ADVANCED OXIDE DISPERSION STRENGTHENED SHEET ALLOYS FOR IMPROVED COMBUSTOR DURABILITY*

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Introduction

Burner durability has become a serious problem in many current generation aircraft gas turbine engines. Advances in structural metal temperature capability and in burner hardware cooling technology have not kept pace with demands for more efficient (higher gas temperature) engine performance. Hastelloy X burners designed for around 871°C (1600°F) metal temperature operation are experiencing hotter streak conditions with heavy penalties to operating life. Both improved burner materials and designs are required to provide the large durability increase essential to future aircraft turbine engine operation and maintenance. A decrease in engine maintenance costs can result both from increased burner life and from reduced turbine section damage caused by burner distortion.

The substitution of advanced oxide dispersion strengthened (ODS) alloy sheet materials with improved creep strength and oxidation resistance compared to Hastelloy X can produce a significant increase in burner durability. Properties of two advanced ODS alloys, Incoloy MA 956 and Haynes Developmental Alloy 8077, compared to Hastelloy X indicate that they exhibit a 167°C (300°F) advantage in creep strength and in cyclic oxidation resistance (Figure 1). However, these ODS materials exhibit low cycle fatigue properties that show no improvement over Hastelloy X.

It is the objective of a NASA/P&WA MATE (Materials for Advanced Turbine Engines) program to evaluate burner design modifications that will take advantage of the improved creep and cyclic oxidation resistance of ODS alloys while accomodating the reduced fatigue properties of these materials. This program will culminate in a JT9D experimental engine test of the selected combustor design and ODS alloy. A status report of this MATE program is the subject of this paper.

Burner Environment

The principal failure modes for louvered combustor liners are creep buckling of the louver lips, oxidation and low cycle fatigue cracking, examples of which are shown in Figure 2. Creep buckling and oxidation are the dominant failure modes in long missions; low cycle fatigue is the dominant failure mode in short missions.

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Creep buckling of the louver lip results from the strain imposed by the constraint between the thermal growth of the hot louver lip and the relatively cooler weld (knuckle) area over an extended period of time (Figure 3). The louver lip develops a high stress that yields the material in compression. Continued cycling produces circumferential distortions which are sufficiently large to close off the louver gap in local areas (Figure 3). These local closures reduce the cooling air flow for the downstream louver, increasing the local temperature, and accelerating the buckling process on the downstream louver lip. Eventually the severity of the process reaches such a magnitude that rapid oxidation produces a burn-through of the cooled liner. When this point is reached, repairs are necessary.

Low cycle fatigue failures of conventional louver liners are the result of high radial temperature gradients through the liner producing excessive thermal strains. The hot side of the liner is subjected to average temperatures of about 871°C (1600°F) in the area of the welds. The cold side of the liner, in the area of the cooling holes, is subjected to temperatures of about 900°F. The severe thermal strain resulting from this radial temperature gradient is aggravated by unavoidable circumferential variations in hot side temperatures of at least 56°C (100°F).

Burner Design and Structural Analysis for ODS Alloys

Structural analysis of combustor liner cooling geometries was conducted to determine the stress and strain distribution produced by thermal and mechanical loads acting on the liner during an engine flight cycle. Using a finite element analysis, the elastic stress state can be defined with elastic modulus and the coefficient of thermal expansion as a function of temperature. While the thermal analysis and elastic stress are affected by the physical properties of the materials, burner life prediction is dependent upon mechanical properties.

The design system (Figure 4) incorporates the technique of "exhaustion of ductility" for calculating life predictions (ref. 1). The interaction of creep and fatigue modes in a cumulative damage model becomes the failure criterion determined for the design system. For ODS sheet alloys, the ductility determined from tensile data and implied from LCF data is about 5%, whereas the creep ductility measured in creep testing can be 0.1-0.2%. An available ductility of 0.1% for ODS alloys was assumed throughout the design phase. The structural analysis and life predictions are based on the engine operating conditions applicable to an advanced energy efficient engine.

In the design phase of this program, the operating strains for the ODS alloys were minimized in a series of five candidate advanced combustor designs. This was accomplished by designing a series of segments in the circumferential direction to significantly reduce the hoop (circumferential) strains and by eliminating fixity between the hot wall and cold wall shell to reduce radial constraint (strain). Based on the thermal and structural analysis for these five combustor designs the predicted lives were calculated for both ODS sheet alloys.

In addition to the predicted lives for these combustor designs, other factors for assessing the relative benefits of the designs and for selecting the final two were considered; these factors included liner fabricability and engine maintenance and operating costs. The maintenance cost (MC) is based on predicted lifetimes, on initial construction cost and on the type of repair procedure employed for the design. The direct operating cost (DOC) is derived by using the initial fabrication cost, the overall weight and the maintenance cost. Equally important in the determination of the particular designs worth pursuing is the consideration of risk for the construction and repairability of a given design. Based on significant life improvement, lower maintenance and direct operating costs and estimated moderate risk factors for fabrication and repairability, two designs were selected for continued evaluation: 1) a mechanically attached, film cooled segmented louver and 2) a mechanically attached, transpiration cooled segmented twin wall. Schematic diagrams of these two designs are presented in Figures 5 and 6. These two designs were assessed relative to a current commercial engine JT9D-59/70 using the same design selection criteria. Comparison of these designs using ODS alloys to the film cooled JT9D combustor of Hastelloy X in Table I shows a four times improvement in life reflecting the high temperature strength of ODS alloys and the reduced strain range present in the two segmented designs. The lower cooling air levels in the transpiration cooled, twin wall reflects the increased effectiveness in that design. While the initial construction cost and the combustor weight are somewhat higher than for the standard combustor, the maintenance cost and direct operating costs of the advanced designs are significantly lower. It must be pointed out that the relative changes in DOC represent decreases in overall engine operating cost and are not limited solely to combustor cost.

Mechanically Attached, Film Cooled Segmented Louver

A mechanically attached, segmented louver using current film cooling techniques (Figure 5) is attractive and can accomodate the low strain capability of ODS alloys. By mechanically attaching with rivets each ODS segment to a Hastelloy X shell (cold wall) rigidly at only one location and providing room at the other rivet and bushing locations for differential thermal expansion of the hot segments relative to the cold shell, circumferential and radial constraint does not occur under these conditions. The only thermal strains present are those generated from the non-linear temperature variation within each segment. The failure mode in this design is established as initiation of a 0.79mm (1/32") crack at the louver lip.

Calculating the combustor liner life based on the number of cycles of exhaust 0.1% strain as the criterion, the predicted life for MA 956 is in excess of 10,000 cycles, while the predicted life for HDA 8077 is 2000 cycles (Table II).

Mechanically Attached, Transpiration Cooled, Segmented Twin Wall

The "twin wall" transpiration cooled design is an advanced cooling technique with the capability of significantly reducing metal temperature and/or cooling flow and thermal strain. A schematic cutaway view of this transpiration cooled, segmented twin wall combustor is shown in Figure 6. The transpiration cooled panel is attached to the impingement plate with a series of studs so that leakage around the edge of the panel at the operating temperature of 1010°C (1850°F) is less than 10% of the panel cooling air. However, to reduce the strain at maximum temperature, the panel is pre-stressed at room temperature to a predetermined contour duplicating the shape it will assume at the operating temperature of 1010°C (1850°F). An impingement plate which serves as a mandrel employs a contoured edge radius and a centeral positioning stud to impart the desired deflected panel shape.

Analysis shows that during simulated engine operation as the average temperature and the through-thickness gradient increase, the mechanically induced pre-stresses are reduced and become essentially nonexistent at the operating temperature. The only stress at operating temperature is a small cooling air pressure load. The nature of this design is such that the largest stress occurs at 20°C (68°F) where the material strength is the highest. The location of the high stresses is in the center of the edges of the panel at room temperature; during heat-up although some stress redistribution occurs, the maximum stress remains at the center of each edge. Throughout the thermal loading, the maximum stress level remains below the proportional limit so that no plastic damage occurs.

The current method for predicting the effect of hole arrays in a transpiration cooled geometry on the thermal-mechanical fatigue life employs the concept of linear elastic, isotropic fracture mechanics (ref. 2). For transpiration cooled designs, failure is defined as linkup of cracks emanating from adjacent cooling holes. As a result of prestress, operating stress,and thermal cycle, the predicted service lives for the ODS alloys are in excess of 10,000 cycles (Table II). Since there is no thermal interaction between the panel and the studs due to prestressing, at the operating temperatures the cooled studs support only a small radial pressure load.

Alloy Evaluation

Mechanical property testing of the two candidate advanced ODS alloys, Incoloy MA 956 and HDA 8077, was directed towards the selection of one alloy for evaluation in the remainder of the program. The three main criteria for this alloy selection were creep, oxidation and thermal fatigue resistance. Three separate measures of thermal fatigue resistance were defined: creep ductility, isothermal LCF life, and hot spot blister (thermal cycling) cracking.

Incoloy MA 956 alloy sheet of 1.1-1.3mm (0.043-0.051") thickness was supplied by Wiggin, Ltd. of the International Nickel Company and HDA 8077 alloy sheet of 1.1-1.4mm (0.043-0.055") thickness supplied by Cabot Corporation. The nominal chemistry of each alloy is shown in Table III; both alloys are strengthened by a fine dispersion of yttrium oxide (Y_2O_3). The sheet materials were produced by mechanical alloying of powder, powder consolidation and a series of hot and/or cold rolling procedures. These processing techniques result in coarse "pancake" grains in the plane of the sheet and elongated grains through the thickness in both alloys (Figure 7) with fine yttria particles dispersed throughout the structure.

Creep evaluation of MA 956 and HDA 8077 ODS alloys and Hastelloy X, bill-of-material in JT9D combustor liners, in the 871-1093°C (1600-2000°F) range demonstrates significant creep strength advantage for both ODS alloys over Hastelloy X at the higher temperatures (Figure 8); approximately 167°C (300°F) for MA 956 compared to Hastelloy X. These Larson-Miller curves represent an average of time to 0.1% creep strain data generated on these sheet alloys within the present program. Comparison of the ODS alloys shows that HDA 8077 sheet possesses time to 0.1% creep strain and final creep ductility superior to those of MA 956 sheet. Figure 8 compares the high creep ductility of Hastelloy X to the limited ductility of the ODS alloys. The final creep ductility is defined as the last creep extension measurement within two hours of specimen failure. The MA 956 sheet, which is not cross rolled, is anisotropic as exhibited by the difference in creep ductility between the longitudinal (parallel to rolling direction) and transverse (perpendicular to rolling direction) orientations. The average transverse creep ductility of MA 956 is lower than the longitudinal ductility, although the minimum values are similar. There is no difference in time to 0.1% creep strain (creep strength) for these orientations; however, the creep-rupture life for the transverse orientation is lower reflecting the decreased ductility.

Cyclic oxidation testing was conducted at 982°C (1800°F) using a six minute cycle with cooling to 316°C (600°F) using a four minute hold at maximum temperature. Specimens of the the three alloys were tested in a rotating fixture subjected to a JP4-R fuel gas flame for heating and forced air for cooling. Surface attack was determined metallographically on tested specimens. The results of this oxidation testing (Figure 9) show that there was insignificant surface attack <.013mm (0.0005") in MA 956 after 1000 hours and that it is superior to HDA 8077 which had .025-0.051mm (.001-.002") of surface oxidation. Both ODS sheet alloys possess excellent oxidation resistance compared to Hastelloy X, which exhibited 0.36mm (.014") of surface oxidation and spallation after 1000 hours. The relative oxidation resistance of MA 956 and Hastelloy X were verified in a duplicate 1000 hour oxidation test using different heats of material.

Isothermal low cycle fatigue (LCF) testing utilizing strip specimens in a fully reversed bending mode was conducted for the three alloys at 760°C (1400°F) and 871°C (1600°F) with a ± 0.25% strain range (Figure 10). Specimen fatigue life is defined as failure into two pieces. At 760°C (1400°F), the Hastelloy X and HDA 8077 showed similar average failure lives, although the latter exhibited a high degree of data scatter, and both were somewhat higher than the MA 956 life. At 871°C (1600°F), Hastelloy X LCF life was lower than MA 956; however, MA 956 demonstrated approximately a five-fold higher life than HDA 8077 sheet. Limited testing at 982°C (1800°F) of the ODS alloys showed this same 5:1 life advantage of MA 956 over HDA 8077.

A "hot spot blister test" was designed to produce localized thermal fatigue cracking and/or deflection similar to that produced by flame impingement on a burner louver in an engine. Seventy-six millimeter (3.0 inch) diameter disks were subjected to a thermal cycle (5 cycles/min.) from a Tmin of 538°C (1000°F) to a Tmax of 982°C (1800°F) by use of an alternating oxy-acetylene flame and a cool air blast (Figure 11). The Tmin temperature of 538°C (1000°F) was maintained on the edge of the disk using a propane gas burner. Strain analysis of this hot spot blister test shows that compressive strain peaks at maximum temperature and tensile strain at minimum temperature; this type of strain-temperature cycle is typical for current engine combustors. At pre-determined cycle intervals the degree of surface cracking was recorded visually and specimen deflection height was measured. Actual crack depths were determined metallographically on discontinued test samples. As strain range on the cold side of the "hot spot blister" specimen is calculated to be much higher than that of the hot side, initial cracking was observed on the cold side of the sheet. Metallographic determination of cold side cracking shows that MA 956 experiences substantially earlier crack initiation and more severe cracking than HDA 8077 which, in turn, displays more cold side cracking than Hastelloy X as shown in Figure 12. Hastelloy X deflects substantially more than the two ODS alloys, while MA 956 and HDA 8077 exhibit similar deflection heights. The specimen deflections reflect the relative creep strengths of each of the three alloys. Additional testing to a Tmax of 1093°C (2000°F) showed an identical ranking of the alloys in cracking and deflection.

Alloy Selection

Both ODS alloys demonstrated the 167°C (300°F) advantage in creep and oxidation resistance over Hastelloy X. Comparing the ODS alloys, MA 956 is superior in oxidation resistance and isothermal LCF life and HDA 8077 is slightly better in creep strength and ductility and is superior in hot spot blister cracking resistance. Under the MATE program, concurrent to the materials evaluation phase, the two alloy manufacturers were engaged in a sheet reproducibility program. Wiggin, Ltd. of INCO successfully demonstrated MA 956 sheet product reproducibility for both sheet quality and mechanical properties in a second heat of material; Cabot Corporation was unable to reproduce the intial excellent formability and creep properties of HDA 8077 in subsequent sheet product. While neither ODS alloy exhibited an obvious overall superiority in properties, on the basis of product reproducibility and excellent life predictions in both combustor designs, Incoloy MA 956 alloy was selected for evaluation throughout the balance of the MATE program, including component and experimental engine testing.

Low Cycle Fatigue Structural Tests

LCF rig testing of components of the two candidate designs using MA 956 and Hastelloy X alloys is directed toward selection of one design for experimental test in a JT9D engine. Such component rig evaluation allows for testing of the structure of each design under simulated combustor conditions. Feasibility studies were conducted to define the best approaches for LCF structural assessment of the two ODS combustor designs.

For the mechanically attached, film cooled, segmented louver design (riveted louver) a single louver segment of MA 956 or Hastelloy X attached to the inside of a Hastelloy X shell in conjunction with a double return pie-wound induction coil and external cooling air successfully simulated the temperature profile along the louver as shown in Figure 13. The test consisted of a 45 second heating cycle to the desired temperature profile with a maximum temperature of 1010°C (1850°F) at the lip, a two minute hold at this condition and a 30 second cooling cycle to a louver lip temperature of 538°C (1000°F).

A total of six (three each) of MA 956 and Hastelloy X riveted louver segments were tested in this induction heated rig; the results are reported in Table IV and Figure 14. MA 956 segments exhibited considerably more dimensional stability (less distortion) than did the Hastelloy X segments. While there was a significant degree of test scatter in both materials, a comparison on the basis of cycles per millimeter points up the greater resistance to buckling for the MA 956 alloy. Typical bow of the panels removed from the Hastelloy X shell are shown in the photograph in Figure 14.

No crack indications were evident by Post Emulsion Fluorescent Penetrant inspection on any of the test segments. The Hastelloy X tests were discontinued when the bow in the segments became excessive and preluded maintaining the axial temperature profile on the bow or distortion; specifically after 66, 242 and 1,500 cycles. The MA 956 tests were discontinued after 4000, 5000 and 6000 cycles. These test results demonstrate the excellent creep resistance of MA 956 compared to Hastelloy X in this component test and the low strain ranges achieved as evident by no cracking in the segmented louvers.

A second component test of the riveted louver design was defined and conducted in a thermal cycle rig (Figure 15). The axial temperature profile established in the louver at transient conditions approximated the steady state profile of the induction heated rig test. Rotating gas burners impinge on the lip of the segmented louvers during heat-up and an air manifold directs cooling air onto the louver lips during the cool-down for a total cycle time of 60 seconds. The lip is cycled between 954°C (1750°F) and 593°C (1100°F), while the Hastelloy X shell is cycled between 538°C (1000°F) and 399°C (750°F). In this test, alternating segments of MA 956 and Hastelloy X were installed around the ID circumference of the Hastelloy X shell. To date, the first test component has achieved 4000 cycles with no distress evident in the attachment rivets or bushings of any of the louver segments. Additional thermal cycle testing of this component and of a duplicate is scheduled.

For LCF structural testing of the transpiration cooled, twin wall design the test rig is shown in Figure 15. A stationary gas burner heats the hot side of the pre-stressed panel/impingement plate assembly which rests on a box providing a plenum of cooling air. The hot side of the panel reaches a maximum temperature of 927°C (1700°F) and an average through-thickness gradient of 22C° (40F°) and is lowered from the flame, applying increased cooling air flow until it cools to 649°C (1200°F) at which time it is raised back into the gas flame and the airflow is reduced. The entire test cycle is 30 seconds in length (22 sec. heating and 8 sec. cooling). An initial MA 956 panel tested for 2000 cycles contained laser drilled cooling holes; all subsequent panels were electrochemical machined (ECM) because of improved cooling hole integrity in the MA 956 panels. The film from the transpiration holes is an effective cooling mechanism and useful in obtaining maximum life of the segment. Since the holes are ECM drilled at an acute angle, one edge of the panel in the rig is void of film. (In actual engine use, a layer of film would be established to provide insulation until the transpiration film became established.) This region of low film in the rig tested panel exhibited numerous hot and cold side cracks between the edge and the middle rivet (Figure 16). The cracks extended from acute corners of the cooling corners of the cooling holes in this high strain region of the panel (edge center); several cracks linked up to form a larger cracks. The laser holes contained pre-existing .08-.10mm (.003-.004") cracks resulting in earlier crack growth than would be expected with ECM holes. MA 956 and Hastelloy X pre-stressed panels have each achieved 10,000 cycles without any evidence of crack initiation at the ECM holes.

Summary

A NASA-sponsored MATE project for ODS alloy combustor liners is in progress; a summary of the program to date follows:

1. Five advanced combustor designs were evaluated based on preliminary analysis and life predictions, on construction and repair feasibility and on maintenance and direct operating costs. Two designs - the film cooled, segmented louver and the transpiration cooled, segmented twin wall - were selected for LCF component testing.
2. Detailed thermal and structural analysis of these designs established the strain range and temperature at critical locations resulting in predicted lives of 10,000 cycles for MA 956 alloy.
3. ODS alloys, MA 956 and HDA 8077, creep strength and oxidation resistance demonstrated a 167°C (300°F) temperature advantage over Hastelloy X alloy. MA 956 alloy was selected for mechanical property and component test evaluations.
4. MA 956 was superior to Hastelloy X in LCF component testing of the film cooled, segmented louver design.
5. Thermal cycle testing of the riveted louver design and LCF structural testing of the twin wall design are in progress.

References

1. Polhemus, J.F., Spaeth, C.E.., and Vogel, W.H., "Ductility Exhaustion Model for Prediction of Thermal Fatigue and Creep Interaction", Fatigue at Elevated Temperatures, ASTM STP 20, American Society for Testing Materials, 1973, Pages 625-636.
2. Gemma, A.E. and Phillips, J.S., "The Application of Fracture Mechanics to Life Predictions of Cooling Hole Configurations in Thermal-Mechanical Fatigue", Engineering Fracture Mechanics, 1977, Vol. 9, Pergammon Press, Great Britain.

LIFE/COST COMPARISON OF DESIGNS

(MA 956)

	Cooling air % W_{AB}	Total strain range (%)	Life cycles/hrs	Cost $ K	Weight lbs	MC $/hr	DOC %
JT9D base	45	~0.40	1.0	1.0	1.0	1.0	Base
Film cooled, segmented louver	45	0.145	4X	1.26x	1.06x	0.63x	– 0.21
Segmented twin wall	33	0.225	4x	1.48x	1.03x	0.65x	– 0.21

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Table I

ODS ALLOY COMPARISON

	MA 956		HDA 8077	
Design	Total strain range (%)	Life (cycles)	Total strain range (%)	Life (cycles)
Film cooled, segmented louver	0.145	>10,000	0.185	2,000
Transpiration cooled, segmented twin wall	0.225	>10,000	0.245	>10,000

- Strain range differences are associated with thermal expansion characteristics

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Table II

CANDIDATE ODS ALLOYS

	Fe	Ni	Cr	Al	Ti	Y_2O_3
Incoloy MA 956	Bal	—	20.0	4.5	0.5	0.5
HDA 8077	—	Bal	16.0	4.0	—	0.8

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Table III

PROPERTIES OF CANDIDATE ODS ALLOYS

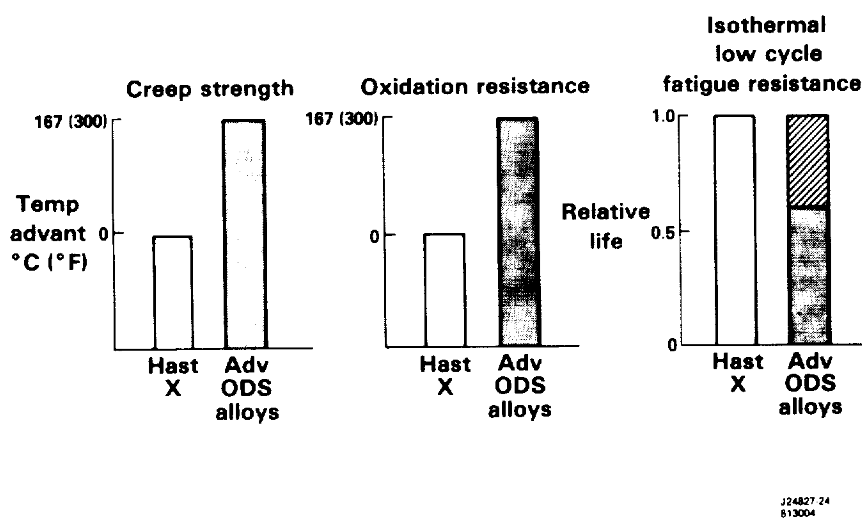


Figure 1

COMBUSTOR FAILURE MODES

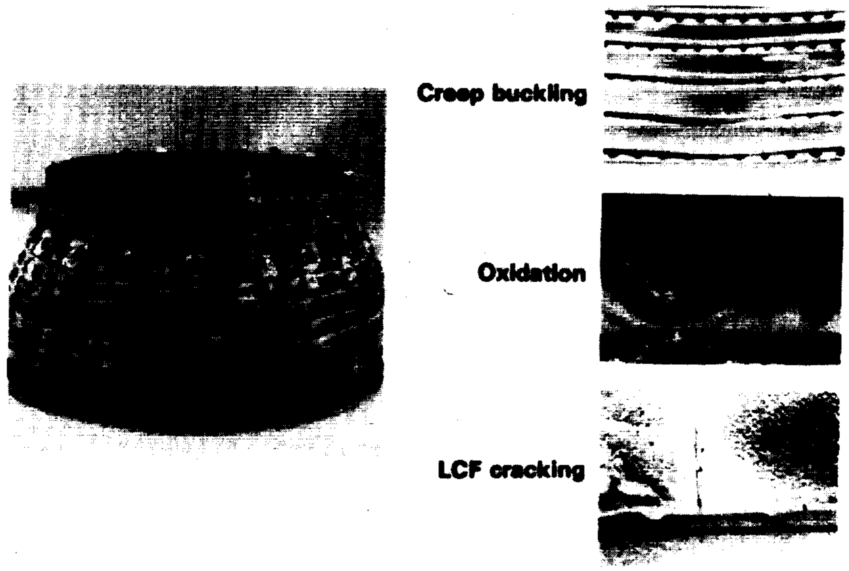


Figure 2

CONVENTIONAL FILM COOLED LOUVER COMBUSTOR

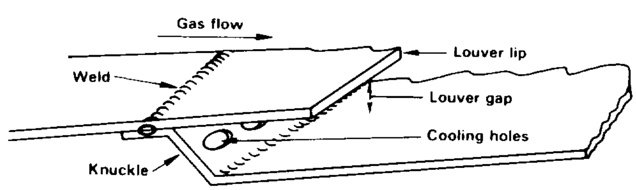


Figure 3

DESIGN SYSTEM

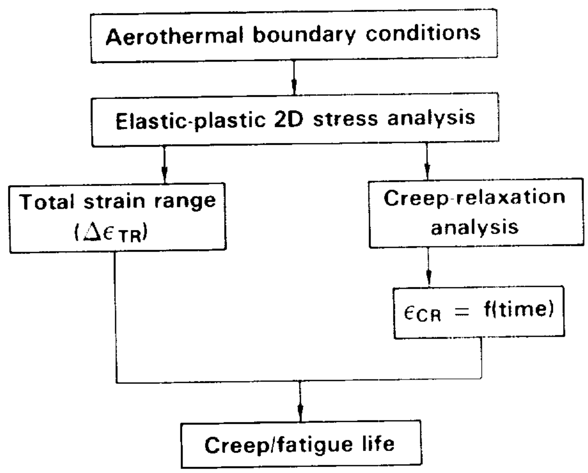


Figure 4

MECHANICALLY ATTACHED, FILM COOLED SEGMENTED LOUVER

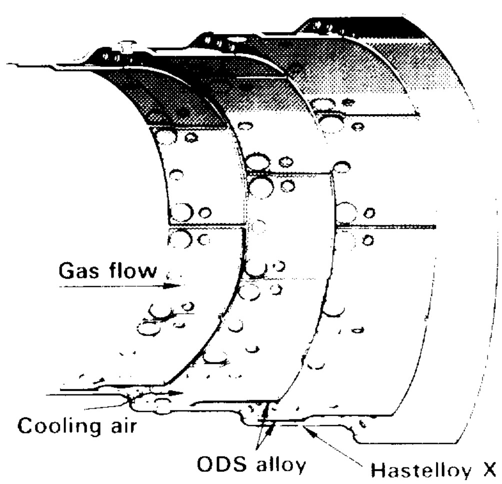


Figure 5

TRANSPIRATION COOLED, SEGMENTED TWIN-WALL DESIGN

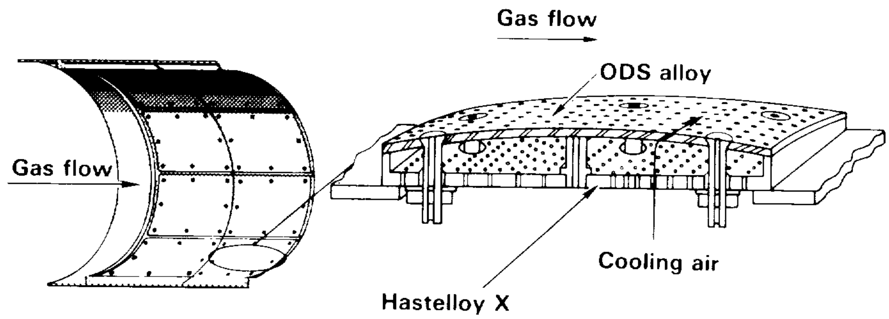
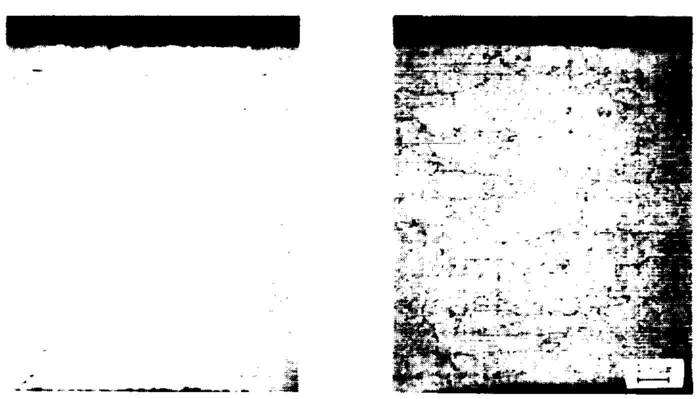


Figure 6

TYPICAL MICROSTRUCTURES OF CANDIDATE ODS SHEET ALLOYS



MA 956

HDA 8077

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Figure 7

CREEP PROPERTIES

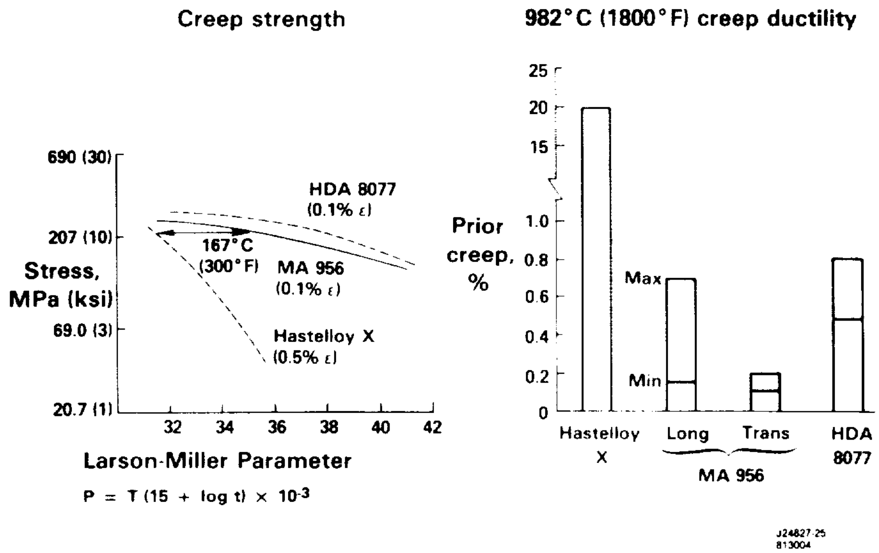


Figure 8

982°C (1800°F) CYCLIC OXIDATION

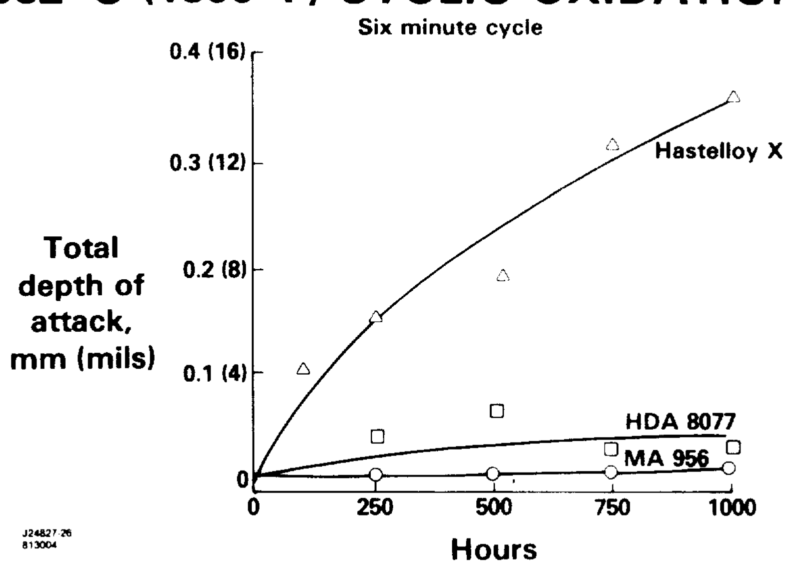


Figure 9

LOW CYCLE FATIGUE

± 0.25% strain, 40 cpm

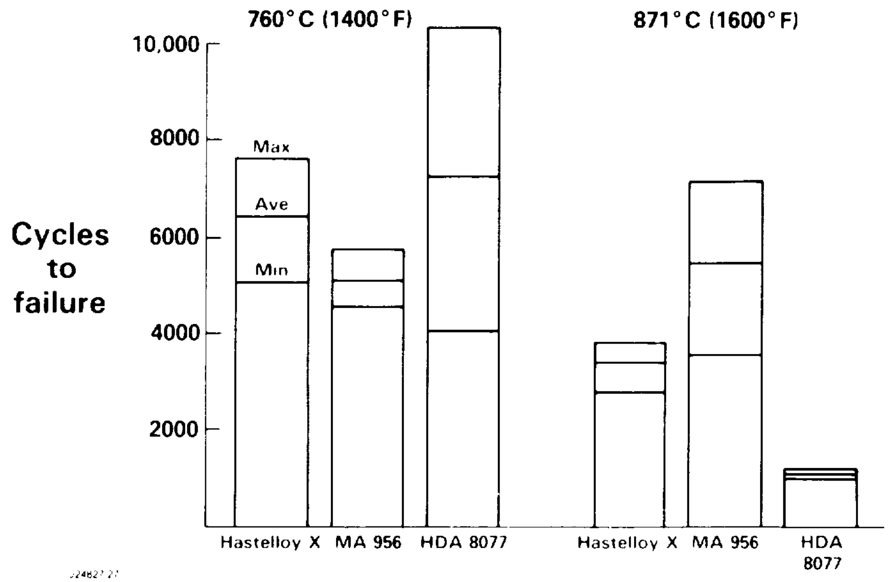


Figure 10

THERMAL FATIGUE

Hot spot blister test

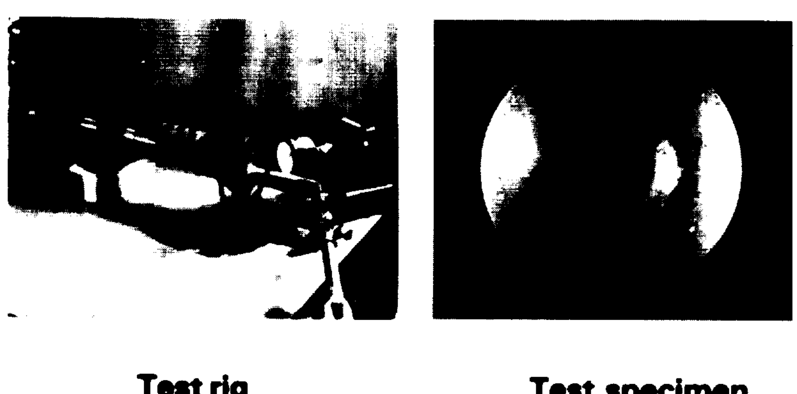


Figure 11

HOT SPOT BLISTER TEST RESULTS

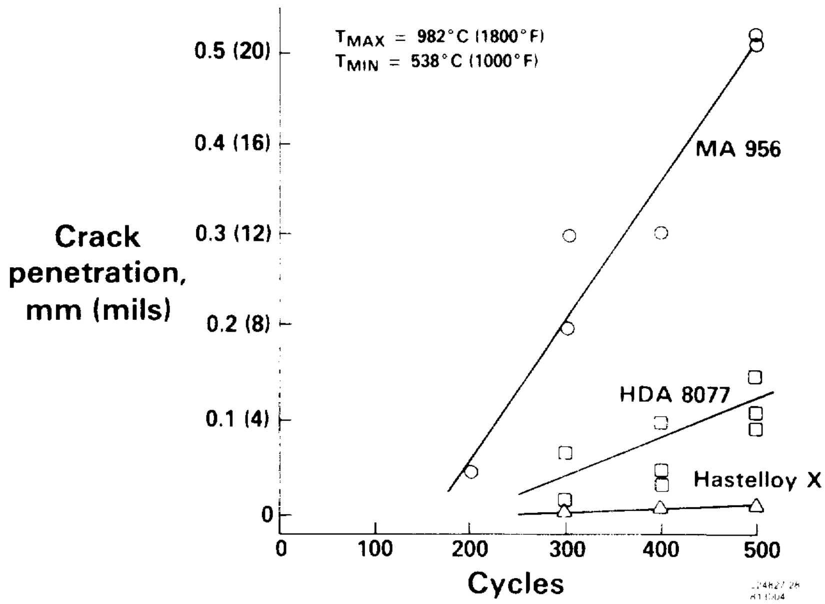
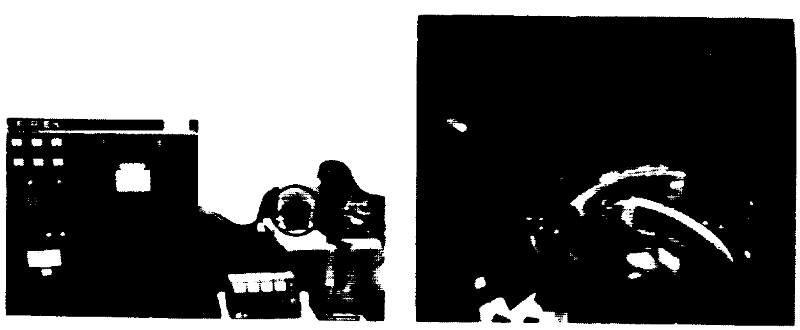


Figure 12

RIVETED LOUVER LCF STRUCTURAL TEST



Test rig

Test specimen

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Figure 13

RIVETED LOUVER LCF TEST RESULTS

- No edge cracking
- Dimensional stability of MA 956 superior to Hastelloy X

<u>Conclusion</u>: MA 956 demonstrates excellent creep resistance with no LCF cracking

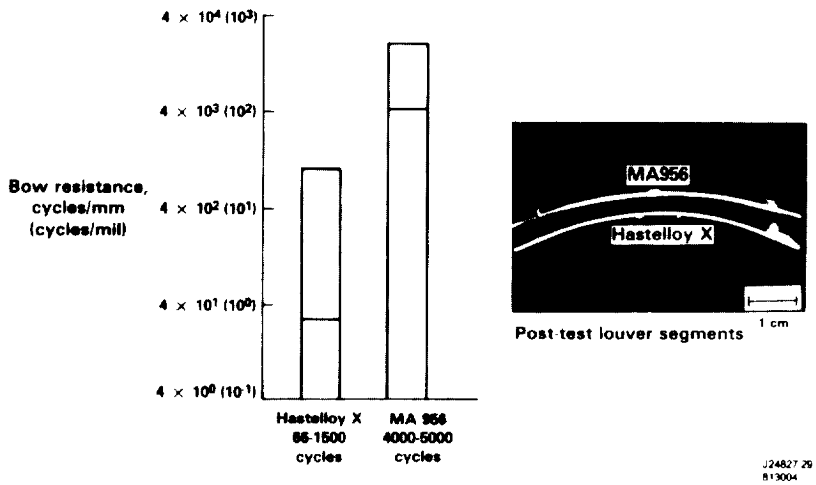
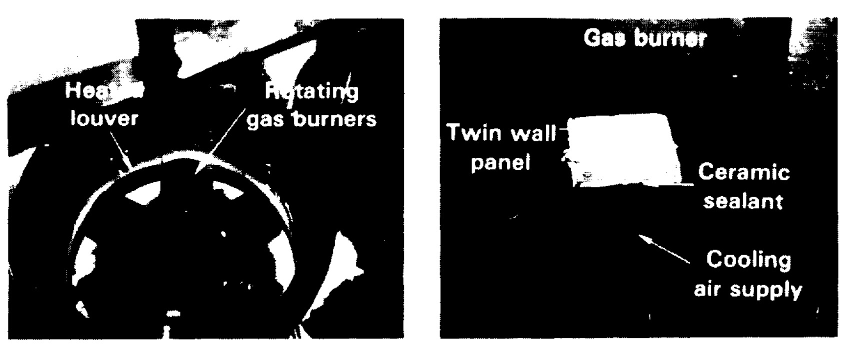


Figure 14

COMPONENT RIG TESTS



Riveted louver thermal cycle test

Twin wall LCF test

Figure 15

TESTED TWIN-WALL PANEL

- Numerous cooling nole cracks
  from laser drilled holes
- Cracks in high strain area

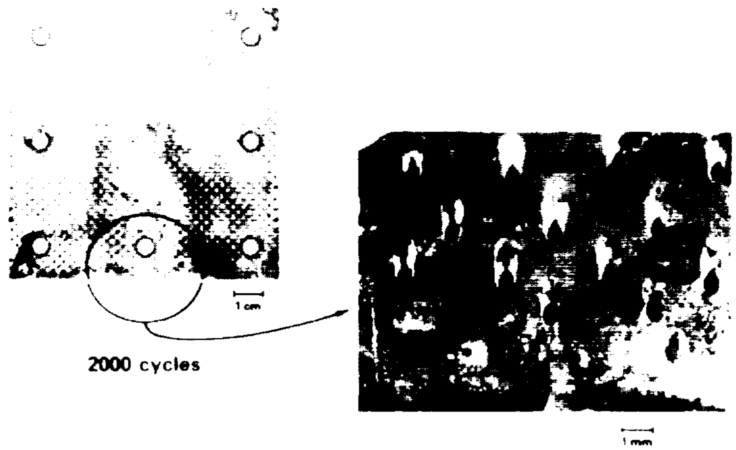


Figure 16