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FABRICATION AND STRUCTURAL EVALUATION FOR REGENERATIVELY COOLED PANELS

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16. Abstract

Results of experimental evaluations to select materials and fabrication techniques for plate-fin sandwiches suitable for regeneratively cooled structural panel applications are presented. Included are results of parent metal tensile tests and burst, creep rupture, and flexure tests of brazed plate-fin specimens of Waspaloy, Inconel 718, Inconel 625, and Hastelloy X.

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FOREWORD

This report was prepared by AiResearch Manufacturing Company, a division of The Garrett Corporation, Los Angeles, California for the Langley Research Center of the National Aeronautics and Space Administration. This report presents the results of an experimental study performed under Task Order No. 3, "Fabrication and Structural Evaluation for Regeneratively Cooled Panels." The work is part of a comprehensive analytical and experimental study of regeneratively cooled panels performed under Contract NAS1-5002. This program was under the cognizance of Mr. R. R. Howell and Mr. H. N. Kelly of the 8-Foot High Temperature Structures Tunnel Branch of the Structures Division and Dr. M. S. Anderson and Mr. J. L. Shideler of the Aerothermoelasticity Section, Langley Research Center.

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FOR REGENERATIVELY COOLED PANELS

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SUMMARY

An experimental evaluation of sheet and sandwich panel specimens was performed to select materials and fabrication techniques for regeneratively cooled panels. Specimens, testing conditions and parent metal choices were based on a previous analytical study of hydrogen-cooled panels. The braze joining process was evaluated for several braze alloys which collectively provide manufacturing flexibility for the desired superalloy panel materials.

Tensile tests showed that the strength properties of Waspaloy, Inconel 718 and Inconel 625 coupons, subjected to heating cycles typical of expected brazing conditions, were comparable to published parent metal properties, whereas ductility values were generally lower than published properties. Similar results were noted for Inconel 625 tensile specimens coated with braze alloy.

Metallurgical examination of brazed sandwich specimens showed that joining quality was acceptable for most alloy combinations evaluated and minimal differences were noted for different brazing times and brazing atmospheres. The superalloy metals formed adequate fin shapes required for brazing of these panels.

Burst and creep rupture tests, performed on single layer panels, determined coolant containment strengths and provided comparisons for braze alloy selections. Burst pressures of Waspaloy, Inconel 718, Inconel 625 and Hastelloy X were about 30 to 90 percent of calculated capabilities, whereas creep rupture strengths were a smaller fraction, about 10 to 50 percent. The more ductile alloys, Hastelloy X and Inconel 625, had the better containment strengths in both tests.

Flexure tests of Waspaloy and Inconel 718 sandwich panels showed that strength was 90 to 100 percent of predicted values. Panel performance for external pressure loads satisfied design objectives and verified that weight estimates developed in a previous study were realistic.

INTRODUCTION

In hypersonic cruise vehicles, where regenerative cooling of large surface areas is required, weight and coolant conservation are of paramount importance. Analytical studies of the interaction between structural weight and coolant requirements (reference 1) showed that sandwich panel construction provides minimum weight structures. Further, based on the assumption that high temperature coatings are not available, the superalloy metals would provide the highest panel operating temperatures and hence the lowest coolant usage. Therefore, the major objective of this program was verification that compact sandwich panel elements could be fabricated with the superalloys recommended in reference 1 and that suitable strength properties are attainable.

Although the materials and structural geometry were extensively evaluated in the reference 1 studies, the joining process was not specified. The process under consideration for these panels is brazing which is one of the best developed joining processes in present day state of the art. Several candidate braze alloys were selected based on their strength, ductility, and potential compatibility with the superalloy parent metals. In the initial evaluation, braze cycle effects were determined by tensile tests of parent metal specimens. Following this, a microscopic examination of brazed plate-fin samples indicated filleting, intergranular corrosion and alloying properties.

For this application, the applicable sandwich panel strength properties pertain to (1) containment of the coolant flowing inside the heat exchanger passages and (2) containment of externally applied loads such as combustion chamber pressure, aerodynamic pressure, gravity loads, etc. Since the previous analytical studies (reference 1) were based on published property data and ideal structural behavior (i.e., perfect geometry, uniform thickness, etc.), these experimental evaluations were intended not only to prove fabrication feasibility but, to provide an accurate measurement of panel strength in simulated design conditions. Therefore, two basically different structural tests were performed on sandwich specimens; (1) burst and creep rupture tests primarily for determining coolant containment capabilities and (2) flexure tests to evaluate external loading strength.

SYMBOLS

A area, in.^{2}/in. (cm^2/cm)

b fin or web spacing, width, in. (cm)

E elastic modulus (including plate correction), psi (MN/m^2)

E_t tangent modulus, psi (MN/m^2)

G shear modulus, psi (MN/m^2)

h height, in. (cm)

I section moment of inertia, in.^{4}/in. (cm^4/cm)

K buckling coefficient; spring rate, lb/in. (N/m)

ℓ length, in. (cm)

M bending moment lb-in./in. (N-m/m)

P load, lb (N); pressure, psi (N/m^2)

p load, lb/in. (N/m)

q/A heat flux, Btu/sec-ft^2 (kW/m^2)

R radius, in. (cm)

RT room temperature

t thickness, in. (cm)

V shear load, lb/in. (N/m)

x distance, in. (cm)

δ deflection, in. (cm)

η plasticity reduction factor; $\eta = (E_t/E)^{1/2}$

θ angle of rotation, radians or degrees

ν Poisson's ratio

σ direct stress, psi (MN/m^2)

τ shear stress, psi (MN/m^2)

Subscripts

c core (chevron fin)

cc critical buckling

eq equivalent

f face sheet

fin fin

m measured

r roller correction

ult ultimate

y yield

GENERAL CONSIDERATIONS

Configurations

Three basic conceptual designs for hydrogen cooled structural panels were evolved in the course of the analytical investigation of reference 1. Each of these designs was found to be best suited to a particular range of thermal and pressure loading. The three conceptual designs and their ranges of applicability are illustrated in figure 1. Concept 1 is a single sandwich concept that combines the load carrying structure and the heat exchanger. Concept 2 is a two-layer composite in which a surface heat exchanger is metallurgically bonded to a load carrying panel. Concept 3 is a cooled shingle concept in which the primary heat exchanger is mechanically attached to a load carrying structure which is maintained at a low temperature by a secondary heat exchanger.

Two typical panel configurations, shown in figure 2 form the nucleus of the present fabrication studies. The first is typical of the single sandwich concept which features an all Waspaloy sandwich and utilizes a plain fin core material. The second is typical of the two layer composite used for concept 2 and the cooled shingle for concept 3. The structural panel for this configuration is of Inconel 718 and utilizes a chevron type web core; the heat exchanger is either Hastelloy X or Inconel 625 and utilizes rectangular offset fins.

Parent Metals

The parent metals used in the study were selected as part of the previous study of reference 1. Important parameters that were considered in the previous study included operating temperatures, temperature differentials, the nature and magnitude of applied stresses, fabricability, configuration life and their effect on configuration weight and coolant consumption. Refractory alloys were specifically excluded from consideration because of poor oxidation resistance and because protective coatings that have extended life of 100 hours or more are unavailable. Although Hastelloy X was preferred for the concepts 2 and 3 heat exchangers in the reference 1 studies, a newer alloy, Inconel 625, was also suggested due to its potential for increased thermal fatigue life and was therefore extensively evaluated in the present study. The potential for increased fatigue strength was indicated by published ductility values exceeding those of Hastelloy X.

Test Temperatures

Maximum test temperatures were based on expected component operating temperatures as they evolved from the reference 1 studies. The concept 1 Waspaloy panel limitation was about 1400°F (1030°K). Thermal, external pressure, and coolant containment stresses in the fin and face plates are substantial, however, the governing strength property above 1200°F (920°k), the stress-rupture strength, is still adequate although diminishing rapidly as temperature increases. A maximum surface metal temperature of 1540°F (1110°K) was considered for the concept 2 heat exchanger because superalloy strength properties and oxidation resistance are inadequate for extended operating times at higher temperatures. The maximum test temperature of 1600°F (1140°K) for Hastelloy X and Inconel 625 was consistent with that choice. For the concept 2 Inconel 718 prime structure, a 1200°F (920°K) maximum is about optimum considering coolant usage and weight limitations. The transition from yield strength limited to creep strength limited designs is at about 1200°F (920°K) and the rapid decrease in rupture properties at higher temperatures increases weight significantly. Also, the maximum heat exchanger temperature, which is roughly the sum of the Inconel 718 maximum and the temperature difference across the heat exchanger height, limits the Inconel 718 portion at the higher heat fluxes.

Brazing Alloys

The criteria for selecting braze alloys in this application were good high temperature strength, compatibility with the parent metal annealing or solution heat treatment temperature and satisfactory brazing characteristics. The brazing characteristics considered include wettability, filleting, amount of parent metal intergranular corrosion and alloying depth. In addition, the general requirements for multistep brazing operations dictate that a range of brazing temperatures be available. Based on these considerations, the following braze alloys were selected for evaluation.

Palniro 1 (50 Au-25 Pd-25 Ni, 2070°F (1410°K) braze temperature)

Palniro 7 (70 Au-8 Pd-22 Ni, 1950°F (1340°K) braze temperature)

Nioro (82 Au-18 Ni, 1800°F (1260°K) braze temperature)

Nicrobraz 65 (23 Mn-7 Si-5 Cu-Balance Ni, 1950°F (1340°K) braze temperature)

The gold-base alloys have good elevated temperature strength and, compared to the nickel-base alloys, they have lower hardness, better ductility and less tendency for intergranular penetration and alloying. The three brazing temperature provide considerable flexibility for multistep braze operations. Another gold-based alloy, Palniro 4 (30 Au-34 Pd-36 Ni, 2175°F (1460°K))was used in the Hastelloy X tests, but was not evaluated in combination with the other three superalloys.

Nickel-based brazing alloys containing silicon and boron have good elevated temperature strength and good brazing characteristics, but one serious drawback of these commonly used alloys is loss of parent metal ductility due to intergranular penetration by boron. Nicrobraz 65 was selected because it is not as aggressive as other nickel-based alloys in terms of either alloying or intergranular penetration. Nicrobraz 65 is available only in powder form whereas braze foil, available with the gold alloys, is preferable because it gives more uniform coverage and composition. In addition, Nicrobraz 65 is not as strong nor as ductile as the gold based alloys, however, it is much less expensive ($5/lb vs $700/lb) and, for this reason, merited consideration.

Fabrication

The fabrication approach used in this program was based on AiResearch state-of-the-art techniques. Existing tooling, to the extent possible, was used because of the limited number of test samples. However, three important fabrication variables were evaluated with regard to plate-fin joint quality; (1) fin formability of the superalloy materials, (2) the effect of pressure loading on the plate-fin sandwich during the brazing process, and (3) methods of applying this loading.

SHEET ALLOY PROPERTIES

Sheet tensile properties of Waspaloy, Inconel 718 and Inconel 625 were determined for conditions typical of their use in brazed sandwich panels. The sheet alloys were subjected to heat treatment cycles characteristic of the various candidate braze processes. Braze process variables included temperature, hold times during brazing, and cooling rates subsequent to brazing. Postbraze heat treatment cycles were also applied to investigate Waspaloy strength for two final aging cycles and to evaluate Inconel 625, property variations due to the Inconel 718 aging cycle. In addition, Inconel 625 tensile specimens were coated with the candidate braze alloys to observe the resulting composite properties and for comparison with the uncoated, but similarly heat treated Inconel 625 specimens. Sheet material, with thickness corresponding to expected dimensions for fabricated panels, was selected for the test specimens to eliminate possible size effects. Since the published properties of the materials are generally reported for considerably larger thicknesses, the results obtained augment available data. Furthermore, reduction in area estimates were obtained for the three materials since this property is not always reported, and in this application, provides data for low cycle fatigue estimates, particularly for Inconel 625 heat exchangers.

The braze alloy-parent metal combinations selected for evaluation were:

Waspaloy	Palniro 7, Nicrobraz 65
Inconel 718	Palniro 7, Nioro
Inconel 625	Palniro 1, Palniro 7, Nioro

Important considerations affecting the above combinations are discussed in the burst and creep rupture test section.

Specimen and Tests

The basic test specimen shown in figure 3, similar to a standard tensile coupon, was cut from 6 in. (15 cm) square sheets of 0.010 in. (0.025 cm) thickness sheet material. The composition of the square sheets was metallurgically verified to be within specifications and the simulated braze cycle or coating operation was performed prior to machining the samples. The applicable aging cycles followed the final machining operation. Except for one test case, the specimens were cut to give transverse (relative to rolling direction) loads on the material since this generally produces the lowest material properties. Except for the coated Inconel 625 specimens, the elevated temperature coupons included 0.04 in. (0.10 cm) thickness reinforcing tabs which were spotwelded at either end to prevent hole deformation.

All of the specimens were tested with an Instron Universal Testing Machine. For the room temperature tests the specimens were loaded at a strain rate of about 0.005 in./in./min (0.00008 cm/cm/sec) to about one percent strain. The specimens were then unloaded and reloaded at a strain rate of about 0.010 in./in./min (0.00016 cm/cm/sec) to failure. At elevated temperatures the procedures were the same except that strain rates of about 0.05 in./in./min (0.0008 cm/cm/sec) were used for both loadings. An extensometer with a 500x magnification was used during the initial loading to measure the specimen extensions from which the strains were calculated. For the second loading, displacement of the crosshead as recorded by the testing machine (50x magnification) was used to determine the strain. Elongation data was reduced on the basis of a 1-in. (2.5-cm) gage length.

In addition to the standard stress-strain data, reduction in area measurements were obtained on the failed specimens. The width and thickness were measured about 0.05 in. (0.13 cm) from the fracture using a standard 1-in. (2.5-cm) micrometer. However, the measuring technique is not accurate for these thin gages due primarily to the irregularity of the fracture and the quoted values in subsequent tables should be considered as an indication rather than an absolute measurement.

Test conditions, test objectives and qualitative results of the tensile tests are summarized in table I.

Waspaloy

The Waspaloy tensile strength results in figure 4 show good agreement with published data and exceeded specified minimums. The same is true of room temperature elongation properties, however, the 1400°F (1030°K) elongation was considerably lower than either published properties or specified minimums. As discussed below, this loss in ductility is partially attributed to work hardening. A complete summary for Waspaloy, including reduction in area measurements which generally agree with elongation trends, is presented in table 2. The yield and ultimate strength values within a sample are very consistent. The elongation and reduction in area values show more scatter probably because in this thin sheet material, local defect size influences crack initiation. Notches, scratches, grain size and local property variations are more important when the size of these defects is a significant percentage of sheet thickness.

Typical room and elevated temperature stress-strain curves, including both the extensometer and crosshead readings, are shown in figure 5. The 0.2 percent offset yield point and elastic line are noted for the extensometer portion of the curve. The shape of the 1400°F (1030°K) curve (crosshead reading) suggests that some creep deformation was recorded since the maximum stress level was displaced toward the lower strain values.

Effect of brazing and aging cycle.- A comparison of Palniro 7 cycles to the reference double-aging at 1550° and 1400°F (1120° and 1030°K) of as-received material indicates that the simulated brazing caused only minor changes in Waspaloy properties. The 1400°F (1030°K) tests, simulating Palniro 7 with vacuum and hydrogen environments, show that the slower vacuum cooldown (about 1500 s to cool below 1000°F (810°K) versus about 480 s for hydrogen) tends to decrease strength and increase ductility. Similar overall results would be expected for Nicrobraz 65 since its brazing temperature is close to that of Palniro 7.

The normal double-aging cycle was compared to a single cycle at 1400°F (1030°K) since the latter would simplify fabrication. The single-aging cycle resulted in substantially lower Waspaloy elongation values and the double-aging cycle was retained in subsequent evaluations. If as surmized, cold working at the specimen edges (see below) contributed to the lower ductility, the double-aging cycle was more effective in relieving undesirable machining effects. In an actual application, the panel braze operation would follow any machining operations, rather than preceding them as in these tests, and the single-aging cycle might prove to be acceptable.

Effect of work hardening.- The low Waspaloy elongation at elevated temperatures was partially attributed to work hardening of the edges during machining. To eliminate the work hardening contribution, a two-hour, 1825°F (1270°K) soak was added after machining the specimens which were then double-aged. In 1400°F (1030°K) tests, the elongation increased by about 100 percent, equal to specified minimum values (figure 4). The yield strength decreased about 10 percent but exceeded specifications whereas the ultimate strength was unaffected. Satisfactory Waspaloy properties are expected for this application since brazing would have an effect similar to the added 1825°F (1270°K) soak.

Additional coupons, treated with the 1825°F (1270°K) soak prior to aging, were tested in the longitudinal direction. As expected, longitudinal properties exceeded transverse properties. However, the difference is slight and directionality does not appear to be a factor for Waspaloy.

Inconel 718

The Inconel 718 tensile properties (figure 6) agree favorably with published data and exceeded specified minimums for all test conditions. A summary of the test results in table 3 indicates that property variations within each sample were comparable to Waspaloy. Typical room and elevated temperature stress-strain curves are shown in figure 7.

The simulated braze cycles, in general, tended to reduce Inconel 718 properties as compared to the as-received and aged condition (table 1). The largest variation occurred in the 1200°F (920°K) tests, where elongation values were 25 to 30 percent lower. Of the two braze cycles, the Palniro 7 cycle produced the lower strength properties, about 10 percent less than Nioro. However, the ductility of the Palniro 7 case exceeded that of Nioro by about 10 percent at elevated temperature.

The slightly higher properties of the as-received material, compared to the Nioro cycle specimens, is attributed to the more rapid cooldown after annealing (annealing temperature and Nioro braze temperature are the same). Although the hydrogen brazing environment was not evaluated, cooldown is faster than for vacuum brazing so slightly higher Inconel 718 properties would be anticipated.

Inconel 625

The ultimate strengths of Inconel 625 specimens generally exceeded specified minimums and published properties. Room temperature yield strengths exceeded reference data except that with the Palniro 1 cycle yield strength was about 10 to 15 percent less than both minimum and published values (figure 8 and table 4). At 1400° and 1600°F (1030° and 1140°K), yield strength was consistently lower than published data, up to about 30 percent in one case. The elongation properties, displayed in figure 8b, tend to agree with room temperature published values and to exceed the minimum specified, whereas the elevated temperature elongation is significantly less than the published properties, a 70-percent reduction in one case (no minimum is specified at elevated temperatures). A partial explanation may be creep deformation which was evident in the high temperature stress-strain curves (typical room and elevated temperatures curves are presented in figure 9). Since creep rupture generally occurs for lower total elongations, the full short-time elongation may not have been realized.

Effect of brazing and aging cycles.- From a comparison of results of the as-received material tests and those with the Palniro 1 and 7 braze cycles it is apparent that the only major effect of the brazing cycles is the 50 percent reduction of the elongation of the specimens with the Palniro 1 braze cycle at 1600°F (1140°K) shown in figure 8b. The difference apparently is the result of the higher brazing temperature of the Palniro 1 alloy, since the close agreement between the as-received and Palniro 7 results indicates that cooling rate has little or no effect on Inconel 625.

Inconel 625 is apparently age hardened by the Inconel 718 heat treatment as evidenced by the higher strength and lower ductility of the heat treated specimens relative to the as-received specimens. This is attributed primarily to the 8-hr soak at 1325°F (990°K), although the aging effect on Inconel 625 properties at higher test temperatures would diminish.

Effects of braze alloy.- In the 1600°F (1140°K) braze alloy coating tests, the ultimate strength (based on the original uncoated sheet thickness) varied from 42 ksi (290 MN/m^2) for Palniro I to 52 ksi (360 MN/m^2) for Nioro compared to 43 ksi (300 MN/m^2) for as-received material. With the braze coating, the material ultimate equaled, or exceeded, the simulated braze cycle samples, however, yield strength variations were negligible between any of the test coupons. Elongation values were fairly consistent between the three braze coated types, ranging from 36 to 45 percent, although they were much lower than the as-received and Palniro 7 cycle values (but slightly higher than the simulated Palniro I cycle elongation). Measurements of braze alloy diffusion into Inconel 625 (0.0004 in. (0.001 cm) for Palniro I and 0.0007 to 0.0010 in. (0.0018 to 0.0025 cm) for Palniro 7 and Nioro) do not indicate any definite trend which would explain the difference between coated and uncoated Palniro I and 7 specimens.

BRAZING CHARACTERISTICS

Metallographic examinations of brazed plate-fin specimens established brazing and forming characteristics of Waspaloy, Inconel 718 and Inconel 625. In addition, the effect of fin and plate contact stress variations was investigated. In this program, the contact stress was applied by deadweight loads, however, an alternate method, evacuated envelope loading, was briefly examined.

As summarized in table 5, the parent metal and braze alloy combinations were retained from the previous evaluation. Vacuum and hydrogen atmospheres were compared with all parent metal-braze alloy combinations except Waspaloy-Nicrobraz 65. The hydrogen brazing environment is preferred because it restricts preferential evaporation of manganese from Nicrobraz 65. Hold times of 300 and 1200 s were used to investigate time-dependent alloying, intergranular penetration and erosion effects.

Specimen Preparation

Geometries of the basic 2 by 3 in. (5 by 8 cm) samples used in the brazing evaluation are indicated in Figure 10 (slightly smaller, 1.5 by 2-in. (4 by 5 cm) Inconel 625 specimens were used in the braze pressure evaluation). Fin geometries were similar but not necessarily identical to those of the reference configurations of figure 2. Prior to panel assembly for brazing, the Waspaloy and Inconel 718 components were nickel plated (0.0002 to 0.0003 in. (0.0005 to 0.0008 cm) thickness) to obtain the required braze alloy wetting action. Inconel 625 components were not nickel plated since previous experience indicated that it was not required. During the assembly operation, which includes insertion of the braze foil or powder, the components are spot-welded together to prevent movement during brazing. Gold alloy braze foil thicknesses of about 0.001 in. (0.0025 cm) were used and the thickness of the sprayed mixture of filler powder and Nicrobraz cement was about the same.

Following brazing and final heat treatment, photomicrographs were taken of the panel cross section. These photographs were used to determine braze characteristics such as depth of braze penetration. In some cases, micrographs were obtained prior to brazing to detect possible fin geometry changes resulting from the braze operation.

Effect of Brazing on Materials

Waspaloy.- The Palniro 7 alloy formed good joints and fillets when brazed with Waspaloy as shown in figure 11. No differences were noted between hydrogen and vacuum environments, however there was a slight increase in diffusion for the longer hold time. Alloying depths were typically about 0.0013 in. (0.0033 cm) and about 0.0004 in. (0.0010 cm) of intergranular penetration was observed. The intergranular penetration is somewhat greater than expected, possibly because of interaction between the nickel plating and Palniro 7. Discounting the contribution of intergranular penetration, the alloying depth was about 0.0009 in. (0.0023 cm) compared to the original separation of 0.001 in. (0.0025 cm) caused by the braze foil between the plate and fin (assuming complete contact prior to brazing).

Increased filleting would be desired for Nicrobraz 65, indicating the need for additional brazing powder. Very little diffusion occurred with this alloy and the lack of intergranular penetration shows that Nicrobraz 65 was not aggressive to Waspaloy.

Inconel 718.- The braze flowing and filleting characteristics of Palniro 7 were good as shown in figure 12a. The Nioro alloy was generally comparable to Palniro 7, however recessed fillets were noted (figure 12b). No significant difference was noted between vacuum and hydrogen brazing or between the two hold times for either alloy. Diffusion was uniform, although the depth was 0.00025 in. (0.00063 cm) for Palniro 7 compared to 0.00015 in. (0.00038 cm) for Nioro. Similarly, intergranular penetration was about 0.0004 in. (0.0010 cm) for Palniro 7 compared to 0.0003 in. (0.0008 cm) for Nioro. The difference may be attributed to the Inconel 718 nickel plating which may have reacted more with Palniro 7 due to its higher brazing temperature.

Inconel 625.- The brazing properties of the three alloys were good with no appreciable differences noted for either brazing environment or the two hold times. The diffusion of Palniro 1 into Inconel 625 was 0.0004 in. (0.001 cm), about one-half of that for Palniro 7 and Nioro. Diffusion was uniform, with minor intergranular penetration observed.

As shown by photomicrographs in figure 13, there is considerable separation between the plates and fins, probably because of the initial rounded fin shape (figure 13a). (The separation may be exaggerated since the apparent metal boundary is shifted by diffusion of the filler alloy in the gap). Capillary action may have caused the braze alloy to concentrate in the initial rounded fin contact area although the load during brazing is sufficient to eventually increase the contact area due to fin creep deformation. A comparison of the Waspaloy and Inconel 625 joints in figures 11 and 13, respectively, supports this explanation since the Inconel 625 braze alloy covers a lower percentage of the potential fin-to-plate contact length.

The ability of the braze alloy to fill small gaps is of prime importance in determining acceptable fabrication tolerances. The relative capability of the various alloys to fill gaps was not determined, however, the following observations were made from the photomicrographs. Nioro failed to fill a gap of 0.004 in. (0.01 cm) in one instance, but this alloy was capable of spanning a 0.003 in. (0.008 cm) spacing. Palniro I filled a gap of 0.003 in. (0.008 cm), whereas filled separations for Palniro 7 did not exceed 0.001 in. (0.003 cm).

Superalloy Fin Formability

Initially some question existed as to the feasibility of forming Waspaloy into the desired compact fin array due to its lower ductility properties as compared to Inconel 625 and Hastelloy X. A fin thickness of 0.003 in. (0.008 cm) was desired, however the available forming die was for 0.004 in. (0.01 cm) material. Both fin sizes were fabricated on the available die and since the 0.003 in. (0.008 cm) fin was acceptable (see figure 11) it was used in the subsequent Waspaloy evaluations. Furthermore, the plain 0.003 in. (0.008 cm) Waspaloy fins were more nearly rectangular than the 0.004 in. (0.01 cm) offset Inconel 625 ones (compare figures 11b and 13a).

Inconel 718 chevron fins initially presented fitup and brazing problems since the brazing tab was not perpendicular to the web due to springback during fabrication. An acceptable fin shape was achieved by hand forming the tabs during the fitup and assembly process. However, the nonuniformity of fin-to-tab angle apparently led to gaps which exceed typical fin height variations in rectangular, plain or offset, fin geometry.

Fin shape did not change during the braze operations in any specimens. The only effect related to fin shape was the increased separation of the fin and plate of the Inconel 625 specimens attributed to the rounded fin and the fit up of the Inconel 718 chevron fins.

Effect of Pressure on Brazing

Increased contact pressures were investigated for the Inconel 625 fins, which had pronounced curvature on the surface contacting the plate, to determine if joint quality was affected. The relatively large plate and fin separation was undesirable and the fillets could be improved. In the previous braze operations a 1.8 psi (12 kN/m^2) deadweight loading provided the fin and plate contact pressure. The test fixture shown in figure 14 applied loading pressures of 2 to 12 psi (14 to 83 kN/m^2) in 2 psi (14 kN/m^2) increments on six 1.5 by 2 in. (4 to 5 cm) Inconel 625 samples.

Metallographic examination revealed no discernable differences in brazing characteristics for the 2 to 12 psi (14 to 83 kN/m^2) pressures as shown in figure 15. The plate and fin separation and filleting agreed closely with the previous 1.8 psi (12 kN/m^2) value of about 0.001 to 0.002 in. (0.003 to 0.005 cm). There was no indication that fin buckling occurred, even for the highest loading. Based on these results, subsequent fabrication was performed with about 2 to 4 psi (14 or 28 kN/m^2) loading, depending on fixturing considerations.

Evacuated Envelope Brazing Method

An alternate method of achieving fin and plate contact pressure, utilizing an evacuated envelope, was evaluated. In this approach, the panel is encapsulated in a sheet metal envelope (see figure 16) which can be evacuated so that atmospheric pressure provides the brazing contact load. This method is attractive because little or no fixturing is required. Furthermore, it avoids undesirable temperature lags and minimizes thermal expansion restraint which result from deadweight loadings on large panel surfaces.

An Inconel 625-Palniro 1 specimen was brazed in an envelope evacuated to provide an external pressure of one atmosphere. The cross section of the brazed sample, shown in figure 15c, shows that contact between fin and plate was similar to the deadweight results, although filleting was not as good. The lower braze quality of this specimen could be attributed to a slightly higher brazing temperature, 2085°F (1410°K) compared to previous temperatures of 2070°F (1410°K), and a 20°F (11°K) overshoot which lasted for about 120 s. In addition, some collapsing of fins is evident, either because of the slightly higher brazing pressure, or a combination of increased temperature and pressure. The evacuated envelope method was not given further consideration in this program because some further development appeared desirable and deadweight loading was satisfactory.

INTERNAL PRESSURE TESTS

Burst and creep rupture tests were conducted on single layer brazed plate-fin sandwich specimens to evaluate the pressure containment properties of several material systems and to provide aid in the selection of braze alloys for the fabrication of specimens for subsequent flexural tests. In addition to quantitative measurements of the pressure containment properties, visual, microscopic, and metallographic examinations were made to determine braze alloy placement and quantity, parent metal erosion, and types of failures. The results of similar tests with Hastelloy X specimens obtained in a related program are also reported since both Hastelloy X and Inconel 625 are prime candidates for the heat exchanger of the two layer panel of figure 2b.

Test Specimen

Single layer sandwich specimens were used to simulate components of the reference configurations of figure 2. Geometries of the 2- by 3-in. (5- by 8-cm) specimens are given in figure 17. With the exception of the thickness of the faceplates for the Inconel 718 specimens the geometries of the fins and faceplates were identical to those of figure 2. Thicknesses of the Inconel 718 specimen faceplates were increased to 0.020 in. (0.05 cm) to ensure that failure would occur in the chevron fins. Geometries of the Hastelloy X specimens were similar; however, 0.015 in. (0.037 cm) faceplates and a variety of fins of the offset type (figure 2b) were used.

The Waspaloy specimens were representative of the materials and geometries proposed for a single layer sandwich (figure 2a). These specimens were tested at 1400°F (1030°K) to evaluate the pressure containment properties under typical operating conditions and to aid in the selection of a braze alloy for subsequent flexural tests. The Inconel 718 specimens were representative of prime structural panel of a two-layer sandwich (figure 2b). Although this section of the two-layer sandwich would probably not be pressurized internally the relative web joint strength at 1200°F (930°K) would indicate the best braze alloy for subsequent flexural tests. The remaining specimens were representative of the heat exchanger section of the two layer sandwich (figure 2b). The Inconel 625-718 specimens were tested at 1200°F (920°K) to evaluate the pressure containment properties of the colder heat exchanger joint near the prime panel and the all Inconel 625 specimens were tested at 1600°F (1140°K) to evaluate the containment properties of the joint next to the hot surface. The Hastelloy X specimens were tested at room temperature, 1200°F (920°K), 1500°F (1090°K), and 1600°F (1140°K).

Brazing Conditions

The four braze alloys evaluated previously were retained, however braze conditions were limited to those providing a desired comparison or a range of strength properties. In cases where the brazing conditions were unlikely to have a large influence on strength, the conditions expected to produce the lowest properties were preferred.

Waspaloy panels. - Due to its good strength and compatibility with the Waspaloy heat treatment, Palniro 7 was evaluated for two braze conditions, vacuum and hydrogen brazing. A range of Waspaloy strength properties would be expected since the slower vacuum cooldown lowered Waspaloy properties as compared to hydrogen brazing. In addition, inclusion of hydrogen brazing provides a comparison with Nicrobraz 65 which was brazed in hydrogen to restrict the evaporation of manganese. Palniro 1 was compared to Palniro 7 because of its potentially greater creep rupture strength. Although the brazing temperature for Palniro I (2070°F (1410°K)) exceeds the maximum recommended solution heat treatment for Waspaloy (1975°F (1350°K)). Recent experience with this alloy indicated that it did not degrade the Waspaloy properties at 1300°F (980°K). The common 1200 s hold times represent conservatively the time for temperature stabilization, and would have the effect, if any, of reducing Waspaloy properties.

Inconel 718 panels. - Palniro 7 exhibits good strength and is compatible with both Inconel 718 and Inconel 625. The braze conditions included vacuum brazing with a 1200 s hold time to give the lowest Inconel 718 properties and hydrogen brazing for 300 s for the best results. The lower melting point alloy, Nioro, permitted multi-step brazing flexibility and was a backup for Palniro 7. Nioro properties were compared for a vacuum environment with a 1200 s hold time.

Inconel 625 - Inconel 718 panels. - Palniro 7 has good high temperature strength and it is compatible with the maximum recommended solution heat treatment temperature for Inconel 718. Because no difference between hydrogen or vacuum brazing was noted for Inconel 625 and only a slight difference for Inconel 718, the panels were vacuum brazed. The 1200 s hold time provided a conservative test because both parent metals tend to have their strength reduced slightly as hold time increases. Nioro was compared to Palniro 7 for the reasons discussed above for Inconel 718.

Inconel 625 panels. - Palniro I has good strength at the 1600°F (1140°K) test temperature and composite properties were desired for 300 and 1200 s hold times. Palniro 7 was included for one step brazing of two layer panels. The comparison between these alloys was made with a 1200 s hold since Palniro 7 brazes near the solution annealing temperature of Inconel 625 and hold time is not a significant factor. Since cooling rate is not a factor with Inconel 625, vacuum brazing was employed.

Hastelloy X panels. - Various fin geometries were tested with two braze alloys, Palniro 4 and Palniro I. Braze foil thicknesses ranged from 0.0005 to 0.0014 in. (0.0013 to 0.0036 cm) and 300 to 1200 s hold times were used in a vacuum environment.

Fabrication

The specimen assembly was the same as that for the brazing evaluation. For the brazing operation a deadweight loading of about 3 psi (21 kN/m^2) was used for all but the Hastelloy X specimens. For the Hastelloy specimens the loading was from 2 to 6 psi (14 to 42 kN/m^2). After examination and proof testing as described in the following section the specimens were subjected to the appropriate heat treatment. For the Waspaloy specimens the standard double aging cycle (1550°F (1120°K) for 4 hours, air cool, 1400°F (1030°K) for 16 hours, air cool) was used. Both the Inconel 625 - 718 and Inconel 718 specimens were subjected to the Inconel 718 aging cycle (1325°F (985°K)) for 8 hours, furnace cool $100^{\circ}F/hr$ ($56^{\circ}K/hr$) to $1150^{\circ}F$ ($895^{\circ}K$), hold for 8 hours, air cool). The Hastelloy X and Inconel 625 specimens were not heat treated.

Preliminary Examination and Proof Tests

Following the brazing cycle and prior to final heat treatment each specimen was subjected to an x-ray examination and 1000 psi (6890 kN/m^2) room temperature proof pressure test to detect voids in the braze or leaks in the specimen. The x-ray examinations were particularly successful in determining if all fins were brazed because the relatively greater density of the gold-base brazing alloys, compared to the plate and fin material, was easily detected. Furthermore, unbrazed fins typically had thinner brazing alloy coatings (about 0.001 in. (0.0025 cm) compared to about 0.0015 in. (0.0038 cm)) and the x-ray density could be adjusted to detect coated but unbrazed regions. Following heat treatment the specimens were again proof pressure tested. If voids or leaks were detected the samples were generally repair brazed and retested until the sample was satisfactory.

Based on the results of the preliminary tests, modifications were made to the test specimens and Nicrobraz 65 was eliminated from further examination. The specimen modification consisted of substituting one-piece, rectangular-frame headers (shown in figure 17) for the separate side and end header strips used in the initial specimens. The modification was made to eliminate recurrent leakage problems at the corner joints of the strip headers. Nicrobraz 65 was eliminated after several unsuccessful attempts to obtain satisfactory specimens. After the first series of Waspaloy panels gave unsatisfactory results, the panels were rebrazed adding additional brazing powder and a flux to increase wettability. The brazing quality improved, but the panels still could not pass the 1000 psig (6890 kN/m^2) room temperature proof test. It was concluded that brazing techniques for Nicrobraz 65 powder would have to be improved considerably to produce satisfactory joints and no further evaluation of Nicrobraz 65 was performed.

Tests

Table 6 shows the test specimen evaluation schedule. Both burst and creep rupture tests were conducted for all configurations except the Inconel 625-Inconel 718 panels which generally simulate operations at temperatures below the transition from yield strength limited to creep strength limited designs. A minimum of three samples were generally tested for each particular configuration to give some indication of test consistency; although one or two samples were tested with some Hastelloy X combinations.

The test setup, shown in figure 18, includes Marshall Tube furnaces. Platinum-10 percent rhodium/platinum thermocouples were placed in the chamber near the specimens for furnace control which is provided by a Leeds and Northrup recorder. In addition, two chromel-alumel thermocouples were spot-welded to each panel and the maximum temperature difference observed between them was $5^{\circ}F$ ($3^{\circ}K$). Nitrogen gas was used to pressurize the samples for shorttime burst testing. For the creep-rupture tests, argon was used to avoid any nitriding effects.

The panels were heated to test temperature in about 1 hr, and were stabilized at temperature for at least 900 s before testing. In the burst tests, nitrogen gas pressure was gradually increased until the panel ruptured, i.e., could not contain pressure. The test time, from zero pressure to failure, was about 120 s. In the stress-rupture tests, argon pressures ranging from about 200 to 1000 psi (1380 to 6890 kN/m^2) were selected to give panel failures in times of 50 to 100 hrs. Pressures were adjusted to give reasonable specimen life if the initial values were out of the desired range. Subsequent to testing, the panels were sectioned in the failure region. Photomicrographs were then obtained of representative cross-sections to analyze brazing characteristics and failure types. Although the exact origin of failure generally could not be pin pointed, the major failure mode and average brazing characteristics were determined. Photographs of typical samples after failure are shown in figure 19.

Results and Discussion

Results of the burst and creep rupture tests are summarized in tables 7 and 8, respectively. In addition to the basic test data the tables present the fin tensile stress (obtained by dividing the pressure load at burst or rupture by the fin tensile area) and the ratio of fin tensile stress to ultimate or rupture stress for parent metals at the same conditions obtained from published data (references 2 to 4).

The fin stress ratio, used extensively in discussions to follow, is a measure of the overall efficiency of the fabricated specimen and indicates the fraction of the parent metal strength potential realized by that configuration. To attain the full potential of the parent metal (stress ratio = 1.0) the face plates and braze material must sustain the load (initial failure must occur in the fin material), the fin loading must be uniform throughout the specimen, the fins must be loaded in pure tension, and the brazing and forming process must not degrade the properties of the fin material. Since (as discussed further in the sections to follow) fin shape, thickness, spacing, and face plate thickness influence the loading and fabrication processes can affect the material properties, the stress ratios are strickly applicable to configurations of identical geometry and caution should be exercised in attempting to apply these data to other configurations.

Failure modes.- Initial failures of the fabricated specimens, as determined from examination of photomicrographs of failed specimens, occurred in the braze joints and in the fins (see figure 20). Thicknesses of the facesheets were sufficient to preclude initial failures of the facesheets themselves. However, as indicated in the following sections, the thin facesheets contributed to the failures which occurred in the braze joints and fins.

Braze joint failures: Braze joint failures occurred in all of the tests of specimens with Waspaloy or Inconel 718 fins, in some of the high temperature burst tests of specimens with Inconel 625 fins and in all of the creep rupture tests of specimens with Inconel 625 fins. Specimens which failed in the braze joints realized strength ratios that ranged from about 0.28 to 0.62 in burst (excluding data obtained with the Nioro braze alloy) and from about 0.07 to 0.25 in creep rupture. As indicated in figure 20a and b, two types of braze joint failure were noted. In one type, (figure 20a), which was encountered with the Waspaloy and Inconel 718 specimens, failure occurred at the interface between the braze material and the nickel plating used with these alloys to promote wetting by the braze alloys. In the other type (figure 20b), which was encountered with the Inconel 625 specimens, failure occurred in the braze material. This latter type of failure is closely associated with the strength and shape of the braze fillet. The increased cross-sectional area of the fillet is required to compensate for the lower strength of the braze alloy relative to the fin material and to offset bending stresses in the fillet. Bending stresses are induced in the joint by bending moments in the facesheets which are functions of the fin spacing and facesheet thickness. Bending stresses may also result from the effects of tensile loads on a poorly shaped fin or from a poorly shaped fillet which does not provide a direct load path to the fin.

Fin failures: Fin failures occurred in some of the burst tests of specimens with Inconel 625 fins and in both the burst and creep rupture tests of specimens with Hastelloy X fins. Specimens which failed in the fin material (figure 20c) realized strength ratios from 0.37 to 0.90 in burst and from 0.34 to 0.48 in creep rupture. In addition to being directly dependent upon the effects of processing on the material properties, the strength of the specimens which failed in the fin material may be influenced by nonuniform load distributions induced by poorly shaped fins (see appendix A), localized braze imperfections or by fin bending stresses which, as in the case of the braze joint stresses, are dependent upon fin spacing and shape, facesheet thickness, and braze fillet shape and quality. Sensitivity of the specimens to load nonuniformity and bending loads is also dependent upon fin height and material ductility since taller more ductile fins can relieve the localized loading through plastic deformation.

Burst tests.- In general, the consistency of the burst strength data presented in table 7 is good with the maximum variation within a given set of samples usually less than 20 present. Exceptions to this may be attributed to test time variations which are important at elevated temperatures where creep deformation occurs.

Waspaloy: The Waspaloy specimens realized from 28 to 34 percent of the parent metal strengths. The results indicate that vacuum brazed specimens were slightly stronger than hydrogen brazed specimens and that Palniro 1 brazed specimens were slightly stronger than those brazed with Palniro 7. Since failures occurred at the interface between the braze alloy and the nickel plating, the higher strength of the vacuum brazed specimens is probably the result of slightly greater diffusion of the braze alloy through the nickel plating into the parent metal due to the longer time at temperature for vacuum brazing (slower cooldown rates) and due to the higher temperatures for the Palniro I braze alloy (2070°F (1410°K) versus 1950°F (1340°K)).

Inconel 718: The Inconel 718 specimens brazed with Nioro realized only about 11 percent of the parent metal strength; whereas the specimens brazed with Palniro 7 realized from 30 to 45 percent of the parent metal strength. In view of the especially poor performance of specimens brazed with Nioro, this alloy was eliminated from further study. The poor performance was attributed to recessed brazed fillets (previously noted in the braze evaluation, see figure 12) which induce high bending stresses in the fins and joints due to the indirect load paths. The brazing atmosphere had little effect on the strength of the specimens brazed with Palniro 7; although, in contrast to the Waspaloy results, the hydrogen braze cycle produced slightly stronger specimens. Specimens held at the brazing temperature for 1200 seconds were stronger than those held at brazing temperature for 300 seconds, a result which is apparently due to greater diffusion of the braze alloy through the nickel plating. In view of the apparent difficulty in obtaining adequate penetration of the nickel plating by the braze alloy, it appears that elimination of the plating might improve the performance of both the Waspaloy and Inconel 718 specimens if adequate wetting by the braze alloy can be obtained without the plating.

Inconel 625: Specimens with Inconel 625 fins realized from 46 to 71 percent of the parent metal strength. As with the Inconel 718 specimens, Inconel 625 specimens brazed with Nioro gave inferior results. Failures in specimens brazed with Palniro 7 transitioned from the fins to the braze joints as the test temperature was increased from 1200° F (920° K) to 1600° F (1140° K). However, the stress ratios were approximately the same at both temperatures. At the 1600° F (1140° K) test temperature specimens brazed with Palniro I were consistently stronger than those brazed with Palniro 7 as might be expected with a braze alloy which has a higher brazing temperature. The shorter braze time (300 s) yielded specimens with higher average strength and the failures occurred in the fins. The scatter in the data for the three specimens with the 1200 s brazing time may be due to varying quality of the specimens, or to creep effects resulting from slight variations in test time or temperature. The inability of specimens which failed in the fin to attain full theoretical strength may be due to creep effects or reduced material properties; however, it is suspected that bending stresses induced by the thin face sheet (0.010 in. (0.025 cm)) and by rounded corners of the fins (see figure 13) are primarily responsible for the reduced performance.

Hastelloy X: A large variety of Hastelloy X specimens were investigated. These specimens, which generally failed in the fin material, realized from 37 to 91 percent of the parent metal strength. Several definite trends can be noted in the Hastelloy X data which are summarized in table 7b. The specimens with more closely spaced fins consistently gave higher average burst strengths. This is to be expected, since closer spacing reduces plate bending stresses and, since each fin carries a smaller fraction of the load, reduces the sensitivity of the specimens to defective fins or localized braze imperfections. Increased hold times at braze temperature from 300 to 1200 s gave lower strengths in all cases and, in comparative tests, the average loss in burst strength was about 33 percent. Decreased fin thickness increased the fraction of the parent metal strength that could be obtained, apparently through better formed fins. For example, a decrease in fin thickness from 0.006 in. (0.015 cm) to 0.004 in. (0.010 cm) results in an increase in stress ratio from 0.57 to 0.85. In a single comparison, increasing braze alloy sheet thickness from 0.0005 to 0.001 in. (0.0013 to 0.0025 cm), gave a 50 percent strength improvement; however, this may be partially attributed to the strength of a coating of braze alloy on the fin which was not considered in computing fin stress. It was noted that the braze alloy formed a significant coating on the 0.002 in. (0.005 cm) fins used in this comparison.

Creep rupture tests. - The creep data are summarized in table 8, and the variations of rupture stress with time are presented in figures 21 through 24. The average fin stress to published strength ratios in the table were obtained from the figures (the test data lines are drawn parallel to the published line unless the tests showed a definite trend otherwise). The average strength ratios were 0.08, 0.11, 0.22 and 0.4 for Waspaloy, Inconel 718, Inconel 625, and Hastelloy X, respectively. These ratios are consistently less than the burst strength ratios, indicating that panel rupture capability must be evaluated for high temperature design since the burst strength does not correlate to creep strength in the plate-fin structure.

The reduced capability of the plate-fin structures in creep rupture, compared to burst, is attributed to possible differences in the effects of processing on creep strength and failure mechanism and to increased sensitivity of the structures to minor fin imperfections. In creep, the loadings are within the elastic range of the material; consequently, relatively large stress increases accompany fin deformations required to accommodate any minor imperfections. By contrast, loadings in the burst tests are in the plastic range and relatively small stress increases accompany the deformations. Because creep life is a strong function of stress level, the initial high stress level resulting from imperfection will cause much more damage to the highly loaded fins than to the adjacent fins. Since the damage is accumulative, it cannot be recovered through subsequent creep relaxation. Furthermore, material plastic deformations due to creep tend to be less than tensile elongations at fracture, lowering the relative capability for redistribution in the creep case.

Waspaloy and Inconel 718: The trends noted in the burst tests with Waspaloy and Inconel 718 were duplicated in the creep testing. Waspaloy panels showed somewhat greater strength when brazed in vacuum and Palniro I gave better results than Palniro 7. It was noted that Waspaloy grain size was slightly larger when Palniro 7 was brazed in vacuum rather than in hydrogen, probably because of the slower heating and cooling rates of the vacuum environment. Since larger grains tend to increase the stress-rupture properties of Waspaloy, the results on figure 21 are consistent with, and may be at least partly attributed to this effect. Inconel 718 brazed with Palniro 7 was stronger after hydrogen brazing and the increased hold time in hydrogen improved strength.

Inconel 625: In the 1600° F (1140° K) Inconel 625 tests, the Palniro 1 alloy brazed for 1200 s gave the highest creep strength. The shorter hold time resulted in an 18 percent lower strength, a reversal of the trend exhibited in burst tests. The Palniro 7 alloy showed a 21 percent lower strength than Palniro 1, consistent with the burst tests. In single point tests at 1400° F (1030° K) the trends noted for the 1600° F (1140° K) creep tests are duplicated as shown by the rupture times at a 10 ksi (69 MN/m^2) fin stress level.

Hastelloy X: The Hastelloy X specimens failed in the fin at higher stress ratios than the other alloys. Furthermore, the absolute strength of Hastelloy X exceeded that of Inconel 625 as shown by the comparison in figure 24. The use of the highest melting point alloy, Palniro 4 for the majority of the Hastelloy X tests is a possible explanation for the improved performance; however, limited tests with Palniro 1 and Hastelloy X did not result in significant loss in rupture strength (the use of slightly increased braze alloy thickness may contribute to the comparatively good performance of Palniro 1 compared to Palniro 4). The Hastelloy X creep results showed about a 50 percent lower strength ratio than the burst results and, in general, showed less variation between tests than the burst tests, although some of the same effects can be noted. The closer spaced fins had improved strength with the exception of the 0.036 in. (0.091 cm) spacing case which did not form as square a fin. As for the burst case, increased hold time decreased strength, and decreased fin thickness increased the percentage of the parent metal strength attained.

Alloy system selection. - The tests indicate that the Palniro 1 alloy gives the strongest Waspaloy panels for internal pressure containment based on both creep rupture (figure 21) and burst strength (table 7). Palniro 1 was therefore selected for the flexure tests. Containment strength was a small fraction of theoretical capability, however, internal pressure containment is of secondary importance in single-layer panels primarily because of the relative insensitivity of panel weight to fin strength.

The burst and creep rupture tests of Inconel 718 chevron fins (table 7 and figure 22) showed that Palniro 7 gave the strongest joints and this alloy was selected for the flexure tests. Also, the longer hold times resulted in highest properties based on both the stress rupture and burst tests.

Comparison of the two, double-layer heat exchanger materials, Inconel 625 and Hastelloy X, at 1600° F (1140° K) shows the latter to be stronger, particularly in creep tests. Based on rupture strength (figure 24) and burst capabilities (for the same fin geometry, the mean burst pressure was 1880 to 2480 psi (13,000 to 17,000 kN/m^2) for Inconel 625 and 1880 to 2690 psi (13,000 and 18,500 kN/M^2) for Hastelloy X) Hastelloy X would be the preferred heat exchanger material; however, in all cases, important specimen differences must be considered which preclude a direct comparison of the two materials. In the Hastelloy X panels, both the Palniro 4 braze alloy and the increased foil thickness would probably contribute to increased fin strength. In addition, the Hastelloy X face sheet thickness was 0.015 in. (0.038 cm) compared to

Results and Discussion

The test results, summarized in table 10, show that the measured panel stiffnesses, yield strengths, and buckling strengths compared favorably with theoretical estimates based on published property data. Load-deflection curves taken at center span, are shown for each specimen in figures 29 and 30. These curves provide the basic data for determining panel stiffness and yield strength following data reduction procedures outlined in appendix B. Ratios between the tested and estimated strengths are also presented in table 10 for the applicable design criteria, yield strength for Waspaloy and test buckling vs theoretical yield for Inconel 718. These strength comparisons are important for panel weight estimates since, as shown in figure 31, variations in panel strength for external pressure loading can appreciably effect reference 1 estimates. The tabulated values from 0.91 to greater than 1.0 for the two panels indicate that the reference 1 weight estimates are realistic.

Pure bending tests. - Measured yield strength of the Waspaloy panels exceeded theoretical estimates by about 40 percent at room temperature and 20 percent at 1400°F (1030°K). The difference between measured and estimated strength can be attributed to several factors; deviations from elastic bending theory, biaxial stresses due to the restraint of free bowing across the panel width, variations from published yield values, and deviations from nominal dimensions used for the estimates of section moment of inertia. As shown in appendix B, elastic bending theory underestimates the panel yield moment by about 8 percent at the 0.1 percent offset engineering yield point and, assuming 50 percent restraint in pure bending, uniaxial stress theory underestimates yielding by about 7 percent. In addition, comparison of published and test yield values in figure 4 indicates that Waspaloy yield properties in the as-received and double-aged condition were 10 percent greater than the value from reference 2. These combined effects reduce the room temperature descrepancy to about 10 percent, well within geometry variations particularly since the braze foil itself could increase section moment of inertia by 10 percent (appendix B). Application of the same corrections to the elevated temperature case would indicate that test values are lower than estimates, probably due to creep deformation.

Visual observations of the room temperature Waspaloy tests showed that unsymmetrical bending was beginning in the 0.1 percent plastic strain region. Post-test photographs of the room and elevated temperature specimens in figure 32 verify the unsymmetrical permanent deformations. This non-circular deformation was attributed to roller friction which developed axial loads sufficient to flatten the central panel region. Because of this, and to provide conservative strength estimates, the 0.1 percent plastic strain point was selected in preference to the general engineering practice of using the 0.2 percent offset.

In addition to the yield properties, the bending stiffness and failure properties of the Waspaloy panel are recorded in table 10. The room temperature bending stiffness exceeded the theoretical estimate although geometry variations could readily account for the difference. However, at elevated temperature, tested stiffnesses were less than the estimate, probably because of creep deformation. This was substantiated by the third sample which was tested at a higher loading rate. The stiffness increased from 488 and 465 lb-in./in.^{2} (86 and 82 kN-m/m^2) to 530 lb-in./in.^{2} (93 kN-m/m^2) and compares more favorably with the calculated estimate of 555 lb-in./in.^{2} (97 kN-m/m^2). The Waspaloy panel failures were fin buckling at room temperature and face sheet creep rupture at 1400°F (1030°K). Both failure types were consistently in the region of smallest curvature near the end reinforcement as shown by the overall failed samples in figure 32 and by closeups in figure 33. Since failure occurred subsequent to yielding in all cases, the design objective was satisfied.

Inconel 718 panel buckling strength exceeded estimated room temperature yield strength and achieved 91 percent of the 1200°F (920°K) theoretical yield. The variation within a sample was relatively small, a maximum of about 10 percent, considering the nature of the buckling phenomena. The biaxial effect due to bowing restraint and the effect of geometry variations would be adequate to explain the higher room temperature value. The other two effects mentioned for Waspaloy are of lesser importance because departure from elastic bending theory is minimal when face sheet thickness is much less than web height and significant material property variations did not occur between tensile tests and published data in figure 6. The lower value in the 1200°F (920°K) test was attributed to creep deformation which reduces buckling strength. Also, predicted panel strengths based on the published 0.2 percent yield strength would be expected to slightly overestimate actual strength since buckling calculations (appendix B) predict failure at 0.1 percent offset (As shown by the load-deflection curves in figure 30, the 0.1 percent offset was reached in the room temperature tests whereas at high temperature there was only a slight departure from the elastic line). It should be noted that these test results verify two important design aspects for this panel configuration; (1) panel strength based on buckling at engineering yield is a reasonable measure of ultimate load capability and (2) the fabrication process is consistent and repeatable.

The design buckling mode of the Inconel 718 panels is simultaneous collapse of the face sheet and webs on the compression side although in the fabricated panel the optimum balance was not achieved and the web was expected to initiate failure. Web buckling may have initiated failure, however, the apparent buckling mode was column failure of the compression sheet. Failure occurred over a notch placed in the chevron fins for fabrication purposes, and the buckle (figures 32 and 33) followed the notches in a straight line across the width of the panel. Room temperature web buckling strain was estimated to be 0.6 percent assuming the face sheets are stronger than the webs due to the reinforcement effect of the chevron fin tabs (appendix B). Column buckling calculations for the unsupported region of the face sheets indicate than an unsupported sheet span of 0.12 in. (0.31 cm) would also produce buckling at about the 0.6 percent strain value. Failed specimens were measured and the length of buckled sheet is from 0.10 to 0.12 in. (0.25 to 0.31 cm), agreeing with the required unsupported length and indicating why sheet column failure may have preceded web buckling. Panel strength might have been slightly improved if the desired failure mode had occurred, however, the potential improvement would be small since the panels had reached the plastic region where buckling strength decreases rapidly.

The agreement between measured and calculated stiffnesses presented in table 10 is reasonably close for the Inconel 718 panels and the test values tend to exceed calculated estimates. This is attributed to variations from the nominal dimensions used for the estimates and to possible braze alloy contributions to face sheet thickness. Non-linearities, recorded in the initial load range, particularly at elevated temperatures, were attributed to warping of the test fixture and Instron machine flexibility. This portion of the curve was deleted in computing the slope for the Inconel 718 pure bending test at 1200°F (920°K).

Combined shear and bending tests.- Waspaloy panel yield strength exceeded theoretical estimates by about 50 percent and also exceeded the pure bending test yield, contrary to theory which indicates that a 1 percent reduction should occur (appendix B). The overall discrepancy may be attributed to the same factors discussed above for Waspaloy. In addition, the apparent contradiction can be explained by assigning full biaxial restraint for the combined loading case (up to 15 percent stress variation for full restraint compared to assumed 7 percent for pure bending) due to the solid bars adjacent to the high stress region.

The Inconel 718 combined shear and bending specimens buckled prior to reaching the 0.1 percent offset point, however some plastic deformation was evident (figure 30). The mode of failure was identical to the pure bending case. A comparison of pure bending and combined loading buckling strengths indicates about a 5 percent reduction for the latter, consistent with a theoretical stress increase of about 5 percent for the combined loading (appendix B).

Panel stiffnesses under combined loadings agreed closely with predicted values for both Waspaloy and Inconel 718. With external reinforcements, both panel types were from 7 to 10 percent less than estimates contrary to pure bending room temperature results which gave tests results exceeding estimates. The internally reinforced Waspaloy specimen average stiffness was practically the same as the estimate. The minor variations in stiffness were attributed to variations in geometry and braze alloy contribution and are not considered to be significant.

CONCLUDING REMARKS

A comprehensive experimental evaluation of sheet and sandwich panel specimen has been performed to select material systems and fabrication techniques and to provide design data for regeneratively cooled panels. Specimen configurations, testing conditions, and superalloy parent metal choices were based on a previous analytical study of hydrogen-cooled panels reported in reference 1. The braze joining process was evaluated for several candidate braze alloys, which collectively provide manufacturing flexibility for the desired parent metals. The study included sheet alloy tensile tests, metallographic joint evaluation, and burst, creep rupture, and flexure tests of sandwich panel specimens.

Room and elevated temperature tensile tests of Waspaloy, Inconel 718, and Inconel 625 sheet alloys, subjected to heating cycles typical of expected brazing conditions, showed that the strength properties were comparable to published values. However, the simulated braze processes tended to reduce sheet alloy ductility properties particularly for Waspaloy and Inconel 625 specimens at elevated temperatures. Inconel 625 tensile specimens coated with braze alloy exhibited similar properties in comparison to published property data.

Photomicrographs of brazed specimens indicated that joining quality was acceptable for all alloy combinations, although the Nioro alloy formed some recessed fillets with the Inconel 718 chevron fins. Minimal differences were noted for various brazing times and hydrogen and vacuum atmospheres. The behavior of the gold-based alloys was more consistent than the Nicrobraz 65 powder and it was concluded that improved brazing techniques would be required to procedure satisfactory Nicrobraz 65 joints. The superalloys metals formed adequate fin shapes for brazing, however, Inconel 625 offset fins were not as square as plain rectangular Waspaloy fins. Dead-weight braze load application was suitable for pressures from 1.8 to 12 psi (12 to 83 kN/m^2) based on metallographic examination of brazed samples. An alternate loading method, utilizing an evaucated sheet metal envelope, did not improve brazing characteristics.

Burst pressures of Waspaloy, Inconel 718, Inconel 625, and Hastelloy X single layer panels were about 30 to 90 percent of calculated material capabilities based on published properties. Creep rupture strengths were a smaller fraction of calculated values, about 10 to 50 percent, apparently because of the lower average fin elongation which diminished load redistribution and the lower braze alloy rupture strength. The relatively lower strengths of Waspaloy and Inconel 718 were attributed to their lower ductilities, nickel plating prior to brazing, and in the case of Inconel 718, higher sheet bending stresses.

In addition to measuring coolant containment capability, the single layer burst and creep rupture panels provided material selections for the reference configurations. The designs were based on two cooled-panel configurations, a single-layer sandwich for low heating and loading conditions and a two-layer panel which separates the cooling and structural functions for high heating and loading conditions. Waspaloy brazed with Palniro 1 proved to be the best candidate for the single-layer sandwich. An Inconel 718-Palniro 7 system was selected for the structural portion of the two-layer panel because Palniro 7 gave superior joint strength and good Inconel 718 strength properties. Several braze alloys were satisfactory with either Hastelloy X or Inconel 625 coolant passages in the two-layer sandwich. Hastelloy X would be the preferred heat exchanger material; however, important specimen differences existed precluding a direct comparison.

Flexure tests, consisting of pure bending and combined shear and bending loads, on Waspaloy and Inconel 718 sandwich panels gave 90 to 100 percent of predicted values based on published property data. Waspaloy panel performance in bending and Inconel 718 panel buckling capability satisfied design objectives. Therefore, this lightweight panel construction will have weights comparable to previous estimates.

APPENDIX A

FIN TENSILE STRENGTH

Fin Stress Calculations

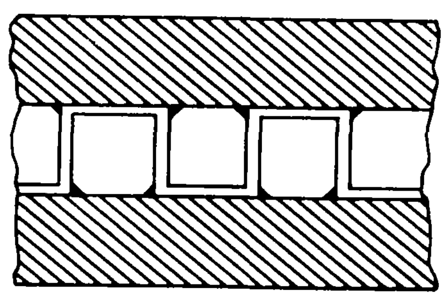
The burst and creep rupture tests conducted in the internal pressure panel tests measured the plate-fin pressure capability for various fin geometeries. For this information to be useful to the designer, a means of correlating tests such as those conducted in the evaluation, with other plate fin geometries is desired. The applied pressure is not a true measure of the severity of the loading on this structure since fin geometry, and, to a lesser extent, face sheet geometry can be widely varied to improve or reduce the plate-fin internal pressure strength. The simplest means of expressing the loading level devised to date is the fin tensile stress, given by

$$\sigma_{fin} = \text{Load/Fin area}$$

$$\sigma_{fin} = P(b_{fin} - t_{fin})/t_{fin}$$

Factors Affecting Fin Strength

The major factors which affect fin strength are fin geometry, plate strength and joint quality. The plate-fin structure capable of achieving 100 percent of theoretical strength (based on the above fin stress equation) includes plates of infinite stiffness and straight, parallel, square-cornered fins with good braze joints (assuming no variation in material properties, no variation in fin thickness, adequate braze strength, etc.), as shown below.



S-45476

Deviations from this ideal structure such as the imperfect fin shown below cause strength reductions. Also, thin plates deviate substantially from the infinite stiffness plates of the ideal structure since they are incapable of transmitting the loads of imperfect fins to all other fins. Rather the load is primarily transmitted to the fins adjacent to the imperfect fin. In this respect, the fin ductility is also important since the elongation before rupture also effects load redistribution. Local deformations of the thin sheets also add bending stresses to the highly loaded adjacent fin. In the thin sheet case it is assumed that complete failure of a single fin results in progressive failure of adjacent fins not only because of load increase but due to the increased bending stresses.

Before pressurization After pressurization

S-45483

An analysis was performed to determine the effect of face sheet thickness on fin strength, assuming the presence of one imperfect fin. The burst pressure of a nine-fin array with weak central fin was determined using a beam-on-an-elastic-foundation model, as shown in figure 34, to simulate a plate on fins. Fin strength, stiffness, and ductility were taken into account by using the complete stress-strain curve for room and elevated temperatures. The calculations were performed for Waspaloy and Inconel 625 at room and elevated temperatures using sheet thicknesses of 0.005, 0.010, and 0.020 in. (0.013, 0.025, and 0.051 cm) and one fin geometry with 0.004 in. (0.010 cm) fin thickness, 0.050 in. (0.130 cm) spacing and a 0.075 in. (0.190 cm) fin height. The weaker-fin failure was simulated by using 100 percent, 50 percent, and zero tensile ultimate strength values (In the zero strength case, failure of the adjacent fins denotes burst pressure).

The fin strength results are tabulated as ratios of a perfect fin array in figure 35. Values as low as 56 percent are predicted for a zero strength fin using the smallest sheet thickness. As expected, increasing sheet thickness increases strength due to the increased capability of the sheet to transfer the load to the stronger fins. Also, the generally lower Waspaloy values, as compared to Inconel 625, are expected since less load redistribution is possible before fin rupture occurs for the lower ductility material, particularly at elevated temperatures. Strength losses are greater for a reduction in weak fin strength from 50 to 0 percent as compared to a reduction from 100 to 50 percent. This indicates that fin strength is a non-linear function of weak fin capability and slightly weaker fins will not appreciably reduce plate-fin internal pressure capability.

The zero strength results compared favorably with the test results although the lower test values, down to 0.28 for Waspaloy, are considerably less than the calculated value of 0.56 (for the Waspaloy zero percent weak fin case). The 1600^{0}F (1140^{0}K) test results for Inconel 625 compare more closely with the analysis giving a test range from 0.54 to 0.71 and analytical values from 0.65 to 0.80 in the zero strength case. These disparities could be partially attributed to strength reduction caused by additional stresses at the plate-to-fin joint due to face sheet bending.

It appears from a practical fabrication standpoint that theoretical maximum fin strength values could be established on the premise that at least one fin in the array is always weaker than the other fins. This premise is probably realistic since minor fin height variations, due to either fabrication or brazing, would produce the uneven loading which was simulated.

APPENDIX B

FLEXURE TEST CALCULATION PROCEDURES

The supporting calculations for the pure bending and combined shear and bending tests are presented in this appendix. The data reduction procedures are provided for converting the measured load-deflection curves in figures 29 and 30 to panel stiffness, yielding moment and buckling moment. Calculated panel properties used for comparison with the measured values are discussed.

Data Reduction

The slopes of the measured load-deflection curves (table 10) were obtained by a least-squares-fit of a straight line to the data in the elastic region (which was determined visually). This slope, or stiffness value, was then adjusted for changes in moment and deflection due to the finite size of the rollers, changes in moment due to rotation at the ends of the panel, and the stiffness effect of the Instron machine. The yield and buckling moments (table 10) also required corrections due to roller size and panel end rotation.

The various corrections were expressed as functions of the center span deflection of the panels. The test corrections for stiffness and bending moment were computed from measured deflections assuming that the relation between angle of rotation at the rollers and center span deflection satisfied beam theory.

In order for the test values to be valid, the panel deflected shape must conform to bending theory throughout the load cycle (figures 29 and 30). This condition was satisfied in the elastic range for all specimens, however in the Waspaloy pure bending tests there was some distortion from the theoretical circular shape above the proportional limit. This distortion was caused by sliding friction at the rollers, especially at the higher loads when larger deflections were required to maintain the circular shape. Typical deflected shapes for Waspaloy tests at room temperature are illustrated in figure 36. Figure 36a shows pure bending deflections at three load levels. The departure from circularity is noticeable at the 550 lb (2450 N) load level. Comparison of this load level with the first load deflection curve in figure 29a shows that this corresponds roughly to an 0.1 percent offset plastic strain. The panel retains a symmetrical deflected shape in the combined shear and bending test as shown by measured data points in figure 36b.

The following is a summary of the corrections applied to the measured properties (figures 29 and 30) to obtain the test values shown in table 10.

Pure bending, room temperature; $\theta = \delta_m$

$$\left(\frac{M}{\delta}\right) = \frac{1}{4}\left(\frac{P}{\delta}\right)_m \left(\frac{1}{\cos\theta}\right)\left(\frac{2\ell_0 - (3R + 2h)\sin\theta}{2\ell_0\cos\theta}\right)\left(\frac{2\theta}{2\theta + (R+h)(1-\cos\theta)}\right)$$

$$M = \frac{P_m}{4}\left(\frac{1}{\cos\theta}\right)\left(\frac{2\ell_0 - (3R + 2h)\sin\theta}{2\cos\theta}\right)$$

Pure bending, elevated temperature; $\theta = \delta_m$

$$\left(\frac{M}{\delta}\right) = \frac{1}{4}\left(\frac{P}{\delta}\right)_m \left(\frac{1}{\cos\theta}\right)\left(\frac{2\ell_0 - (3R + 2h)\sin\theta}{2\ell_0\cos\theta}\right)\left(\frac{2\theta}{2\theta + (R+h)(1-\cos\theta)}\right) \times$$

$$\times\left(\frac{K_I}{K_I - (P/\delta)_m}\right)$$

$$M = \frac{P_m}{4}\left(\frac{1}{\cos\theta}\right)\left(\frac{2\ell_0 - (3R + 2h)\sin\theta}{2\ell\cos\theta}\right)$$

Combined shear and bending; $\theta = 0.75\delta_m$

$$\frac{P}{\delta} = \frac{1}{2}\left(\frac{P}{\delta}\right)_m\left(\frac{1.33\theta}{1.33\theta - (R + h/2)(1-\cos\theta)}\right)$$

$$M = P_m\left(\frac{\ell - b - (2R + h)\sin\theta}{8}\right)$$

<u>Bending moment corrections</u>. - In pure bending tests, the load for calculating applied moment must be normal to the panel surface. The relation between applied load and normal load for an end rotation of θ degrees is

Normal load = (Applied load)/cos θ

The angle of rotation is equal to the center panel deflection for a 4 in (10 cm) long panel in pure bending. The center deflection was obtained from linear transducers at room temperature and Instron crosshead movement at elevated temperatures. This estimate ignores secondary effects such as deflection of the solid overhanging sections on either end. The increase in moment for Waspaloy was from 1 to 2 percent for this correction. An increase of 0.05 to 0.3 percent resulted for Inconel 718.

The moment arm varies during loading since the rollers and knife edge are fixed. This is illustrated in figure 26 for the two-roller end of the pure bending setup. In the pure bending tests, the moment arm at the two-roller end is

$$\ell_1 = \left[\ell_0 - (2R + h) \sin\theta\right] / \cos\theta$$

where ℓ_0 is the initial center-to-center roller spacing and R is the roller radius. At the single roller end the moment arm is

$$\ell_2 = \left[\ell_0 - (R + h) \sin\theta\right] / \cos\theta$$

The correction for pure bending was taken to be the average of ℓ_1 and ℓ_2. The correction factor to be multiplied by measured load was

$$\left[2\ell_0 - (3R + 2h) \sin\theta\right] / 2\ell_0 \cos\theta$$

The adjustment for Waspaloy represented a decrease of about 6 percent at room temperature and 2 to 4 percent at elevated temperature. The Inconel 718 moments decreased by 3 to 5 percent.

The moment arm for combined shear and bending is obtained from the measured load and moment arm by the relation (A sample width of 2 in (5 cm) was used)

$$M = P\left[\ell - b - (2R + h) \sin\theta\right] / 8$$

where the roller separation, ℓ, is 4 in (10 cm) and b is the width of the central reinforcement (figure 26). The angle of rotation at the rollers is three-fourths of the center deflection based on elastic bending theory. The effect of rotation produced a change in moment of about 1 to 5 percent for Waspaloy and 0.6 percent for Inconel 718.

Deflection corrections. - The vertical reference point for deflection measurements shifts due to panel movement over the rollers. In the pure bending case the deflection at the two-roller end is

$$\delta_1 = (R + h/2)(1 - \cos\theta)$$

The movement at the knife edge is

$$\delta_2 = (h/2)(1 - \cos\theta)$$

The average correction for the two ends is

$$\delta_r = (\delta_1 + \delta_2)/2 = (R + h)(1 - \cos\theta)/2$$

The movement over the rollers reduces the measured deflection so the true deflection at the center is

$$\delta = \delta_m + \delta_r$$

and the correction factor to the stiffness in terms of the angle of rotation, which is equal to the center deflection, is

$$\delta_m/\delta = 2\theta/\left[2\theta + (R + h)\ (1 - \cos\theta)\right]$$

This deflection adjustment reduces the measured Waspaloy and Inconel 718 panel stiffnesses by about 1 percent.

There are rollers at each end in the combined shear and bending tests so the correction is

$$\delta_r = \delta_1 = (R + h/2)(1 - \cos\theta)$$

The movement over the rollers is in the same direction as panel movement so the correction subtracts from the measured value. The angular rotation is related to center deflection by

$$\delta = \theta\ell/3 = 1.33\theta$$

so the correction to the stiffness is

$$\delta_m/\delta = 1.33\theta/\left[1.33\theta - (R + h/2)\ (1 - \cos\theta)\right]$$

The Waspaloy and Inconel 718 panel stiffnesses are increased by about 1 percent and 0.5 percent, respectively, due to this correction.

Instron flexibility correction. - The room temperature deflection measuring system was independent of the Instron machine motion. However, in the high temperature pure bending tests the Instron machine provides the most convenient deflection readout because the furnace encloses the specimen. The measured slopes therefore include panel, Instron stiffness and test fixture (figure 28), measured in series. The true panel stiffness is therefore

$$\frac{1}{K} = \left[\frac{1}{(P/\delta)_m} - \frac{1}{K_I}\right]$$

where K_I is the combined Instron and fixture stiffness. The correction factor relating panel stiffness to measured stiffness is therefore

$$K_I/\left[K_I - (P/\delta)_m\right]$$

The stiffness of the Instron machine and test fixture was measured in a separate load-deflection test. The fixturing curves exhibited non-linearities in the 0 to 400 lb (1780 N) load range which correspond to non-linearities noted in the Inconel 718 tests. This effect is attributed primarily to non-parallel plates on the test fixture. The Waspaloy test loads in the elastic range correspond to the non-linear portion of the curve. Therefore, an average stiffness of 83,000 lb/in (15,000 kN/m) over the 0 to 400 lb (1780 N) range was used for the Waspaloy correction. The elastic portion of the Inconel 718 data was used for stiffness calculations and the measured fixture stiffness for loads greater than 400 lb (1780 N) was 266,000 lb/in (47,000 N/m). The increase in stiffness for these corrections was about 2 percent for Waspaloy and 12 to 13 percent for Inconel 718.

Calculated Panel Properties

The equations for obtaining the calculated panel properties listed in table 10 are presented below. Published material properties were taken from reference 2 using he nominal specimen dimensions in figure 2. Refinements to the calculations of the Waspaloy bending moments are included in the following bending moment discussion. The refinements were not used for the estimates in table 10.

Stiffness. - The panel deflection is obtained from the equations for strain energy in the elastic range. The maximum deflection in pure bending is

$$\delta = \int_0^{\ell/2} \frac{Mxdx}{EI} \qquad (1)$$

and for the combined shear and bending test is

$$\delta = \int_0^{\ell/2} \frac{px^2\,dx}{2EI} = \int_0^{\ell/2} \frac{pdx}{2AG} \qquad (2)$$

The plate effect is included by considering the elastic modulus, E, in the equation to be the material elastic modulus divided by $1 - \upsilon^2$. The expression for section moment of inertia of the solid portions is

$$I_2 = h^3/12$$

The plate-fin section properties are obtained from the idealized rectangular cross-sections assuming the face sheet and fin material are 100 percent effective. The resulting expression for the Waspaloy sandwich is

$$I_1 = \frac{\left(h_{fin} + 2t_f\right)^3}{12} - \frac{\left(b_{fin} - t_{fin}\right)}{24\ b_{fin}}\left[h_{fin}^{\ 3} + (h_{fin} - 2t_{fin})^3\right] \qquad (3)$$

The moment of inertia expression for the Inconel 718 sandwich is similar to the above and includes the contribution of a nominal 0.084 in (0.21 cm) chevron fin tab length but not the effect of the chevron bend angle.

Since the section properties vary along the panel, equations (1) and (2) must be integrated piecewise from edge to center. In addition, the panel lengthening or shortening due to movement over rollers is included in the limits of integration. As an example, the approximate equation for deflection of a panel in pure bending is (all dimensions are in inches):

$$\delta = \int_{0}^{(0.075 + \ell_r)} \frac{Mxdx}{EI_2} + \int_{(0.075 + \ell_r)}^{(2.0 + \ell_r)} \frac{Mxdx}{EI_1}$$

where $\ell_r = (R + h/2) \sin \theta/2$. The panel travel over one roller is halved since one end rests on the knife edge.

To a close approximation we may ignore all terms except the upper limit of the second integral, giving:

$$\delta = \frac{M\ (2 + \ell_r)^2}{2E\ I_1}$$

or

$$(M/\delta) = \frac{2E\ I_1}{(2 + \ell_r)^2}$$

The above derivation assumes that the panel takes a circular deflected shape, consistent with the previous discussions.

Variation in material dimensions will have a noticeable effect on the calculated value of plate-fin section moment of inertia. For fin thickness much less than fin height, equation (3) can be written in the approximate form

$$I = \frac{t_f\ h^2_{fin}}{2} + \frac{t_{fin}\ h^3_{fin}}{12b_{fin}}$$

Since the major contribution to moment of inertia is represented by the first term in this equation, the variation in inertia is roughly proportional to variations in sheet thickness. Typical thickness tolerances for this sheet material are about 10 percent above and below the mean, amounting to about ±0.001 in. (0.0025 cm) for the sheets and ± 0.0005 in. (0.0013 cm) for the fins or webs. Typical braze alloy thickness are in this same range.

Yield strength. - The panel yield strength estimates in table 10 are based on elastic bending theory. The governing equation for maximum principle stress, σ, in a stress field with one shear component is

$$\sigma = \sigma_1/2 + \sqrt{(\sigma_1/2)^2 + \tau^2} \tag{4}$$

This equation can be used for both loading conditions since $\tau = 0$ gives $\sigma = \sigma_1$. Equating σ_1 to the maximum elastic bending stress we have

$$\sigma_1 = Mh/2I$$

The maximum shear stress for a centrally loaded panel is approximately

$$\tau = pb_f/2ht_c$$

This may be rewritten in terms of the applied moment and moment arm, $\ell/2$, to give

$$\tau = (2b_f/\ell ht_c)\ M$$

The principle stress, σ, in equation (4) is then equated to publish engineering yield properties and the yielding moment can be calculated from

$$M_y = \sigma_y / \left[h/4I + \sqrt{\left(\frac{h}{4I}\right)^2 + \left(\frac{2b_f}{\ell ht_c}\right)^2} \right]$$

In the pure bending case the above equation simplifies to

$$M_y = 2\sigma_y\ I/h \tag{5}$$

The above expression for yielding moment assumes a linear stress distribution across the panel height. However, plastic deformations are present at engineering yield and the stress distribution in the outer fibers becomes nonlinear. This is illustrated in figure 37 by superimposing the Waspaloy room temperature stress-strain curve (figure 5a) on the panel cross-section. The stress at the outer fiber is the 0.1 percent plastic strain offset value from the stress-strain curve. The elastic line for equation (5) is shown for the same maximum stress. The difference between the two curves represents the additional moment that is developed for the actual case as opposed to the moment calculated by equation (5). The following equation,

$$M = \int \sigma_y \, dA$$

was used to compute the bending moment for the inelastic curve. The inelastic result was 123 lb-in/in (548 N-m/m), compared to 114 lb-in/in (507 N-m/m) for the elastic case, an 8 percent increase. This effect is also present for Inconel 718, although to a much lower degree, because the ratio of web height to face sheet thickness is much greater.

In some cases the specimen is held flat during testing and a biaxial stress state is produced. The relation between the developed stress, σ_2 in the width and the applied stress, σ_1, in the length is determined by the boundary condition for the flat surface which is that the total strain in the width must be zero. The two stress components are then related by Poisson's ratio, i.e.,

$$\sigma_2 = \nu\sigma_1$$

In distortion energy theory, the equivalent stress in the biaxial case is:

$$\sigma_{eq} = (\sigma_1{}^2 - \sigma_1 \sigma_2 + \sigma_2{}^2)^{1/2}$$

Substituting for σ_2 we get

$$\sigma_{eq} = \sigma_1 (1 - \nu + \nu^2)^{1/2}$$

The equivalent stress is 87 percent of σ_1 using an average Poisson's ratio of 0.4 since the value must be between about 0.3 for the elastic case and 0.5 for plastic flow. This corresponds to an effective yield stress reduction of 15 percent and a corresponding apparent increase in panel yield strength.

Complete restraint is expected for combined shear and bending tests because the central high stress region was reinforced locally to provide means of applying the load. However, for the pure bending tests, only 7 percent restraint was assumed since the panel was not held completely flat over the rollers.

Inconel 718 panel buckling. - Calculated estimates of the buckling strength of the Inconel 718 panels presented in the flexure test summary (table 10) were obtained by the procedures outlined in reference 1. The critical buckling stresses for the webs and face plates are written in the form

$$\sigma_{cc\ web}\Big] = \eta\, K_2 E\, (t_c/h)^2$$

$$\sigma_{cc\ plate}\Big] = \eta K_1 E\, (t_f/b_f)^2$$

where η is the plasticity reduction factor defined as

$$\eta = (E_t/E)^{1/2}$$

Typical reference 1 calculations were performed with $\eta = 1$, i.e., elastic stresses were considered. However, the tangent modulus, E_t, may be determined when a stress-strain curve is available and the reduction in buckling stress due to yielding may be evaluated. The curve of buckling stress vs applied strain can then be superimposed on the material stress-strain curve to determine the buckling stress of the panel.

Figure 38 shows the web buckling stress and the Inconel 718 room temperature stress-strain curve from figure 7 indicating that buckling will occur at a strain of about 0.6 percent. The web buckling stress defines panel buckling since face sheet buckling occurs at a higher stress level. A web buckling coefficient, K_2, of a 35.5 was used on the assumption that the stronger face sheets will provide a fixed ended condition for the webs. The extreme slope of the buckling stress curve illustrates the rapid loss in strength that accompanies plastic flow

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TABLE I

TENSILE TEST SUMMARY

Parent material	Simulated brazing atmosphere as it affects cooling rate	Brazing temperature, $^\circ F(^\circ K)$	Reference or brazing alloy	Simulated heat treatment	Test objective	Results as compared to standards		
						Tensile strength	Yield strength	Ductility
Waspaloy	Rapid cooling (similar to hydrogen)	1950(1340)	As-received condition	Waspaloy double aging (1)	Standard for comparison	-	-	-
	Vacuum	1950(1340)	Palniro 7	Waspaloy double aging (1)	Effect of slower cooling rate	Slightly lower	Slightly lower	No change
	Hydrogen	1950(1340)	Palniro 7	Waspaloy double aging (1)	Effect of rapid cooling rate	No change	No change	RT - 15% higher, no change at $1400^\circ F(1030^\circ K)$
	Rapid cooling (similar to hydrogen)	1950(1340)	As-received condition	Waspaloy single aging (2)	Effect of different aging cycle	RT - slightly lower, $1400^\circ F(1030^\circ K)$ - no change	RT - slightly lower, $1400^\circ F(1030^\circ K)$ - no change	RT - 25% less, $1400^\circ F(1030^\circ K)$ - 50% less
Inconel 718	Rapid cooling (similar to hydrogen)	1800(1260)	As-received condition	Inconel 718 aging (3)	Standard for comparison	-	-	-
	Vacuum	1950(1340)	Palniro 7	Inconel 718 aging (3)	Effect of temperature higher than solution heat treat temperature	Slightly lower	Slightly lower	Slightly lower
	Vacuum	1800(1260)	Nioro	Inconel 718 aging (3)	Effect of slower cooling rate	No change	Slightly lower	RT - no change, $1200^\circ F(920^\circ K)$ - 25% less
Inconel 625	Rapid cooling (similar to hydrogen)	1800(1310)	As-received condition (Nioro)	None	Standard for comparison	-	-	-
	Rapid cooling (similar to hydrogen)	1800(1310)	As-received condition (Nioro)	Inconel 718 aging (3)	Effect of Inconel 718 aging cycle	15% higher at RT	50% higher at RT	30% less at RT
	Vacuum (slow cooling)	2070(1410)	Palniro 1	None	Effect of higher temperature then normal annealing temperature	RT - slightly lower. $1600^\circ F(1140^\circ K)$ - 15% less	RT - 10% lower. $1600^\circ F(1140^\circ K)$ - no change	RT - No change. $1600^\circ F(1140^\circ K)$ - 50% less
	Vacuum	1950(1340)	Palniro 7	None	Effect of slower cooling rate	No change	No change	No change
	Vacuum	2070(1410)	Coated one side with Palniro 1	None	Effect of brazing alloy on ductility (Palniro 1)	No change at $1600^\circ F(1140^\circ K)$	No change at $1600^\circ F(1140^\circ K)$	40% less at $1600^\circ F(1140^\circ K)$
	Vacuum	1950(1340)	Coated one side with Palniro 7	None	Effect of brazing alloy on ductility (Palniro 7)	No change at $1600^\circ F(1140^\circ K)$	No change at $1600^\circ F(1140^\circ K)$	25% less at $1600^\circ F(1140^\circ K)$
	Vacuum	1800(1260)	Coated one side with Nioro	None	Effect of brazing alloy on ductility (Nioro)	20% higher at $1600^\circ F(1140^\circ K)$	No change at $1600^\circ F(1140^\circ K)$	30% less at $1600^\circ F(1140^\circ K)$

(1) Waspaloy double aging cycle; $1550^\circ F(1120^\circ K)$ for 4hr., air cool. $1400^\circ F(1030^\circ K)$ for 16 hr., air cool.

(2) Waspaloy single aging cycle, $1400^\circ F(1030^\circ K)$ for 16 hr., air cool.

(3) Inconel 718 aging cycle; $1325^\circ F(985^\circ K)$ for 8 hr., furnace cool $100^\circ F(56^\circ K)$/hr. to $1150^\circ F(895^\circ K)$, hold at $1150^\circ F(895^\circ K)$ for 8 hr., air cool.

TABLE 2

WASPALOY TENSILE TEST SUMMARY

a. U.S. CUSTOMARY UNITS

Simulated braze cycle and/or heat treatment	Test temperature, °F	Specimen width, in.	Specimen thickness, in.	Ultimate strength, ksi		Yield strength, ksi		Elongation, percent (2)		Reduction in area, percent	
				Test	Average	Test	Average	Test	Average	Test	Average
As received (mill annealed at 1975°F; rapid cooled) plus aging (3)	Room temperature	0.250	0.0103	195		130		27.5		24	
		.250	.0103	192	193	130	129	21.0	24.2	21	23
		.250	.0103	191		128		24.0		25	
	1400	0.250	0.0103	113		106		6.0		8	
		.250	.0103	112	113	105	105	6.0	6.7	8	8
		.250	.0103	113		105		7.0		8	
As received plus Palniro 7 cycle, vacuum, 1200 sec, and aging (3)		0.250	0.0103	106		103		7.0		8	
		.250	.0103	104	103	101	101	8.5	7.8	10	9
		.250	.0103	100		98		8.0		10	
As received plus Palniro 7 cycle, hydrogen, 1200 sec, and aging (3)	Room temperature	0.250	0.0103	191		125		28.0		24	
		.250	.0103	193	192	127	126	27.0	27.7	24	23
		.250	.0103	192		127		28.0		22	
	1400	0.250	0.0103	114		108		7.0		7	
		.250	.0103	113	114	105	107	7.0	6.8	10	7
		.250	.0103	115		107		6.5		3	
As received plus aging at 1400°F for 16 hr	Room temperature	0.250	0.0103	185		124		19.5		20	
		.250	.0103	182	184	125	124	16.0	18.0	17	19
		.250	.0103	186		124		18.5		19	
	1400	0.250	0.0103	113		104		4.0		3	
		.250	.0103	115	113	106	105	2.5	3.3	4	4
		.250	.0103	113		103		3.5		6	
		.250	.0103	110		105		- (4)		-	
As received plus 1825°F for 2 hr plus aging (3)	1400	0.250	0.0102	110		89		13.0		18	
		.250	.0102	111	110	89	89	15.0	14.7	17	18
		.250	.0102	109		88		16.0		19	
As received plus 1825°F for 2 hr plus aging, (3) longitudinal	1400	0.250	0.0102	114		90		- (4)		-	
		.250	.0102	113	114	90	90	16.5	16.3	19	18
		.250	.0102	114		90		16.0		17	

NOTES: (1) Specimens were tested transverse to the rolling direction, except as noted.

(2) Extensometer readings and elongation were taken on a 1.0 in. gage length.

(3) 1550°F for 4 hr, air cool, 1400°F for 16 hr, air cool.

(4) Specimen failed at gage mark.

TABLE 2. Concluded

WASPALOY TENSILE TEST SUMMARY

b. SI UNITS

Simulated braze cycle and/or heat treatment	Test temperature, °K	Specimen width, cm	Specimen thickness, cm	Ultimate strength, MN/m^2		Yield strength, MN/m^2		Elongation, percent (2)		Reduction in area, percent	
				Test	Average	Test	Average	Test	Average	Test	Average
As received (mill annealed at 1350°K; rapid cooled) plus aging (3)	Room temperature	0.635	0.0262	1340		900		27.5		24	
		.635	.0262	1320	1330	900	890	21.0	24.2	21	23
		.635	.0262	1320		880		24.0		25	
	1030	0.635	0.0262	780		730		6.0		8	
		.635	.0262	770	780	720	720	6.0	6.7	8	8
		.635	.0262	780		720		7.0		8	
As received plus Palniro 7 cycle, vacuum, 1200 s, and aging (3)	1030	0.635	0.0262	730		710		7.0		8	
		.635	.0262	720	710	700	700	8.5	7.8	10	9
		.635	.0262	690		680		8.0		10	
As received plus Palniro 7 cycle, hydrogen, 1200 s, and aging (3)	Room temperature	0.635	0.0262	1320		860		28.0		24	
		.635	.0262	1330	1320	880	870	27.0	27.7	24	23
		.635	.0262	1320		880		28.0		22	
	1030	0.635	0.0262	790		740		7.0		7	
		.635	.0262	780	790	720	730	7.0	6.8	10	7
		.635	.0262	790		740		6.5		3	
As received plus aging at 1030°K for 16 hr	Room temperature	0.635	0.0262	1280		850		19.5		20	
		.635	.0262	1250	1270	860	850	16.0	18.0	17	19
		.635	.0262	1280		850		18.5		19	
	1030	0.635	0.0262	780		720		4.0		3	
		.635	.0262	790	780	730	720	2.5	3.3	4	4
		.635	.0262	780		710		3.5		6	
		.635	.0262	760		720		- (4)		-	
As received plus 1270°K for 2 hr and aging (3)	1030	0.635	0.0259	760		610		13.0		18	
		.635	.0259	770	760	610	610	15.0	14.7	17	18
		.635	.0259	750		610		16.0		19	
As received plus 1270°K for 2 hr and aging (3), longitudinal	1030	0.635	0.0259	790		620		- (4)		-	
		.635	.0259	780	790	620	620	16.5	16.3	19	18
		.635	.0259	790		620		16.0		17	

NOTES: (1) Specimen were tested transverse to the rolling direction, except as noted.

(2) Extensometer readings and elongation were taken on a 2.5 cm gage length.

(3) 1120°K for 4 hr, air cool, 1030°K for 16 hr, air cool.

(4) Specimen failed at gage mark.

TABLE 3

INCONEL 718 TENSILE TEST SUMMARY

a. U.S. CUSTOMARY UNITS

Simulated braze cycle and/or heat treatment	Test temperature, °F	Specimen width, in.	Specimen thickness, in.	Ultimate strength, ksi		Yield strength, ksi		Elongation, percent (2)		Reduction in area, percent	
				Test	Average	Test	Average	Test	Average	Test	Average
As received (mill annealed at 1800°F, 1 hr) and aged (3)	Room temperature	0.251	0.0101	207		176		16.5		20	
		.249	.0101	206	206	175	176	19.0	19.8	22	23
		.247	.0101	206		176		21.0		26	
	1200	0.250	0.0102	167		145		18.0		23	
		.250	.0102	166	167	144	145	16.5	16.5	19	21
		.245	.0102	168		146		15.0		20	
As received plus Palniro 7 cycle, 1200 sec, vacuum, plus aging (3)	Room temperature	0.250	0.0102	192		160		21.0		20	
		.250	.0102	199	197	167	164	18.5	19.7	19	20
		.250	.0102	200		166		19.5		20	
	1200	0.250	0.0102	155	153	136	133	16.0	18.0	16	16
		.250	.0102	151		130		20.0		15	
As received plus Nioro cycle, 1200 sec, vacuum, plus aging (3)	Room temperature	0.250	0.0102	204		167		16.5		16	
		.250	.0102	205	205	171	169	19.5	18.7	22	20
		.250	.0102	206		168		20.0		22	
	1200	0.250	0.0102	166		141		11.0		12	
		.250	.0102	163	164	139	140	13.0	11.7	17	14
		.250	.0102	164		141		11.0		12	

NOTES: (1) Test loads applied transverse to rolling direction.

(2) Extensometer readings and elongation were taken on a 1.0 in. gage length.

(3) Inconel 718 aging: 1325°F for 8 hr, furnace cool 100°F/hr to 1150°F, hold at 1150°F for 8 hr, air cool.

b. SI UNITS

Simulated braze cycle and/or heat treatment	Test temperature, °K	Specimen width, cm	Specimen thickness, cm	Ultimate strength, MN/m^2		Yield strength, MN/m^2		Elongation, percent (2)		Reduction in area, percent	
				Test	Average	Test	Average	Test	Average	Test	Average
As received (mill annealed at 1260°K, 1 hr) and aged (3)	Room temperature	0.638	0.0257	1430		1210		16.5		20	
		.632	.0257	1420	1420	1210	1210	19.0	19.8	22	23
		.627	.0257	1420		1210		21.0		26	
	920	0.635	0.0259	1150		1000		18.0		23	
		.635	.0259	1140	1150	990	1000	16.5	16.5	19	21
		.635	.0259	1160		1010		15.0		20	
As received plus Palniro 7 cycle, 1200 s, vacuum, plus aging (3)	Room temperature	0.635	0.0259	1320		1100		21.0		20	
		.635	.0259	1370	1360	1150	1130	18.5	19.7	19	20
		.635	.0259	1380		1140		19.5		20	
	920	0.635	0.0259	1070	1050	940	920	16.0	18.0	16	16
		.635	.0259	1040		900		20.0		15	
As received plus Nioro cycle, 1200 s, vacuum, plus aging (3)	Room temperature	0.635	0.0259	1410		1150		16.5		16	
		.635	.0259	1410	1410	1180	1160	19.5	18.7	22	20
		.635	.0259	1420		1160		20.0		22	
	920	0.635	0.0259	1140		970		11.0		12	
		.635	.0259	1120	1130	960	970	13.0	11.7	17	14
		.635	.0259	1130		970		11.0		12	

NOTES: (1) Test loads applied transverse to rolling direction.

(2) Extensometer readings and elongation were taken on a 2.5 cm gage length.

(3) Inconel 718 aging: 985°K for 8 hr, furnace cool 55°K/hr to 895°K, hold at 895°K for 8 hr, air cool.

TABLE 5

SPECIMEN BRAZING CONDITIONS

Parent material	Braze alloy	Braze atmosphere	Braze temperature, $^{0}F(^{0}K)$	Braze time, s
Waspaloy	Palniro 7	Vacuum	1950(1340)	300
	Palniro 7	Vacuum		1200
	Palniro 7	Hydrogen		300
	Palniro 7	Hydrogen		1200
	Nicrobraz 65	Hydrogen		300
	Nicrobraz 65	Hydrogen		1200
Inconel 718	Palniro 7	Vacuum	1950(1340)	300
	Palniro 7	Vacuum		1200
	Palniro 7	Hydrogen		300
	Palniro 7	Hydrogen		1200
	Nioro	Vacuum	1800(1260)	300
	Nioro	Vacuum		1200
	Nioro	Hydrogen		300
	Nioro	Hydrogen		1200
Inconel 625	Palniro 1	Vacuum	2070(1410)	300
	Palniro 1	Vacuum		1200
	Palniro 1	Hydrogen		300
	Palniro 1	Hydrogen		1200
	Palniro 7	Vacuum	1950(1340)	300
	Palniro 7	Vacuum		1200
	Palniro 7	Hydrogen		300
	Palniro 7	Hydrogen		1200
	Nioro	Vacuum	1800(1260)	300
	Nioro	Vacuum		1200
	Nioro	Hydrogen		300
	Nioro	Hydrogen		1200

TABLE 6

BURST AND CREEP RUPTURE TEST SCHEDULE

	Brazing conditions			Post braze heat treatment*	Test temperature, $^{o}F(^{o}K)$	Tests	
Material	Alloy	Atmosphere	Time, s			Burst	Creep rupture
Waspaloy	Palniro 7	Vacuum	1200	Waspaloy	1400(1030)	Yes	Yes
	Palniro 7	Hydrogen					
	Nicrobraz 65	Hydrogen					
	Palniro 1	Vacuum					
Inconel 718	Palniro 7	Vacuum	1200	Inconel 718	1200(920)	Yes	Yes
	Palniro 7	Hydrogen	1200			Yes	Yes
	Palniro 7	Hydrogen	300			Yes	Yes
	Nioro	Vacuum	1200			Yes	No
Inconel 625 sheet, Inconel 625 fins, Inconel 718 sheet	Palniro 7	Vacuum	1200	Inconel 718	1200(920)	Yes	No
	Nioro						
Inconel 625	Palniro 7	Vacuum	1200	Inconel 718	1600(1140)	Yes	Yes
	Palniro 1		1200				
	Palniro 1		300				
Hastelloy X	Palniro 1	Vacuum	300	None	1600(1140)	No	Yes
	Palniro 4		300		RT	Yes	No
	Palniro 4		300		1200(920)	Yes	No
	Palniro 4		300		1500(1090)	Yes	Yes
	Palniro 4		300		1600(1140)	Yes	Yes
	Palniro 4		600		1600(1140)	Yes	Yes
	Palniro 4		1200		1500(1090)	Yes	No
	Palniro 4		1200		1600(1140)	Yes	Yes

*Waspaloy heat treatment: $1550^{o}F$ ($1120^{o}K$) for 4 hr, air cooled plus $1400^{o}F$ ($1030^{o}K$) for 16 hr, air cooled.

Inconel 718 heat treatment: $1325^{o}F$ ($990^{o}K$) for 8 hr, furnace cooled at $100^{o}F$ per hr ($56^{o}K$ per hr) to $1150^{o}F$ ($890^{o}K$), held at $1150^{o}F$ ($890^{o}K$) for 8 hr, air cooled.

TABLE 7

BURST TEST SUMMARY

a. WASPALOY, INCONEL 718 AND INCONEL 625

Material and test temperature	Brazing conditions	Test burst pressure, psi (kN/m^2)	Average burst pressure, psi (kN/m^2)	Average fin tensile stress at burst, (1) ksi (MN/m^2)	Average fin stress divided by ultimate stress (2)	Predominant failure location
Waspaloy, 1400°F(1030°K)	Palniro 7, vacuum, 1200 s	2110(14 500)				Brazing alloy
		1900(13 100)	2330(16 100)	36.7(253)	0.32	
		2990(20 600)				
	Palniro 7, hydrogen, 1200 s	2100(14 500)				
		2020(13 900)	2060(14 200)	32.4(223)	0.28	
		2050(14 100)				
	Palniro 1, vacuum 1200 s	2660(18 300)				
		2550(17 600)	2490(17 200)	39.1(270)	0.34	
		2260(15 600)				
Inconel 718, 1200°F(920°K)	Palniro 7, vacuum, 1200 s	1770(12 200)				Brazing alloy
		2310(15 900)	1990(13 700)	64.6(445)	0.43	
		1900(13 100)				
	Nioro, vacuum, 1200 s	600(4140)				
		410(2830)	490(3380)	15.9(110)	0.11	
		470(3240)				
	Palniro 7, hydrogen, 1200 s	2180(15 000)				
		2040(14 100)	2100(14 500)	67.9(468)	0.45	
		2080(14 300)				
	Palniro 7 hydrogen, 300 s	1380(9520)				
		1320(9100)	1380(9250)	44.7(308)	0.30	
		1450(10 000)				
Inconel 625, Inconel 718, 1200°F(920°K)	Palniro 7, vacuum, 1200 s	5280(36 400)				Fins
		4980(34 300)	5280(36 400)	60.8(419)	0.53	
		5580(38 500)				
	Nioro, vacuum, 1200 s	4330(29 900)				
		4520(31 200)	4480(30 900)	51.6(356)	0.46	
		4600(31 700)				
Inconel 625, 1600°F(1140°K)	Palniro 7, vacuum, 1200 s	1550(10 700)				Brazing alloy
		2300(15 900)	1880(13 000)	21.7(150)	0.54	
		1800(12 400)				
	Palniro 1, vacuum, 1200 s	2150(14 800)				Brazing alloy
		2920(20 100)	2320(16 000)	26.8(185)	0.67	Fins
		1900(13 000)				Brazing alloy
	Palniro 1, vacuum, 300 s	2200(15 200)				Fins
		2700(18 600)	2480(17 100)	28.6(197)	0.71	
		2550(17 600)				

NOTES: (1) Fin stress = (pressure load at burst)/(fin tensile area).

(2) Published ultimate stress values for the Waspaloy, Inconel 718 and Inconel 625 fins are quoted in figures 4, 6 and 8, respectively. Hastelloy X published ultimate stress values were taken from reference 4.

TABLE 7. Concluded

BURST TEST SUMMARY

b. HASTELLOY X

Fin dimensions, (3) in. (cm)			Time at braze temperature, (4) s	Palniro 4 braze foil thickness, in. (cm)	Test temperature, °F(°K)	Test burst pressure psi (kN/m^2)	Average burst pressure, (5) psi (kN/m^2)	Average fin tensile stress at burst, (1) ksi (MN/m^2)	Average fin stress divided by ultimate stress (2)
b_{fin}	h_{fin}	t_{fin}							
0.063 (0.159)	0.153 (0.390)	0.006 (0.015)	300	0.001(0.0025)	1600(1140)	2130(14 700)	2130(14 700)	20.2(139)	0.548
			1200	0.001(0.0025)	1600(1140)	1610(11 100)			
						1700(11 700)	1660(11 400)	15.8(109)	0.427
						1680(11 600)			
			600	0.001(0.0025)	1600(1140)	1480(10 200)			
						1580(10 900)	1530(10 500)	14.5(100)	0.391
						1530(10 500)			
			300	0.001(0.0025)	1200(920)	3600(24 800)			
						3600(24 800)	3650(25 200)	34.7(239)	0.413
						3750(25 900)			
			300	0.001(0.0025)	Room temperature	7400(51 000)			
							7350(50 700)	69.8(481)	0.605
						7300(50 300)			
0.050 (0.127)	0.050 (0.127)	0.006 (0.015)	300	0.001(0.0025)	1600(1140)	2750(19 000)			
							2790(19 200)	20.5(141)	0.571
						2830(19 500)			
0.050 (0.127)	0.075 (0.191)	0.004 (0.010)	300	0.001(0.0025)	1600(1140)	2680(18 500)			
						2380(16 400)	2690(18 500)	30.9(213)	0.847
						3020(20 800)			
			1200	0.001(0.0025)	1600(1140)	2080(14 300)			
							1880(13 000)	21.6(149)	0.592
						1680(11 500)			
0.029 (0.074)	0.025 (0.064)	0.002 (0.005)	300	0.001(0.0025)	1500(1090)	3650(25 200)	3450(23 800)	46.6(321)	0.909
						3250(22 400)			
			1200	0.001(0.0025)	1500(1090)	2130(14 700)	2130(14 700)	28.8(199)	0.561
			1200	0.0005(0.0013)	1500(1090)	1400(9700)	1400(9700)	18.4(130)	0.370
			300	0.0005(0.0013)	1500(1090)	2580(17 800)			
							2530(17 400)	34.2(236)	0.677
						2480(17 100)			
			300	0.0005(0.0013)	1600(1140)	1980(13 700)			
							2240(15 400)	30.2(208)	0.841
						2500(17 200)			

NOTES: (1) Fin stress = (pressure load at burst)/(fin tensile area).

(2) Published ultimate stress values for the Waspaloy, Inconel 718 and Inconel 625 fins were taken from figures 4, 6 and 8, respectively. Hastelloy X ultimate stress values were taken from reference 4.

(3) Rectangular offset fin geometry as shown in figure 2b. Face sheet thickness was 0.015 in. (0.038 cm).

(4) The majority of the Hastelloy X specimens were vacuum brazed.

TABLE 8

CREEP RUPTURE TEST SUMMARY

a. WASPALOY, INCONEL 718 AND INCONEL 625

Material and test temperature	Braze conditions	Test pressure, psi (kN/m^2)	Time to rupture, hr	Fin tensile stress, (1) ksi (MN/m^2)	Published rupture stress, (2) ksi (MN/m^2)	Average ratio of fin stress to published stress
Waspaloy, 1400°F(1030°K)	Palniro 7, vacuum, 1200 s	400(2760)	24.3	6.3(43)	74(510)	0.076
		300(2070)	27.7	4.7(32)	73(500)	
		300(2070)	83.2	4.7(32)	62(430)	
		350(2410)	26.7	5.5(38)	74(510)	
		350(2410)	32.0	5.5(38)	72(500)	
		325(2240)	44.5	5.1(35)	67(460)	
	Palniro 7, hydrogen, 1200 s	325(2240)	30.2	5.1(35)	72(500)	0.067
		275(1900)	38.3	4.3(30)	70(480)	
		225(1550)	64.5	3.5(24)	64(440)	
		300(2070)	117.3	4.7(32)	59(410)	
	Palniro 1, vacuum, 1200 s	600(4140)	3.6	9.4(65)	100(690)	0.087
		400(2760)	33.9	6.3(43)	71(490)	
		400(2760)	54.0	6.3(43)	66(460)	
		350(2410)	63.3	5.5(38)	64(440)	
		350(2410)	43.5	5.5(38)	68(470)	
		350(2410)	38.1	5.5(38)	70(480)	
Inconel 718, 1200°F(920°K)	Palniro 7, vacuum, 1200 s	400(2760)	34.0	12.9(89)	115(790)	0.118
		400(2760)	60.2	12.9(89)	110(760)	
		400(2760)	113.0	12.9(89)	104(720)	
	Palniro 7, hydrogen, 1200 s	400(2760)	284.0 (3)	12.9(89)	95(660) (3)	0.128
		400(2760)	89.6	12.9(89)	106(730)	
		500(3450)	8.2	16.2(112)	130(900)	
	Palniro 7, hydrogen, 300 s	400(2760)	12.4	12.9(89)	126(870)	0.097
		400(2760)	8.7	12.9(89)	130(900)	
		300(2070)	69.7	9.7(67)	109(750)	
Inconel 625, 1600°F(1140°K)	Palniro 7, vacuum, 1200 s	520(3590)	1.3	6.0(41)	26(180)	0.207
		260(1790)	35.0	3.0(21)	14(97)	
		390(2690)	7.5	4.5(31)	19(130)	
		175(1210)	128.0	2.0(14)	11(76)	
		175(1210)	82.5	2.0(14)	12(83)	
		220(1520)	81.8	2.5(17)	12(83)	
		870(6000) (4)	12.5	10.0(69)	39(270)	
	Palniro 1, vacuum, 1200 s	390(2690)	39.6	4.5(31)	14(97)	0.251
		260(1790)	37.5	3.0(21)	14(97)	
		220(1520)	82.9	2.5(17)	12(83)	
		260(1790)	54.0	3.0(21)	13(90)	
		390(2690)	14.6	4.5(31)	16(110)	
		870(6000) (4)	18.7	10.0(69)	37(260)	
	Palniro 1, vacuum, 300 s	390(2690)	15.5	4.5(31)	16(110)	0.212
		260(1790)	52.5	3.0(21)	13(90)	
		260(1790)	11.8	3.0(21)	18(120)	
		390(2690)	5.2	4.5(31)	20(140)	
		220(1520)	16.0	2.5(17)	16(110)	
		870(6000) (4)	4.3	10.0(69)	42(290)	

NOTES: (1) Fin stress = (pressure load)/(fin tensile area)

(2) Values obtained from figures 21, 22 and 23 for the test rupture life of Waspaloy, Inconel 718 and Inconel 625, respectively. Hastelloy X values obtained from figure 24 and reference 4 for the test rupture life.

(3) Test discontinued, no rupture occurred. Published rupture stress is based on 284 hr rupture life.

(4) Test at 1400°F(1030°K), not included in average ratio.

(5) Failure occurred in the braze alloy for all panels.

TABLE 8. Concluded

CREEP RUPTURE TEST SUMMARY

b. HASTELLOY X

Fin dimensions, (6) in. (cm) b_{fin}	h_{fin}	t_{fin}	Braze alloy	Time at braze temperature, (7) s	Braze foil thickness, in. (cm)	Test temperature, °F(°K)	Test pressure, psi (kN/m^2)	Time to rupture, hr	Fin tensile stress, (1) ksi (MN/m^2)	Published rupture stress, (2) ksi (MN/m^2)	Average ratio of fin stress to published stress
0.063 (0.159)	0.153 (0.390)	0.006 (0.015)	Palniro 4	1200	0.0010 (0.0025)	1600(1140)	550(3790)	10.8	5.2(36)	14.7(101)	0.342
							700(4830)	2.5	6.6(46)	20.0(138)	
				600	0.0010 (0.0025)	1600(1140)	550(3790)	7.7	5.2(36)	15.8(109)	0.351
							550(3790)	5.3	5.2(36)	17.0(117)	
							550(3790)	26.0(8)	5.2(36)	12.2(84)	
0.050 (0.127)	0.050 (0.127)	0.006 (0.015)	Palniro 4	300	0.0010 (0.0025)	1600(1140)	650(4480)	15.4	4.8(33)	13.8(95)	0.365
							700(4830)	12.6	5.1(35)	14.2(98)	
							750(5170)	11.5	5.5(38)	14.5(100)	
				300	0.0013 (0.0033)	1600(1140)	700(4830)	14.1	5.1(35)	13.9(96)	0.402
							750(5170)	17.2	5.5(38)	13.4(92)	
							800(5520)	15.3	5.9(41)	13.7(94)	
			Palniro 1	300	0.0014 (0.0036)	1600(1140)	800(5520)	11.6	5.9(41)	14.4(99)	0.414
							800(5520)	12.0	5.9(41)	14.3(99)	
							800(5520)	15.6	5.9(41)	13.7(94)	
0.036 (0.091)	0.050 (0.127)	0.006 (0.015)	Palniro 4	300	0.0013 (0.0033)	1600(1140)	950(6550)	18.0	4.8(33)	13.3(92)	0.339
							1000(6890)	13.7	5.0(34)	14.0(97)	
							1050(7240)	10.7	5.3(37)	14.7(101)	
			Palniro 1	300	0.0014 (0.0036)	1600(1140)	1000(6890)	11.3	5.0(34)	14.4(99)	0.336
							1000(6890)	8.8	5.0(34)	15.2(105)	
							1000(6890)	9.3	5.0(34)	15.0(103)	
0.050 (0.127)	0.075 (0.191)	0.004 (0.010)	Palniro 4	300	0.0010 (0.0025)	1600(1140)	780(5380)	3.4	9.0(62)	18.6(128)	0.435
							650(4480)	5.2	7.5(52)	16.9(117)	
							700(4830)	3.5	8.1(56)	18.5(128)	
							600(4140)	8.3	6.9(48)	15.5(107)	
							600(4140)	3.3	6.9(48)	18.8(130)	
				1200	0.0010 (0.0025)	1600(1140)	600(4140)	5.6	6.9(48)	16.9(117)	0.362
							550(3790)	4.4	6.3(43)	17.7(122)	
							550(3790)	2.8	6.3(43)	19.5(134)	
0.029 (0.074)	0.025 (0.064)	0.002 (0.005)	Palniro 4	300	0.0010 (0.0025)	1500(1090)	850(5860)	6.4	11.5(79)	23.0(159)	0.485
							750(5170)	4.7	10.1(70)	24.0(165)	
				300	0.0010 (0.0025)	1600(1140)	600(4140)	5.1	8.1(56)	17.0(117)	0.476
				300	0.0005 (0.0013)	1500(1090)	750(5170)	6.8	10.1(70)	22.5(155)	0.450
							700(4830)	10.6	9.5(65)	21.0(145)	

NOTES: (1) Fin stress = (pressure load)/(fin tensile area).

(2) Values obtained from figures 21, 22 and 23 for the test rupture life of Waspaloy, Inconel 718 and Inconel 625, respectively. Hastelloy X values were obtained from figure 24 and reference 4 for the test rupture life.

(6) Rectangular offset fin geometry as shown in figure 2b. Face sheet thickness was 0.015 in. (0.038 cm).

(7) The majority of the specimens were vacuum brazed.

(8) 26 hr at 550 psi (3790 kN/m^2) is equivalent to the actual test of 10 hr at 550 psi (3790 kN/m^2) and 5.3 hr at 700 psi (4830 kN/m^2).

TABLE 9

FLEXURE TEST SPECIMEN DETAILS

	Waspaloy panel	Inconel 718 panel
Braze alloy	Palniro 1	Palniro 7
Brazing conditions	Vacuum, 1200 s at 2070°F (1410°K)	Vacuum, 1200 s at 1950°F (1340°K)
Heat treatment	1550°F (1120°K) - 4 hr, air cooled 1400°F (1030°K) - 16 hr, air cooled	1325°F (990°K) - 8 hr, furnace cooled from 1325°F (990°K) to 1150°F (890°K) at the rate of 100°F (56°K) per hour, 1150°F (890°K) - 8 hr, air cooled
Cross section geometry	Same as figure 26e	Same as figure 26f

TABLE 10

FLEXURE TEST SUMMARY

Material	Test	Test temperature, °F(°K)	Stiffness: (M/δ), lb-in./in.² (kN-m/m²), for pure bending, (p/δ), lb/in.² (kN/m²), for combined loading: Test values	Test Average	Theoretical value	Yield moment, lb-in./in. (N-m/m): Test values	Test average	Theoretical value	Buckling moment, lb-in./in. (N-m/m): Test values	Test average	Theoretical value	Ratio of test to theoretical values, yield for Waspaloy and buckling vs yield for Inconel 718
Waspaloy	Pure bending	RT	708(124)	750(132)	700(123)	133(592)	141(627)	102(454)	155(690)	161(716)		> 1.0
			798(140)			147(654)			159(708)		-	
			745(131)			142(632)			169(752)			
		1400(1030)	488(86)	493(86)	555(97)	107(476)	104(463)	87(387)				> 1.0
			465(82)			96(427)			- (3)	- (3)	-	
			530(93)			109(485)						
	Bending plus shear, internal rein-forcement	RT	1220(8410)	1180(8130)	1110(7650)	152(676)	148(659)	101(450)	173(770)	170(801)		> 1.0
			1250(8620)			148(659)			172(765)		-	
			1080(7450)			144(641)			166(738)			
	Bending plus shear, external rein-forcement	RT	1200(8270)	1180(8130)	1200(8270)	151(672)	147(654)	101(450)	165(734)	159(708)		> 1.0
			1180(8130)			149(663)			154(685)		-	
			1160(8000)			141(627)			159(708)			
Inconel 718	Pure bending	RT	12 900(2260)	11 600(2030)	10 700(1880)	620(2760) (4)	636(2830)	643(2860)	641(2850)	649(2890)	622(2770)	0.99
			10 500(1840)			620(2760) (4)			620(2760)			
			11 500(2020)			667(2970) (4)			686(3050)			
		1200(920)	8380(1470)	7940(1390)	8780(1540)			529(2350)	478(2130)	478(2130)	525(2340)	0.91
			7850(1380)			- (5)	- (5)		473(2110)			
			7580(1330)						484(2150)			
	Bending plus shear	RT	15 000(103 000)	15 600(107 000)	16 000(114 000)			610(2710)	584(2600)	569(2530)	590(2630)	0.93
			16 400(113 000)			- (5)	- (5)		564(2510)			
			15 400(106 000)						558(2480)			

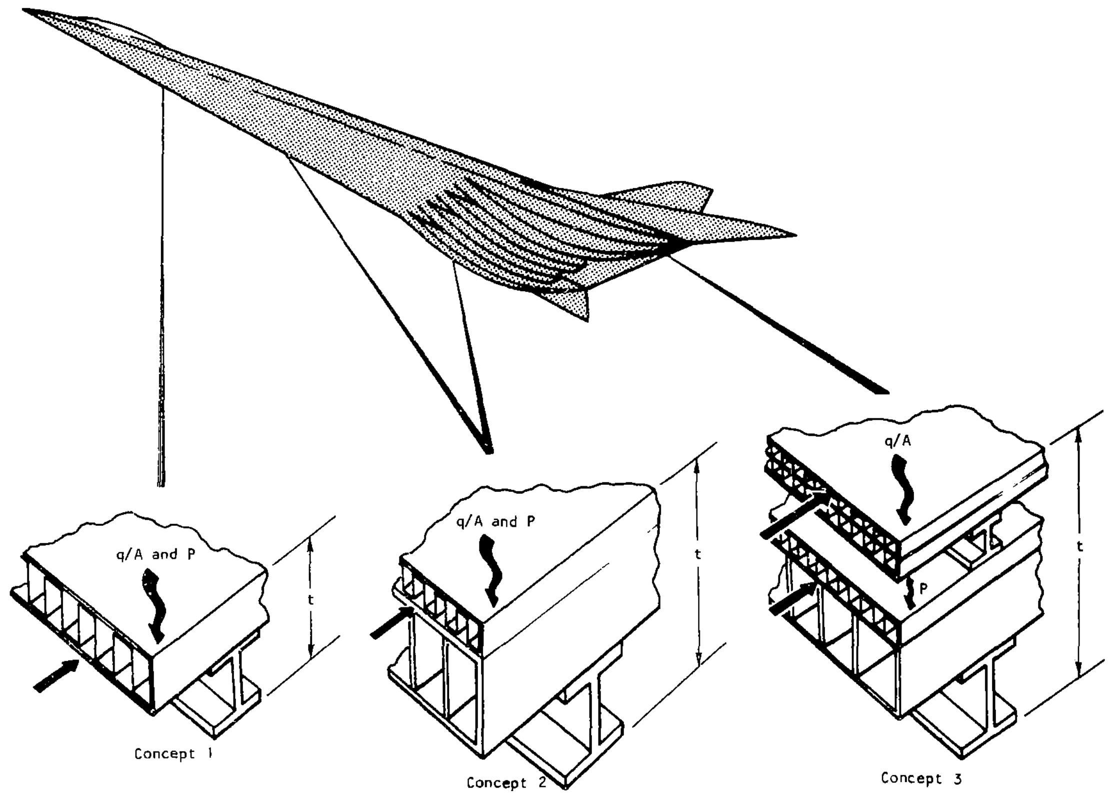
NOTES: (1) All units and values in parenthesis are S.I. units.

(2) All values per inch of panel width as indicated by the units.

(3) Failure occurred in creep rupture.

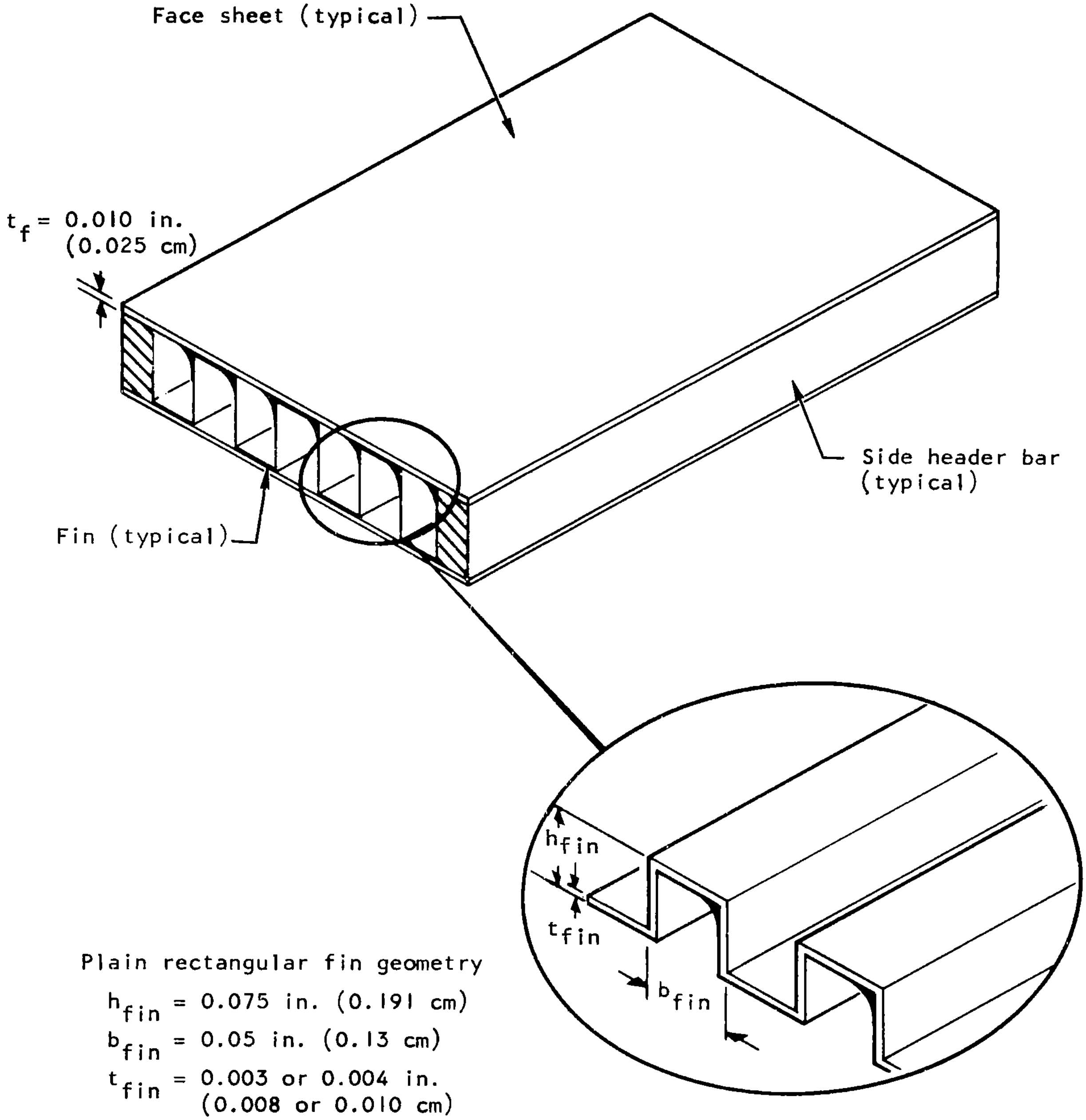
(4) Taken at last deflection point which is extremely close to 0.1 percent offset point.

(5) Buckling occurred prior to reaching 0.1 percent offset point.



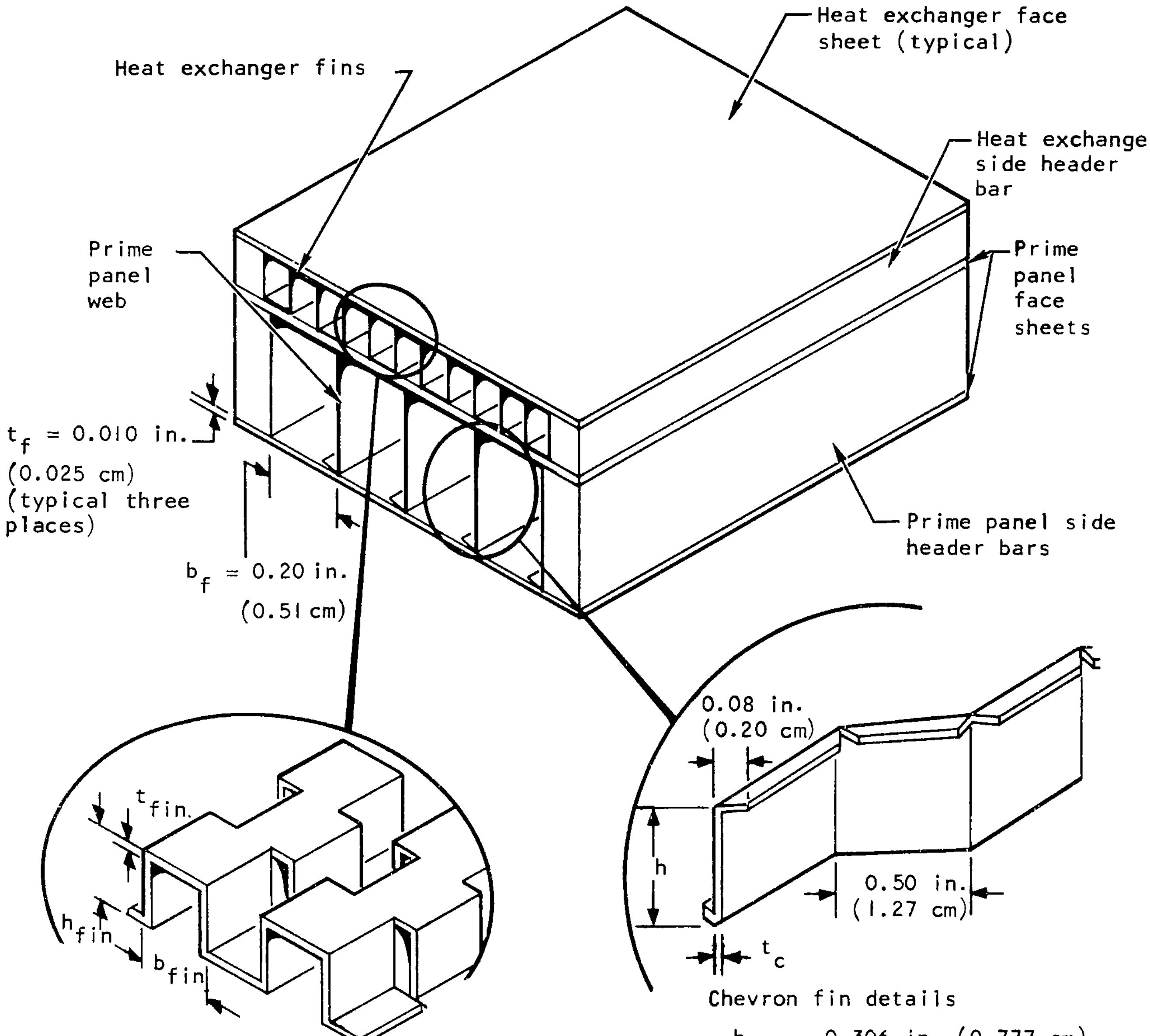
	Concept 1	Concept 2	Concept 3
Heat flux, q/A, Btu/sec ft^2 (kW/m^2)	5 to 100 (57 to 1140)	10 to 500 (110 to 5700)	10 to 500 (110 to 5700)
Pressure, P, psi (kN/m^2)	5 to 50 (35 to 350)	5 to 100 (35 to 690)	50 to 250 (350 to 1730)
Total weight, lb/ft^2 (kg/m^2)	2 to 4 (10 to 20)	3 to 6 (15 to 29)	5 to 8 (24 to 39)
Thickness, t, in. (cm)	1 to 3 (3 to 8)	2 to 5 (5 to 13)	3 to 7 (8 to 18)

Figure 1. Operating Conditions and Configuration for Regeneratively Cooled Panel Applications



a. Single layer panel

Figure 2. Geometry of Reference Panels



Rectangular offset fin geometry

h_{fin} = 0.05 in. (0.13 cm)

b_{fin} = 0.05 in. (0.13 cm)

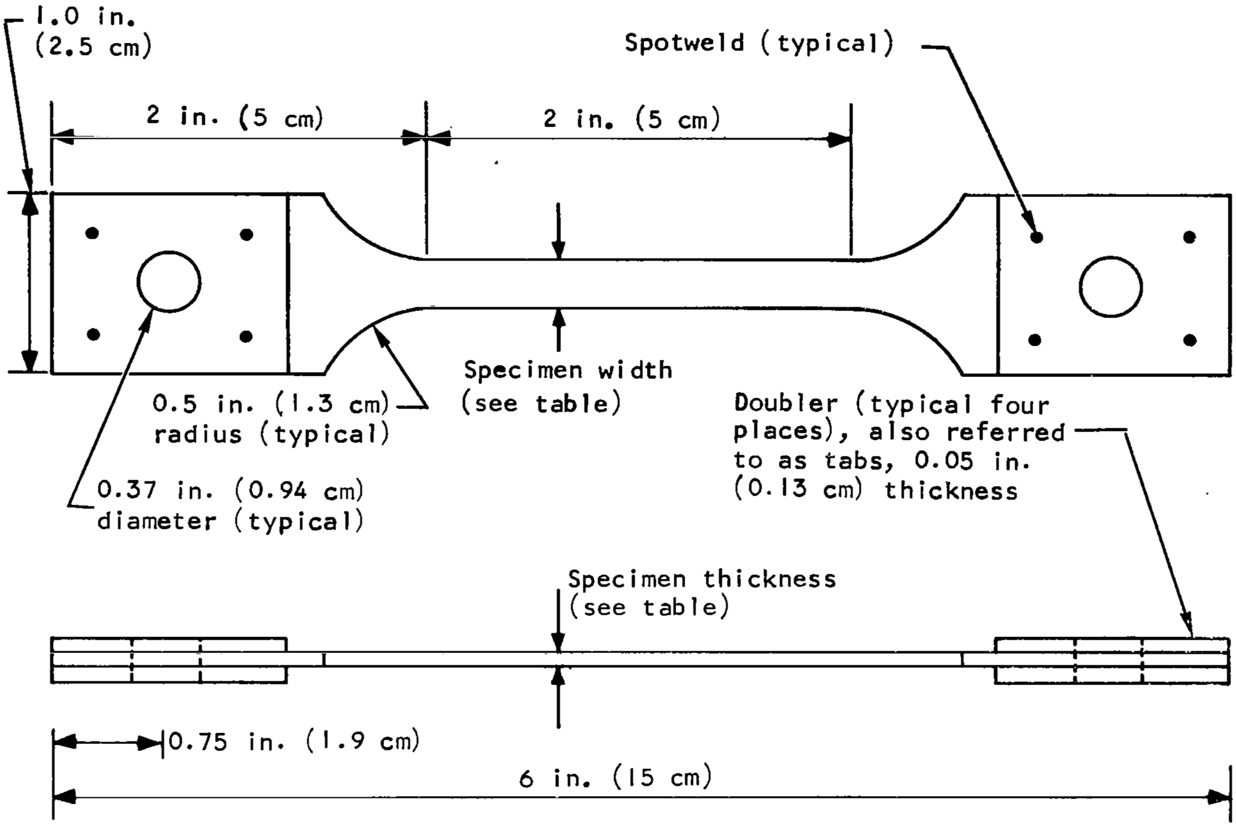
t_{fin} = 0.004 in. (0.010 cm)

h = 0.306 in. (0.777 cm)

t_c = 0.006 in. (0.015 cm)

b. Two layer panel

Figure 2. Concluded



Material	Specimen width, in. (cm)	Specimen thickness, in. (cm)
Waspaloy	0.25(0.64)	0.010(0.025)
Inconel 718	.25(.64)	.010(.025)
Inconel 625	.25(.64)	.010(.025)
Coated Inconel 625	.15(.64)	.010(.025)

Figure 3. Tensile Specimen Configuration (Nominal Dimensions)

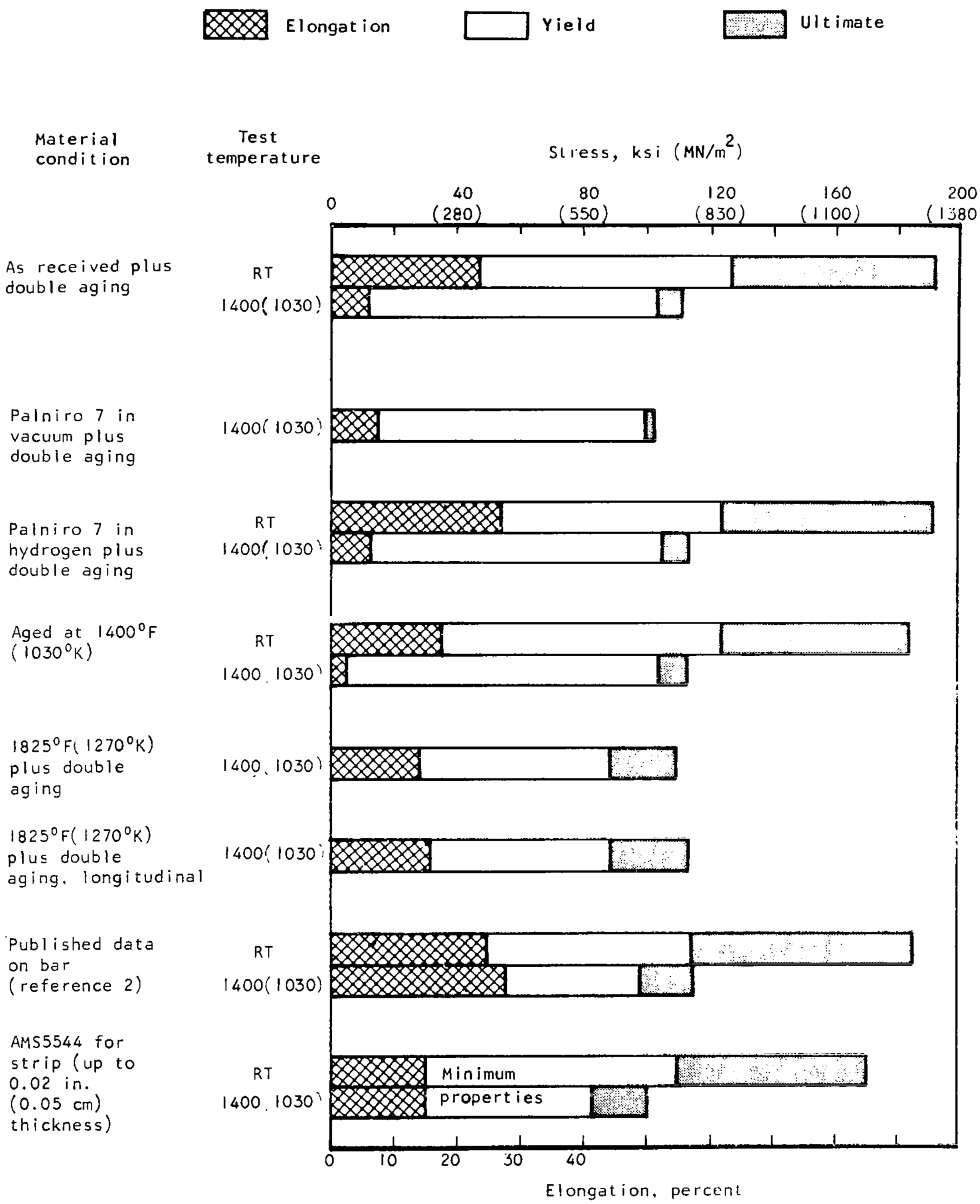


Figure 4. Ultimate Strength, Yield Strength and Elongation For Waspaloy at Room Temperature and 1400°F(1030°K)

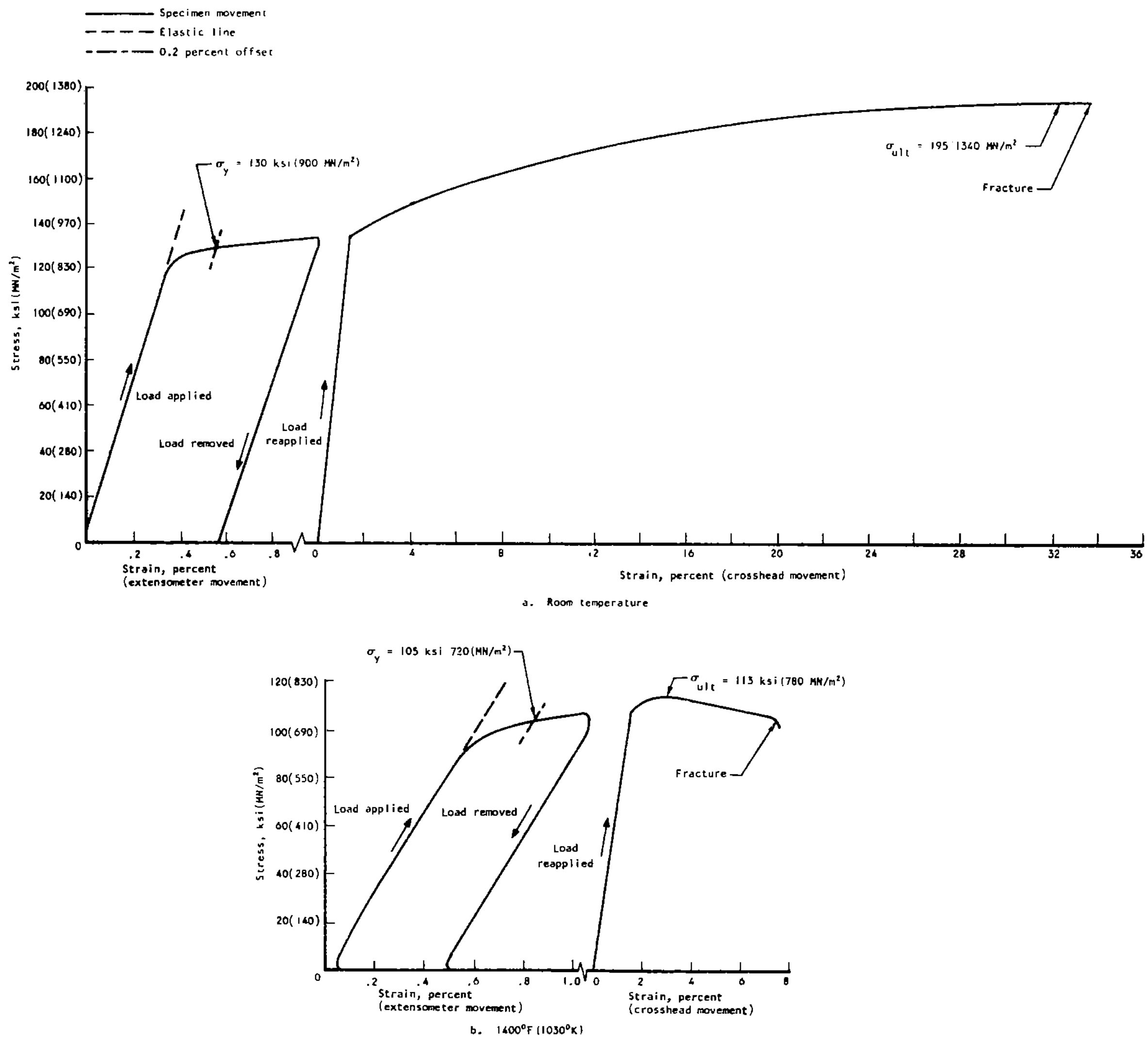


Figure 5. Typical Waspaloy Stress-Strain Curves at Room and Elevated Temperatures, As-received with Double Aging Condition

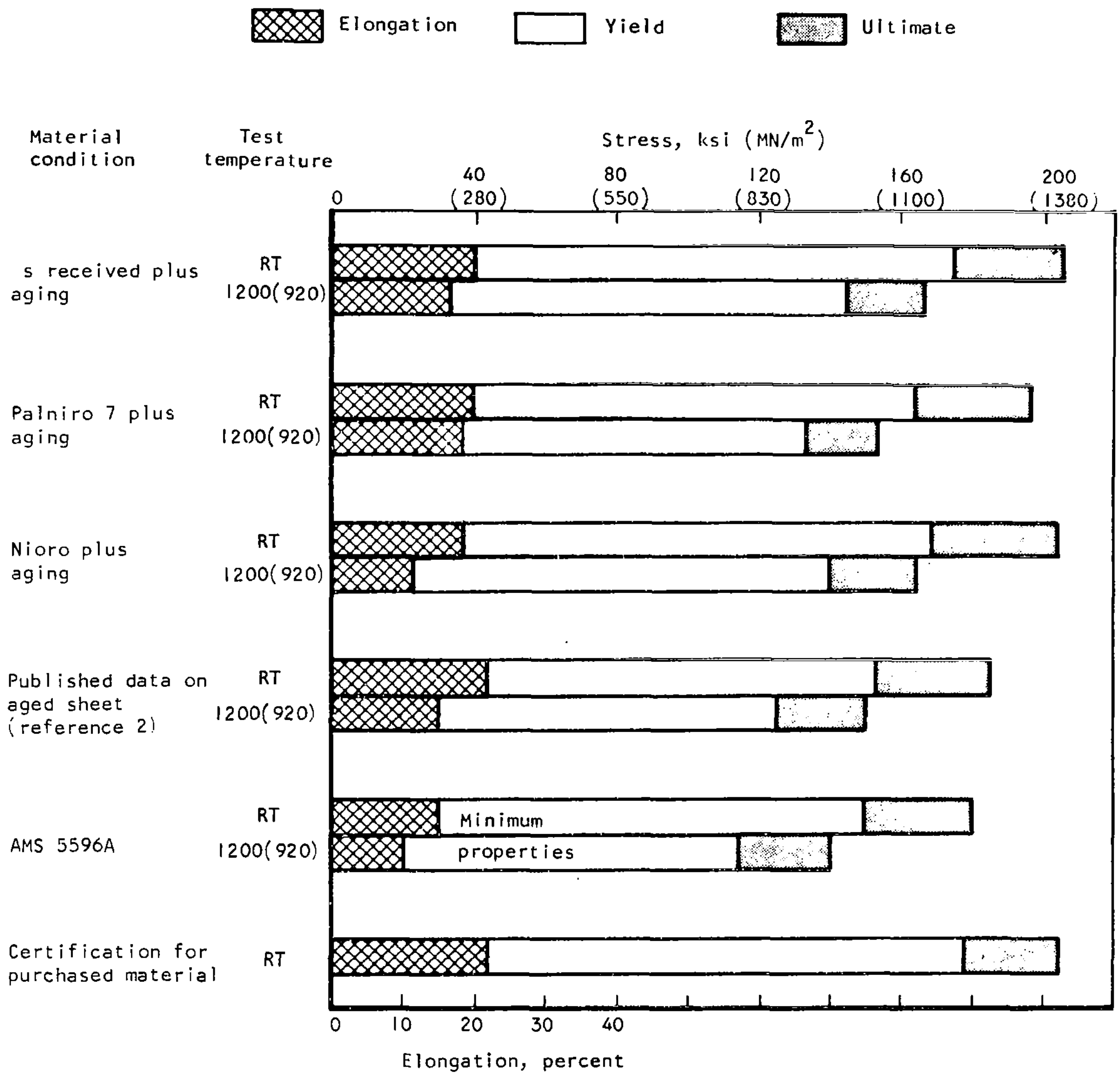
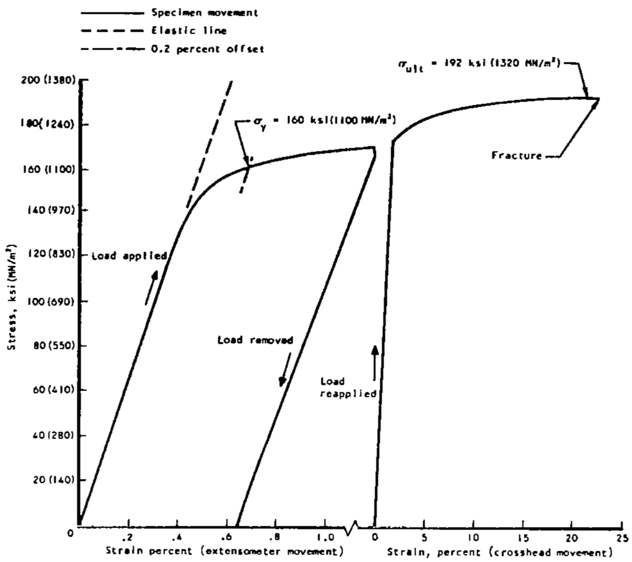
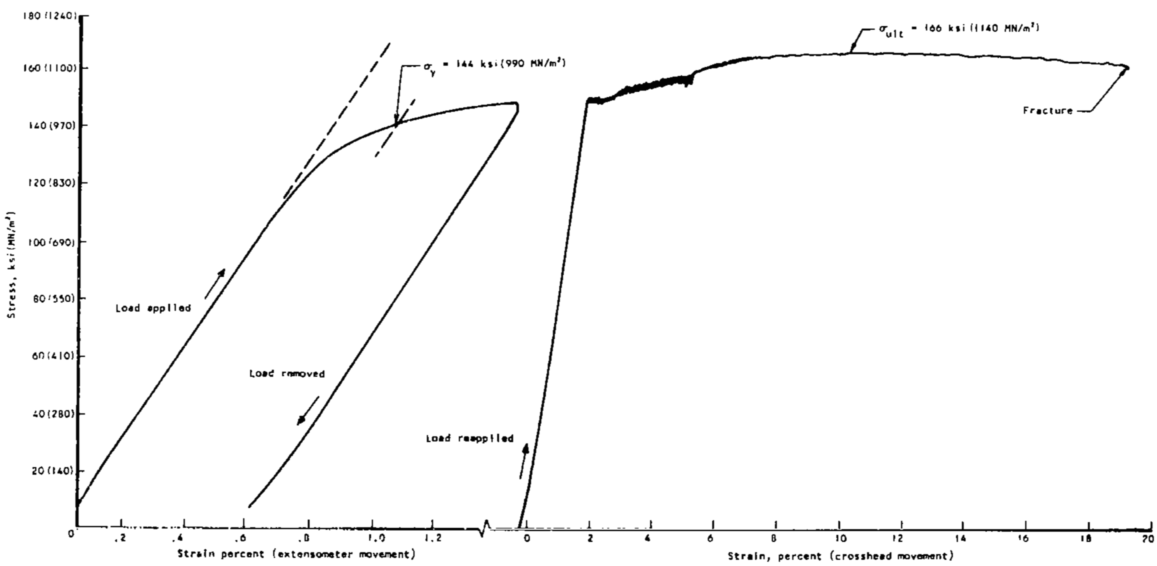


Figure 6. Ultimate Strength, Yield Strength, and Elongation For Inconel 718 at Room Temperature and 1200°F (920°K)

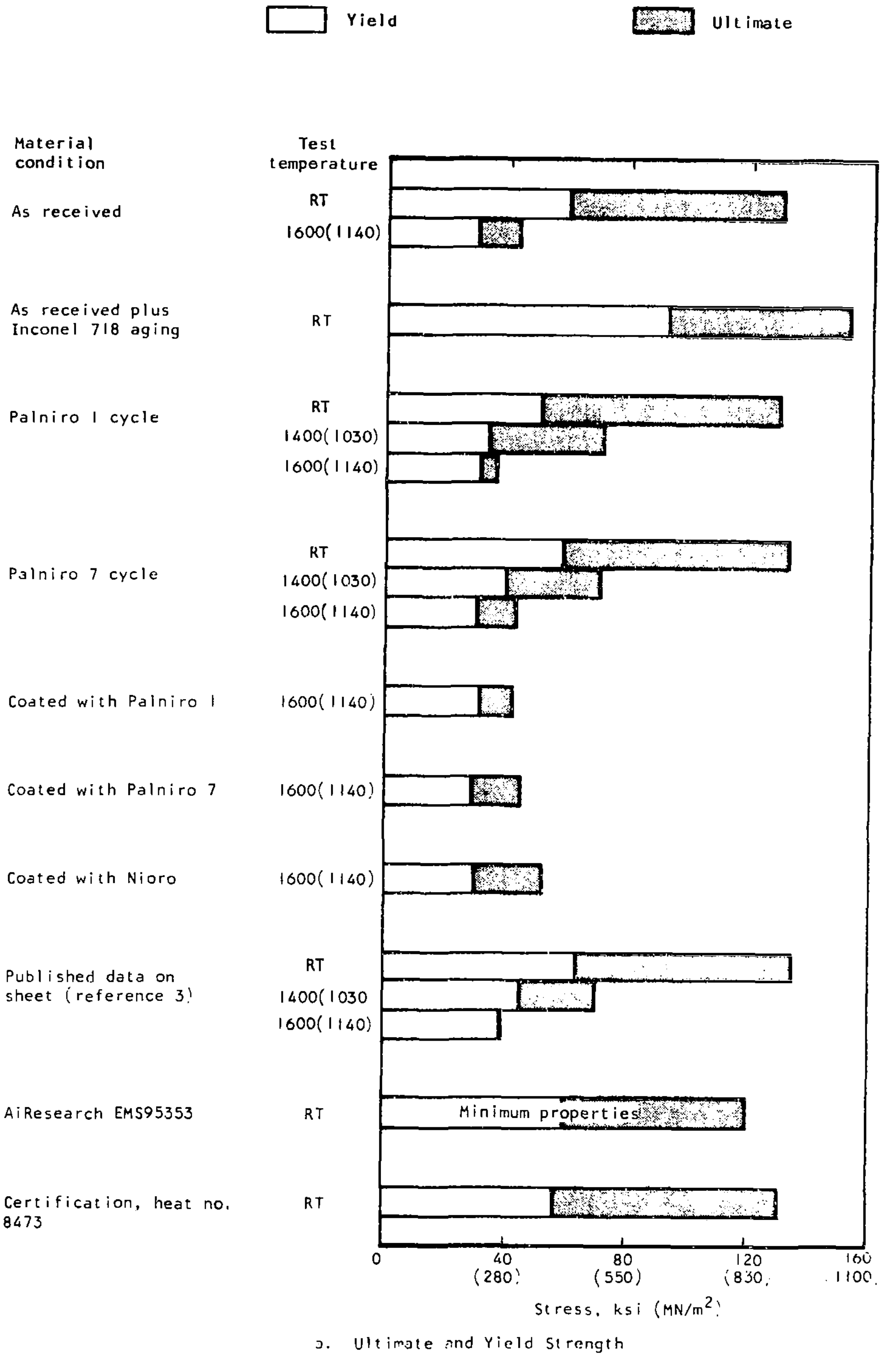


a. Room temperature, Painino 7 cycle plus aging condition



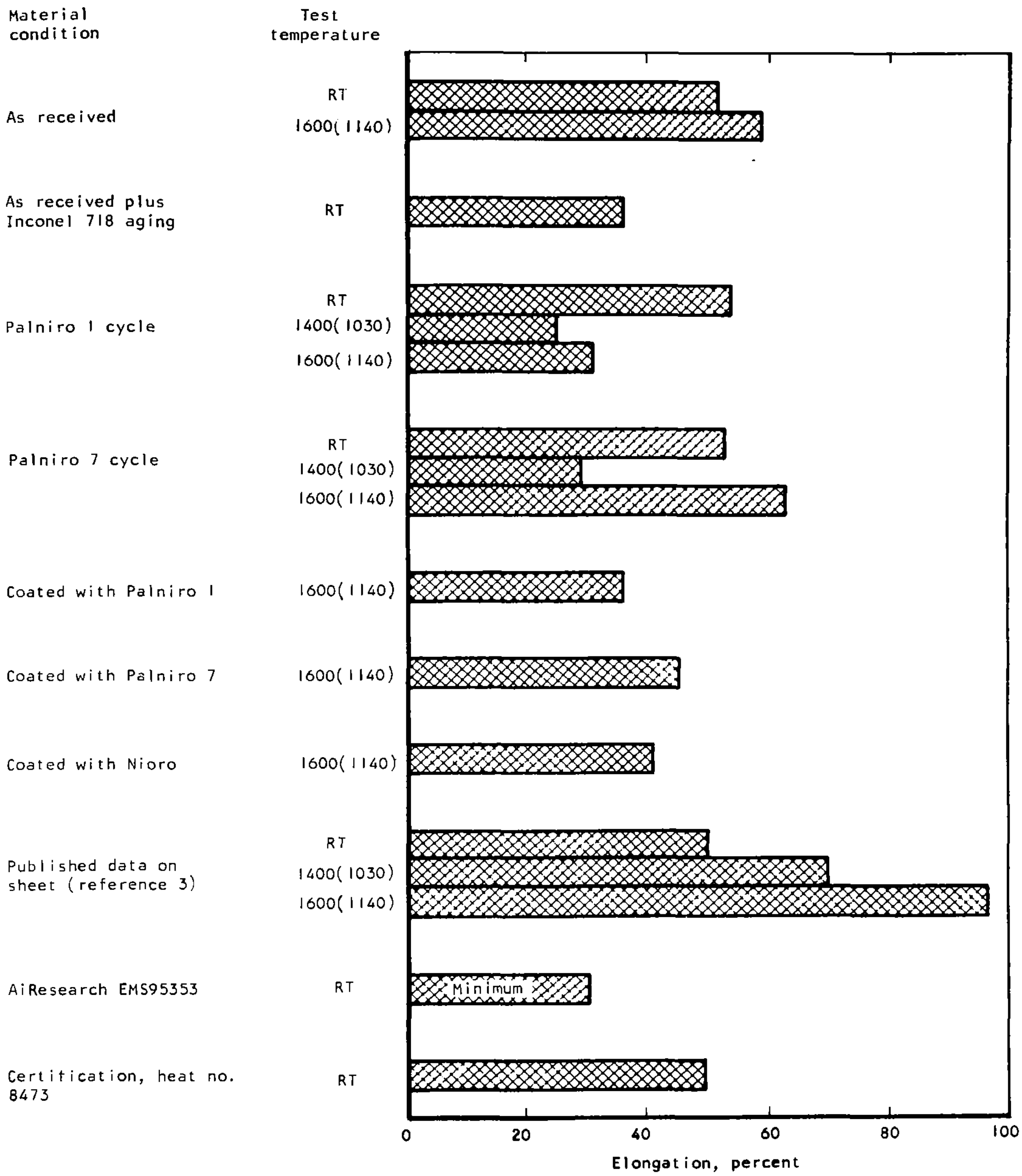
b. 1200°F (920°K), as received and aged condition

Figure 7. Typical Inconel 718 Stress-Strain Curves at Room and Elevated Temperatures



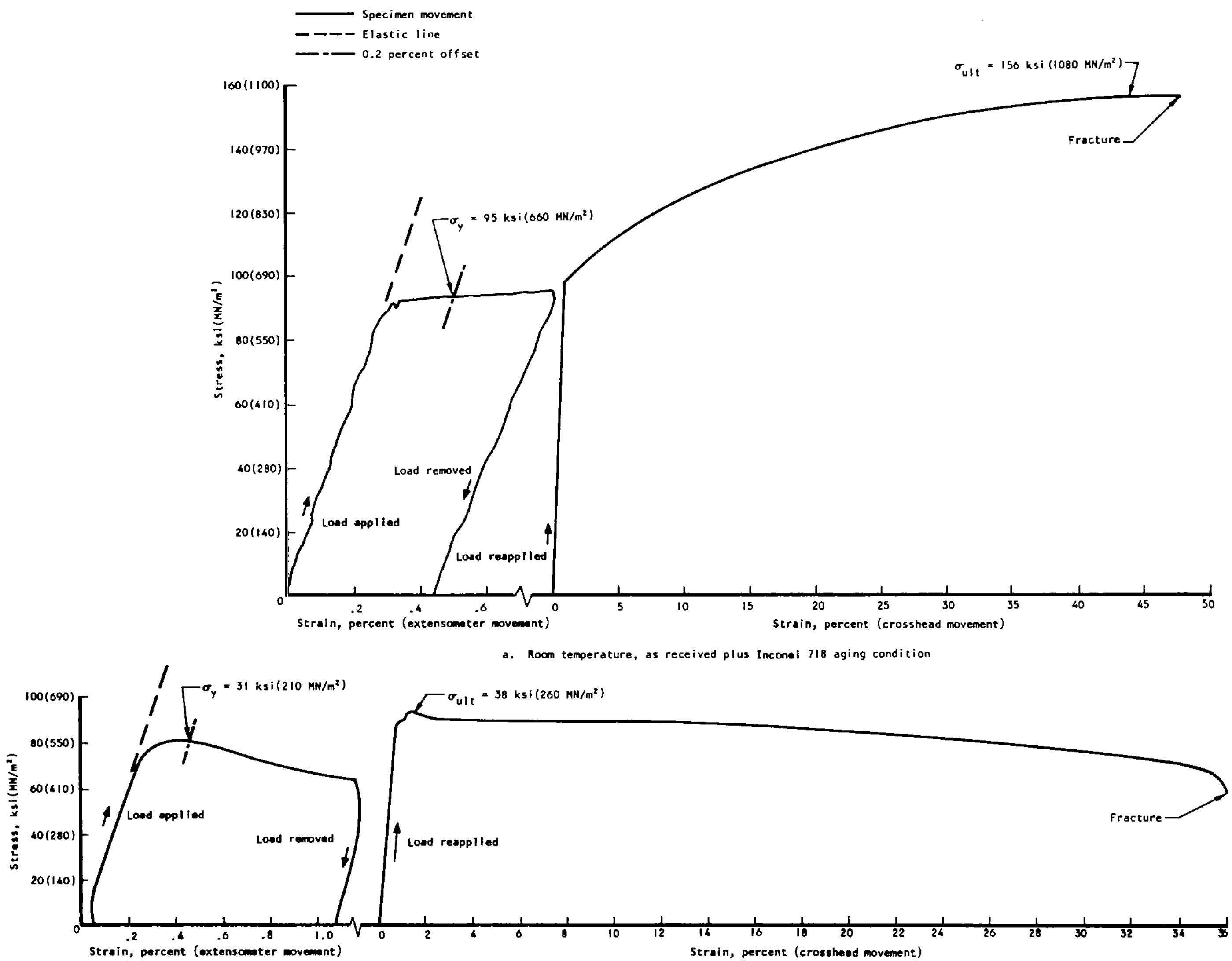
a. Ultimate and Yield Strength

Figure 8. Inconel 625 Tensile Test Results



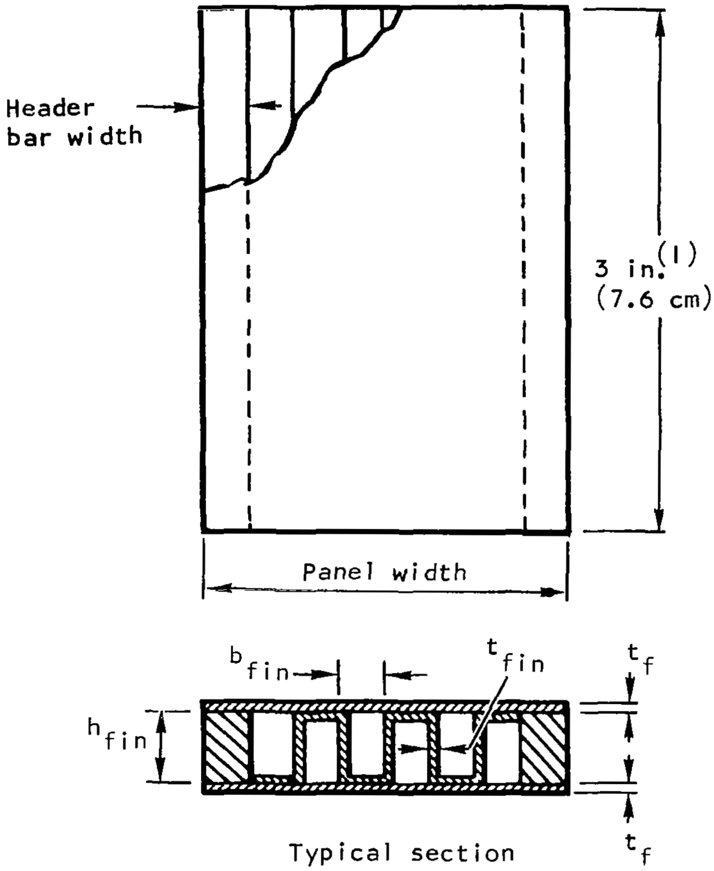
b. Elongation

Figure 8. Concluded



b. 1600°F(1040°K), Palnino I cycle, vacuum, 900 s condition

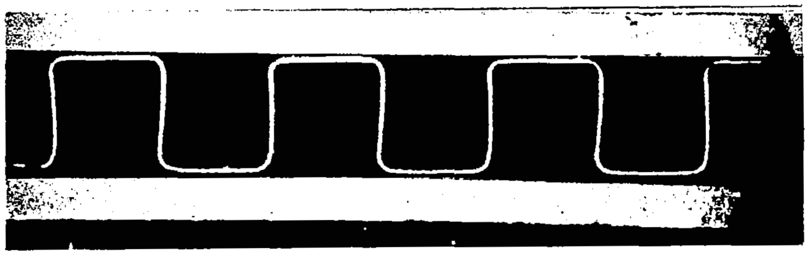
Figure 9. Typical Inconel 625 Stress-Strain Curves at Room and Elevated Temperatures



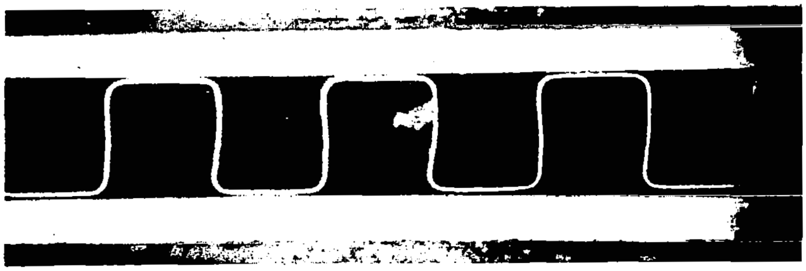
Material	Fin type (figure 2)	h_{fin}		b_{fin}		t_{fin}		t_f		Header width		Panel width	
		in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm
Waspaloy	Plain rectangular	0.100	0.254	0.09	0.23	0.003	0.008	0.010	0.025	0.068	0.173	2.2	5.6
		.100	.254	.09	.23	.004	.010	.010	.025	.068	.173	2.2	5.6
Inconel 718	Chevron	0.306	0.777	0.20	0.51	0.006	0.015	0.010	0.025	0.113	0.288	2.7	6.9
Inconel 625	Rectangular offset	0.075	0.191	0.05	0.13	0.004	0.010	0.010	0.025	0.068	0.173	2.2	5.6
		.075	.191	.05	.13	.004	.010	.010	.025	-(2)	-	1.5	3.8

(1) Panel length was 2 in. (5 cm) for the braze pressure evaluations with Inconel 625.
(2) The panel for the braze pressure evaluations (figures 14 and 16) did not have header bars.

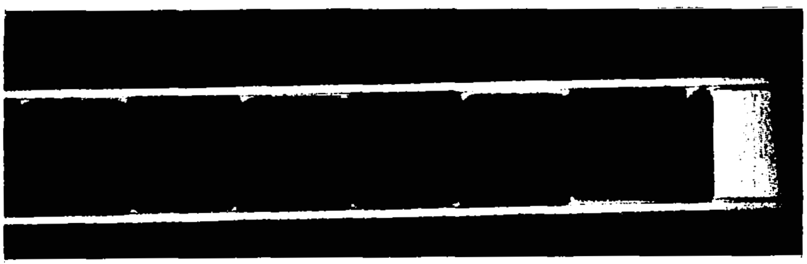
Figure 10. Brazing Evaluation Specimen (Nominal Dimensions)



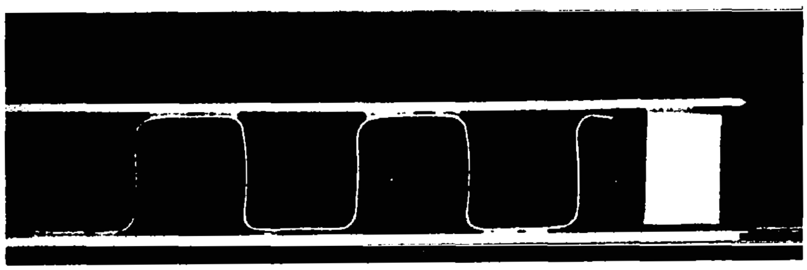
a. Shape of 0.004 in. (0.010 cm) thick Waspaloy fins before brazing (Strips above and below fins are not faceplates)



b. Shape of 0.003 in. (0.008 cm) thick Waspaloy fins before brazing (Strips above and below fins are not faceplates)

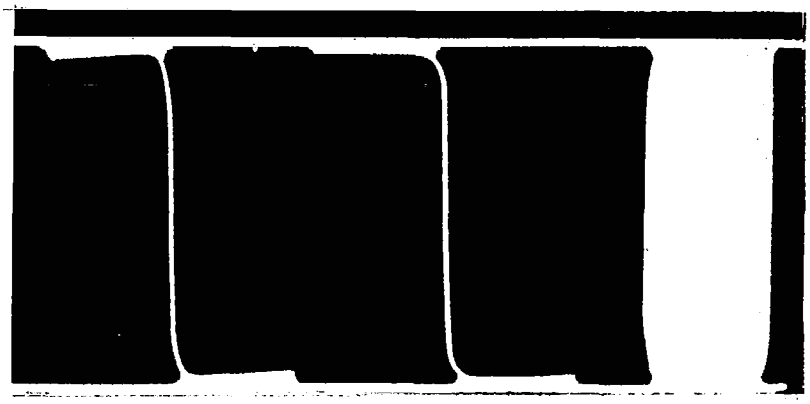


c. Typical cross section of panels brazed with Palniro 7

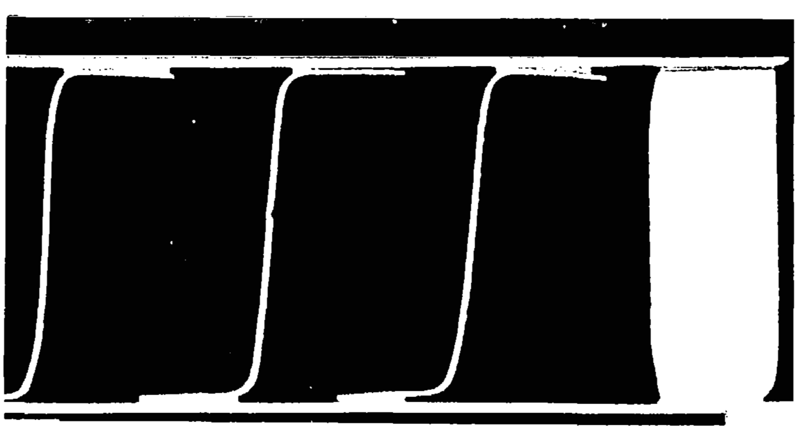


d. Cross section of panels brazed with Nicrobraz 65

Figure 11. Cross Sections of Waspaloy Plain Rectangular Fins and Brazed Specimens

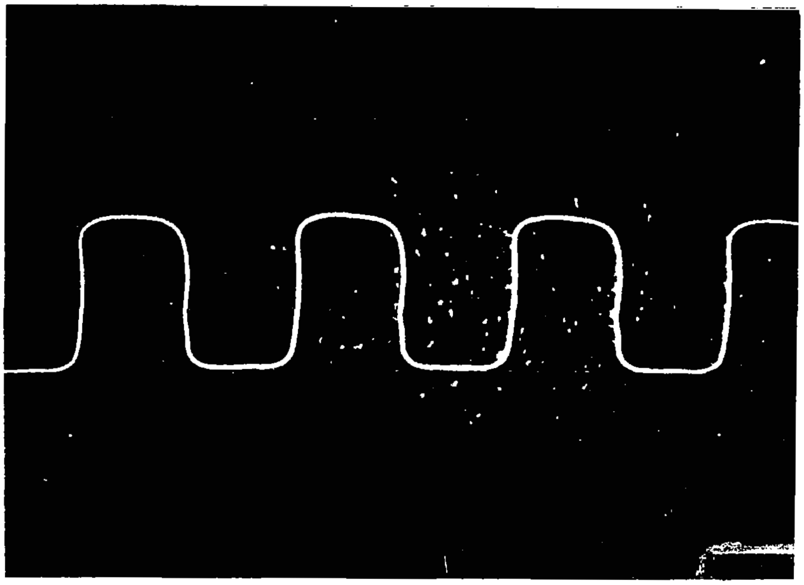


a. Typical joints for Palniro 7 brazing alloy

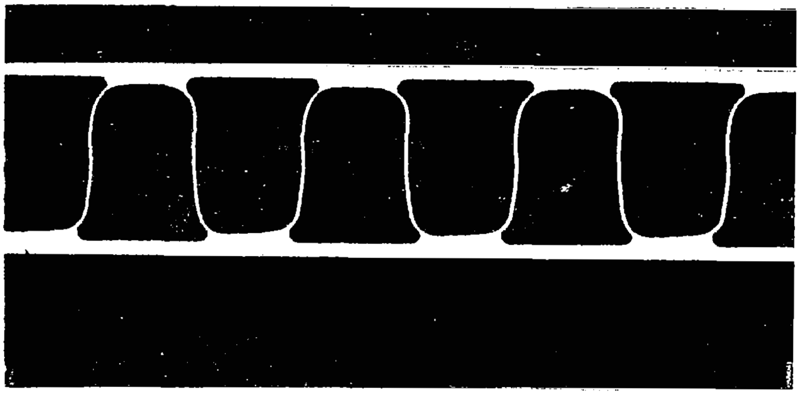


b. Typical joint for Nioro brazing alloy

Figure 12. Cross Sections of Brazed Inconel 718 Chevron Fin Specimens



a. Shape of Inconel 625 offset fins before brazing



b. Typical Inconel 625 panel after brazing

Figure 13. Cross Sections of Inconel 625 Rectangular Offset Fins and Brazed Specimens

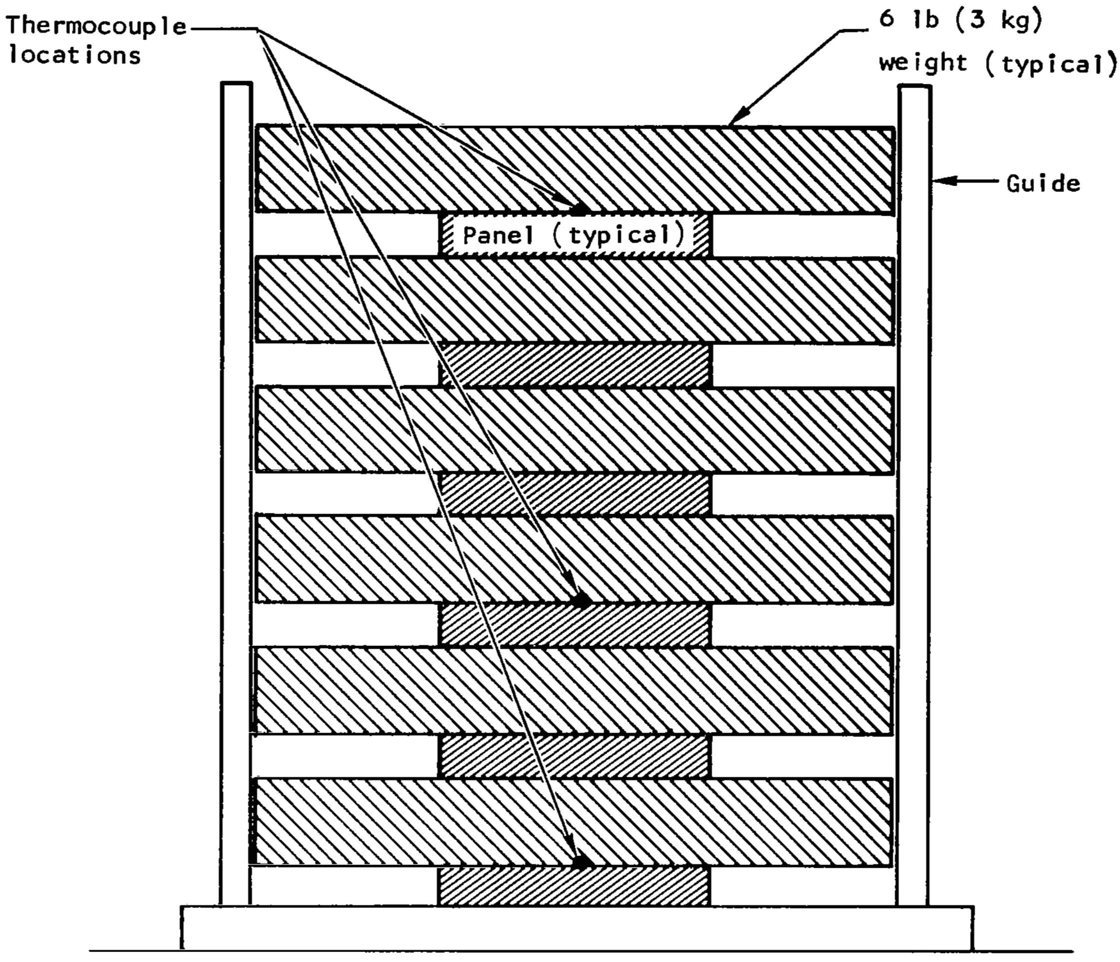


Figure 14. Schematic for Deadweight Loading Inconel 625 Panels (Brazed With Palniro I in Vacuum for 1200 s) to Obtain a 2 to 12 psi (14 to 83 kN/m^2) Pressure Range on Plate-Fin Joints During Brazing

a. Deadweight loading at 2 psi (14 kN/m^2)

b. Deadweight loading at 12 psi (83 kN/m^2)

c. Envelope brazing at 14.7 psi (101 kN/m^2)

Figure 15. Photomicrographs of Inconel 625 Specimens Brazed with Palniro I at Three Pressures by Deadweight and Evacuated Envelope Methods

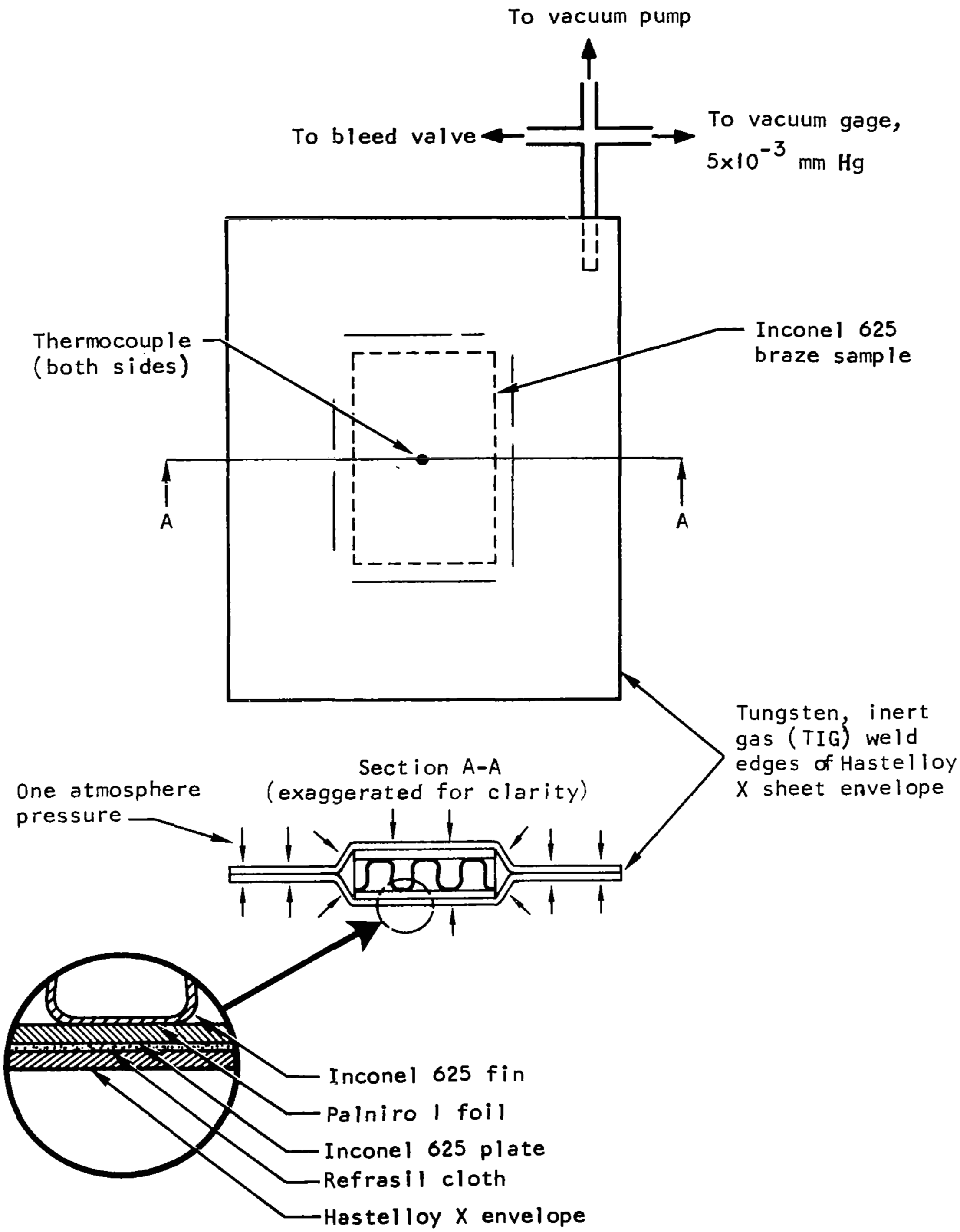
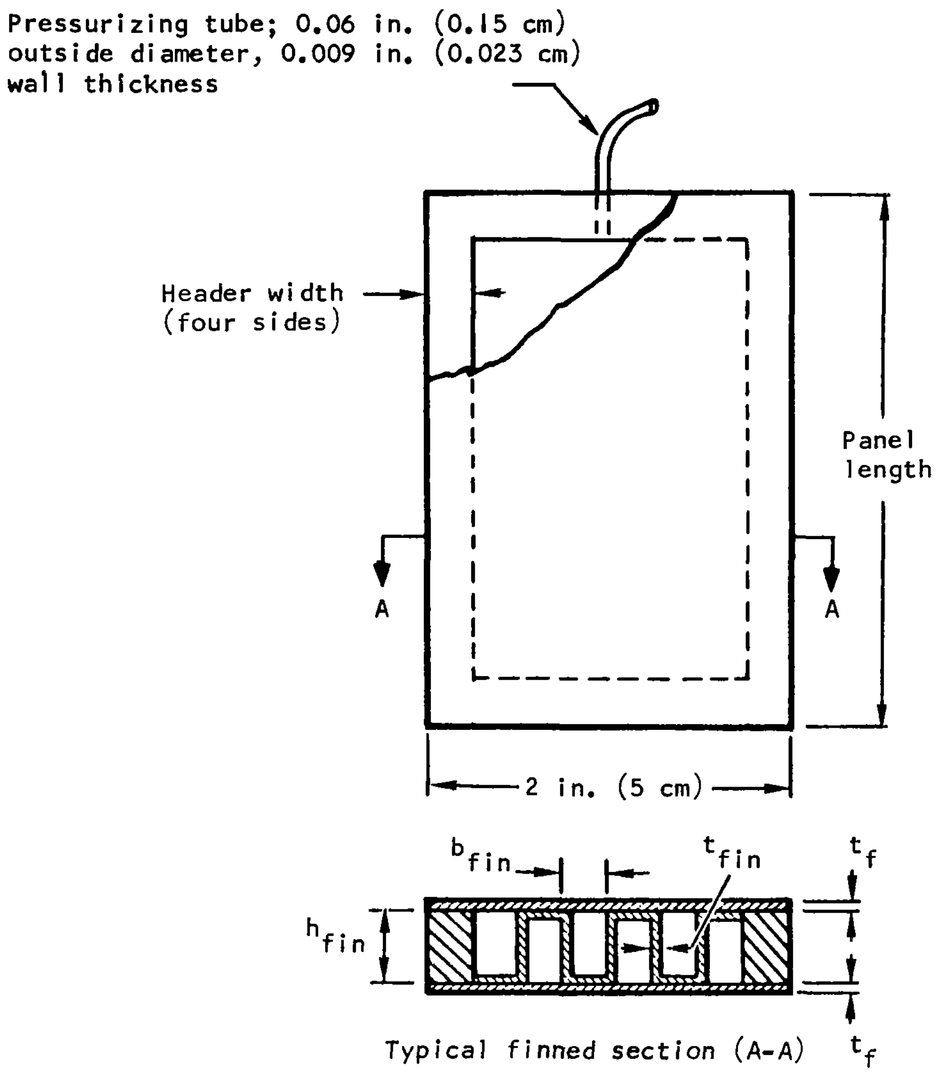


Figure 16. Schematic of Evacuated Envelope Method for Brazing Inconel 625 Panels



Material	Fin type (figure 2)	h_{fin}		b_{fin}		t_{fin}		t_f		Header width		Panel length	
		in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm
Waspaloy	Plain rectangular	0.075	0.191	0.05	0.13	0.003	0.008	0.010	0.025	0.20	0.51	3.0	7.6
Inconel 718	Chevron	.306	.777	.20	.51	.006	.015	.020	.051	.13	.33	3.3	8.4
Inconel 625 -718*	Rectangular offset	.050	.127	.05	.13	.004	.010	.010	.025	.20	.51	3.0	7.6
Inconel 625	Rectangular offset	.050	.127	.05	.13	.004	.010	.010	.025	.20	.51	3.0	7.6

*One faceplate of Inconel 718

Figure 17. Burst and Creep Rupture Specimens (Nominal Diminesions)

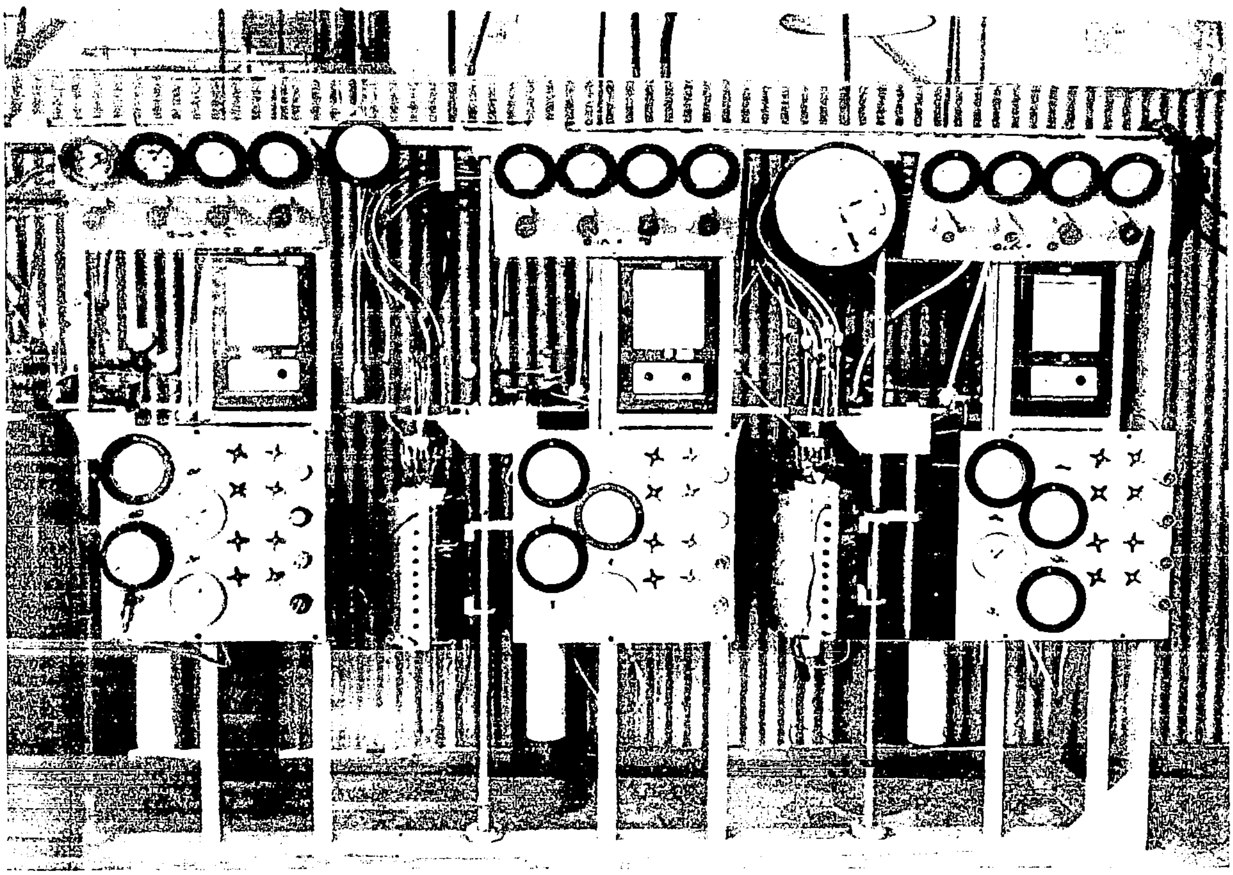
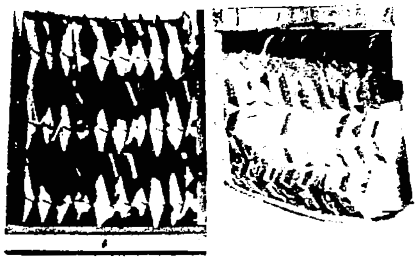
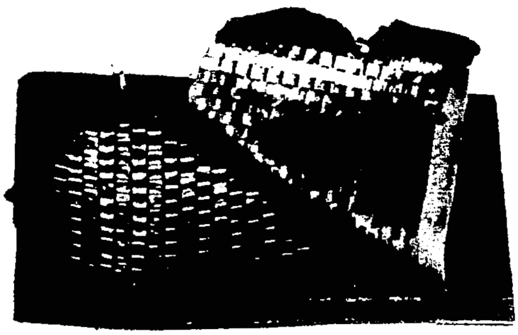


Figure 18. Internal Pressure Test Facility

a. Waspaloy burst specimen



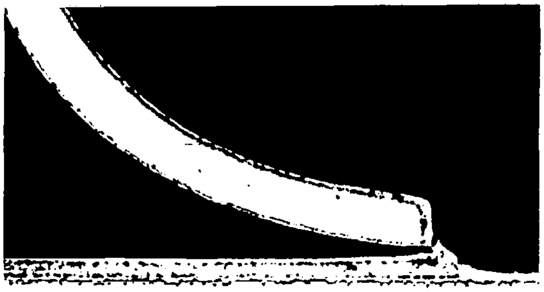
b. Inconel 718 burst specimen



c. Inconel 625-Inconel 718 burst specimen

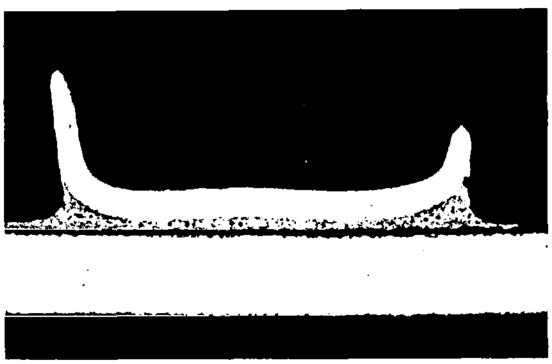
d. Inconel 625 creep rupture specimen

Figure 19. Typical Burst and Creep Rupture Failed Specimens



a. Failure at the nickel plating interface

b. Failure through the braze joint



c. Failure through the fin

Figure 20. Typical Burst and Creep Rupture Joint Failures

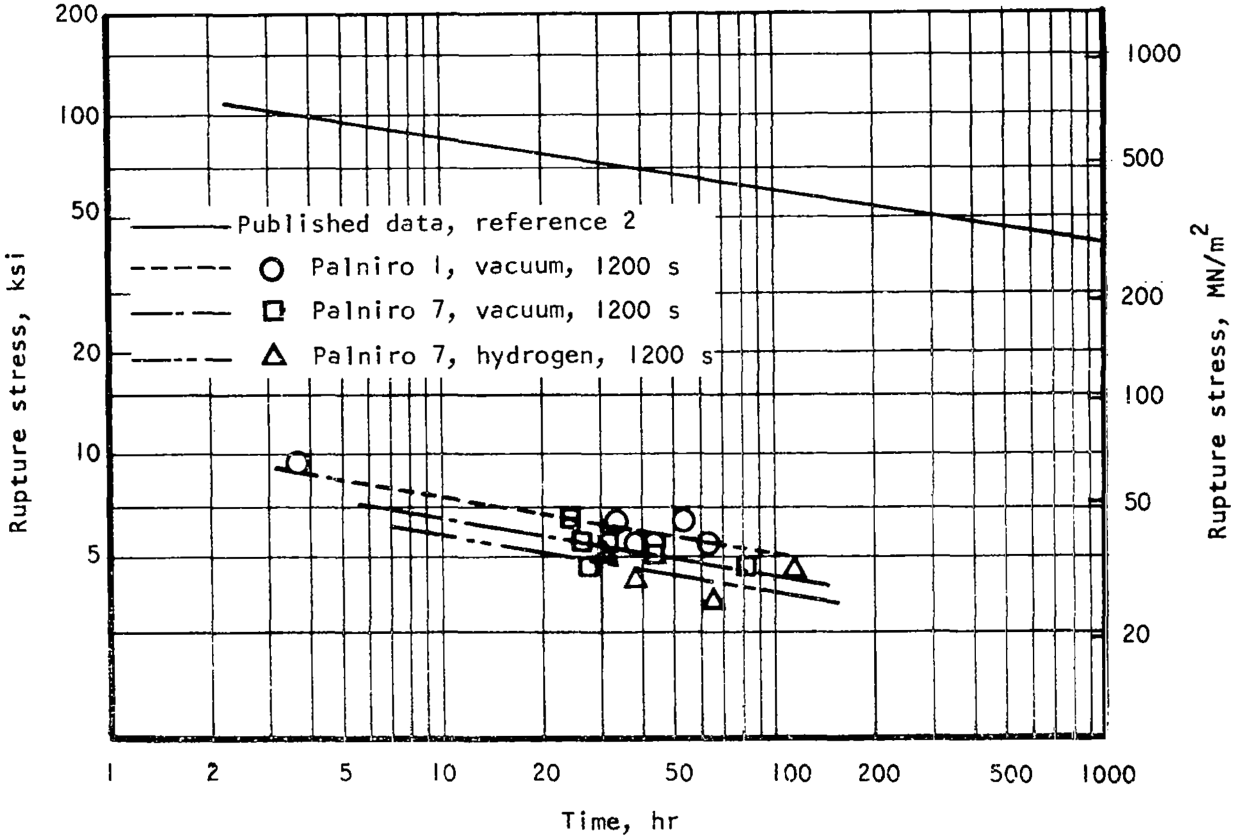


Figure 21. Stress Rupture Data for Waspaloy Panels at 1400°F (1030°K)

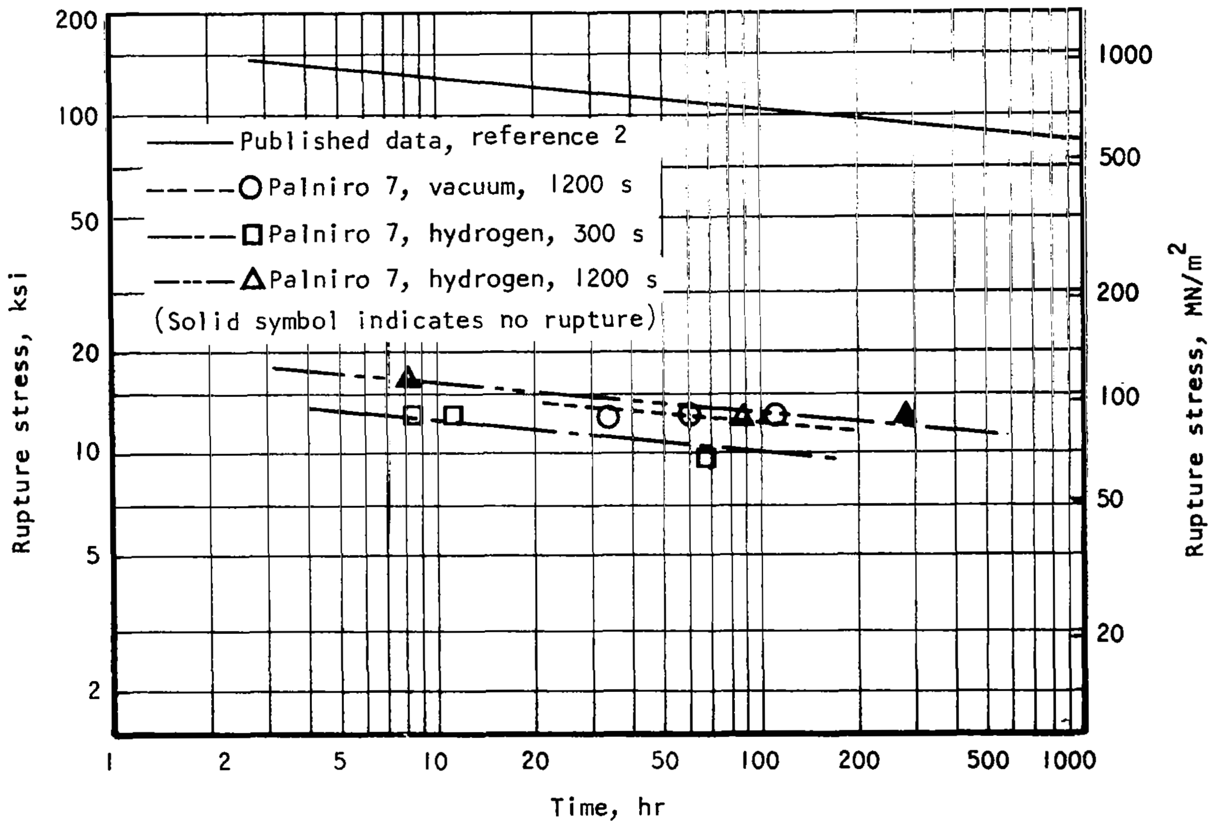


Figure 22. Stress Rupture Data for Inconel 718 Panels at 1200°F (920°K)

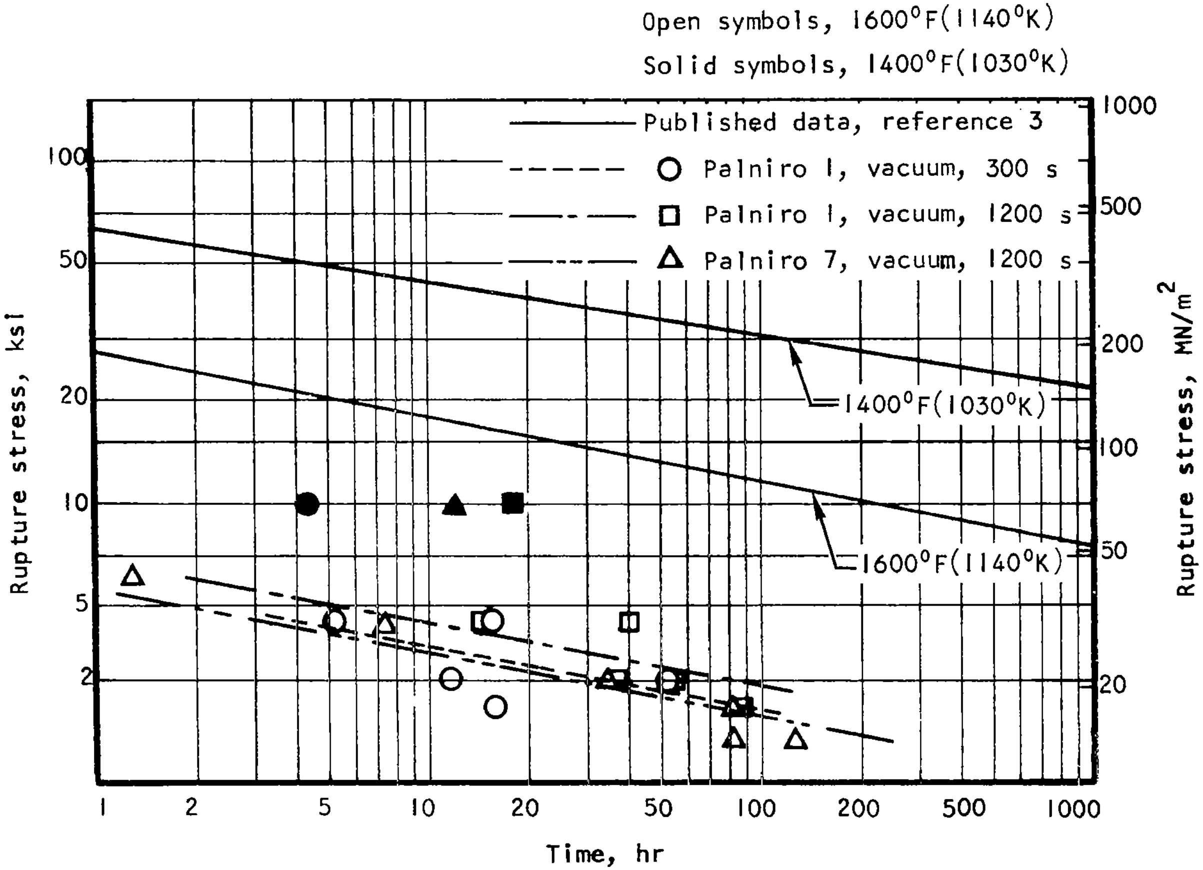


Figure 23. Stress Rupture Data for Inconel 625 Panels at 1400°F(1030°K) and 1600°F(1140°K)

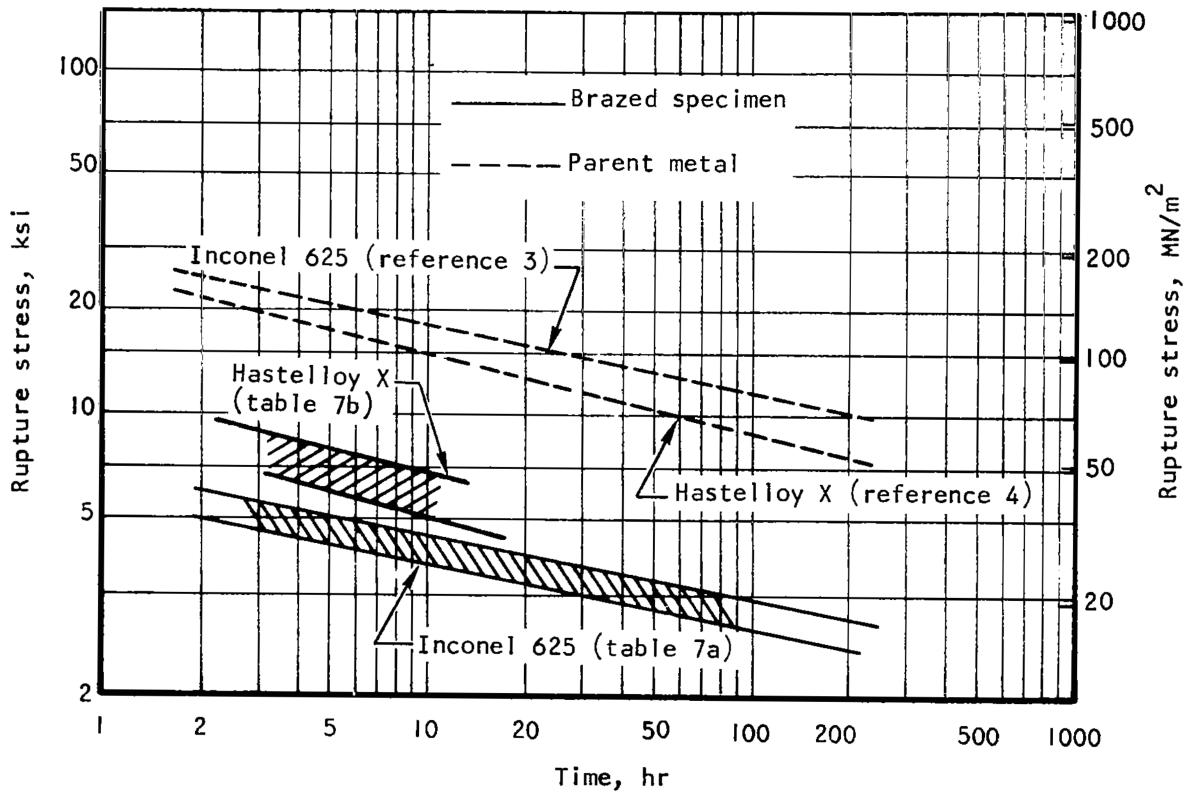


Figure 24. A Comparison of Stress Rupture Results for Brazed Plate-fin Specimens with Parent Metal Properties. Hastelloy X and Inconel 625 Specimens Tested at 1600°F(1140°K)

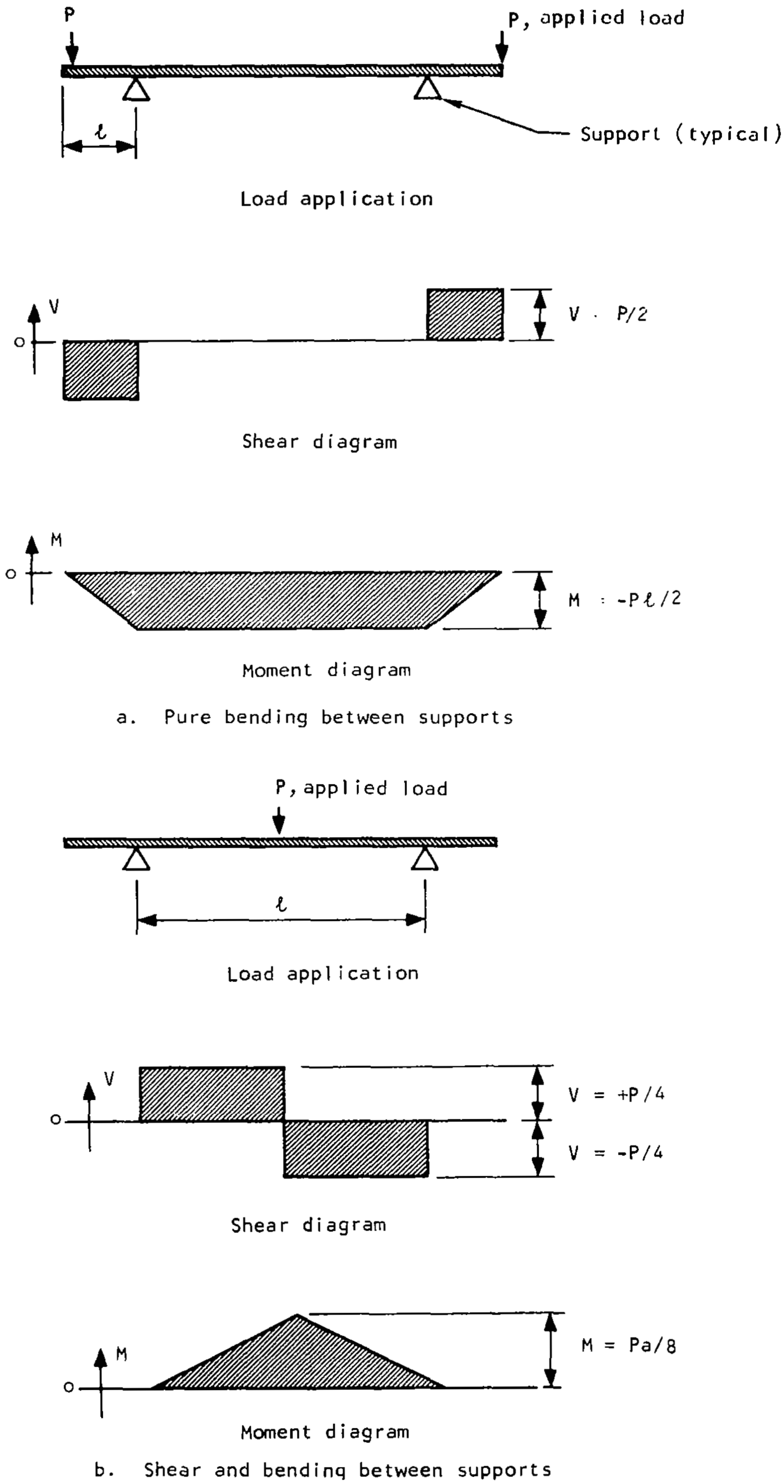
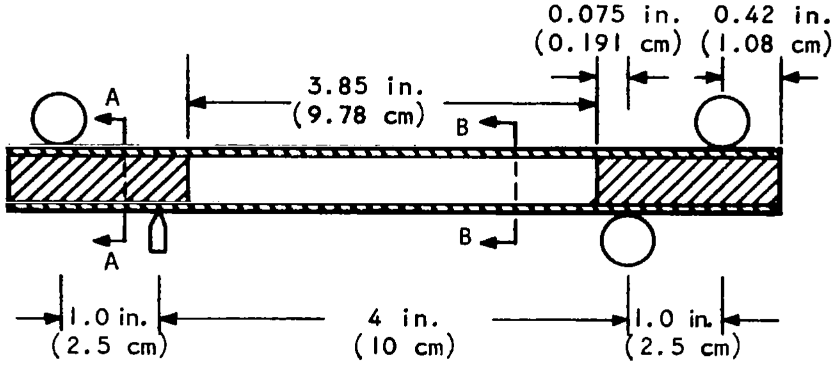
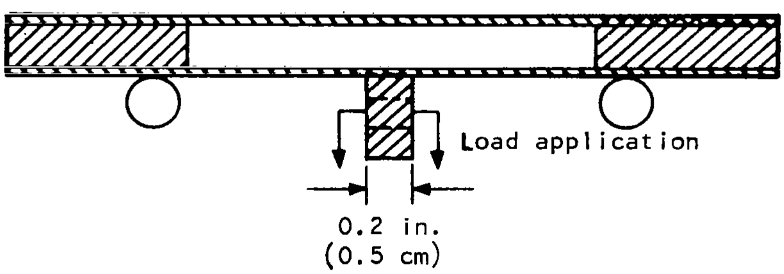


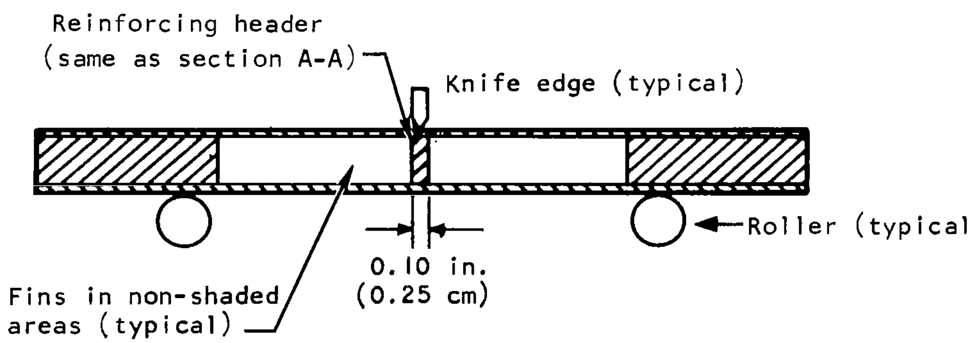
Figure 25. Flexure Loadings and Shear and Moment Diagrams (2 in. (5 cm) beam width)



a. Pure bending

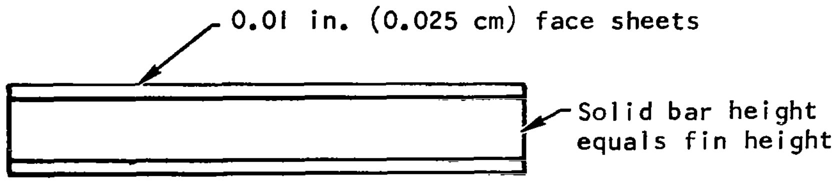


b. Combined shear and bending, external reinforcement

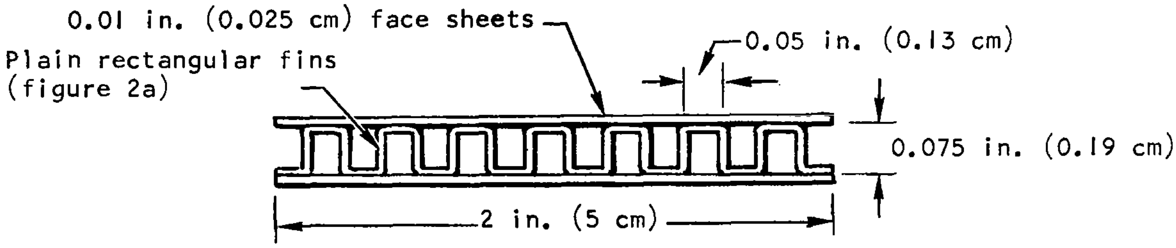


c. Combined shear and bending, internal reinforcement

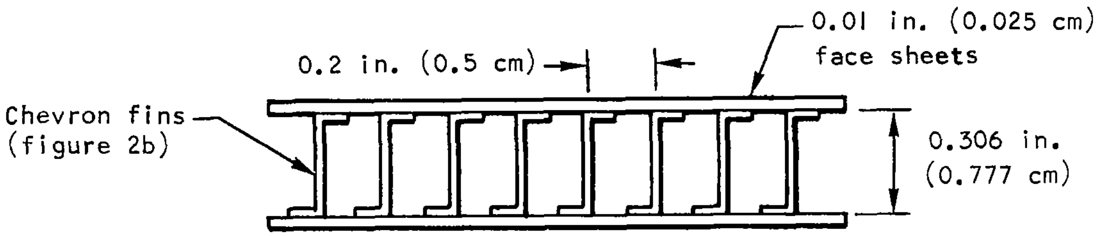
Figure 26. Specimen and Loading Details



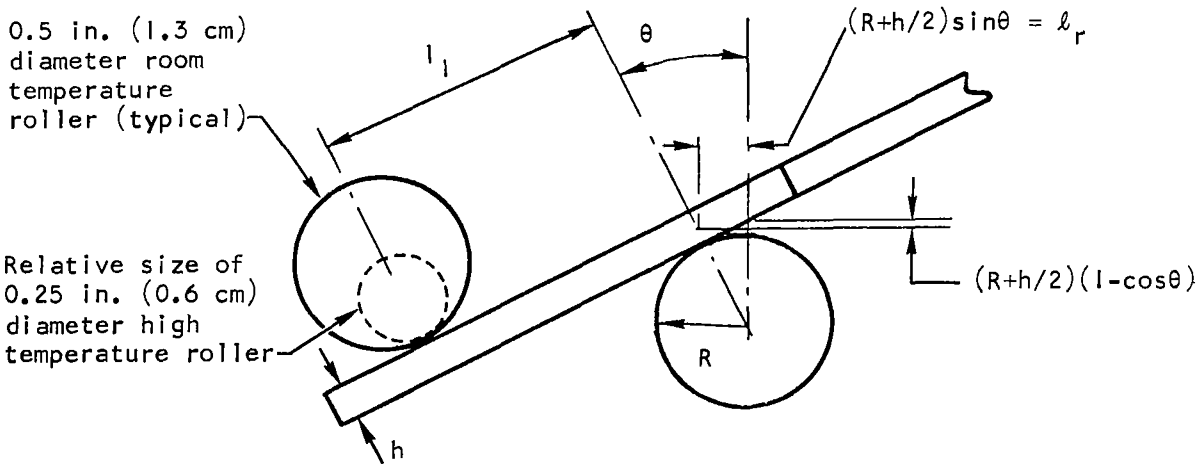
d. Section A-A (not to scale)



e. Section B-B, Waspaloy

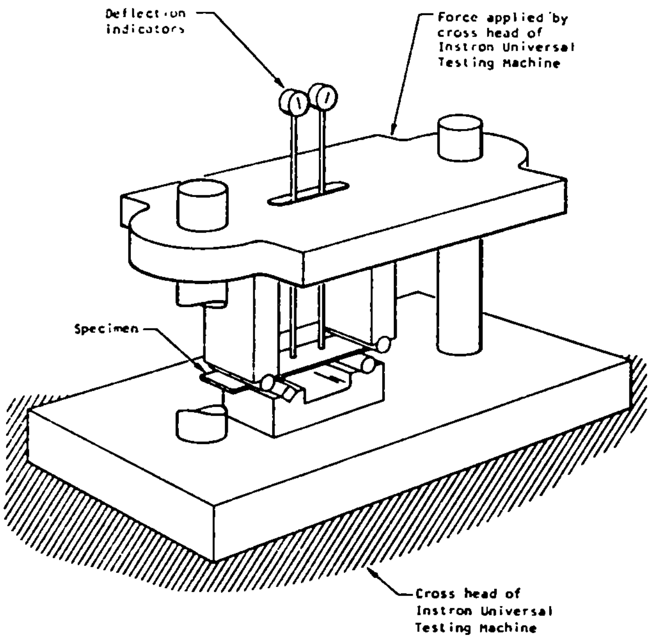


f. Section B-B, Inconel 718

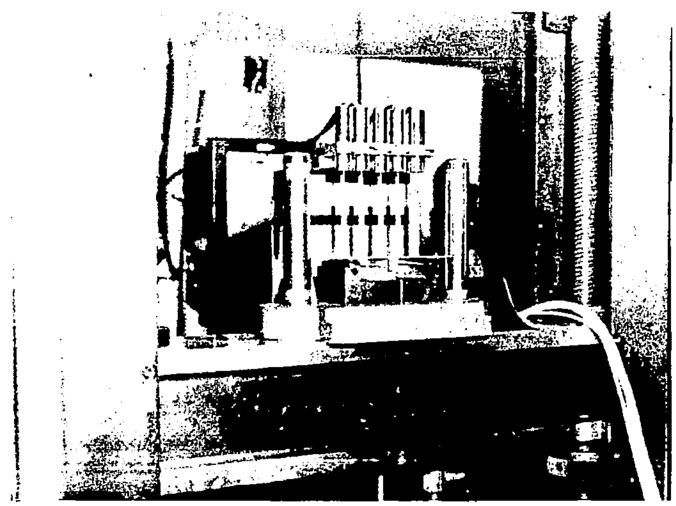


g. Loaded position of two-roller end in pure bending

Figure 26. Concluded



a. Schematic of test fixture setup for pure bending



b. Combined shear and bending test setup with external reinforcement Waspaloy specimen installed

Figure 27. Room Temperature Flexure Test Fixture

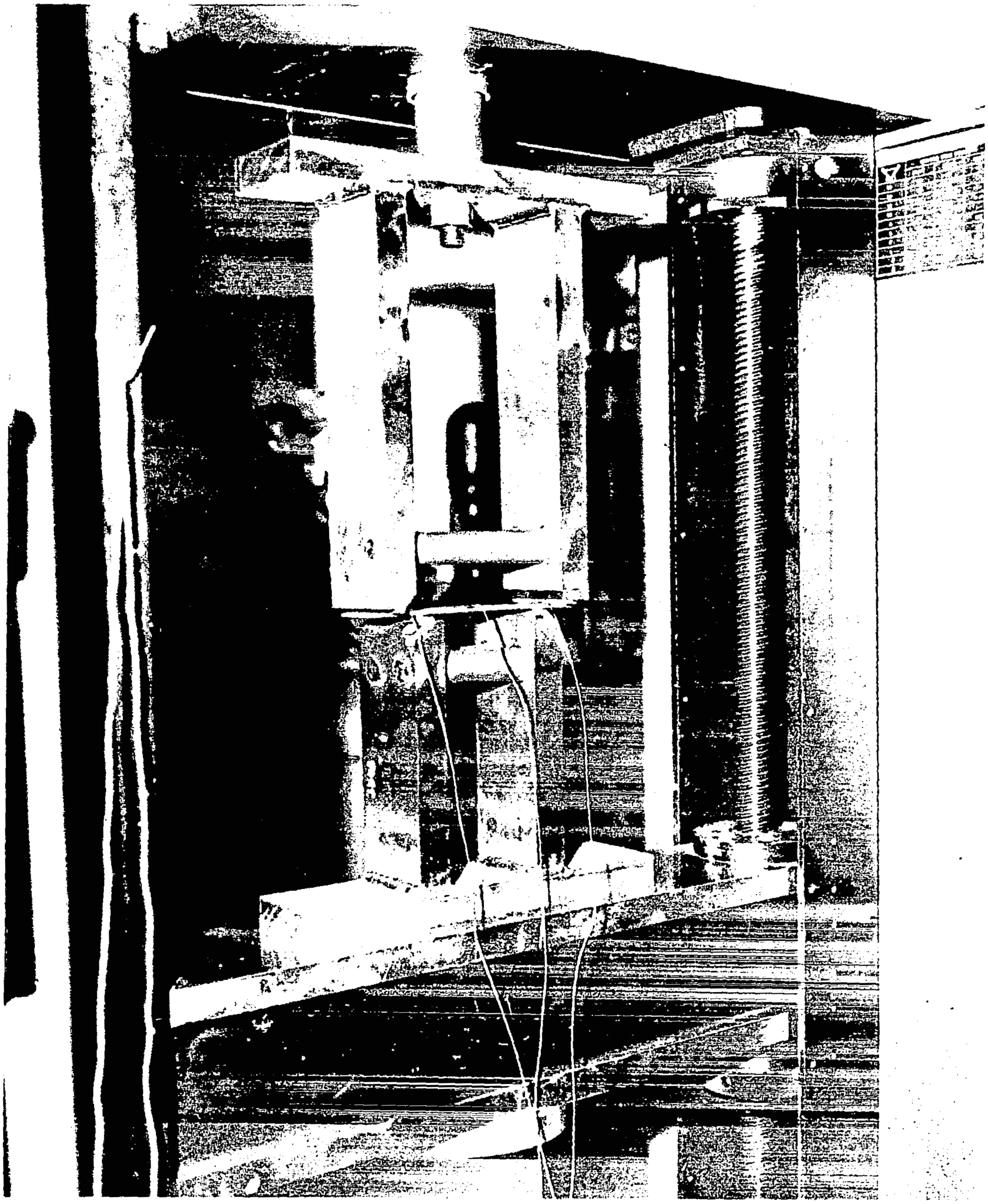


Figure 28. High Temperature Test Fixture With Waspaloy Specimen Installed and Furnace Removed

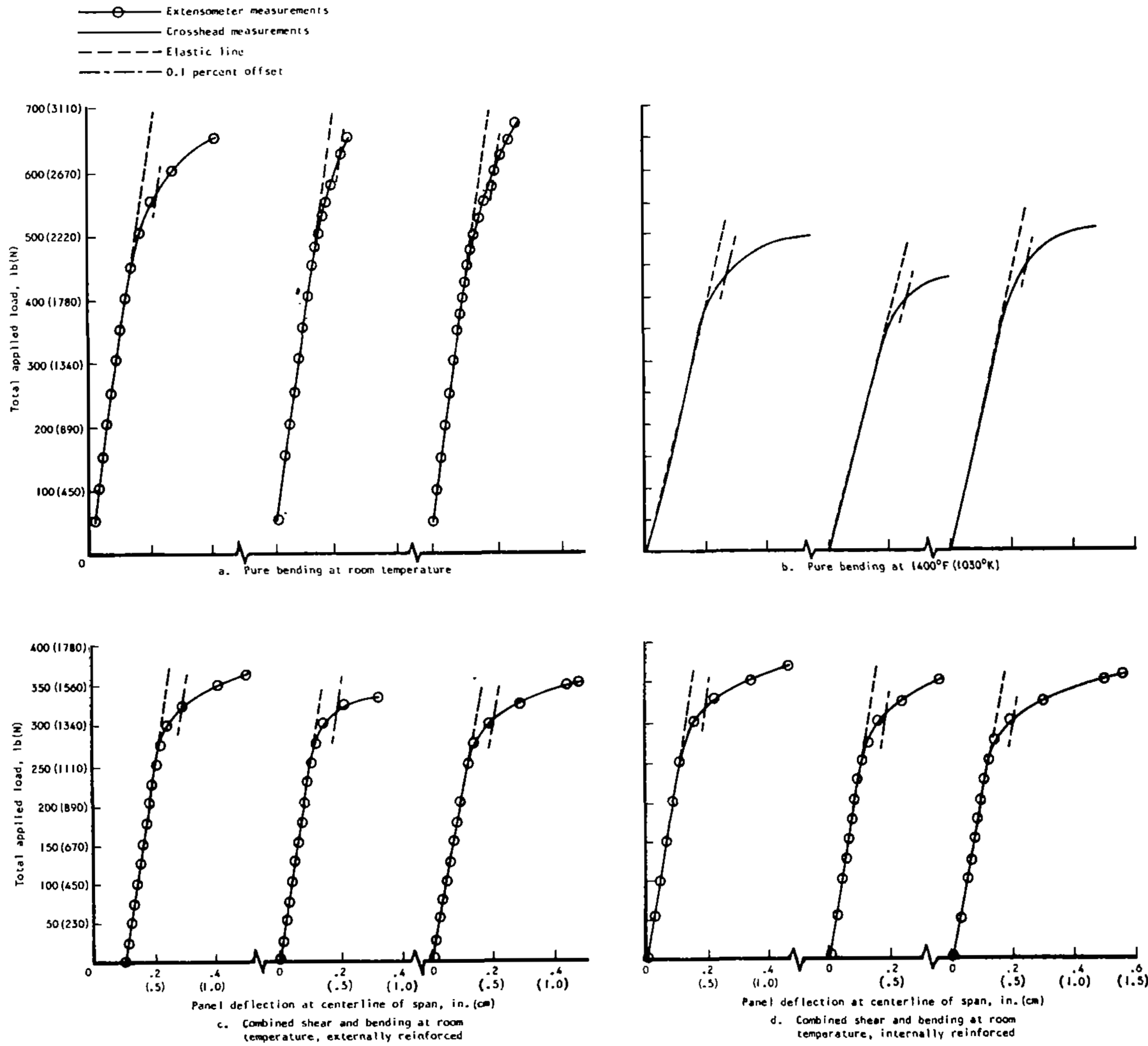


Figure 29. Load-Deflection Results For Waspaloy

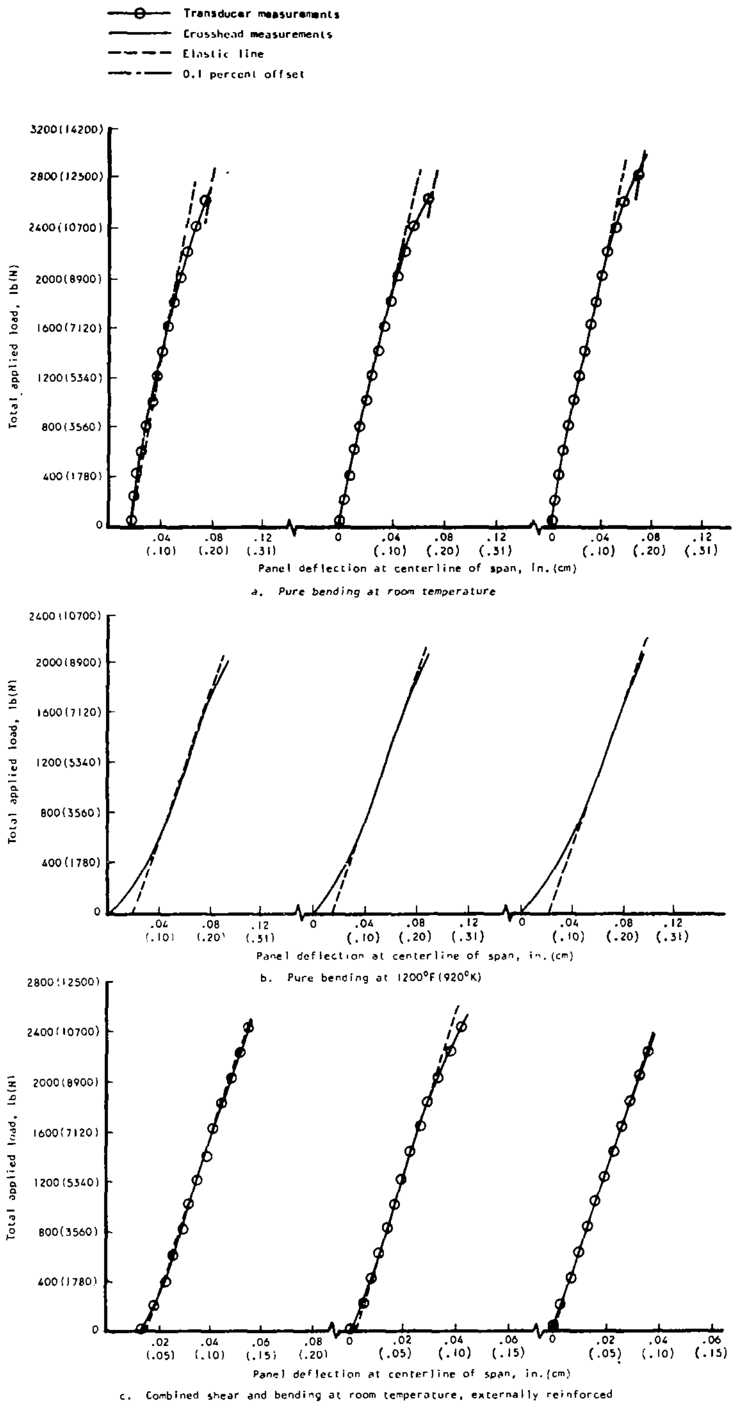


Figure 30. Inconel 718 Load-Deflection Curves

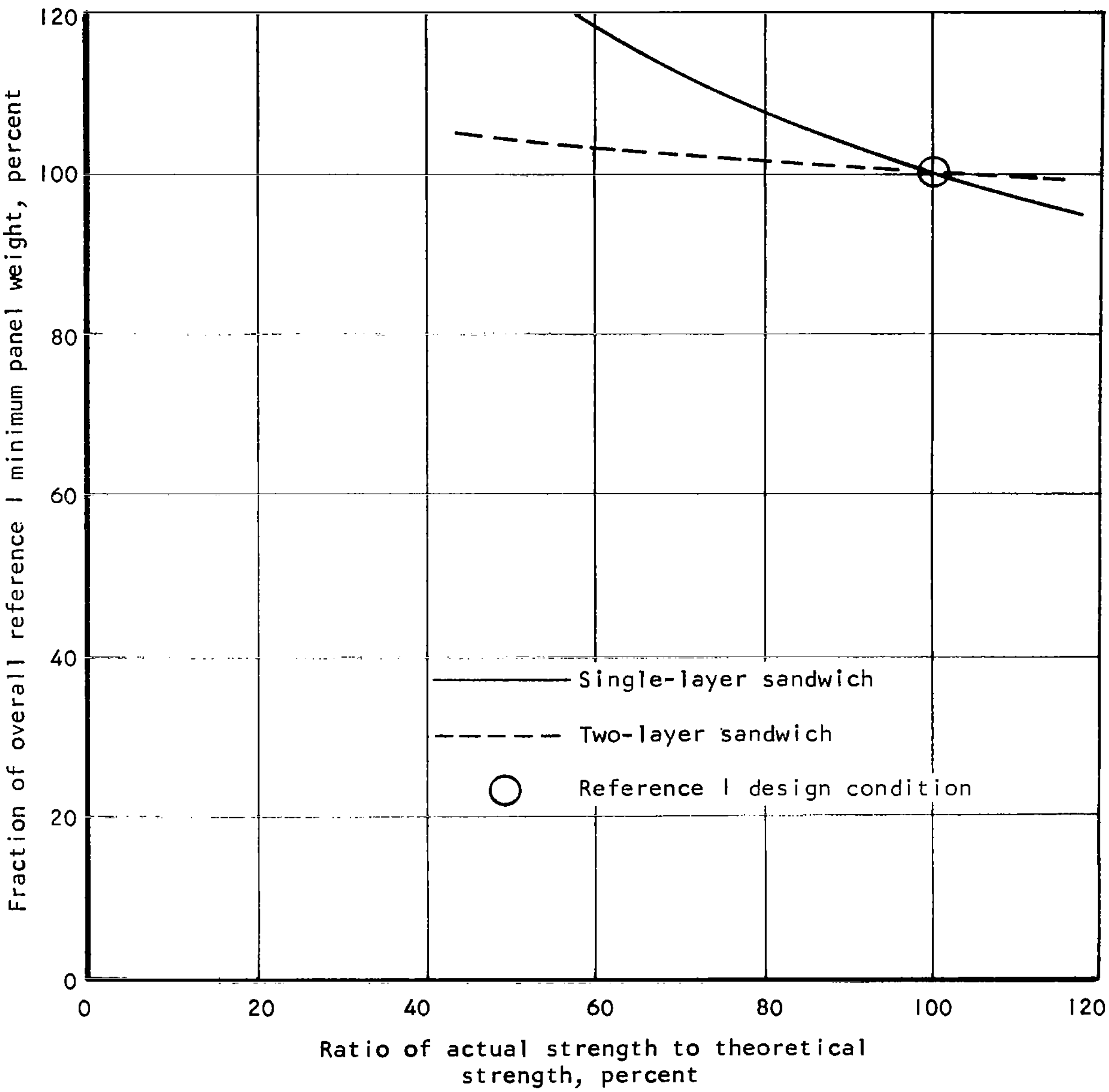
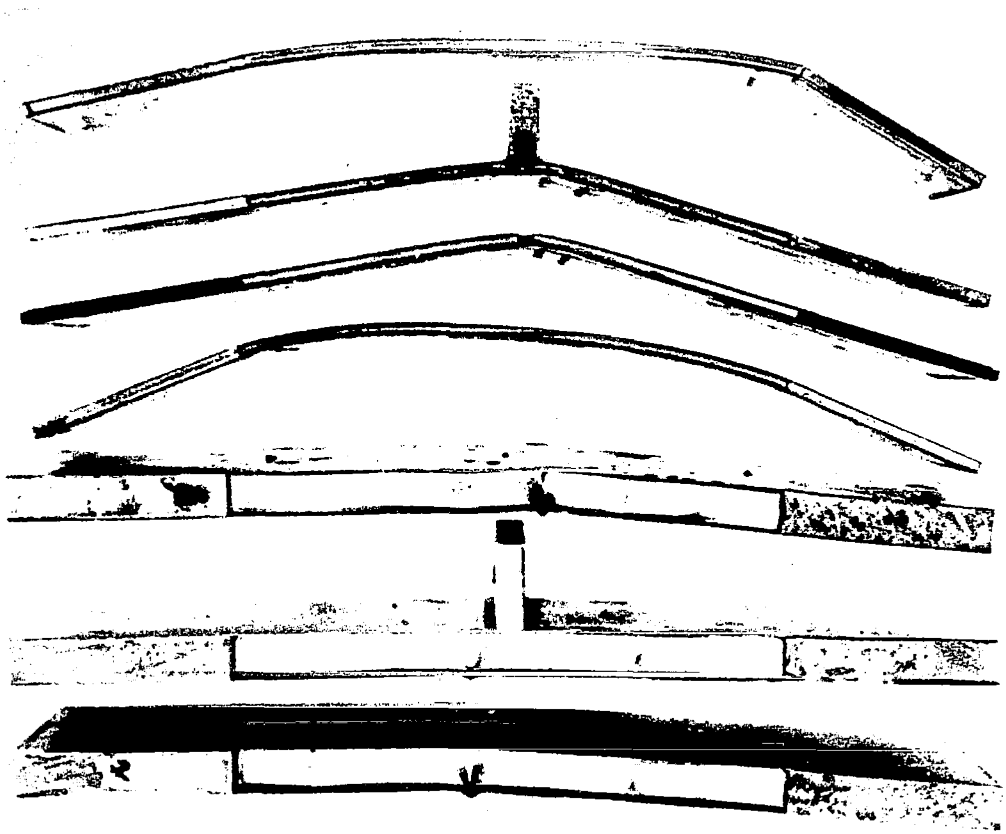


Figure 31. Effect of Panel Strength for External Pressure Loading on Overall Panel Weight



From top to bottom the specimens are;

(1) Waspaloy pure bending at 1400°F (1030°K)

(2) Waspaloy shear and bending, externally reinforced

(3) Waspaloy shear and bending, internally reinforced

(4) Waspaloy pure bending at room temperature

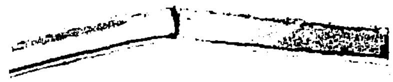
(5) Inconel 718 pure bending at room temperature

(6) Inconel 718 shear and bending

(7) Inconel 718 pure bending at 1200°F (920°K)

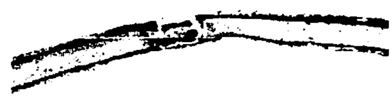
Figure 32. Flexure Test Specimens After Testing

a. Waspaloy pure bending at room temperature

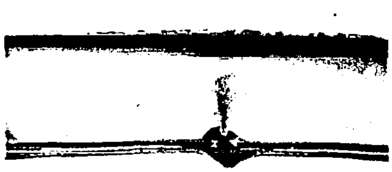


b. Waspaloy pure bending at 1400°F (1030°K)

c. Waspaloy bending plus shear at room temperature, external reinforcement



d. Waspaloy bending plus shear at room temperature, internal reinforcement



e. Inconel 718 pure bending at room temperature

f. Inconel 718 pure bending at 1200°F (920°K)

g. Inconel 718 bending plus shear at room temperature

Figure 33. Closeups of Flexure Test Failures

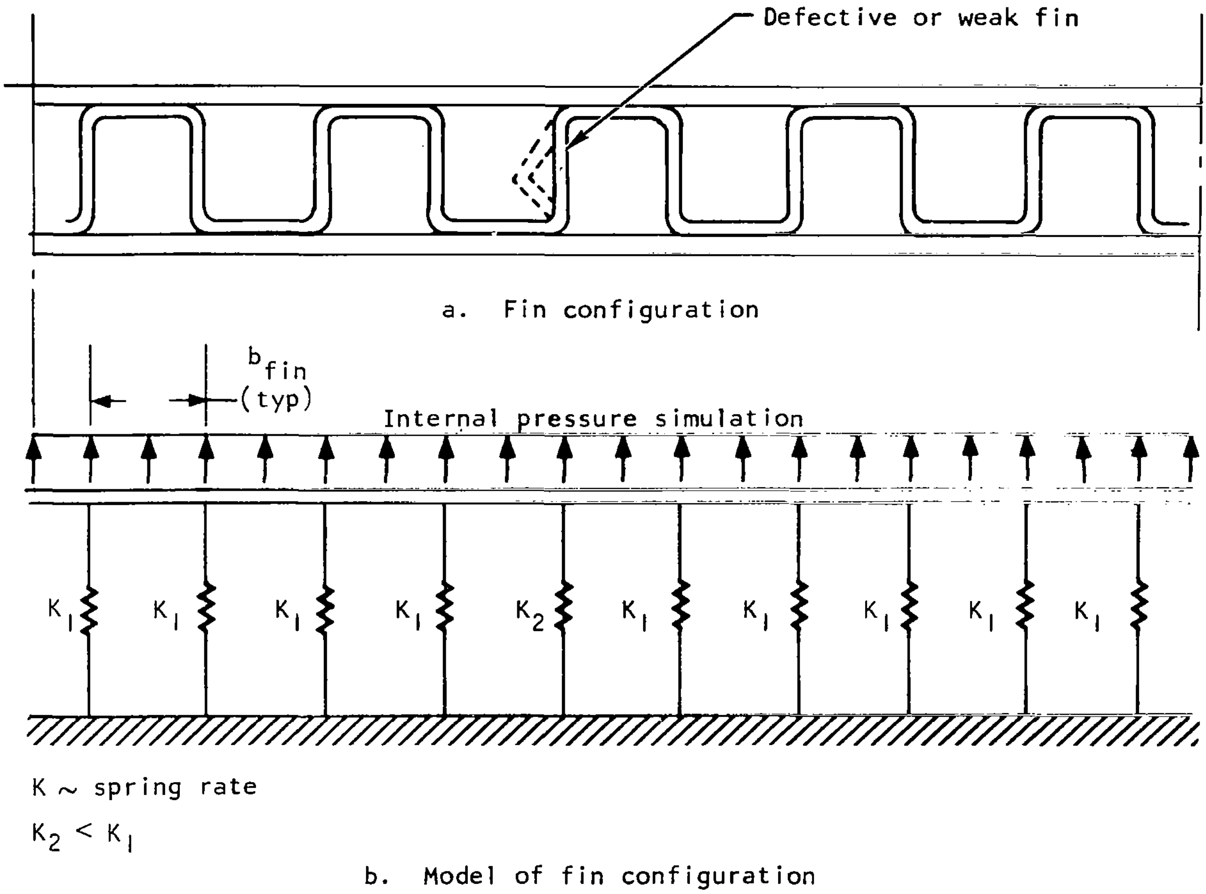


Figure 34. Defective Fin Analysis Model

Material	Temperature, °F(°R)	Defective fin strength, percent	Face sheet thickness, in. (cm)
Waspaloy			
	RT	0	0.005(0.013)
	RT	0	0.010(0.025)
	RT	0	0.020(0.051)
	RT	50	0.005(0.013)
	RT	50	0.010(0.025)
	RT	50	0.020(0.051)
	1400(1030)	0	0.005(0.013)
	1400(1030)	0	0.010(0.025)
	1400(1030)	0	0.020(0.051)
	1400(1030)	50	0.005(0.013)
	1400(1030)	50	0.010(0.025)
	1400(1030)	50	0.020(0.051)
Inconel 625			
	RT	0	0.005(0.013)
	RT	0	0.010(0.025)
	RT	0	0.020(0.051)
	RT	50	0.005(0.013)
	RT	50	0.010(0.025)
	RT	50	0.020(0.051)
	1400(1030)	0	0.005(0.013)
	1400(1030)	0	0.010(0.025)
	1400(1030)	0	0.020(0.051)
	1400(1030)	50	0.005(0.013)
	1400(1030)	50	0.010(0.025)
	1400(1030)	50	0.020(0.051)

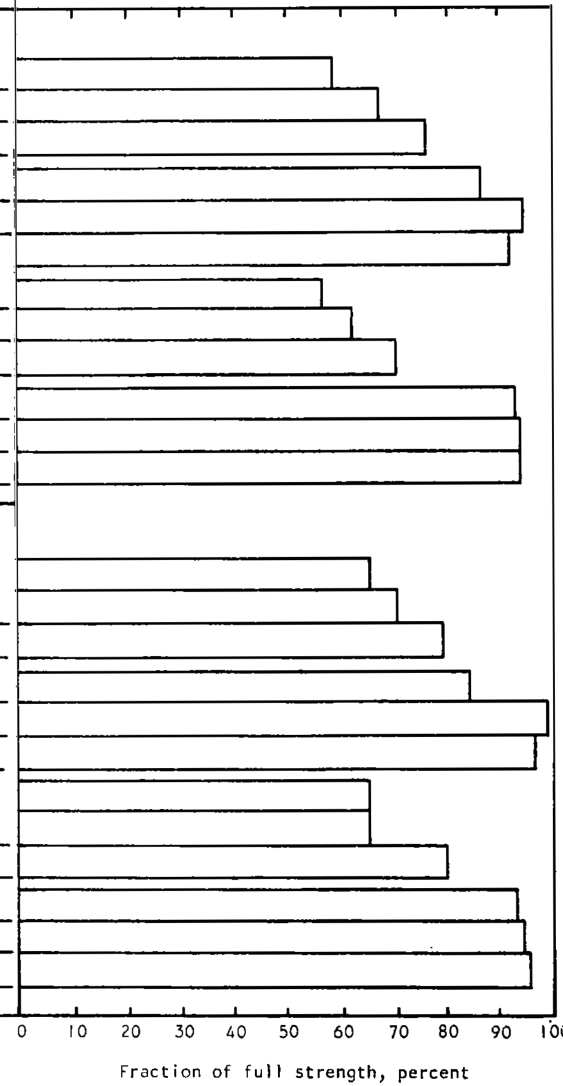
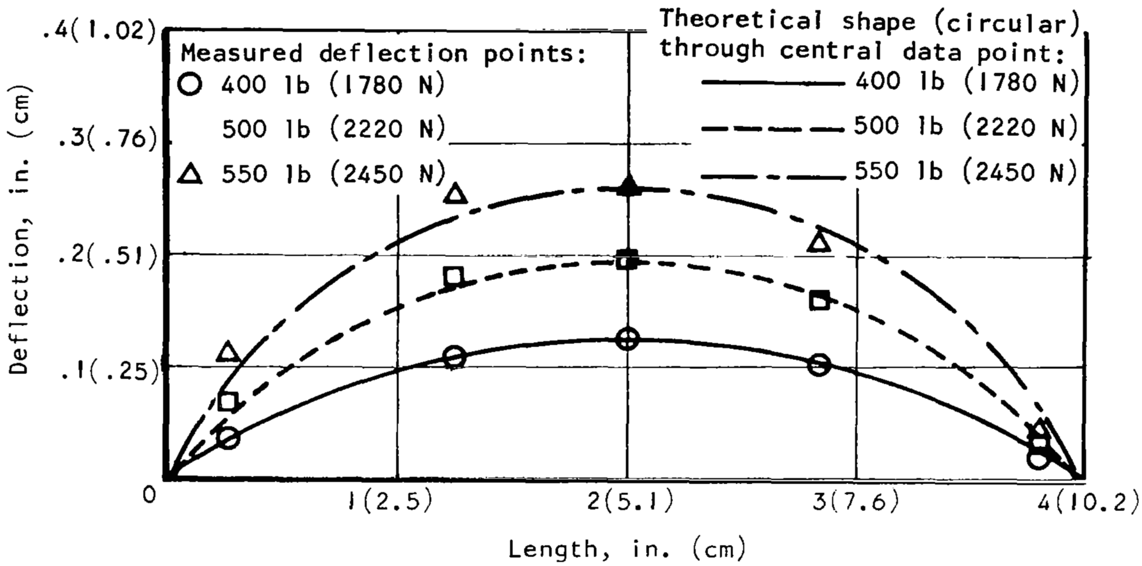
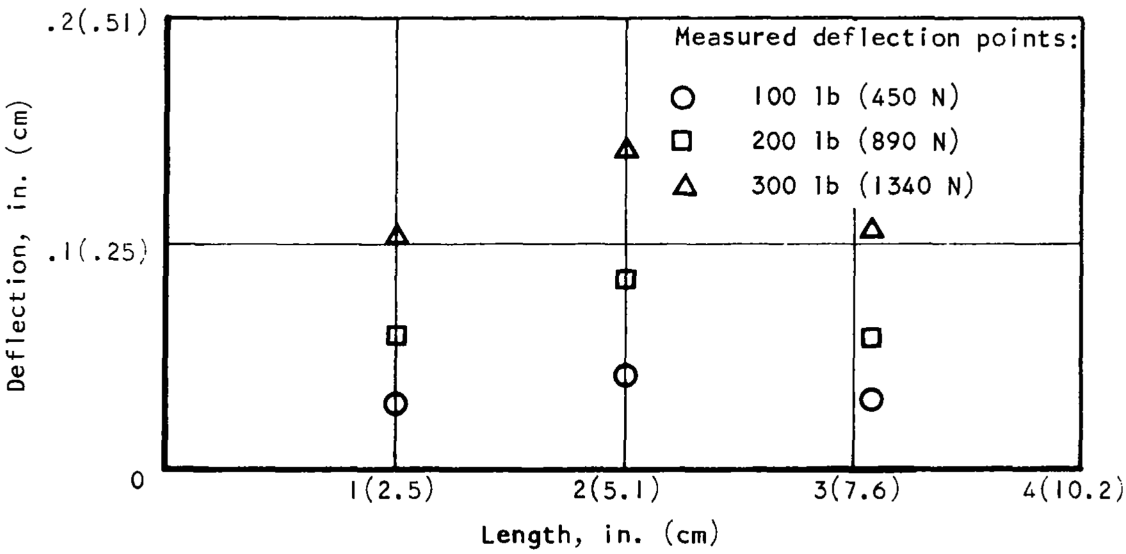


Figure 35. Theoretical Burst Strength Ratio For a Panel With One Defective Fin. Fin Geometry Consists of 0.004 in. (0.010 cm) Thickness, 0.075 in. (0.191 cm) Height and 0.05 in. (0.13 cm) Spacing



a. Pure bending measured at five points along the specimen compared to circular shape



b. Combined shear and bending at three points along the specimen

Figure 36. Typical Waspaloy Panel Deflected Shapes at Room Temperature

Elastic stress distribution

Elastic-plastic stress distribution, Waspaloy stress-strain curve (figure 5)

σ_y = 128 ksi (880 MN/m^2)

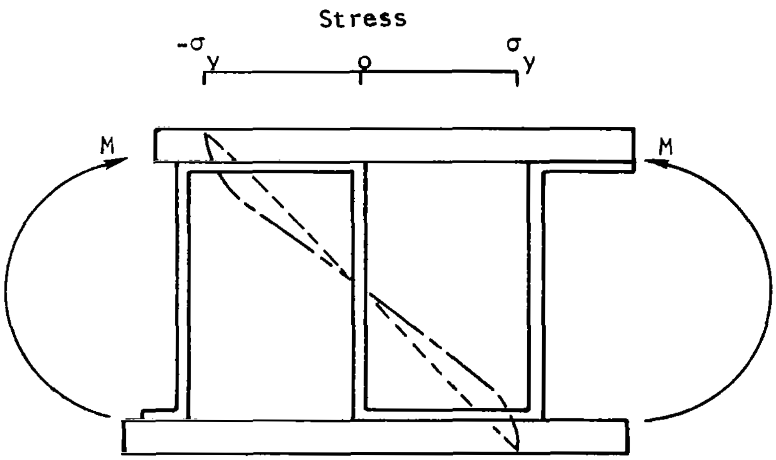


Figure 37. Comparison of Elastic and Elastic-Plastic Stress Distributions for Pure Bending

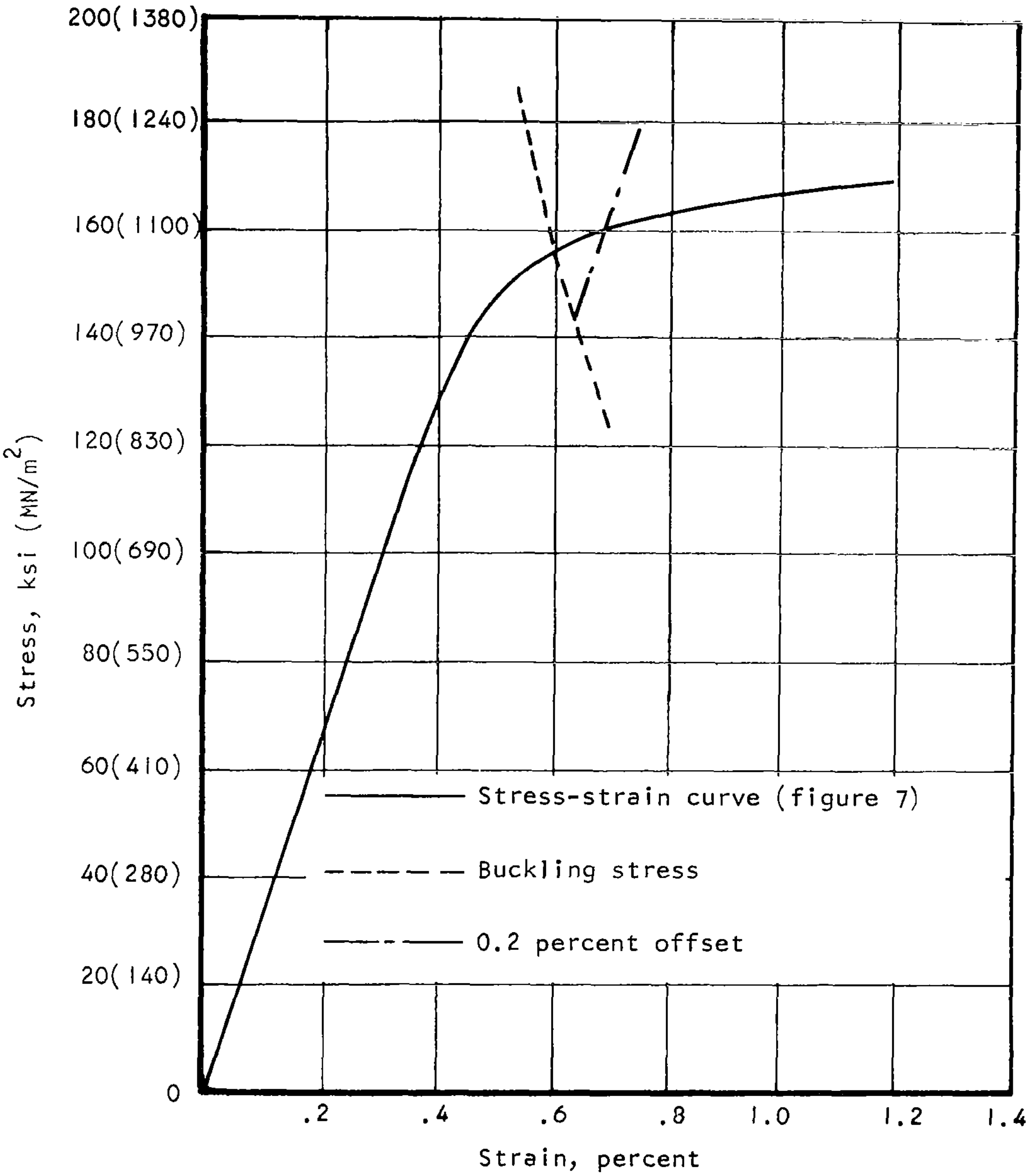


Figure 38. Inconel 718 Buckling Stress at Room Temperature for Fully Supported Chevron Web

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