ADVANCED FABRICATION TECHNIQUES FOR COOLED ENGINE STRUCTURES*

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INTRODUCTION

Past studies of hydrogen-cooled hypersonic propulsion systems led to the use of rectangular-offset-fin, plate-fin coolant passages, culminating in the successful design, fabrication, and test of the structural assembly model of the hypersonic research engine (HRE). The design life of the HRE cooled structures was 100 cycles and 10 hr and was limited by creep and low-cycle fatigue.

The purpose of this program is to develop coolant passage geometries, material systems, and joining processes that will produce long-life hydrogen-cooled structures. The goal is to produce structures with a fatigue life that is one order of magnitude greater than that of the HRE. The selected panel must yield adequate heat transfer with an acceptable pressure drop, and suitable structural properties with reasonable weight and fabrication complexity.

During the initial phase of the contract, studies have been conducted to finalize the configuration design, material selection, and fabrication process. Tensile and fatigue tests were performed to establish basic material properties. Small samples were constructed to substantiate the fabrication process and inspection techniques. Development tests, including burst and creep rupture, were performed to validate structural performance.

The program has produced configuration, design, and materials selections for the application. Panel fatigue tests are required to determine the capability of these selections to meet the goal set for the program. The presentation will show the configuration and materials that were studied and summarize the test data, as well as present preliminary conclusions regarding the potential of the selections.

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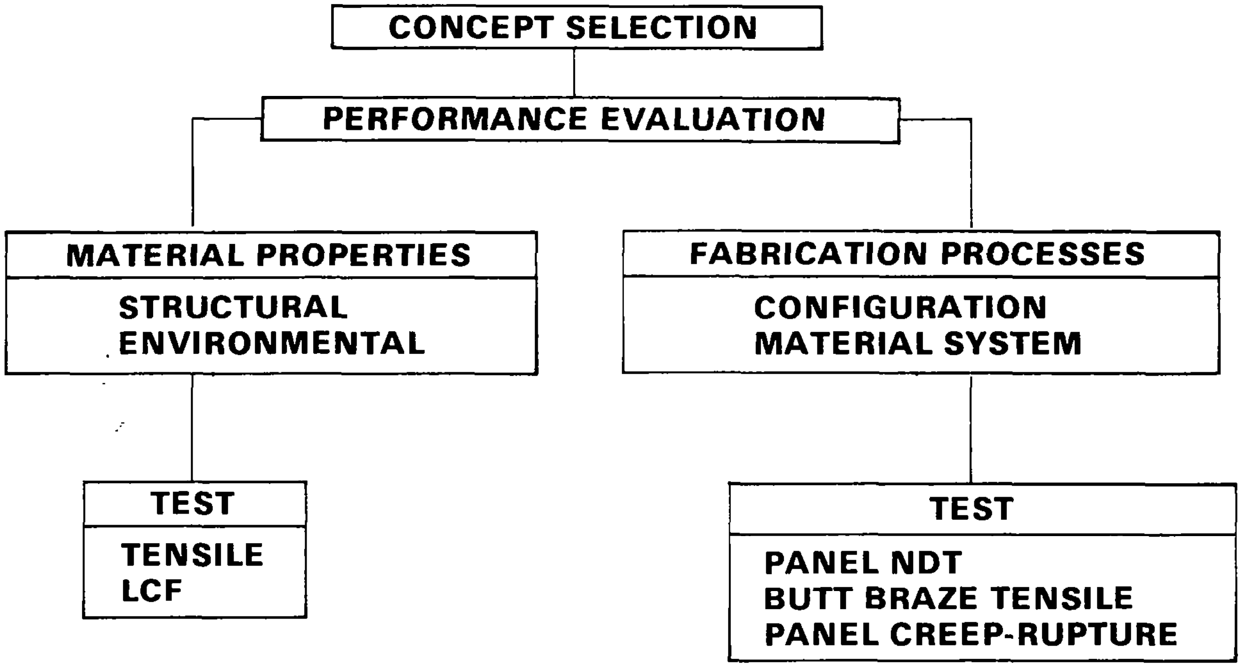
PROGRAM APPROACH

(Figure 1)

Following concept selection, the performance of different configurations and materials was evaluated at the operating conditions. The program then proceeded along two branches. One was aimed at evaluating the material properties from a structural and environmental point of view. The tests were tensile and low-cycle fatigue. The tensile tests were run on sheet specimens. Low-cycle fatigue testing was done on hollow bar specimens to simulate the sheet properties. Evaluation of fabrication processes considered different configurations and different materials for face sheet, back panel, and the braze filler alloy. Butt-braze tensile tests were run on bars and panel creep-rupture tests were run using the selected configurations and materials. All panels were non-destructively evaluated using holography prior to tests. That was an important part of the program.

PROGRAM APPROACH



CONCEPT SELECTION

PERFORMANCE EVALUATION

MATERIAL PROPERTIES

STRUCTURAL
ENVIRONMENTAL

TEST

TENSILE
LCF

FABRICATION PROCESSES

CONFIGURATION
MATERIAL SYSTEM

TEST

PANEL NDT
BUTT BRAZE TENSILE
PANEL CREEP-RUPTURE

Figure 1

PROGRAM GOAL

(Figure 2)

The goal is a design with a life of 10,000 cycles and 1,000 hours at Scramjet operating conditions. The delta-T plotted here is the delta-T through the thermal protection system of the structure. Parent metal performance is predicted from published literature properties. The design condition used and the data obtained on the HRE Program are shown, along with an extrapolation to lower delta-T's. The NASA 3-D Scramjet study operates near 200°K delta-T, approximately half the delta-T of the HRE. It has a design goal of 1,000 cycles for 100 hours. The reduction in severity of the operating condition was achieved by aerodynamic design. The improvement in life being sought on this program is based on a change in materials or fabrication techniques rather than a reduction in operating parameters.

PROGRAM GOAL

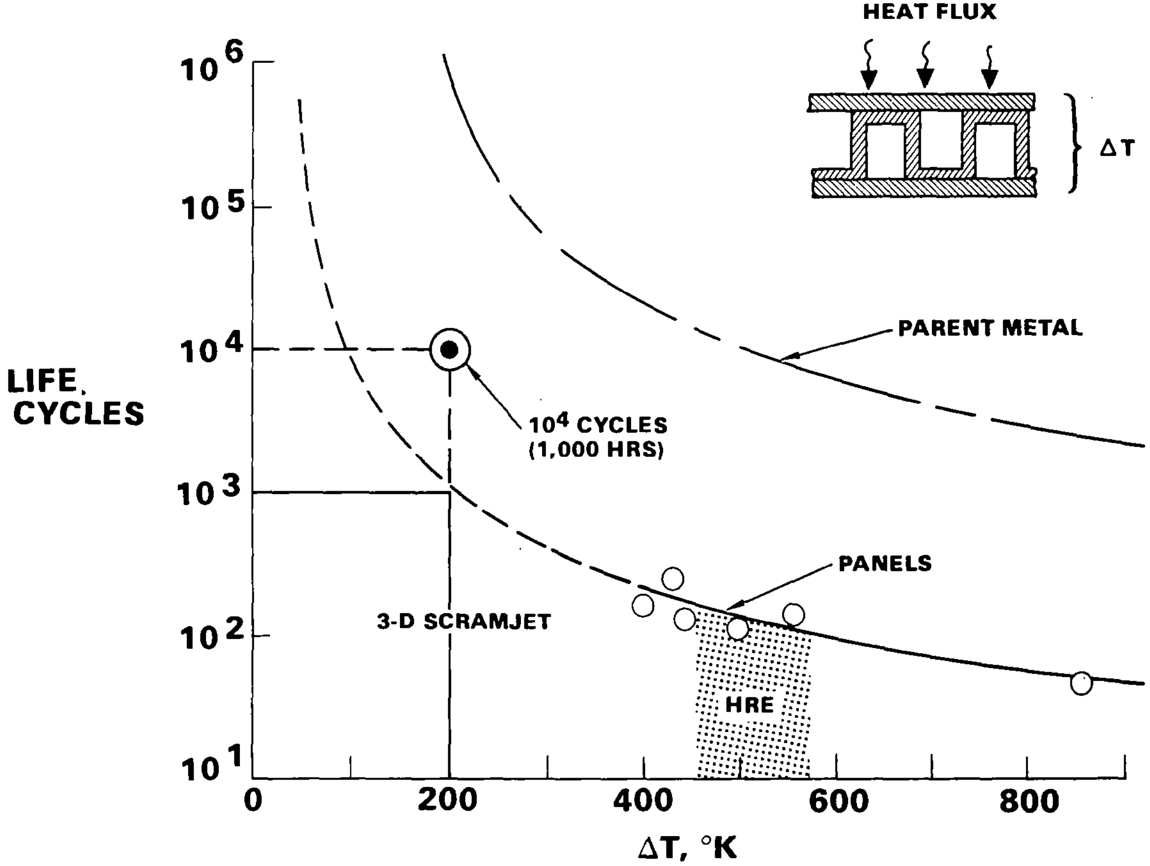


Figure 2

PANEL THERMAL DESIGN

(Figure 3)

The heat fluxes imposed are typical of the maximums and averages encountered in the 3-D Scramjet design. The inlet temperatures are consistent with the use of liquid hydrogen as a fuel; the outlet temperature is consistent with elastic operation in the primary structure of the engine. Outlet pressure is set to be compatible with the required fuel injection pressure; inlet pressure is compatible with high-pressure, liquid hydrogen pumps.

PANEL THERMAL DESIGN

- **PANEL LENGTH** — — — — — — 0.6m (2 FT)
- **HEAT FLUX** - MAXIMUM – 565 X 10^4 W/m^2 (500 BTU/SEC-FT^2)
  AVERAGE – 340 X 10^4 W/m^2 (300 BTU/SEC-FT^2)
- **TEMPERATURE** - INLET – – 55-280°K (100 - 500 °R)
  OUTLET – – 900 °K (1600°R)
- **PRESSURE** - INLET – – 6.9 MPa (1000 PSIA)
  OUTLET – – 5.2 MPa (750 PSIA)

Figure 3

CANDIDATE CONFIGURATIONS

(Figure 4)

These configurations are the ones that were considered as candidates on the program. The plate-fin configuration was used on the Hypersonic Research Engine (HRE). It uses a thin, formed sheet metal fin and has a braze joint next to the hot face sheet. This results in relatively high stress concentrations and in high joint temperatures. Consequently, low-cycle fatigue and creep-rupture life are too limited at the selected operating conditions.

The other configurations shown use machined coolant passages and have their braze joints remote from the face sheet. This is an important feature. They also have a certain amount of flexibility in shaping of the coolant passage. This allows stress concentrations near the hot face sheet to be minimized. On the other hand, the applicable machining processes tend to limit the proportions that can be achieved in terms of passage height and width and of land thickness.

CANDIDATE CONFIGURATIONS

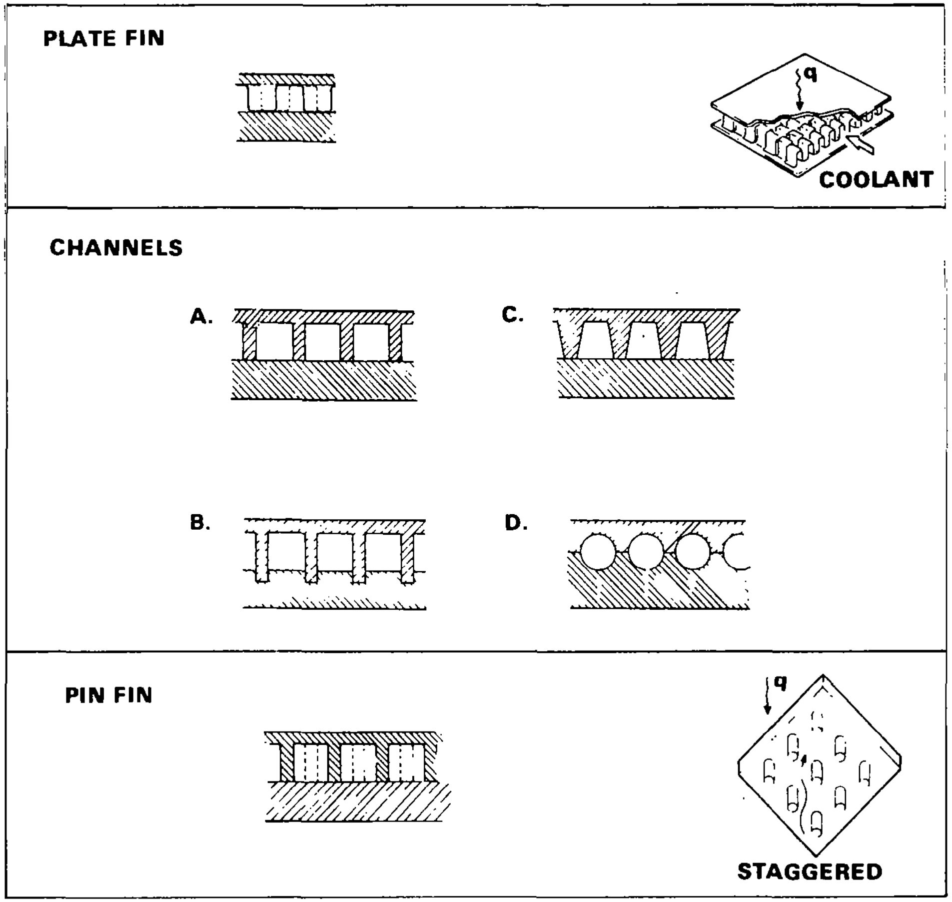


Figure 4

LOW CYCLE FATIGUE LIFE--CONFIGURATION EFFECTS

(Figure 5)

This comparison of the candidate configurations is based on published properties. The objective here was to select configuration rather than material. Hastelloy X was used for all configurations. The best of these is the one having a circular passage. It shows 60 percent longer life than any of the other machined configurations and four times longer life than plate-fin. The trapezoidal configuration is nominally a rectangular passage. It was selected as the baseline for the program because of its simplicity. Data obtained with it can be used to predict the performance of the other machined passages. In addition, a staggered pin-fin configuration was selected for evaluation because of its applicability in engine design to localized regions of high flux.

To summarize, the remote (cool) braze joint and the low stress concentrations are desirable features of the machined coolant passages. The two configurations that were selected for evaluation evolved from the Scramjet design studies. The plain channel is the most generally applicable. It has low pressure drop, but it also is limited as to the heat transfer coefficients that are obtainable. The pin-fin is used where high heat transfer coefficients are needed and the higher pressure drop can be tolerated.

LOW CYCLE FATIGUE LIFE CONFIGURATION EFFECTS

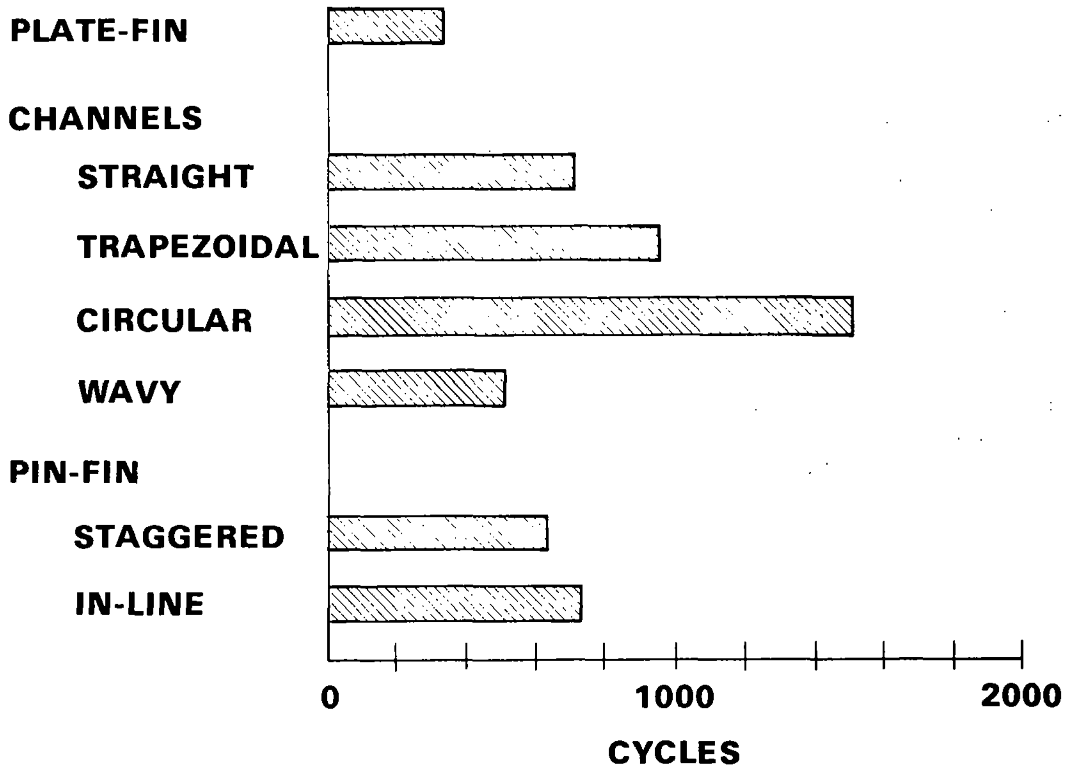


Figure 5

LOW CYCLE FATIGUE LIFE--MATERIAL EFFECTS

(Figure 6)

Nickel 201 and Inconel 617 were selected for the program, based on this comparison. Published properties were used, with emphasis on sheet properties where available. The effects of aging, which have been determined to be important for many of the nickel-base superalloys, were not included because they were not generally available. Inconel 617 is limited by low-cycle fatigue; its creep-rupture properties are excellent and are not expected to pose a constraint. Nickel 201 is creep-rupture and oxidation limited.

Narloy-Z, although it looks excellent from the standpoint of low-cycle fatigue, overages during extended exposure (time greater than 100 hours) above 920°K (1200°F). The properties then revert to those of annealed material.

TZM was rejected because of the lack of an oxidation-protection coating and because of its relatively high ductile-to-brittle transition temperature (in the range of 200°K).

LOW CYCLE FATIGUE LIFE
MATERIAL EFFECTS

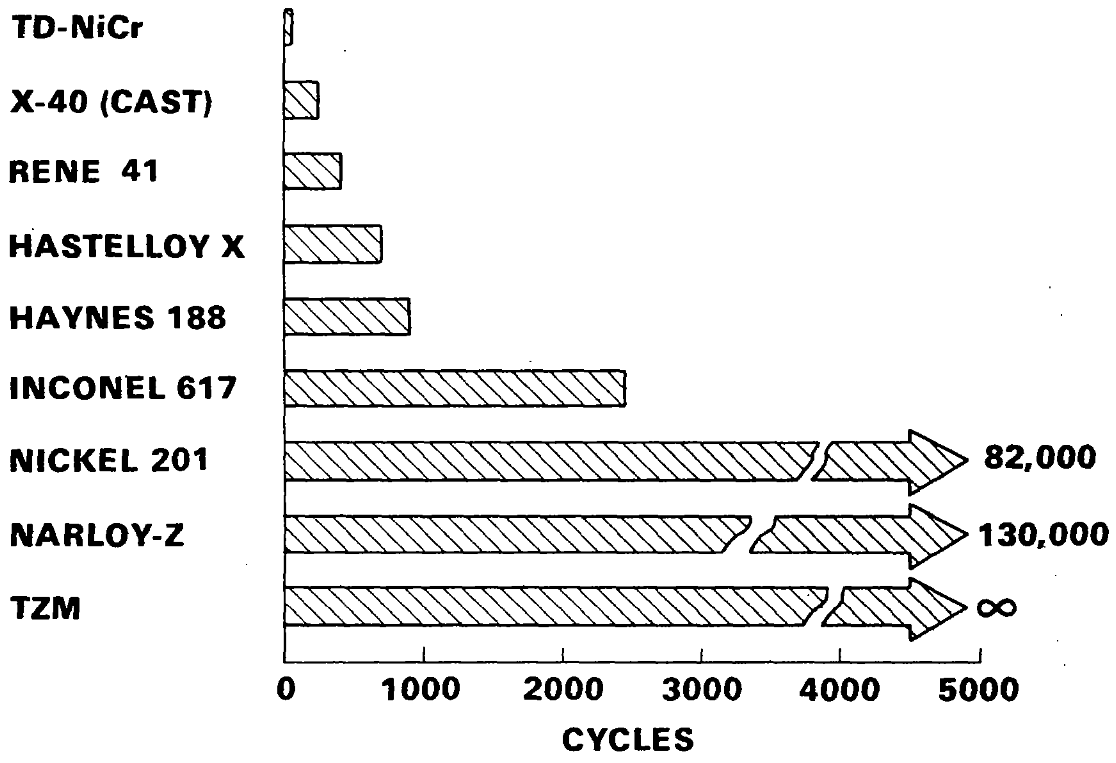


Figure 6

FABRICATION DEVELOPMENT

(Figure 7)

Given a configuration and a material, selection of the method of fabrication becomes the next consideration. The Scramjet engine is 2.4 m (8 ft) long and has large, multiplanar surfaces. Any fabrication process has to lend itself to that kind of configuration. When various processes are considered, photochemical machining (PCM) appears most applicable and was selected.

At program start, limited data was available on PCM of Nickel 201 in the required configurations. There was no data on PCM of Inconel 617 and, again, only limited data for Hastelloy X. Hastelloy X was tested to establish general applicability. It is the material about which most is known at the program conditions. For brazing, there is a good deal of data on Hastelloy X that can be used as a reference. For Inconel 617, no data was available, while for Nickel 201, there was a limited amount of data applicable to the selected configurations.

FABRICATION DEVELOPMENT

- PHOTOCHEMICAL MACHINING
  - NICKEL 201
  - INCONEL 617
  - HASTELLOY X
- BRAZING
  - NICKEL 201
  - INCONEL 617
  - HASTELLOY X

Figure 7

PCM FACE SHEETS--CREEP-RUPTURE PANELS

(Figure 8)

These face sheets were made to evaluate the photochemical milling and for use in creep-rupture test panels. The plain channels are approximately 0.5 mm (0.02 in.) deep, the lands are 0.5 mm (0.02 in.) wide with grooves that are 1.5 mm (0.06 in.) wide. Pin-fin panels have a pin height of 0.65 to 1.55 mm (0.025 to 0.06 in.) and 0.75 mm (0.03 in.) diameter pins on 2.0 mm (0.08 in.) centers. The spaced channel specimen eliminated a channel and replaced it with solid material. This was done to provide a large braze surface area and to be able to apply high pressures, as a test of the face sheet in creep-rupture.

PCM FACE SHEETS
CREEP-RUPTURE PANELS

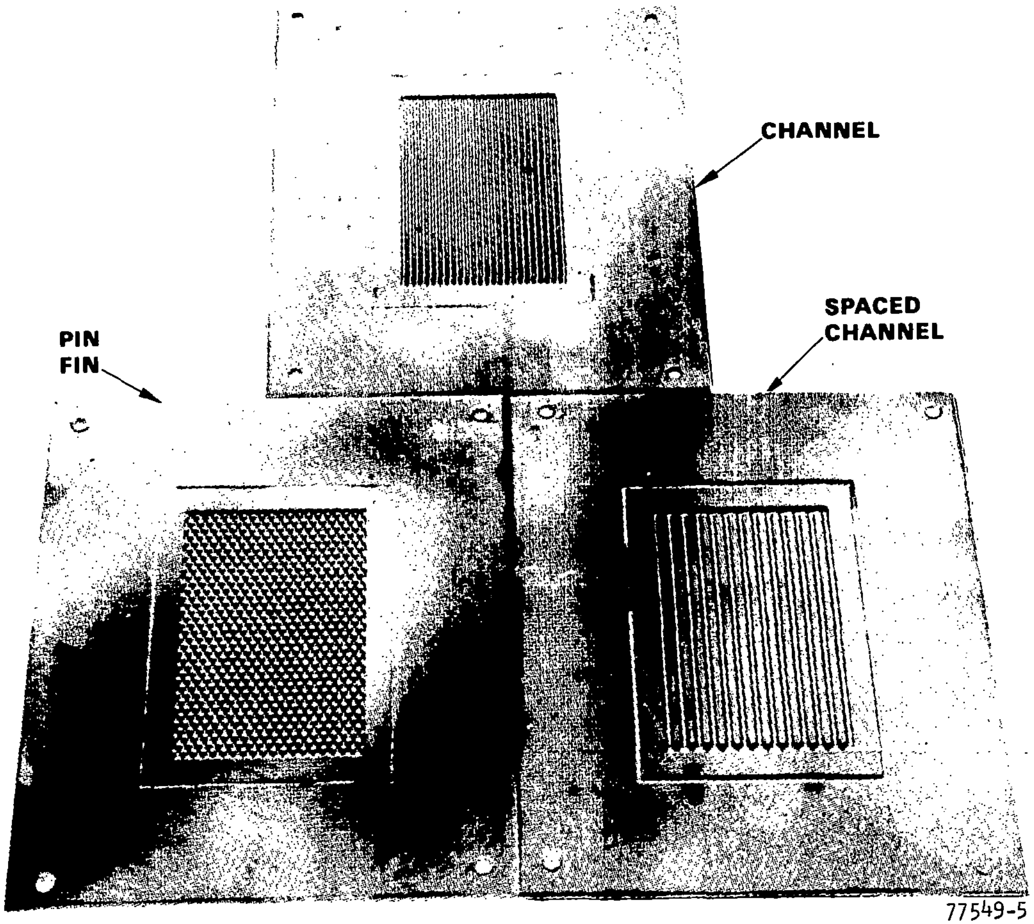


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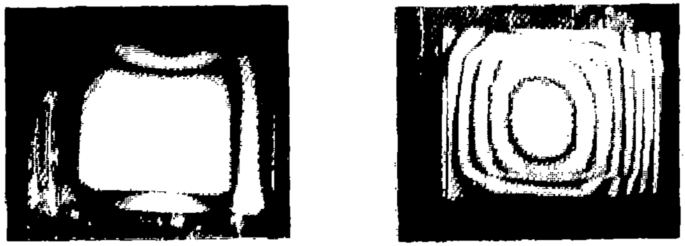
Figure 8

PANEL HOLOGRAPHY

(Figure 9)

As mentioned previously, non-destructive testing was important on this program for establishing the quality of the test panels. It also would certainly be important on an engine development program. This shows Inconel 617 pin-fin and channel specimens tested at 13.8 MPa (2,000 psig). At 13.8 MPa, the quality of the braze is such that the channel looks like a solid piece of material. There is no print-through. In the case of the pin-fins, a slight print-through appears at 13.8 MPa. The Nickel 201 panels show print-through in all cases. For both materials, it was possible to detect a void of a single pin.

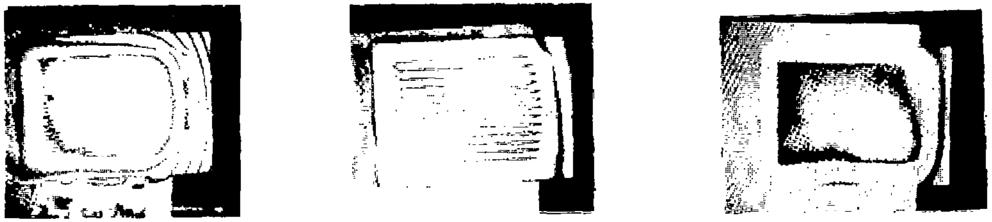
PANEL HOLOGRAPHY



INCONEL 617

CHANNEL
13.8 MPa

PIN-FIN
13.8 MPa



NICKEL 201

CHANNEL
13.8 MPa

SPACED
CHANNEL
13.8 MPa

PIN-FIN
2.8 MPa

Figure 9

CREEP-RUPTURE LIFE--NICKEL 201 PANELS

(Figure 10)

In the case of the Nickel 201 panels, the concern is more with the face sheet than with the braze joint. The braze joint in this case is operating at 920 to 950°K (1200 to 1250°F), while the face sheet is operating at 1030°K (1400°F), a high temperature for pure nickel. The required creep-rupture life is shown for three cases with relation to the published properties. The test life that was obtained for the different panels is also shown. In each case, the tests show the capability for meeting the design requirements.

CREEP-RUPTURE LIFE
NICKEL 201 PANELS

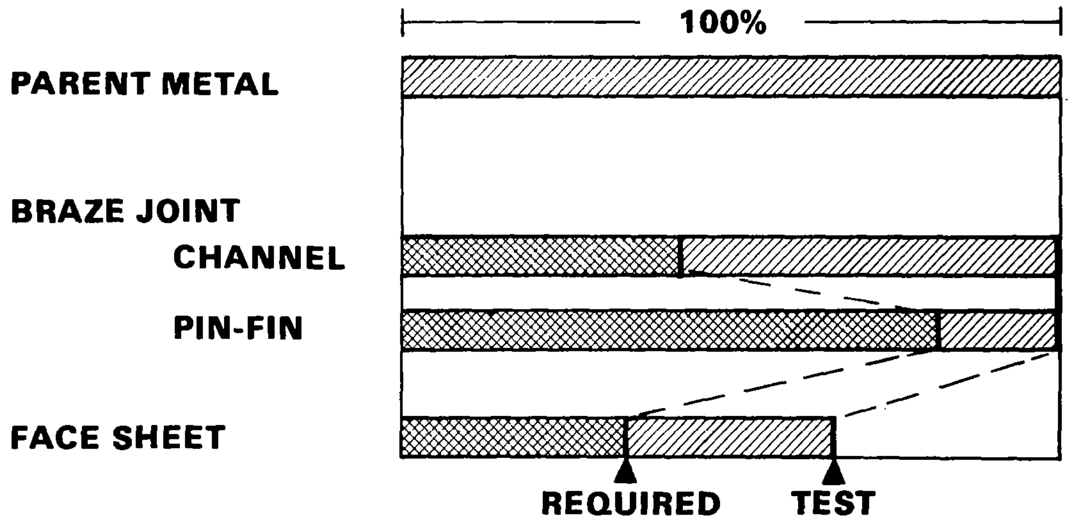


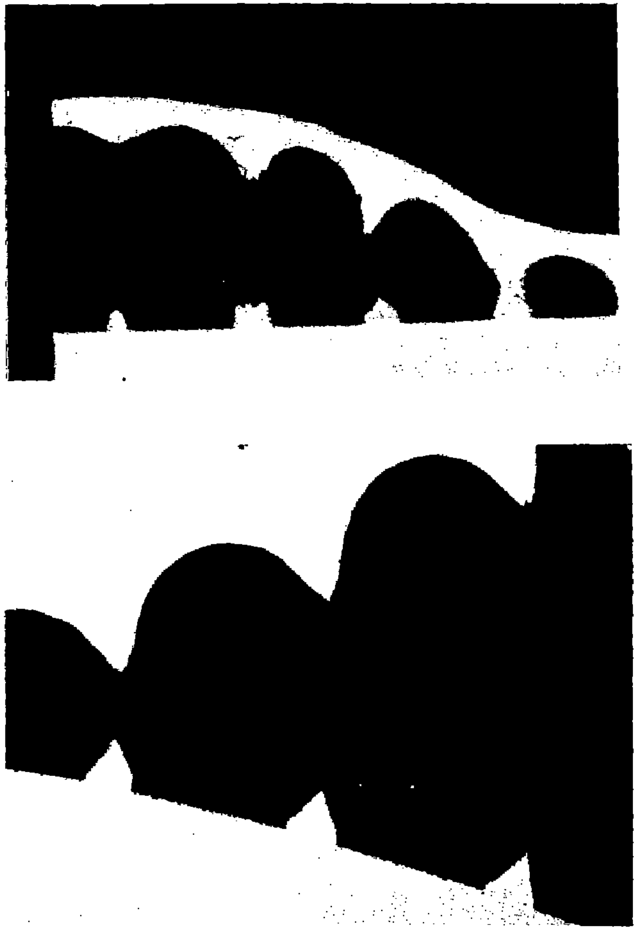
Figure 10

PANEL CREEP-RUPTURE--NICKEL 201

(Figure 11)

The braze joint looks quite sound using Palniro 1 as the filler alloy. The breaks are ductile and are through the pins and the lands of the channels. In each case, the high stress occurs not at the joint, but above the joint. A finite element analysis of the configuration confirmed this.

PANEL CREEP-RUPTURE
NICKEL 201



PIN FIN

CHANNEL

Figure 11

CREEP-RUPTURE LIFE--INCONEL 617 PANELS

(Figure 12)

These panels were tested at 920°K (1200°F) to evaluate the strength of the braze joint rather than of the face sheet. The configuration is not creep-rupture limited in the parent metal.

With the Palniro 1 joint, rupture was considered to be premature, even though the test life exceeds the required life. Metallography showed that the brazing was erratic and somewhat unpredictable. As a result, alternative braze materials and techniques were investigated. The method selected used boronized nickel-chrome in an isothermal solidification process. The test results for this process were equivalent to 100 percent of parent metal. Test times ranged to over 2000 hours with these joints.

CREEP-RUPTURE LIFE
INCONEL 617 PANELS

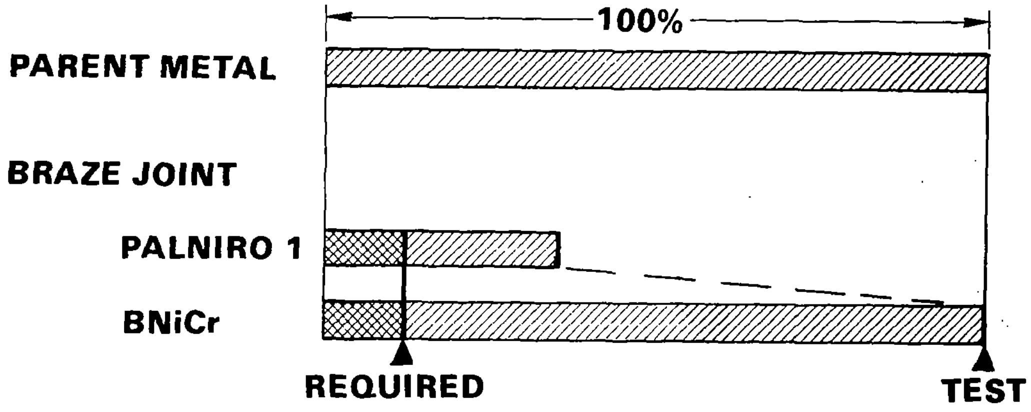


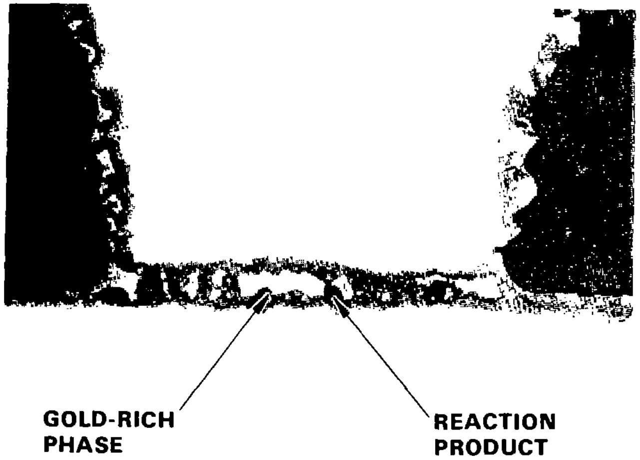
Figure 12

BRAZE ALLOY SEGREGATION--INCONEL 617

(Figure 13)

A joint in Inconel 617 made with Palniro 1 braze alloy is shown in the upper photograph. This cross-section has been metallographically polished and etched to show the light-colored, gold-rich phase as well as the darker reaction product. The reaction product is actually a mixture of gold-rich and nickel-rich phases. The separated joint shown in the lower photograph shows that rupture of this joint occurred through the gold-rich phase, which is expected to be considerably softer than the reaction product. Experiments with Palniro 1 using various plating techniques, surface preparation techniques, and brazing cycles produced similar structures. Such discrete phases of relatively large size can generally be expected to result in low strength and relatively short life. As a result, a number of alternate braze alloys for Inconel 617 were investigated in an attempt to obtain a braze joint that would be more uniform in structure. The alloys and processes that were investigated included: (1) NB30, a nickel-boron braze alloy in powder form, brazed conventionally; (2) boron-nickel-chrome foil brazed by isothermal solidification; and (3) other gold-base braze alloys (Palniro 7, Palniro RE, and Nioro).

BRAZE ALLOY SEGREGATION
INCONEL 617



CONTINUOUS JOINT

SEPARATED JOINT

Figure 13

INCONEL 617--BRAZING ALLOY EFFECTS

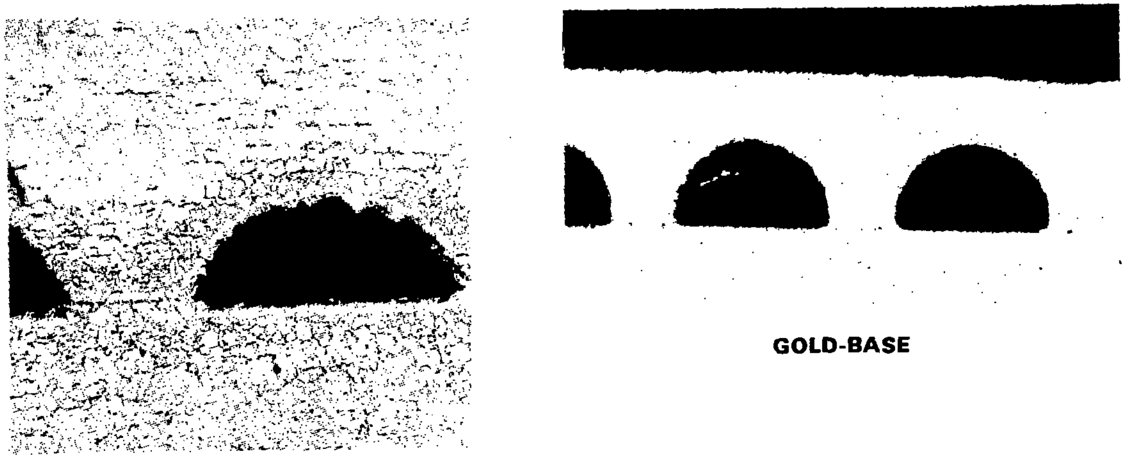
(Figure 14)

The boron-nickel-chrome brazed sample prepared by isothermal solidification is shown in cross-section in the upper left hand corner. It shows a number of favorable characteristics. (1) There is only moderate grain growth in the parent metal away from the braze joint and grains have grown across the joint. This indicates that the strength, ductility and elastic properties of the joint can approach those of the parent metal. (2) There is not a discrete layer of a soft braze alloy of a brittle phase. (3) There are essentially no voids visible in this picture, and likewise, there is no segregation of phases present within the braze joint.

In the case of the gold-base braze alloys that were investigated, the appearance of all three was quite similar. There was good filleting, but there were also voids.

In joints made with NB30 alloy, there was a notable lack of filleting, and indications of poor flow, of lumpiness in the alloy, and voids. The voids and lumpiness are shown more clearly in the right hand lower photograph. There is no segregation, however; rather, a single phase was observed in the braze joint.

INCONEL 617
BRAZING ALLOY EFFECTS



BNI Cr

GOLD-BASE

NICKEL BORON (NB30)

Figure 14

BNiCr BRAZE ALLOY--ISOTHERMAL SOLIDIFICATION TIME EFFECT

(Figure 15)

These two photographs show the effect of increasing time at the 1420°K (2100°F) brazing temperature with the boron-nickel-chrome braze alloy. For a one-hour brazing cycle, there is a ten-point variation in hardness between the adjacent parent metal and the center of the joint. This variation indicates incomplete boron diffusion. There is an excess amount of boron immediately next to the joint and a hardness variation of this magnitude would be expected to result in different mechanical properties in the two regions. This would localize any plastic flow and probably result in low strength. By extending the time to ten hours, the hardness variation has been reduced to a mere three points. This indicates that the boron has diffused much more completly into the parent metal. Much more uniform mechanical properties at the joint can be expected at this condition.

BNiCr BRAZE ALLOY
ISOTHERMAL SOLIDIFICATION
TIME EFFECT

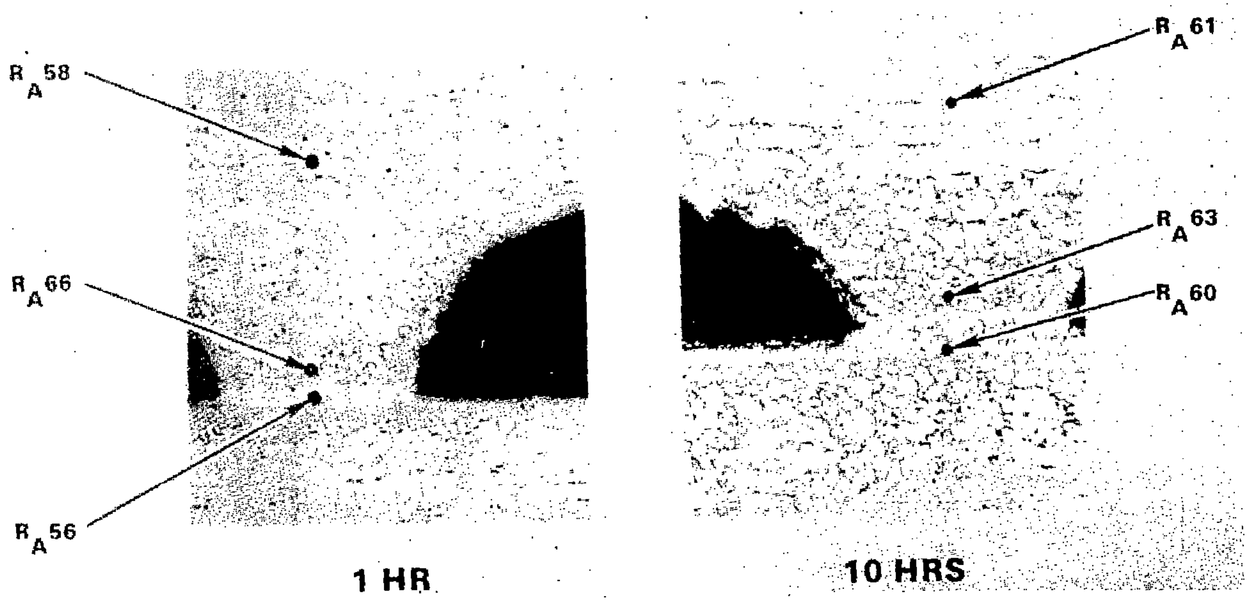


Figure 15

MATERIAL TEST SPECIMENS

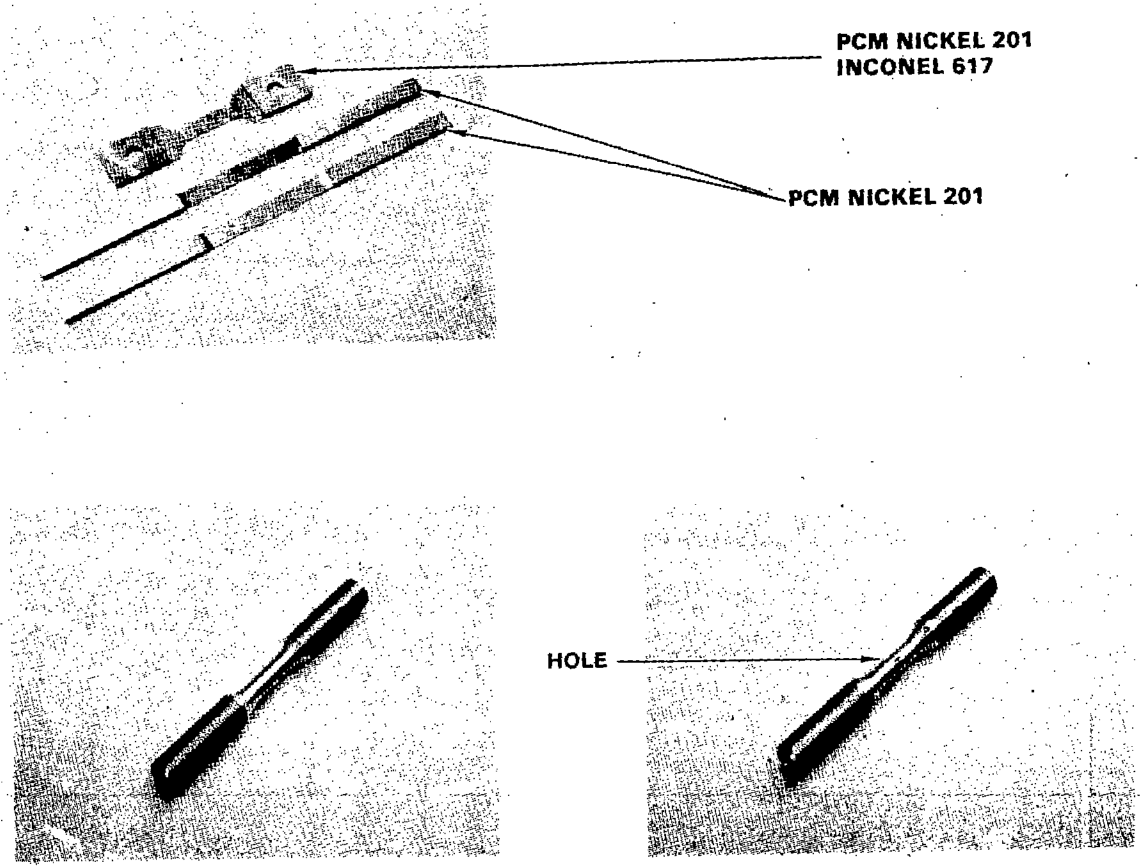
(Figure 16)

Photochemically machined (PCM) Nickel 201 and Inconel 617 specimens were made to determine the tensile properties of sheet material having the same surface condition as a PCM panel would have. These specimens were made in two configurations as shown in the upper picture. The lower specimens were used for room temperature tensile tests with friction grips. The upper specimens were used for elevated temperature tensile tests, where pin-loading was used.

The lower picture on the left shows the standard Inconel 617 tensile test bar. This is a solid bar that was used to determine Inconel 617 properties at elevated temperature and room temperature.

To more closely simulate the behavior of sheet material, hollow specimens, such as that shown on the lower right, were made. This tubular specimen simulated the sheet material in that the tube wall thickness was of the same order as the sheet material that would be used. An elliptical hole was machined in the center of the gage length as a strain concentrator, to further simulate the effect of the geometry of the PCM panel.

MATERIAL TEST SPECIMENS



INCONEL 617
TENSILE BAR

INCONEL 617
FATIGUE BAR

Figure 16

MATERIAL TESTS--INCONEL 617

(Figure 17)

Tests were conducted at room temperature, 900°K (1150°F) and 1150°K (1600°F), on sheet and bar tensile specimens and on bar fatigue specimens. Specimens were tested in the as-received condition, solution-treated after receipt, braze-coated and air aged for 1000 hours, braze-cycled and air aged, and only air aged. The tests of the braze-coated and air aged samples were expected to have the lowest properties and were, therefore, emphasized in the high temperature tests.

MATERIAL TESTS
NICKEL 201

	°K		
	290	1030	1060
AS-RECEIVED SHEET	X		
ANNEALED SHEET	X		X
PCM + BRAZE-COATED + AIR AGED	X		X
PCM + BRAZE-CYCLED	X		X
PCM + BRAZE-CYCLED + AIR AGED	X		X
PCM + AIR AGED	X	X	
PCM + BRAZE-CYCLED + ARGON AGED	X	X	
PCM + ARGON AGED	X	X	

Figure 17

INCONEL 617 TENSILE TESTS--LCF PARAMETER (1150°K)

(Figure 18)

The low-cycle fatigue (LCF) parameter is the yield strength multiplied by the reduction of area. It provides an indication of the LCF life of a material. The LCF parameter for solution-treated sheet was taken to be 100 percent as the baseline. Braze coating and aging reduced the LCF parameter to approximately 25 percent of the value for solution-treated sheet material value. Solid bar samples experienced a reduction of about 50 percent of the original value; i.e., they compared very well with the braze-coated and aged sheet material. The butt-brazed joints made with nickel-chrome-boron foil showed a relatively high LCF parameter though not equal to that for the parent material. Thus, some braze cycle degradation in the material did occur.

INCONEL 617 TENSILE TESTS
LCF PARAMETER (1150 °K)

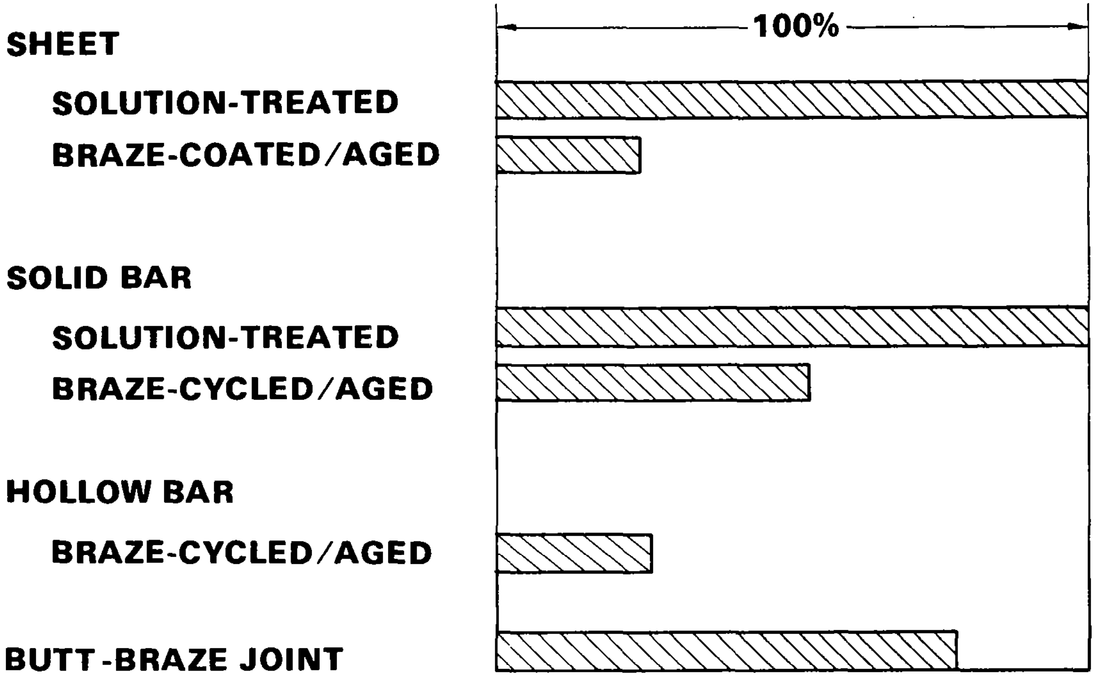


Figure 18

INCONEL 617 BUTT-BRAZE TENSILE BARS

(Figure 19)

Bars of Inconel 617 were machined with flat ends. These were then brazed in the center of the gage section. From these brazed bars (shown at the top) tensile specimens were machined. The third specimen from the top was tested at 950°K (1250°F). It fractured at the braze joint with an elongation of 36 percent. A test at 1150°K (1600°F) resulted in an elongation of 52 percent. This specimen fractured in the parent metal, remote from the braze joint, indicating that the braze joint was stronger than the parent metal at this temperature.

INCONEL 617
BUTT-BRAZE TENSILE BARS

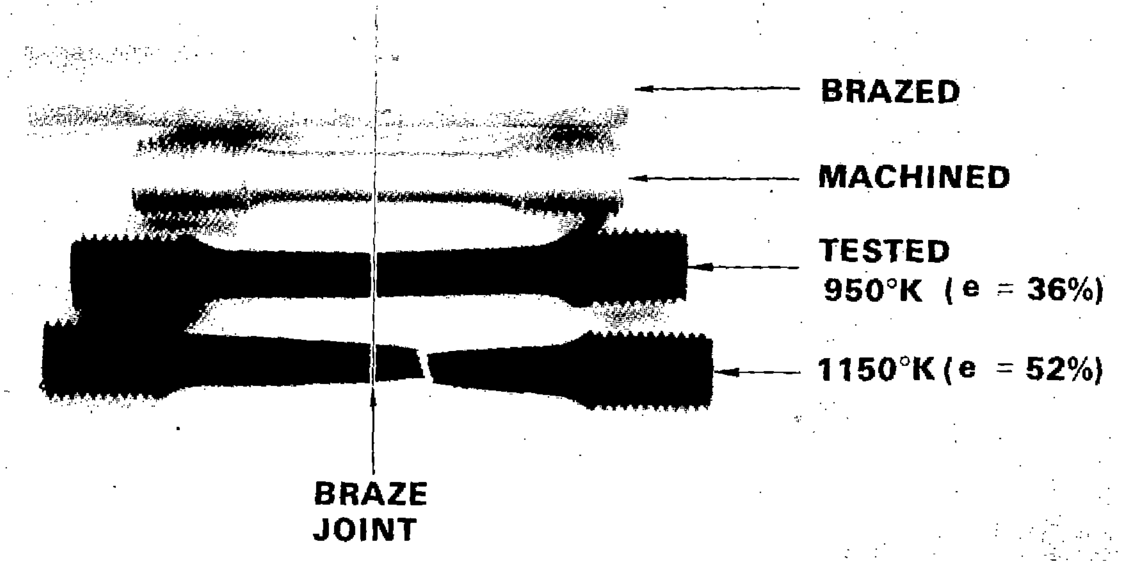


Figure 19

MATERIAL TESTS--NICKEL 201

(Figure 20)

Nickel 201 tests were conducted on as-received and annealed sheet material; on photochemically machined sheet; and on sheet material exposed to braze coating, braze cycling, air aging, and argon aging. Tests were run at room temperature as well as elevated temperatures. The highest temperature used for Nickel 201 was 1060°K (1450°F). This reflects the expected surface temperature in the Nickel 201 panel and is lower than for Inconel 617 due to its higher conductivity compared to Inconel 617. Tests at the elevated temperature are particularly significant for Nickel 201 because of oxidation effects.

MATERIAL TESTS
NICKEL 201

	°K		
	290	1030	1060
AS-RECEIVED SHEET	X		
ANNEALED SHEET	X		X
PCM + BRAZE-COATED + AIR AGED	X		X
PCM + BRAZE-CYCLED	X		X
PCM + BRAZE-CYCLED + AIR AGED	X		X
PCM + AIR AGED	X	X	
PCM + BRAZE-CYCLED + ARGON AGED	X	X	
PCM + ARGON AGED	X	X	

Figure 20

NICKEL 201 TENSILE TESTS--LCF PARAMETER (1030°K)

(Figure 21)

Published data on Nickel 201 was used to calculate the LCF parameter at 1030°K (1400°F), which was taken to be 100 percent. The results of the tests are shown as a percentage of that computed value. Annealed sheet material tested at AiResearch showed a yield strength and reduction of area that resulted in approximately one-third of the value computed from published data. Air aging for 1,000 hours at 1060°K (1450°F) reduced that initial value to approximately one half. Braze cycling and aging had about the same effect. Argon aging for 1,000 hours at 1060°K (1450°F) gave a somewhat lower LCF parameter than that obtained from air aging of specimens. Braze-cycled samples aged in argon also showed a lower LCF parameter.

NICKEL 201 TENSILE TESTS
LCF PARAMETER (1030 °K)

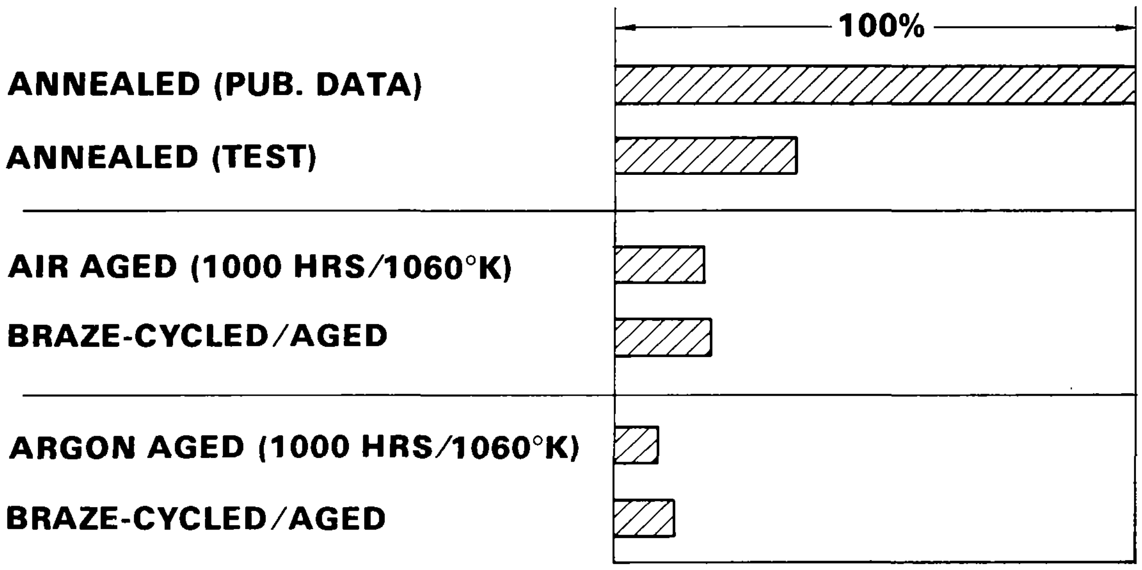


Figure 21

OXIDATION OF NICKEL 201

(Figure 22)

On the left is a braze-cycled specimen: it was not braze coated or exposed to oxidation, but only vacuum brazed-cycled. The original surface roughness is due to etching. During exposure, the oxide grows in both directions, into the material and outward. This reflects an increase in mass due to the formation of nickel oxide. After aging for 1,000 hours at 1060°K (1450°F), specimens had approximately 0.05 mm (0.002 in.) oxide coating, which is significant compared with the design material thicknesses.

OXIDATION OF NICKEL 201

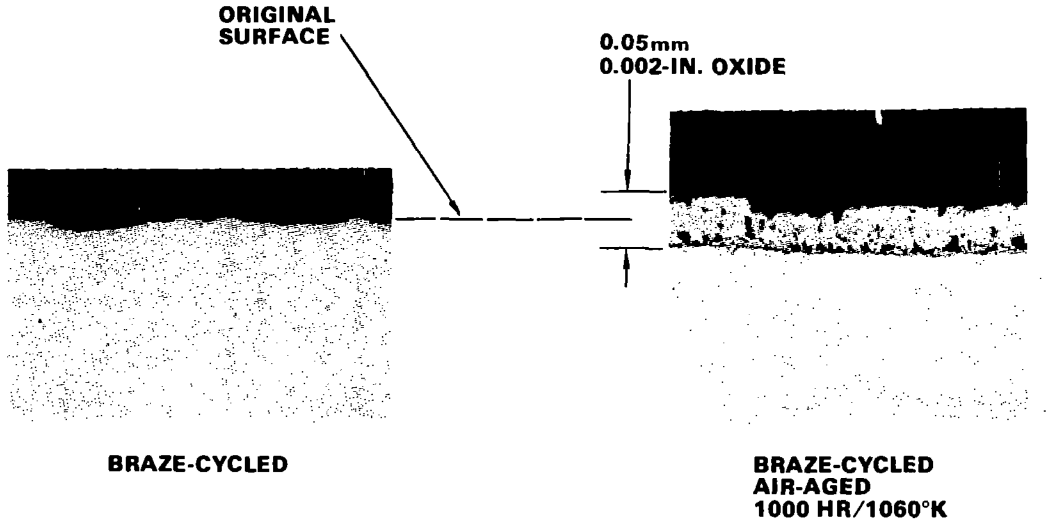


Figure 22

PREDICTED LCF LIFE

(Figure 23)

Given the test data, an assessment of Inconel 617 performance is of interest, i.e., the capability of the Inconel 617 to meet the desired life requirements and its capability relative to Hastelloy X. As noted previously, Nickel 201 is predicted to meet the specified cycle life.

This chart compares the predicted lives of Inconel 617 and Hastelloy X based on published data. Then, using the results of tensile and low cycle fatigue tests, the performance of Inconel 617 and Hastelloy X is again shown. There is a significant reduction in Inconel 617 life predicted under actual operating conditions based on sheet metal properties and performance. This performance, however, still appears superior to that predicted for Hastelloy X. The Hastelloy X predictions, it should be noted, are extrapolations. No data was available for Hastelloy X aged in a manner comparable to what was done with Inconel 617.

Based on these predictions, therefore, Inconel 617 remains the choice with respect to Hastelloy X. The actual performance of Inconel 617 under realistic plastic loading must be experimentally explored. Until that data becomes available, final conclusions cannot be drawn.

PREDICTED LCF LIFE

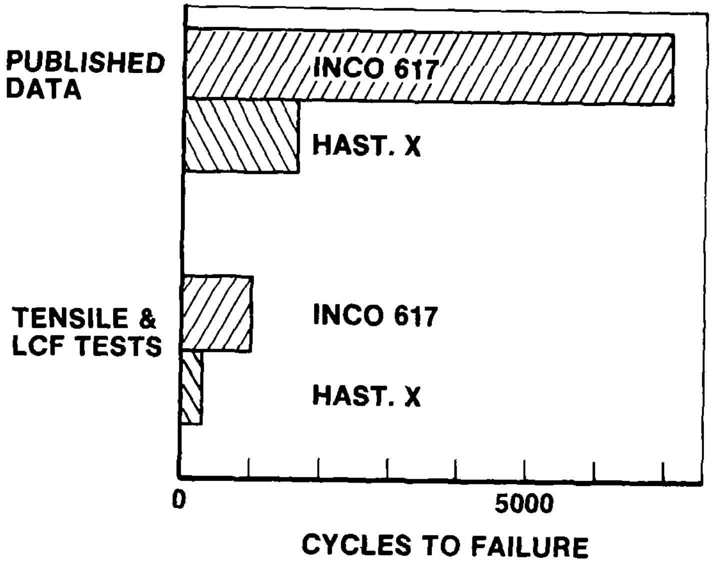


Figure 23

SUMMARY

(Figure 24)

The program has identified an improved design for regeneratively cooled engine structures. This design uses photochemically machined (PCM) coolant passages. It permits the braze joint to be placed in a relatively cool area, remote from the critical hot face sheet. The geometry of the passages at the face sheet also minimizes stress concentration and, therefore, enhances the low-cycle fatigue performance.

The two most promising alloys identified for this application are Inconel 617 and Nickel 201. Inconel 617 was selected because it has excellent creep-rupture properties, while Nickel 201 was selected because of its predicted good performance under low-cycle fatigue loading. The actual capability of both alloys needs to be verified in actual low-cycle fatigue tests using panels before final conclusions can be drawn as to the ultimate capabilities of these alloys.

The fabrication of the PCM coolant passages in both Inconel 617 and Nickel 201 was successfully developed. During fabrication of Inconel 617, undesirable characteristics were observed in the braze joints. A development program to resolve this condition was undertaken and led to definition of an isothermal solidification process for joining Inconel 617 panels. This process produced joints which approach parent metal strength and homogeneity.

SUMMARY

- IMPROVED DESIGN IDENTIFIED
  - PCM COOLANT PASSAGES
  - INCO 617 AND Ni-201
  - ISOTHERMAL SOLIDIFICATION

- FURTHER WORK
  - LCF TESTS
  - H2 EMBRITTLEMENT TESTS
  - ALTERNATE CONFIGURATIONS
  - FABRICATION TECHNIQUE SCALING

Figure 24