow	=	600 lb/hr.

A

The heat exchanger is a fluxless brazed aluminum unit. It consists of eleven parallel single pass air passages for the purpose of air cooling and moisture condensation. Cooling is accomplished by means of (two) redundant cooling loops. Each cooling loop consists of twelve parallel six pass water passages. Parting sheets, separating the fluid passages, are a composite aluminum/titanium corrosion barrier.

3.2 Test Facilities

Unless specifically excepted, all testing shall be conducted in the Space System Department test laboratories at Hamilton Standard.

4.0 TESTS

4.1 Program Description

The test program discussed herein will be conducted on two LLL-HX's. S/N 1 heat exchanger will undergo design evaluation testing which will consist of a performance test series. S/N 2 heat exchanger will then be tested to demonstrate suitability for the Shuttle application. A

4.2 Test Sequence

Testing shall be performed in the sequence listed below. Deviations from this sequence shall be authorized in writing by the cognizant Project Engineer.

Test	Title	Paragraph
Heat Exchanger S/N 1		
1	Weight	4.3.1
2	Visual Examination	4.3.2
3	Leakage	4.3.4
4	Performance	4.3.5
Heat Exchanger S/N 2		
1	Weight	4.3.1
2	Visual Examination	4.3.2
3	Leakage	4.3.4
4	Proof Pressure	4.3.3
5	Performance	4.3.5
6	Leakage	4.3.4
7	Vibration	4.3.6
8	Leakage	4.3.4
9	Proof Pressure	4.3.3
10	Leakage	4.3.4
11	Performance base Point	4.3.7
12	Simulated Shuttle Mission	4.3.8
13	Performance base Point	4.3.7
14	Leakage	4.3.4
15	Thermal Cycling and Shock	4.3.9
16	Performance base Point	4.3.7
17	Leakage	4.3.4
18	Visual Examination	4.3.2

A

4.3 Test Definitions

4.3.1 Weight

4.3.1.3 Description of Procedure

The unit shall be weighed to the nearest 0.5 lb.

4.3.1.4 Special Instructions

(a) The visual scale readings shall be recorded on a Log of Test, HSF 175.1A.

(b) No data reduction is required.

(c) The recorded weight shall be acceptable.

(d) The recorded weight shall be compared to the analytical target by the Cognizant Project Engineer.

4.3.2 Visual Examination

4.3.2.1 The objective of the visual examination is to define a baseline of the visual appearance of the heat exchanger, describing apparent defects or damage for comparison before and after test.

4.3.2.2 Description of Test Setup

(a) The visual examination of the heat exchanger shall be conducted on a bench within the SSD laboratory or inspection department.

(b) No instrumentation is required.

(c) No STE is required.

(d) No schematic is required.

(e) Visual observation shall be recorded.

(f) The unit shall be free of external dirt, chips and manufacturing residue and without fixture attachments and free of liquid.

(g) No fluids shall be used.

4.3.2.3 Description of Procedure

(a) The heat exchanger shall be visually examined on exterior surfaces for evidence of dirt, manufacturing residues, stains, dents and burrs. Particular attention shall be paid to the appearance of connection fittings.

(b) The appearance of the inlet and outlet air fins and cavities shall be similarly examined.

(c) On the initial examination or as convenient the fit of the heat exchanger to rigs and fixtures shall be checked. This shall be done as soon as the rig and/or equipment is available.

4.3.2.4 Special Instructions

(a) Visual observations shall be recorded on a Log of Test, HSF 175.1A.

(b) No data reduction is required.

(c) Observations recorded shall be accepted or rejected by the cognizant Project Engineer.

4.3.2.4 (Continued)

(d) At completion of the test program, the initial and final examinations shall be compared by the cognizant Project Engineer.

4.3.3 Proof Pressure

4.3.3.1 The objective of the Proof Pressure test is to verify the pressure integrity of the heat exchanger.

4.3.3.2 Description of Test Setup

The setup shall be as described in section 4.3.4, except temperature monitoring is not required.

4.3.3.3 Description of Procedure

(a) The heat exchanger is comprised of an air circuit and a primary and a redundant water circuit. These circuits may be tested in the most convenient sequence. This test may be combined with the leakage by leak testing at proof pressure levels.

A (b) Closure attachment and pressurant connection shall be per paragraph 4.3.4.3 b and c (Reference Figure 4.1.) Untested circuits shall be vented to ambient.

(c) Slowly, pressurize each circuit separately to the specified level. Maintain pressure for 10 minutes minimum. Record pressure attained and time at pressure on the data sheet provided.

Circuit	Units	Pressure
Air	psid	0.8 - 1.8
Water	psig	90 - 95

A

(d) If leakage is noted, locate leak and mark location. Weld repairs are acceptable.

4.3.3.4 Special Instructions

(a) Proof Pressure data shall be recorded for each run on the data sheet provided in this section.

(b) Data reduction and analysis is not required.

(c) The unit shall pass the subsequent leakage test.

PROOF PRESSURE TEST
DATA SHEET

Test Date ___________

Operator ___________

Engineer ___________

PRIMARY WATER CIRCUIT

Barometric Pressure ______________ in Hg Time __________
Ambient Temperature ______________ °F
A Pressure Applied ___________ psig
Time at Pressure ___________ minutes (10 min.)
Leakage Test Passed ____________

REDUNDANT WATER CIRCUIT

Barometric Pressure ______________ in Hg Time __________
Ambient Temperature ______________ °F
A Pressure Applied ___________ psig
Time at Pressure ___________ minutes (10 min.)
Leakage Test Passed ____________

AIR CIRCUIT

Barometric Pressure ______________ in Hg Time __________
Ambient Temperature ______________ °F
A Pressure Applied ___________ psid
Time at Pressure ___________ minutes (10 min.)
Leakage Test Passed ____________

4.3.4 Leakage

4.3.4.1 The objective of the leakage test is to verify the leak tight integrity of the following:

(a) Air passages to external

(b) Water passages to air passages

(c) Water passages to external

(d) Water passages to water passages

4.3.4.2 Description of Test Setup

(a) The leakage test shall be conducted on a bench within the SSD laboratory.

(b) The following instrumentation is required:

Instrument	Min. Range	Units	Type	Accuracy
Thermometer	32-100	°F	Hg	±1/2F°
Thermocouple	32-100	°F	Copper/ Const.	±1F° System
Pressure Gage	0-100	psig	Bourdon	±1% F.S.
Pressure Gage	0-5	psid	Bourdon	±1% F.S.

A (c) Test equipment shall include the following:

Item	HS Identification
He Mass Spectrometer w/Sniffer	-
Leak Fixture	(TBD)

(d) Typical setup is given in Figure 4.1.

(e) The unit shall be clean per paragraph 4.3.1.2.f. Pressurant supply shall be from the SSD gas supply farm and filtered for usage with the Mass Spectrometer.

4.3.4.2 (Continued)

(f) Pressurant shall be laboratory air and/or gaseous Helium per MIL-P-27407.

4.3.4.3 Description of Procedure

(a) The heat exchanger is comprised of an air circuit and a primary and a redundant water circuit. These circuits may be tested in the most convenient sequence. The test may be conducted at proof pressure levels.

(b) Attach air circuit closures, SVSK (TBD) using all twelve bolting holes (1/4 dia. bolts Ref.).

(c) To test a circuit, attach regulated pressure supply to the circuit inlet with the outlet sealed. The other two circuits should be vented to ambient.

(d) Pressurize, slowly, to the pressure specified below. Close the supply shutoff and record the supply pressure. Record a second reading after ten minutes. If pressure decay is apparent, continue recording at 5 minute intervals for a total of 30 minutes max.

Note: Item and ambient temperatures shall be stable within ±2F° during the test.

(e) If the pressure cannot be maintained, attempt to locate the leak using a sniffer gun attached to a Helium Mass Spectrometer. Mark any leaks located and advise the cognizant Engineer. Weld repairs are acceptable.

(f) Repeat the procedure above for the other two circuits.

Heat Exchanger Circuit	Pressure (min.)	Units
Air	0.5	psid
Water (2)	60	psig

A

4.3.4.4 Special Instructions

(a) Data shall be recorded for each run on the data sheets provided in this section.

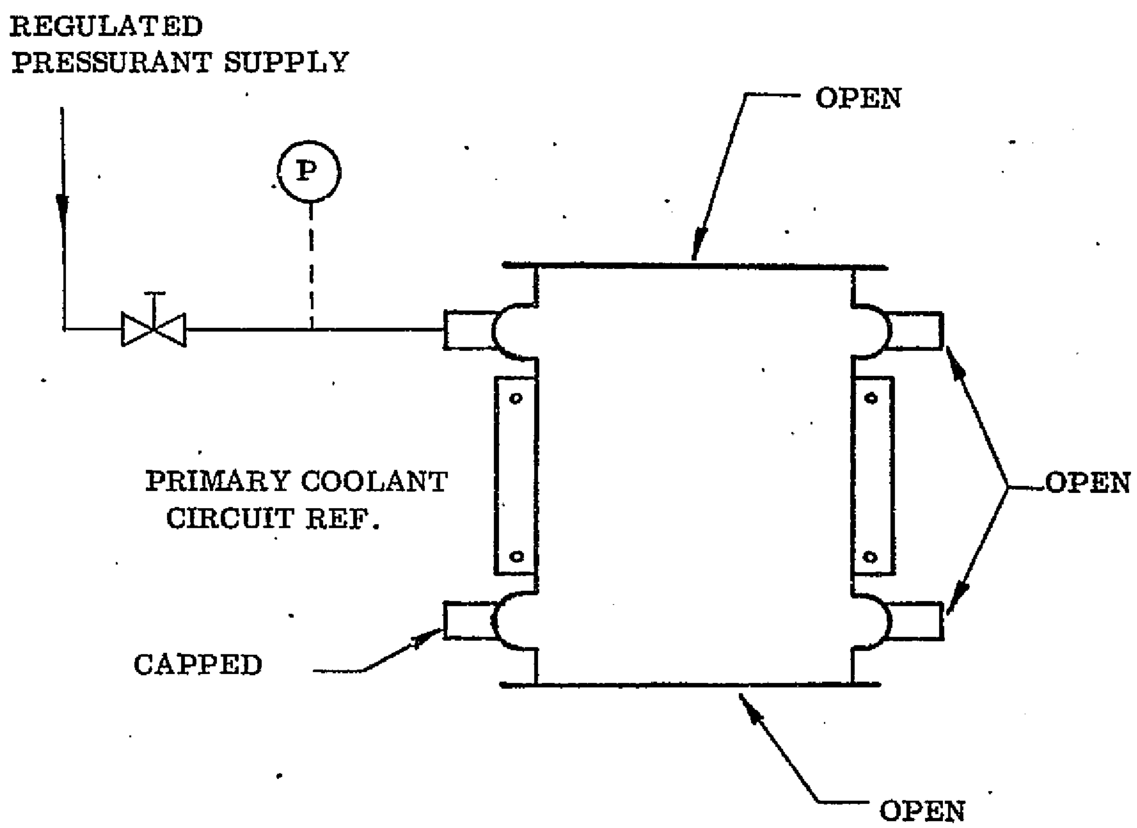
(b) Data corrections shall be required for variations in ambient and/or item temperature.

4.3.4.4 (Continued)

(c) There shall be no detectable leakage in ten minutes, after temperature corrections.

(d) Data Analysis not required.

(e) A photograph of a typical test setup shall be taken prior to removal of the heat exchanger to the next test, on the first test only.



NOTE: AIR CIRCUIT PRESSURE GAGE SHALL REFERENCE AMBIENT (PSID)

FIGURE 4-1

TYPICAL PROOF & LEAK TEST SETUP

LEAKAGE TEST

DATA SHEET

Test Date ________

Operator ________

Engineer ________

PRIMARY WATER CIRCUIT

Barometric Pressure __________ in. Hg   Time __________
Ambient Temperature __________ °F
Initial Pressure ________ psia; Item Temp. ________ °F

Press.	10 min ______ psig	Temp.	10 min ______ °F		
	15 min ______ psig		15 min ______ °F		
A	20 min ______ psig		20 min ______ °F		
	25 min ______ psig		25 min ______ °F		
	30 min ______ psig		30 min ______ °F		

REDUNDANT WATER CIRCUIT

Barometric Pressure __________ in. Hg   Time __________
Ambient Temperature __________ °F
Initial Pressure ________ psia; Item Temp. ________ °F

Press.	10 min ______ psig	Temp.	10 min ______ °F		
	15 min ______ psig		15 min ______ °F		
A	20 min ______ psig		20 min ______ °F		
	25 min ______ psig		25 min ______ °F		
	30 min ______ psig		30 min ______ °F		

AIR CIRCUIT

Barometric Pressure __________ in. Hg   Time __________
Ambient Temperature __________ °F
Inital Pressure ________ psia; Item Temp. ________ °F

Press.	10 min. ______ psid	Temp.	10 min ______ °F		
	15 min ______ psid		15 min ______ °F		
A	20 min ______ psid		20 min ______ °F		
	25 min ______ psid		25 min ______ °F		
	30 min ______ psid		30 min ______ °F		

Photograph Taken ______________.
date

4.3.5 Performance

4.3.5.1 The objective of the performance test is to evaluate the heat transfer and flow characteristics of the heat exchanger.

4.3.5.2 Description of Test Setup

(a) The performance test shall be conducted within the Space System Department Laboratory.

(b) The required instrumentation is listed on Table 5-1. Data omitted from Table 5-1 shall be completed prior to starting test.

A (c) The test shall be conducted on test rig 61 using an ancillary coolant water supply. In addition, a means for supporting the heat exchanger outside the rig shall be provided, to facilitate air flow vertically downward (See Figures 5-2 and 5-3).

(d) The heat exchanger shall be set up and instrumented per Figures 5-1, 5-2, and 5-3.

(e) Data shall be visually read and recorded on the data sheets provided. In addition the serial number and calibration date of all instrumentation shall be recorded as provided for on Table 5-1.

A (f) Fluid cleanliness inherent to the test rigs shall be adequate.

(g) Test fluids shall be laboratory quality air and steam, provided by Rig 61 and the ancillary coolant water supply.

4.3.5.3 Description of Procedure

(a) Mount the heat exchanger, make fluid connections (air and water) as shown on Figures 5-1, 5-2, and 5-3, and instrument per Figures 5-2 and 5-3 and Table 5-1. During instrumentation, record the identification, serial number and calibration date of each instrument used on Table 5-1.

Note: Any instrument changes during test shall be recorded on the test data sheet.

(b) With the water circuit empty, measure the air flow pressure drop across the unit at 440, 880, and 1320 lb/hr. Fill both water circuits and obtain pressure drop at 5, 7.5, and 10 lb/hr on both circuits. Record data on HSF 175.1A.

(c) The twelve conditions to be tested are listed in Table 5-2. The sequence of runs shall be that providing maximum test efficiency.

4.3.5.3 (Continued)

(d) Conditions per Table 5-2 shall be established for each run per procedures inherent to rig operation. Before recording data allow for conditions to stabilize for at least ten minutes. Record data on log sheet provided at the start and end of a five minute period. Inlet and outlet temperatures shall not vary in excess of 0.5F° on both air and water circuits. Continue recording at five minute intervals until temperature stability criteria is established.

(e) Proceed to next test condition and repeat the above procedure until all conditions have been tested and are accepted by Engineering.

A (f) Upon completion of heat balance calculations, the cognizant Engineer shall indicate rejection or acceptance of the run by so noting and initialing on the data sheet. If a balance cannot be obtained, the operator shall repeat the run in the most efficient operating sequence.

A (g) At completion of testing, the air and water circuits shall be dried by purging with dry air at 160-200°F for one hour. Air and water circuits shall be capped or covered with polyethylene film.

4.3.5.4 Special Instructions

(a) Data for each run shall be recorded on the data sheets provided.

(b) Data reduction not required.

A (c) A heat balance shall be conducted by the cognizant test Engineer for each test run. A balance of ±10% shall be achieved before the run may be considered acceptable.

(d) Data analysis, conducted by Engineering, shall yield the following:

1. Variation of effectiveness for various sensible heat loading.
2. Variation of effectiveness for various latent heat loading.
3. Tabulated pressure drop of air and water circuits including air side changes due to condensing mode operation.

(e) A photograph of the test setup shall be taken prior to removal of the heat exchanger from the test rig.

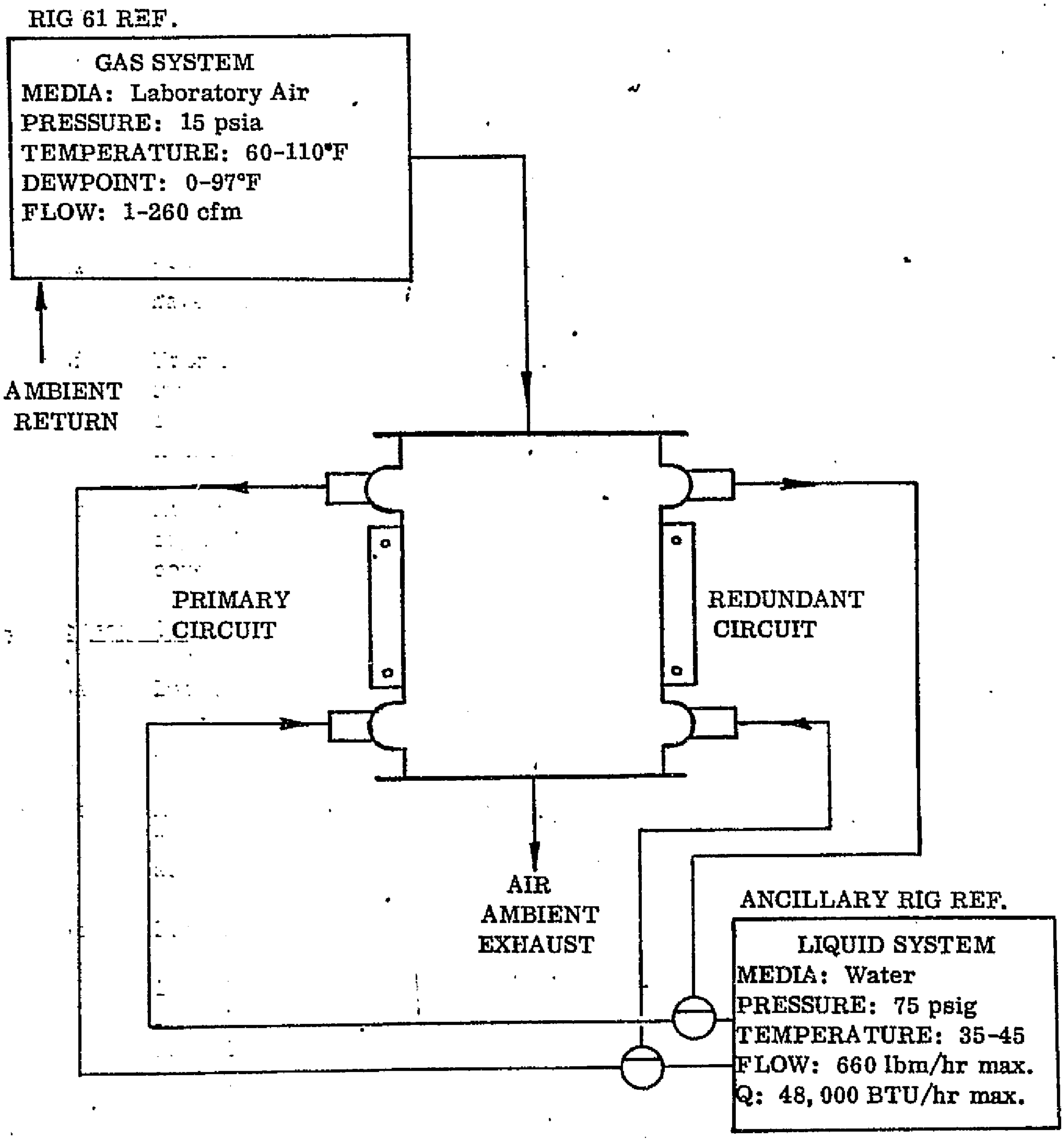


FIGURE 5-1

PERFORMANCE RIG BLOCK DIAGRAM

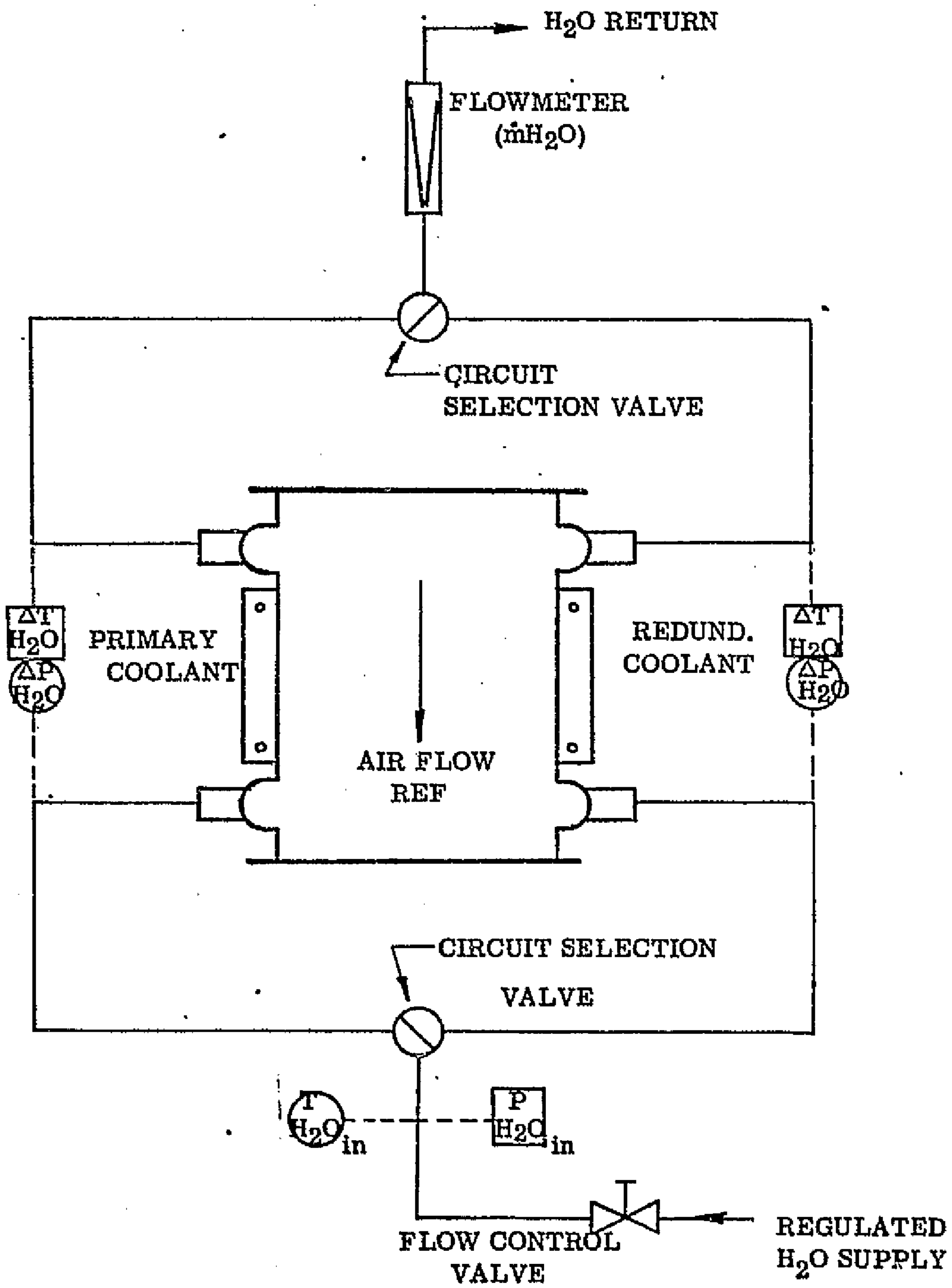


FIGURE 5-2
PERFORMANCE TEST COOLANT CIRCUIT SCHEMATIC

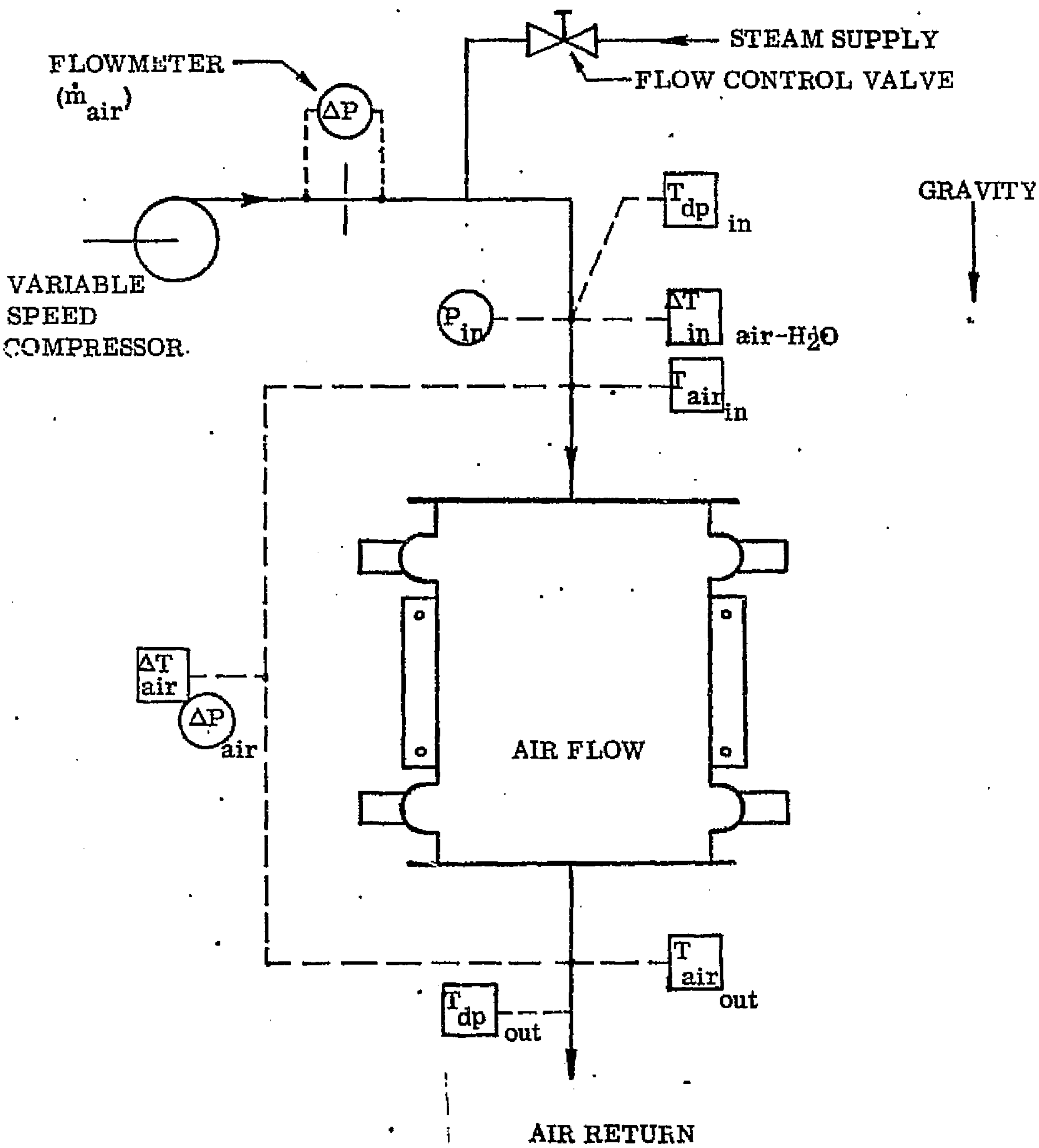


FIGURE 5-3

PERFORMANCE TEST

CONDENSING CIRCUIT SCHEMATIC

TABLE 5-1

INSTRUMENTATION LIST

Sym.	Parameter	Measurement Device	Mfgr.	Model Ident	Minimum Range	Minimum Accuracy	S/N	Calib. Date
$\dot{m}_{H_2O}$	Inlet H_2O flow				12 lbm/min	± 3%		
$T_{H_2O\ in}$	Inlet H_2O temp.				0-100°F	± 1°Fsys		
$P_{H_2O\ in}$	Inlet H_2O Press				0-(TBD) psid	± 0.5 psid		
$\dot{m}_{air}$	Inlet Air Flow	Flow Computer	Daniel Indust.	1244X	170-340 SCFM	± 3%		
$T_{air_{in}}$	Inlet Air Temp				35-160°F	± 2°Fsys		
$T_{DP_{in}}$	Inlet Air Dew Pt				0-100°F	± 1°Fsys		
$P_{air_{in}}$	Inlet Air Press				0-20 psia	± 0.1 psia		
ΔP_{H_2O}	Press. Drop H_2O				0-20 psid	± 0.1 psid		
ΔP_{air}	Press. Drop Air	U Tube Man			0-30 in H_2O	± 0.01 in H_2O		
ΔT_{H_2O}	Temp. Rise H_2O				0-50°F	± 0.5°F sys		

TABLE 5-1 (Continued)

Sym	Parameter	Measurement Device	Mfgr	Model Ident	Minimum Range	Minumin Accuracy	S/N	Date
ΔT_{air}	Temp. Drop Air				0-100°F	± 0.5°F sys		
$T_{air\ out}$	Temp. Air Out				35-160°F	± 2°F sys		
$T_{DP\ out}$	Temp. Dew Point out				0-100	± 1°F sys		
$\Delta T_{air-H_2O\ in}$	Temp. Diff Inlet				0-100	± 0.5°F sys		

NOTE: See paragraph 4.3.5.2.b and 4.3.5.2.e

TABLE 5-2

TEST CONDITIONS

	Run Number	Inlet Air Temp. (±3°F)	Humidity Relative % Ref.	Humidity Dew Point (±2°F)	Air Flow ±10 lbm/hr	Coolant Flow lbm/hr	Coolant Circuit
	1	97	–	Rig Min	880	575-600	Primary
	2	97	–	Rig Min	1320		
	3	97	–	Rig Min	440		
	4	71	–	Rig Min	880		
	5	84	–	Rig Min	880		
	6	97	17	45	880		
	7	97	26	56	880		
A	8	97	34	64	880		
	9	84	51	64	880		
	10	71	79	64	880		Primary
	11	71	79	64	880		Redundant
	12	71	59	56	880		Redundant
	13	71	39	45	880	575-600	Redundant

TEST DATA SHEET

A

PARAMETER	RUN													
	1		2	3	4	5	6	7	8	9	10	11	12	13
	Start	End												
Time														
$\dot{m}_{H_2O}$														
$T_{H_2O\ In}$														
$P_{H_2O\ In}$														
H_2O Circ.														
$\dot{m}_{air}$														
$T_{air_{in}}$														
$T_{DP_{in}}$														
$P_{air_{in}}$														
ΔP_{H_2O}														
ΔP_{air}														
ΔT_{H_2O}														
ΔT_{air}														
$T_{air\ out}$														
$T_{DP\ out}$														
$\Delta T_{ln\ air\text{-}H_2O}$														
Heat Bal. Check														

Photograph Taken ____________
date

Hamilton Standard

Hamilton Standard
WINDSOR LOCKS, CONNECTICUT 06096

TEST DATA SHEET

TEST DATA VERIFICATION - HEAT BALANCE

Step	Item	From	Units	CONDITIONS 1	2	3	4	5	6	7	8	9	10	11	12
A	ΔTa	log	F°												
B	$q_{air\ sens}$	A x 0.24	Btu/lb d.a												
C	Inlet Vapor	W/7000	lb H_2O/lb/d.a.												
D	h Vapor in	Steam Tab.	Btu/lb H_2O												
E	Qv_{in}	C x D	Btu/lb d.a.												
F	Outlet Vapor	W_L/7000	lb H_2O/lb d.a.												
G	h Vapor out	Steam Tab	Btu/lb H_2O												
H	qv out	F x Q	Btu/lb d.a.												
J	q v sens	E-H	Btu/lb d.a.												
K	ΔW_u	C-F	lb H_2O/lb d.a.												
L	h l	Steam Tab	Btu/lb H_2O												
M	q v lat.	K x L	Btu/lb d.a.												
N	qtotal	B+J+M	Btu/lb d.a.												
O	ma	log	lb d.a. hr												

ORIGINAL PAGE IS OF POOR QUALITY

TEST DATA VERIFICATION - HEAT BALANCE (Continued)

Step	Item	From	Units	1	2	3	4	5	6	7	8	9	10	11	12
P	Q air	N x O	Btu/hr												
Q	m_{H_2O}	log	lb H_2O/hr												
R	ΔTl	log	F°												
S	Q_{H_2O}	(1.0) x Q x R	Btu/hr												
T	Balance	$\frac{P-S}{S}$ x 100 (0±10%)	%												

4.3.6 Vibration

A 4.3.6.1 The objective of the vibration test is to determine the ability of the laminate construction of the heat exchanger to withstand 'shuttle' level vibration as defined herein.

4.3.6.2 Description of Test Setup

(a) The test shall be conducted on the vibration test rig in the Hamilton Standard Space Systems Laboratory, or at an approved vendor facility.

(b) Instrumentation indigenous to the vibration test rig shall be used. A triaxial accelerometer, or equivalent, shall be used as the control accelerometer located by resonance search to provide the following criteria:

(1) The control input shall maintain levels at the test frequency within ±3 db of the requirements.

(2) The input level at other locations shall be within ± 4 db of the required level at the test frequency.

(3) The overall g RMS shall be within ±10% of the nominal specification level.

(c) The following special test equipment shall be utilized.

STE	Identification
Vibration Fixture	SVSK (TDB)

Note: A fixture evaluation shall be conducted prior to testing. This evaluation may be combined with the resonance search or, in the event an existing fixture is used, from previous testing programs.

A (d) The heat exchanger water circuits (2) shall be completely filled with water and capped. The air passages shall be taped closed with polyethelyne film. All testing shall be conducted at atmospheric temperature and pressure. The heat exchanger shall be hard mounted to the vibration fixture and instrumented as shown schematically in Figure 6.1.

(e) Data acquisition shall be on magnetic tape, except that control response shall also be recorded on a plot of g^2/Hz vs. frequency.

(f) Laboratory water and air may be used.

4.3.6.3 Description of Procedure

(a) Prior to running a low level resonance search shall be conducted. Fixture evaluation may be combined with this search. The resonance search need be conducted once only for this heat exchanger design.

(b) Vibrate the heat exchanger to the levels defined in Figure 6.2 for 2 minutes in each axis.

4.3.6.4 Special Instructions

(a) A test report including a sketch or photo of the setup, block diagram of the system, instrument list, and control plots shall be provided.

(b) The filtered response of the primary control accelerometer shall be provided on a plot of g^2/Hz vs. frequency in each axis. Other response accelerometer response shall be reduced at the specific request of the cognizant Engineer.

(c) After vibration the unit shall pass a subsequent Proof Pressure and Leakage Test. There shall be no visible evidence of damage or permanent deformation.

(d) No further data analysis is required.

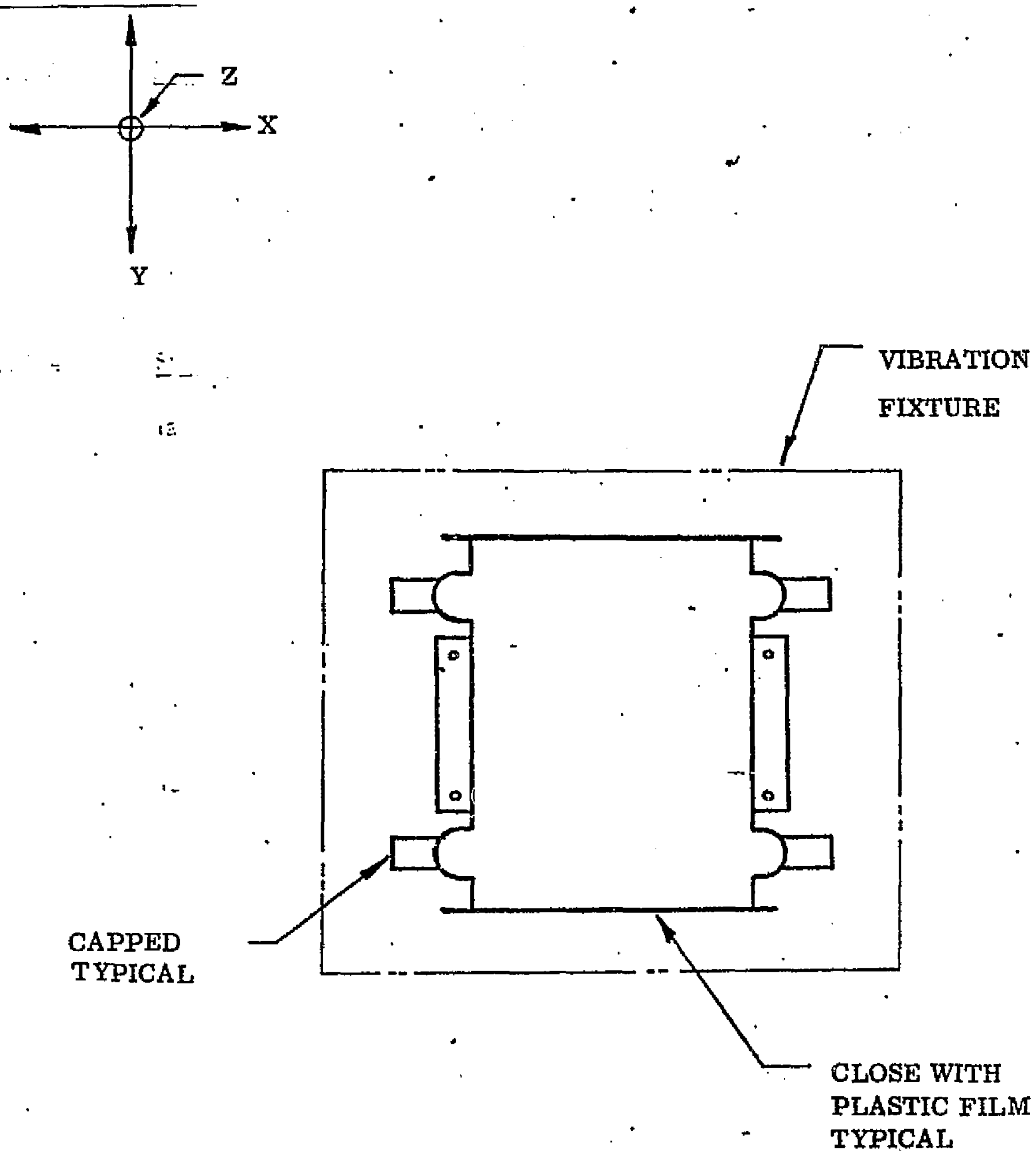
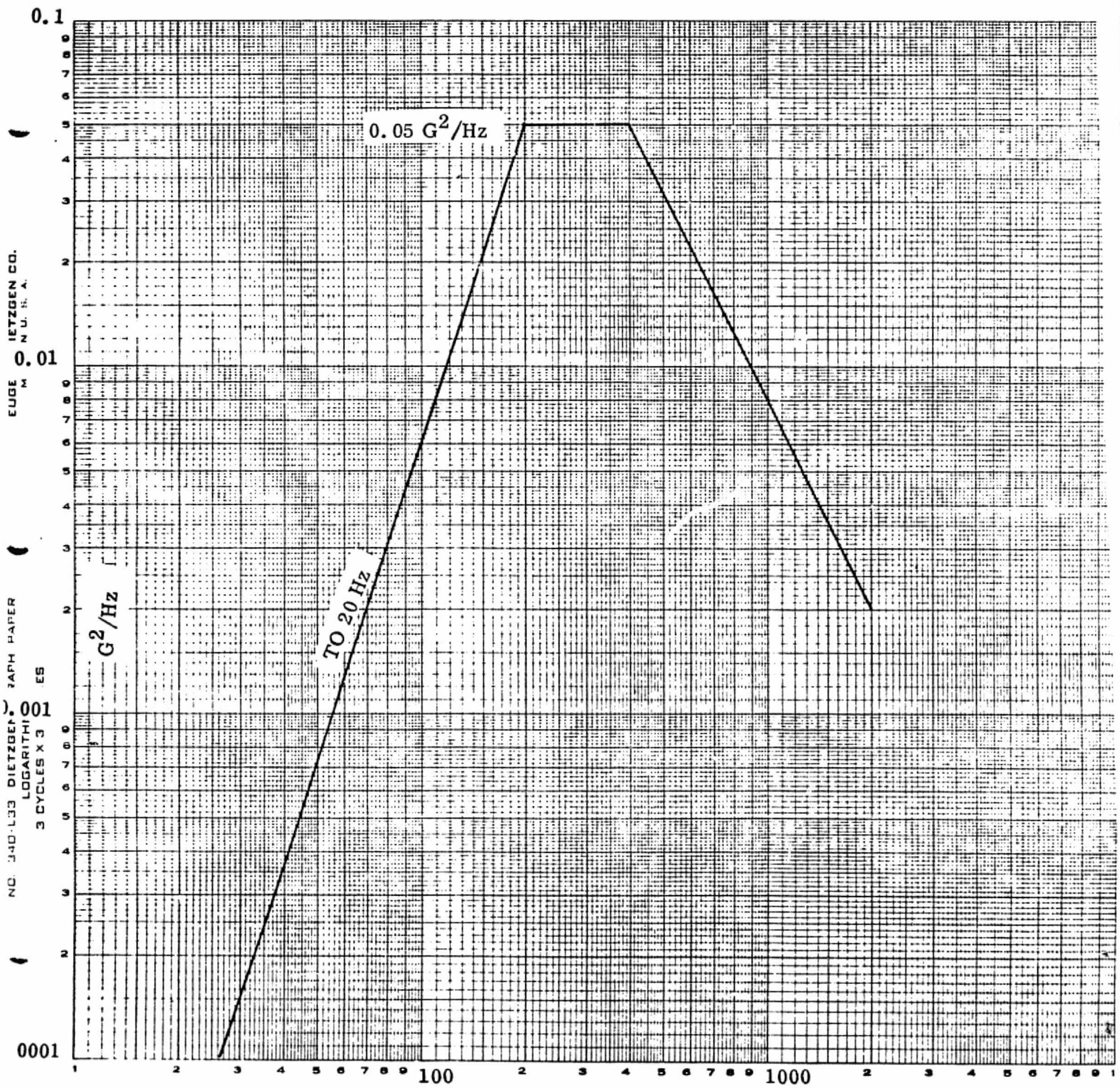


FIGURE 6-1

VIBRATION TEST SETUP



FREQUENCY - Hz

FIGURE 6-2
RANDOM VIBRATION SPECTRUM

ORIGINAL PAGE IS
OF POOR QUALITY

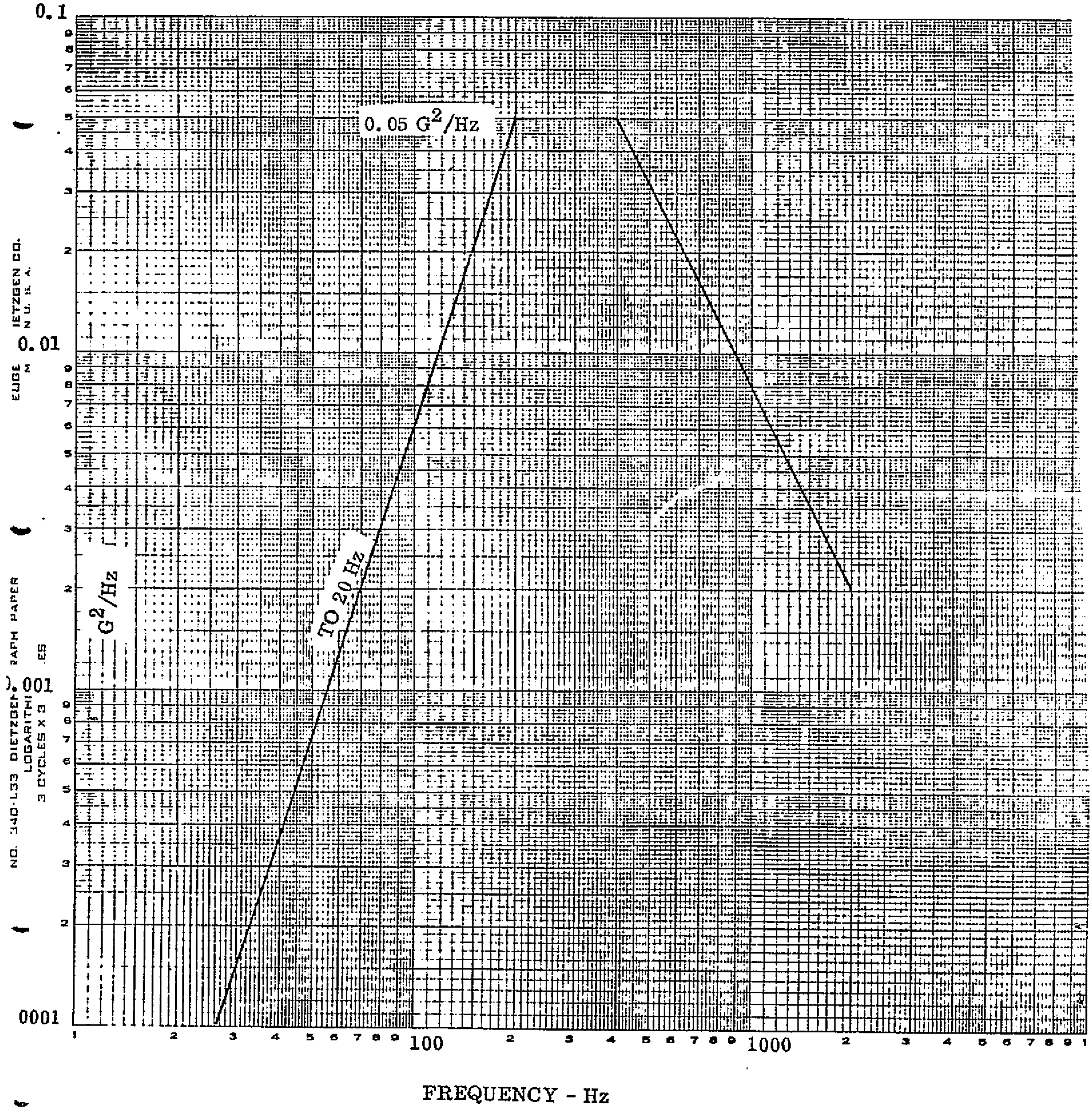


FIGURE 6-2

RANDOM VIBRATION SPECTRUM

4.3.7 Performance Base Point

4.3.7.1 The objective of the performance base point test is to allow evaluation of the performance of the LLL-HX at a single condition prior to and after the simulated shuttle mission and thermal cycling and shock tests. The condition utilized will be that one specified in Table 5-2 that approximates the design point.

4.3.7.2 Description of Test Set-Up

(a) The test set-up will be as described in Paragraph 4.3.5.2 of this procedure.

4.3.7.3 Description of Procedure

(a) Mount the heat exchanger, make fluid connections (air and water) as shown on Figures 5-1, 5-2, and 5-3, and instrument per Figures 5-2 and 5-3 and Table 5-1. During instrumentation, record the identification, serial number and calibration date of each instrument used on Table 5-1.

Note: Any instrument changes during test shall be recorded on the test data sheet.

(b) With the water circuit empty, measure the air flow pressure drop across the unit at 440,880 and 1320 lbs/min. Fill both water circuits and obtain pressure drop at 5,7.5 and 10 lb/min on both circuits. Record data on HSF 175.1A. A

(c) Set-up test condition 8 per Table 5-2 per procedures inherent to rig operation. Before recording data, allow for conditions to stabilize for at least ten minutes. Record data on log sheet provided, at the start and end of a five minute period. Inlet and outlet temperature shall not vary in excess of ± 0.5° on both air and water circuits. Continual recording at five minute intervals until temperature stability criteria is established.

(d) Upon completion of a heat balance calculation, the cognizant Engineer shall indicate rejection or acceptance of the run by so noting and initialing on the data sheet. If balance cannot be obtained, the operator may repeat the run at the discretion of the cognizant engineer.

(e) At completion of testing, the air and water circuits shall be dried by purging with dry air at 160-200°F for one hour. Air and water circuits shall be capped or covered with polyethylene film.

4.3.7.4 Special Instructions

(a) Data for each run shall be recorded on the data sheets provided.

4.3.7.4 (Continued)

(b) Data reduction not required.

(c) A heat balance shall be conducted by the cognizant Engineer for each test run. A balance of ±10% , should be achieved before the run may be considered acceptable.

4.3.8 Simulated Shuttle Mission

4.3.8.1 The objective of the simulated shuttle mission test is to demonstrate the ability of the LLL-HX to meet its performance requirements during repeated simulated mission cycles. Observation will be made to note any performance degradation due to the corrosive environment. The test will also serve to test the resistance of the laminate construction to corrosion. Coolant water will be in accordance with MSC-SD-W-0020, specifically SVP 114.

4.3.8.2 Description of Test Setup

(a) The simulated shuttle mission test set-up will be the same as that utilized for the performance tests as specified in Paragraph 4.3.5.2 with one addition. An auxiliary CO_2 supply will be added to the air supply line to introduce CO_2 into the gas going to the LLL-HX to further duplicate Shuttle conditions. Since the test setup is an open loop system, all that is required is a bottled CO_2 supply and flow meter. A

(b) CO_2 flow will be added to the data recorded on the data sheets provided.

4.3.8.3 Description of Procedure

(a) Mount the heat exchanger, make all fluid connections (air and water) as shown on Figures 5-1, 5-2, and 5-3, and instrument per Figures 5-2 and 5-3 and Table 5-1.

During instrumentation, record the identification, serial number and calibration data of each instrument used Table 5-1. Be sure and hook up the auxiliary CO_2 Supply.

Note: Any instrument changes during the test shall be recorded on the test data sheet.

(b) With the water circuit empty, measure the air flow pressure drop across the unit at 440 and 880 lb/hr. Fill both water circuits and obtain pressure drop at 10.0 lb/min. on both circuits. Record data on HSF 175.1A.

(c) Setup test condition 8 per table 5-2 per procedure inherent to rig operation.

4.3.8.3 (Continued)

(d) Turn on CO_2 flow meter. Set flow to insure gas going through heat exchanger contains at least 5 mm Hg of CO_2. A

(e) Before recording data allow for conditions to stabilize for at least ten minutes. Record data on log sheet provided at the start and end of a five minute period. Continue recording data at fifteen minute intervals until condensing operation has continued for one hour.

(f) At the end of the one hour of condensing operation, reduce the humidity to the rig minimum, continue the test for two hours or until the outlet dew point has stabilized for at least one-half hour. Record data every fifteen minutes until stabilized, then take three readings five minutes apart. B

(g) Repeat the test cycle specified in (e) and (f) above 100 times.

(h) If the test rig is to be shutdown for any period either overnight or a weekend, at the completion of testing, the air and water circuits shall be dried by purging with dry air at 160 to 200 °F for one hour. Air and water circuits shall be capped or covered with polyethylene film. A

4.3.8.4 Special Instructions

(a) If the test is shutdown between cycles for any period exceeding 24 hours, the startup procedure will include the pressure drop test specified in step (b) of paragraph 4.3.8.3. If the shutdown is less then 24 hours step (b) may be omitted.

(b) Data for each run shall be recorded on the data sheets provided.

(c) Data Reduction not required.

(d) A heat balance shall be conducted by the cognizant Test Engineer at every tenth run during the course of testing to note any performance changes or trends in performance characteristics.

(e) A photograph of the test setup shall be taken prior to removal of the heat exchanger from the test rig.

(f) Post test data analysis by Engineering shall yield the following:

(1) Any variation of effectiveness for sensible and latent heat loading due to performance changes during the test.

(2) Any changes in pressure drop of air and water circuits including air side changes due to the condensing mode

4.3.8.4 (Continued)

operation.

4.3.9 Thermal Cycling and Thermal Shock Test

4.3.9.1 The objective of the thermal cycling thermal shock test is to expose the LLL-HX to an operating condition that will exceed the expected Shuttle vehicle conditions. Performance tests will then be conducted to determine any degradation in LLL-HX performance as a result of the test.

4.3.9.2 Description of Test Setup

(a) The test setup will be as described in Paragraph 4.3.5.2 of this procedure.

4.3.9.3 Description of Test Procedure

(a) Mount the heat exchanger, make fluid connections (air and water) as shown in Figures 5-1, 5-2, and 5-3, and instrument per Figures 5-2 and 5-3 and Table 5-1. During instrumentation record the identification, serial number and calibration date of each instrument used on Table 5-1. A

Note: Any instrument changes during test shall be recorded on the test data sheet.

(b) With the water circuit empty, measure, the air flow pressure drop across the unit at 440,880 and 1320 lb/min. Fill both water circuits and obtain pressure drop at 5, 7.5 and 10 lb/min. both circuits. Record data on HSF 175.1A.

(c) Shutoff water flow but insure that water circuit is filled with water.

(d) Flow dry air at 140°F through the heat exchanger for a period of two hours.

(e) At the completion of the two hour period initiate water flow at the minimum temperature attainable by the test facility. At the same time reduce air temperature as rapidly as possible to the rig minimum temperature; if the temperature capability of the rig is such that a temperature below 74° cannot be achieved in 15 minutes then the air flow will be shutoff.

(f) Soak the unit for one hour at the condition established in Step (e). At the completion of the one hour period, the circulating water will be shutoff and the air temperature brought back to 140°F.

4.3.9.3 (Continued)

(g) Perform steps (d) through (f) three times. At the conclusion sion of the third cycle purge the air and water circuits with dry air at 160 to 200°F for one hour. Air and water circuits shall be capped or covered with polyethylene film.

4.3.9.4 Special Instructions

(a) Data for each run shall be recorded on the data sheets provided. The cognizant Test Engineer will specificy the parameter to be recorded. A

(b) Data reduction is not required

(c) Performance will not be evaluated during the test.