NASA Contractor Report 3418

Service Evaluation of Aluminum-Brazed Titanium (ABTi)

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Service Evaluation of Aluminum-Brazed Titanium (ABTi)

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1.0 SUMMARY

Previous work on the DOT/SST follow-on program showed that the environmental corrosion resistance of aluminum-brazed titanium honeycomb sandwich was basically satisfactory. Short term investigations indicated that titanium brazed with 3003 aluminum alloy was inherently resistant to corrosion under anticipated aircraft service conditions. Passivation films on both the aluminum and titanium surfaces effectively prevented galvanic coupling in the service environments evaluated. Chromate-inhibited primers provided additional corrosion protection for exposed panel edges.

The present program was designed to continue the long term creep-rupture, flight service, and jet engine exhaust tests initiated under the original program. The program included three types of specimens that were exposed to ambient environments on commercial airplane landing gears, jet engine test stands, the YF-12A airplane, and laboratory elevated-temperature, creep-rupture tests for periods up to 6 years.

The results of the investigation confirm previous conclusions that the corrosion resistance of ABTi structure is satisfactory for commercial airline service. The only deviation from this general conclusion is for sandwich structure, which is designed for sound attenuation and incorporates a perforated face skin that fosters entrapment of water. In this case, the braze must be protected by either a protective finish or by drying, such as heating in a jet engine tailpipe.

ABTi was shown to have usable (flatwise tension) creep strength up to 425°C (800°F). The braze was also shown to be metallurgically stable for approximately 50,000 hours at 425°C (800°F) and for progressively shorter times at increasingly higher temperatures.

2.0 INTRODUCTION

Aluminum-brazed titanium (ABTi) honeycomb sandwich is attractive for aircraft structural and acoustic applications, especially at service temperatures between 150° and 425°C (300° and 800°F).

The corrosion resistance of the ABTi system during short and intermediate time exposure to a broad range of service environments was established by a program under the sponsorship of the Department of Transportation (DOT, report FAA-SS-73-5-6).

The purpose of this NASA-sponsored program was to perform additional tests to evaluate degradation of ABTi during extended exposure to extreme service environments. Flight service, jet engine exhaust exposure, and creep-rupture tests initiated under the DOT contract were also continued, in order to provide 4- to 8-year environmental service data under the conditions encountered during actual usage. Extreme environment tests were conducted to determine the effects of flight service environmental fluids, temperatures, and stresses on ABTi structures for exposures of up to 7 months. The overall scope of the DOT and NASA corrosion programs is shown in table 1.

The results of the "Accelerated Lab Tests" and "Fundamental Studies" were reported in reference 1. The results of the "Extreme Service Tests," phases II, III, and IV of this contract, were reported in reference 2.

This report covers "Service Evaluations" (with the exception of 737 airplane flight spoilers, which are carried on NASA contract NAS1-13897, phase I of this contract, and 737 tailpipe extensions which will be covered in a supplementary report).

All brazed test parts were fabricated from Ti-6Al-4V titanium sheet, Ti-3Al-2.5V titanium core if honeycomb sandwich, and 3003 aluminum braze alloy. Specimens were vacuum retort brazed per Boeing specification XBAC 5967 (see DOT report FAA-SS-73-5-8) by shop personnel under production conditions.

Because of significant differences in processing and corrosion parameters, three different types of parts are described in this report:

1. Structural honeycomb panels—honeycomb sandwich panels with solid face sheets.
2. Acoustic honeycomb panels—honeycomb sandwich panels that have one solid face sheet and one perforated face sheet. These panels are designed for noise attenuation applications.
3. Faying-surface panels—two solid sheets directly brazed together.

Table 1.— Corrosion Test Summary and Schedule

Test	Years									
	½	1	1½	2	3	4	5	6	7	8
Service Evaluation										
Creep rupture	● ▲	●	● ▲	● ▲	○ △	○ △	○ △	○ △		
727 landing gear	●■▲	●■▲	●■▲	●■▲	○□△	○□△	○□△	○		
737 flight spoilers	○ △	○ △		○ △	○ △	○ △	⊗ ▲	⊗ ▲	⊗ ▲	⊗ ▲
YF-12A wing bay		●		○	○	○	○	○		
Jet engine exhaust	●■	●■	○■	○■	○□	○□	○□	○□		
737 tailpipe extensions		■		■	⊠					

	Months								
Accelerated Lab Tests	½	1	2	3	4	6	12	18	
Salt spray	▲	● ■ ▲	▲	● ■ ▲	▲	● ■	● ■	●	
Alternate immersion	▲	● ▲	▲	● ▲	▲	●	●	●	
Acidified salt spray	▲	▲	▲	▲	▲				
Tidal immersion	▲	▲	● ■ ▲	▲	▲		● ■	●	
Stress corrosion		● ▲	● ▲		●	●	●	●	
Faying-surface joints	▲	▲	▲	▲	▲	▲			
Fundamental Studies									
Solution potential	⧫	⧫							
Polarization	⧫ ▲	⧫ ▲							
Weight loss	⧫	⧫	⧫		⧫		⧫		
Effect of pH	⧫ ▲	⧫ ▲	▲	▲	▲				
Crevice mechanism	⧫ ▲	⧫ ▲	▲	▲	▲	▲			

	Days								
Extreme Service Tests	4	7	30	60	90	120	180	210	390
Thermal exposure	○ □	○ □						○ □	
Service fluids								○ □	
Coatings	○ □	○ □				○ □			
Phosphate lubricants	○ □								
Salt spray						○ □			
Humidity							○ □		
Alternate immersion							○ □		
Stress corrosion							○ □	○ □	○ □

Solid figure = test completed during DOT contract
Open figure = test completed during NASA contract
X = test in progress
● Structural honeycomb;
■ Acoustic honeycomb;
▲ Brazed faying-surface joint
⧫ Open-faced brazed specimen

The code used to define the configuration of the honeycomb core is as follows:

S C 4 - 20 N M (Example)

M = Machined both surfaces
R = Rough, as fabricated
M/R = Machined one side only

N = Cell walls nonperforated
P = Cell walls perforated

Cell wall thickness in 0.001ths of an inch, e.g., 20 = 0.0020 inch (0.051 mm)

Cell size in 1/16ths of an inch, e.g., 4 = 4/16 or 1/4 inch (6.4 mm)

C = Corrugated cell wall
S = Smooth cell wall

S = Square cell shape
H = Hexagonal cell shape

ACKNOWLEDGMENTS

The sustained efforts of the following organizations over a period of several years made this study possible:

Air France

All Nippon Airways

Braniff Airways

Continental Air Lines

Deutsche Lufthansa

Eastern Air Lines

Libyan Arab Airlines

Northwest Airlines

Trans World Airlines

Western Air Lines

General Electric Company, Aircraft Engine Group

Pratt & Whitney Aircraft

NASA Flight Research Center

3.0 SERVICE EVALUATION TESTS

The service evaluation tests included:

1. Samples mounted on the main landing gear of Boeing 727 airplanes in commercial airline service
2. Samples mounted in a dry wing bay of the NASA YF-12A airplane
3. Samples mounted in the exhaust plume of jet engine test stands
4. Laboratory stress-rupture tests

4.0 TEST SPECIMENS AND PROCEDURES

727 AIRPLANE LANDING GEAR

Three types of specimens were used, representing structural honeycomb, acoustic honeycomb, and faying-surface joints. The honeycomb sandwich specimens were fabricated using 0.5-mm (0.020-in.) Ti-6Al-4V skins. For the acoustic samples, one skin was perforated with a staggered array of 1.3-mm (0.050-in.) holes to produce a 9 percent open area. Core in all cases was 2.54-cm deep (1.00-in.) Ti-3Al-2.5V. The structural specimens were half SS2-20N and half SC4-20N; the acoustic specimens were all SC4-20N. The lap shear specimens were fabricated from 2.7-mm (0.106-in.) Ti-6Al-4V sheet. Figures 1, 2, and 3 give the details of the three types of specimens. The specimens were assembled as test kits, figure 4, using titanium alloy bolts and washers to preclude any external galvanic effects. The kits were bolted to the landing gear mud flaps as shown in figure 5.

The flight test specimens were enclosed in the unheated, unpressurized wheel well during flight and were partially sheltered by the wing when the airplane was on the ground. During takeoff and landing, the specimens were exposed to rain, spray, slush, runway deicing materials, reverted rubber deposits, engine exhaust fumes, and the local corrosive atmospheric contaminants. The specimens were mounted on 18 aircraft flown under routine conditions by nine commercial airlines (Air France, All Nippon, Braniff, Continental, Libyan Arab, Lufthansa, Northwest, Trans World, and Western). Flights were operated in Europe, Japan, the Middle East, North Africa, and the United States, exposing sets of specimens ranging from temperate-inland to tropical-marine (mild to highly corrosive).

Individual specimens were removed by the airlines at intervals of 6 to 12 months and shipped to Boeing for examination, test, and analysis.

JET ENGINE EXHAUST

Test specimens were open-edge (core exposed) 3.8- by 7.6- by 2.5-cm-thick (1.5- by 2- by 1-in.) structural and acoustic honeycomb sandwich. They were fabricated, finished, and assembled as test kits similar to those shown in figures 1, 2, and 4. The test kits were bolted onto special frames located in the exhaust gas stream of the engine test installation. Specimens were tested in the General Electric (Evendale, Ohio) and the Pratt & Whitney (East Hartford, Connecticut) facilities in indoor cells, sheltered from the rain but otherwise exposed to the ambient outdoor temperature, pressure, and humidity conditions. During engine operation, specimens were subjected to the exhaust blast at 69° to 113°C (155° to 236°F) in the General Electric facility and at 425° to 482°C (800° to 900°F) in the Pratt & Whitney facility.

Specimens also were tested in the Pratt & Whitney Florida Research and Developmental Center (FRDC) (West Palm Beach, Florida) facility in an outdoor test stand, completely exposed to the Florida weather. The facility is approximately 32 km (20 mi) inland from the east Florida coast and subject to prevailing force 4 winds from the ocean. During engine operation, the FRDC specimens were subjected to the exhaust blast at a location 5 m (16.5 ft) to the rear and 1 m (3.5 ft) left of engine centerline, as shown in figure 6. The FRDC specimen temperature ranged from 85°C (185°F) during unaugmented operation (approximately 38 percent of the

1▷ $\begin{matrix}5.08\\5.03\end{matrix}$ mm $\begin{pmatrix}0.200\\0.198\end{pmatrix}$ in.) dia hole 1.5 mm (0.06 in.) dia hole through panel. DeSoto 825-009 primer applied in holes of 50 percent of specimens

2▷ 0.06 dia hole through top face sheet into center of one 0.35 mm (¼-in.) cell.

3▷ Two edges coated with DeSoto 825-009 primer, other edges bare.

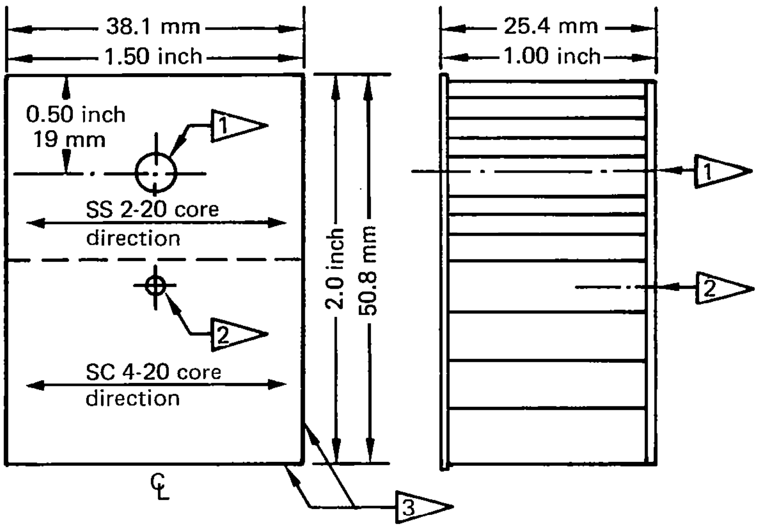


Figure 1.— Structural Honeycomb Flight Test Specimen

1▷ $\begin{matrix}5.08\\5.03\end{matrix}$ mm $\begin{pmatrix}0.200\\0.198\end{pmatrix}$ in.) dia hole through panel.

2▷ Top face sheet perforated with 1.27 mm (0.05 in.) dia holes on staggered pattern, 5 percent open area. No protective finish.

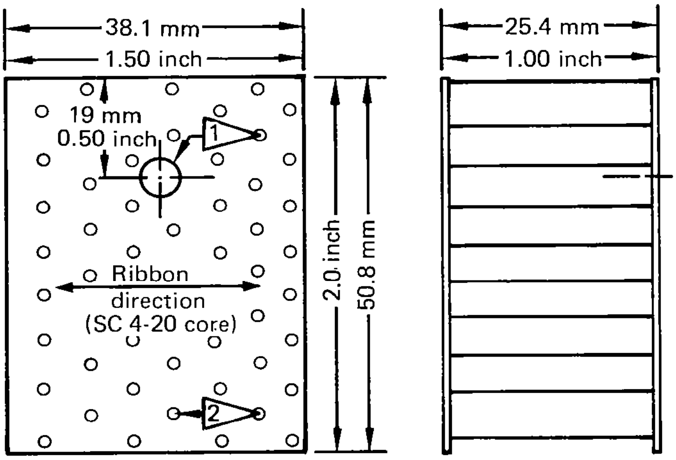


Figure 2.— Acoustic Honeycomb Flight Test Specimen

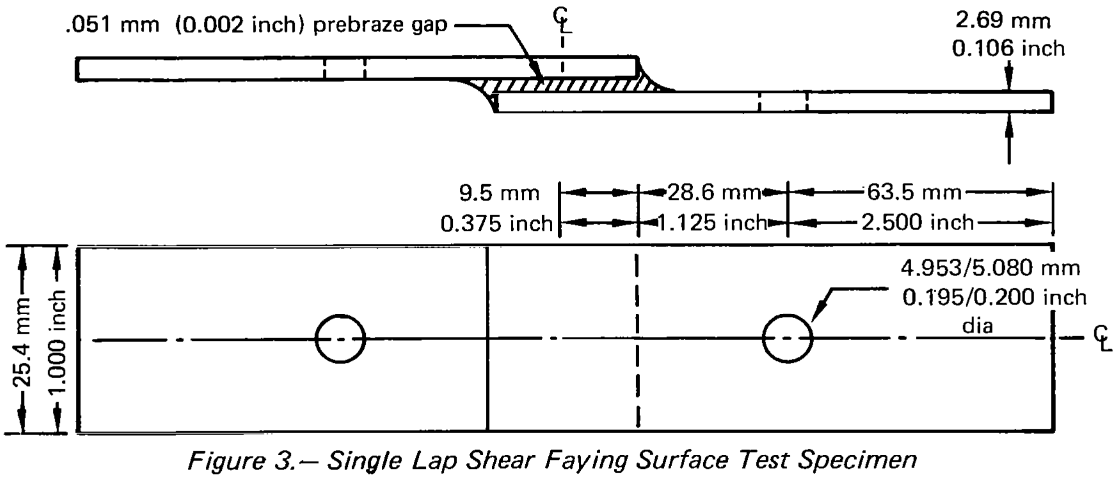
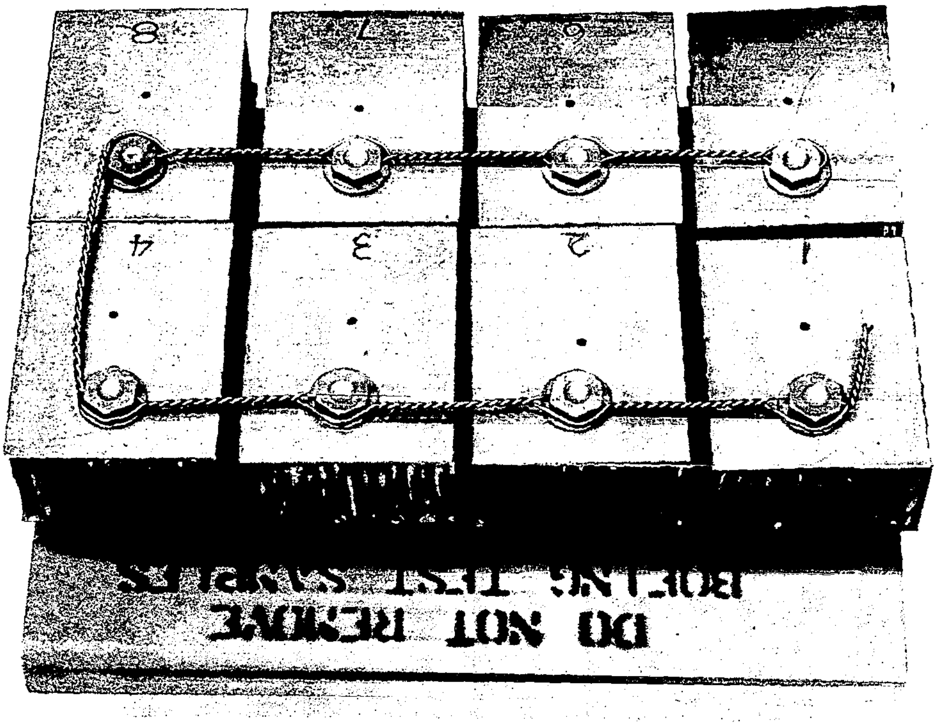
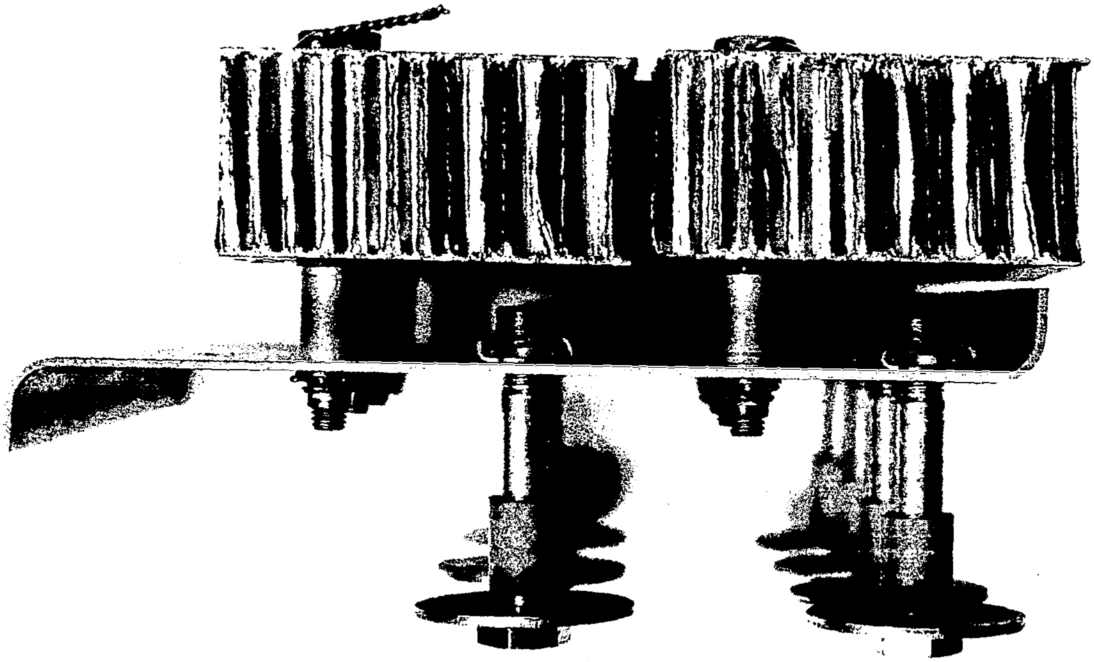


Figure 3.— Single Lap Shear Faying Surface Test Specimen

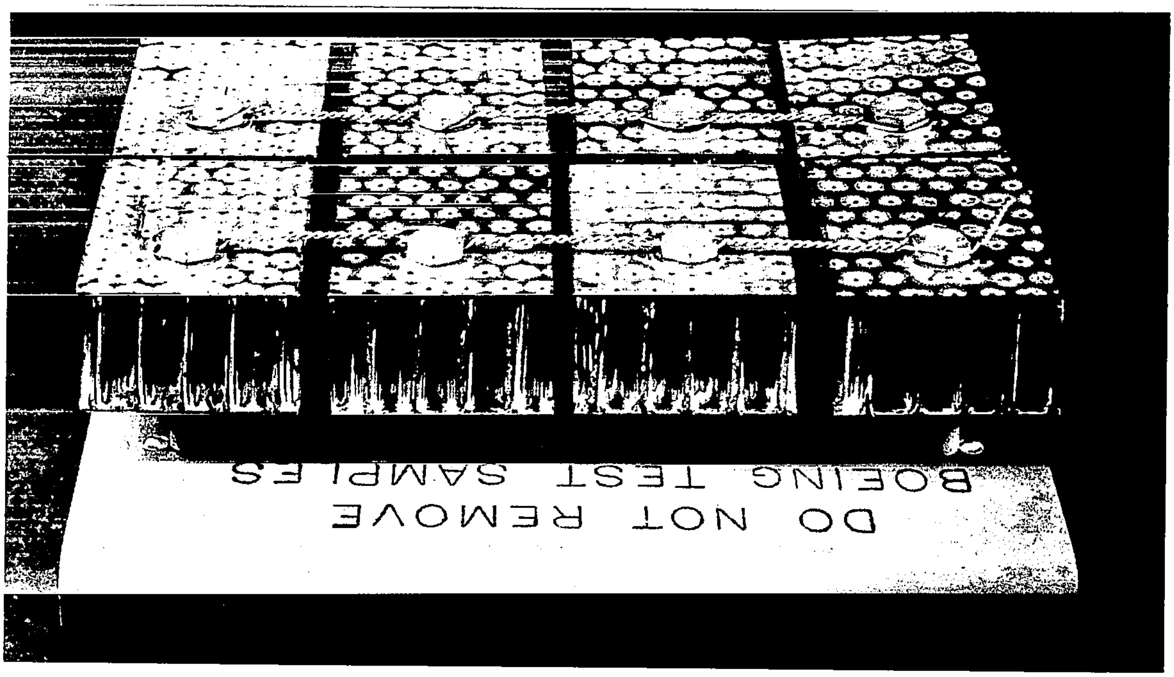


(a) Structural Honeycomb Specimens

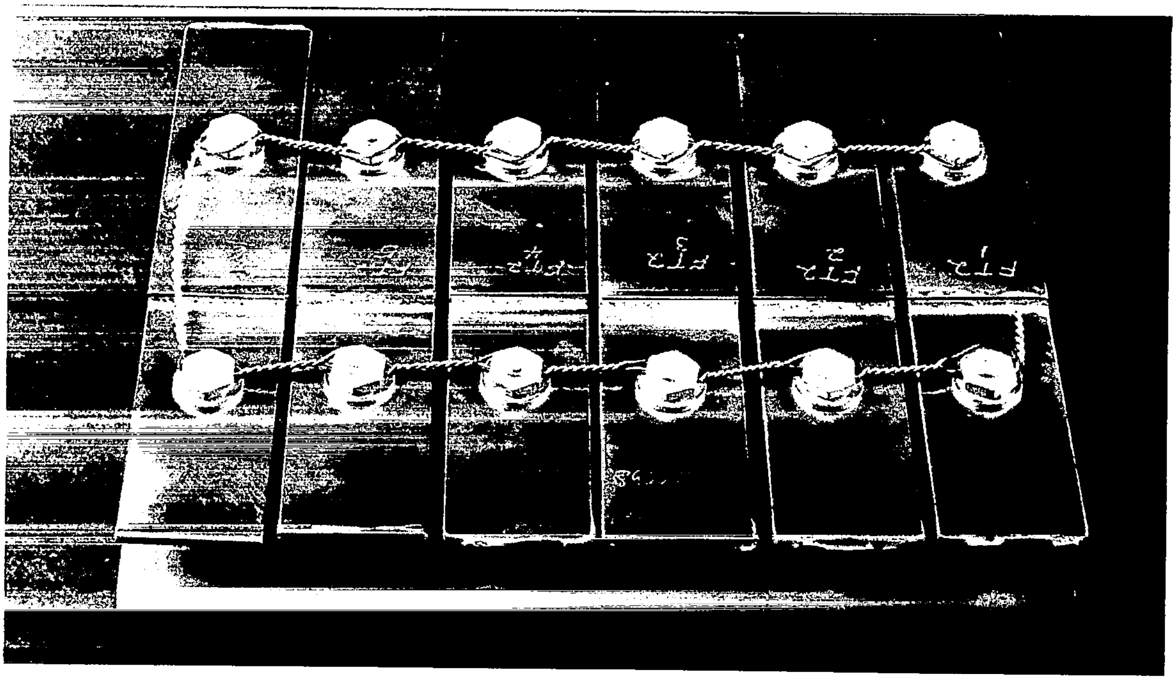


(b) Honeycomb Specimens and Attachment Hardware

Figure 4.— Model 727 Flight Test Kits



(c) Acoustic Honeycomb Specimens



(d) Faying-Surface Joint Specimen

Figure 4.— (Concluded)

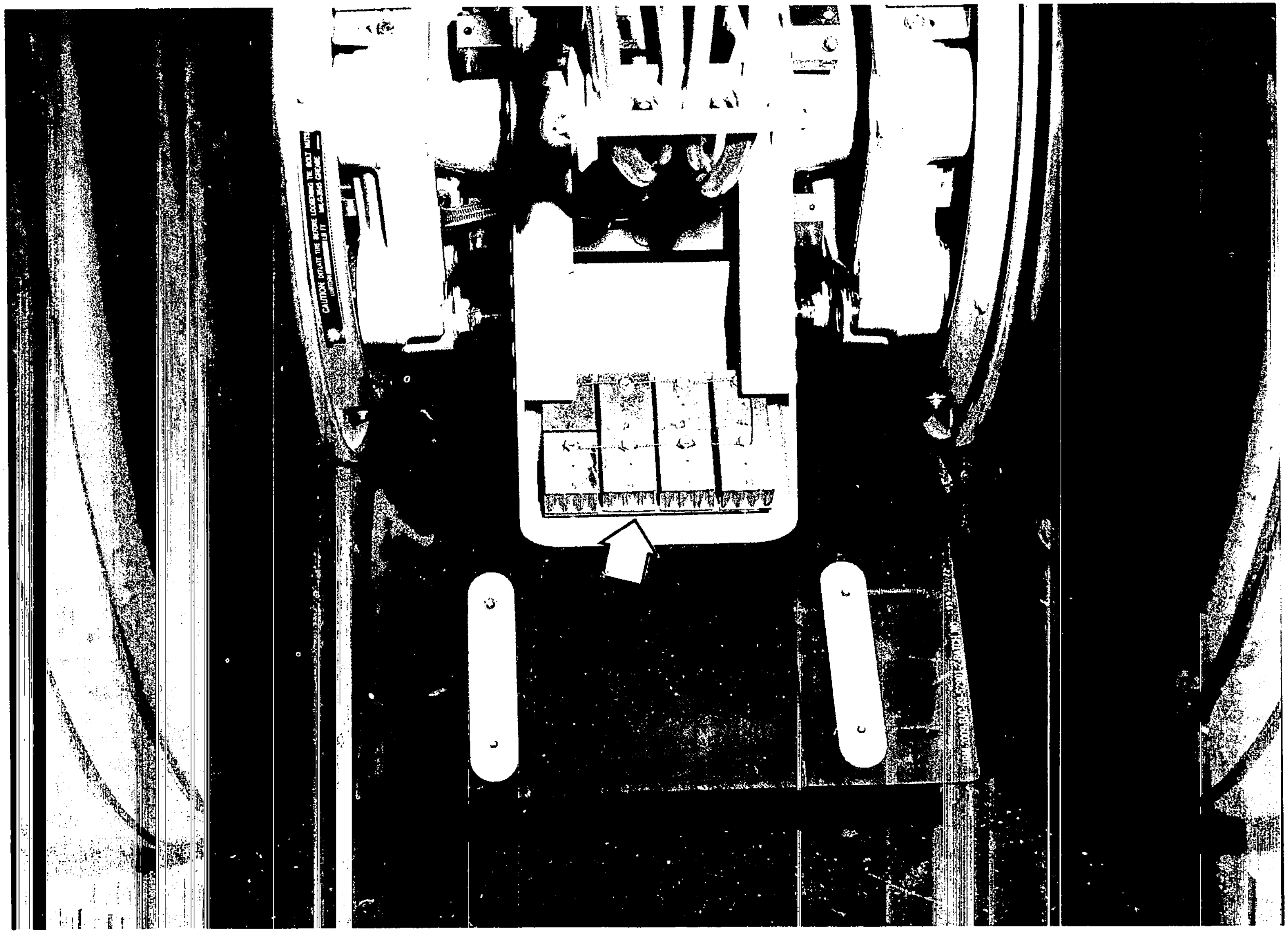


Figure 5.— Corrosion Flight Test Kit Mounted on Model 727 Main Landing Gear

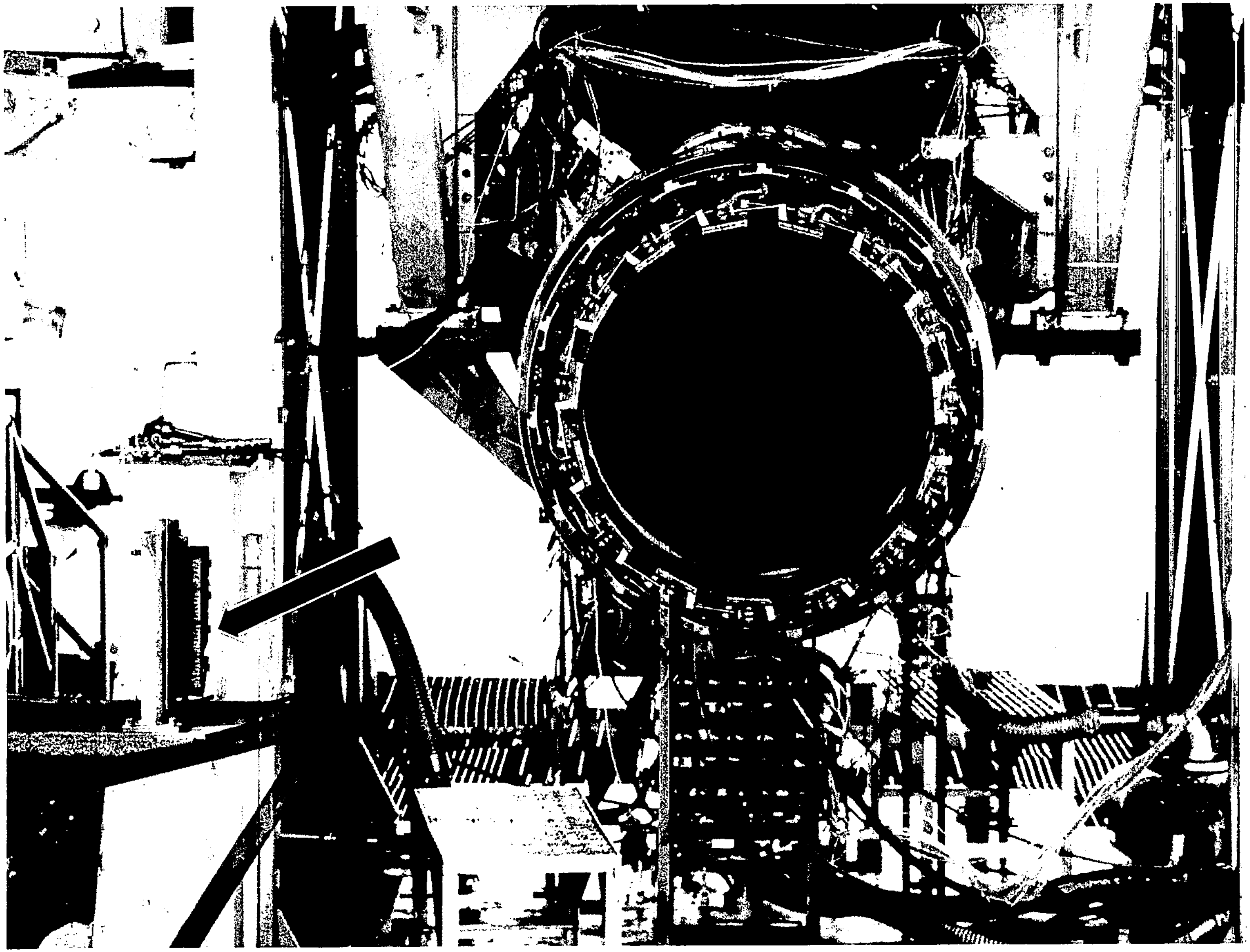


Figure 6.— Corrosion Specimen Kit Mounted in a Jet Engine Exhaust Zone (Pratt & Whitney — Florida)

engine time) to 425°C (800°F) during the 5 percent of the time that the engine operated with maximum augmentation.

YF-12A AIRPLANE

Test specimens were 5- by 5- by 2.5-cm-thick (2- by 2- bv 1-in.) structural honeycomb sandwiches, with 0.5-mm (0.020-in.) face sheets and SS2-20 core. The two adjacent edges of each specimen were left unfinished and the other two edges were protected with Alodine 1200, DeSoto 825-009, Dow Corning XR-62205, or Sermetal 385 coatings. The specimens were assembled into test kits as shown in figure 7. Some of the fastener holes were left bare and others were protected by filling with Dow Corning 77-028 sealant or by flushing with a saturated solution of magnesium chromate or strontium chromate corrosion inhibitors.

The flight test specimens were mounted in an unpressurized dry wing bay and were sheltered from direct contact with the weather. The specimens were subjected to low temperatures and periodic moisture condensation during subsonic flights and to 200° to 260°C (400° to 500°F) temperatures at very low atmospheric pressures during Mach 3+ supersonic flights.

EVALUATION

Upon receipt, specimens were examined visually for evidence of corrosion or mechanical damage. Following visual inspection, the specimens were tested to destruction statically.

The honeycomb sandwich specimens were bonded to loading blocks and pulled to failure in flatwise tension. In a specimen of this size, 3.8 by 5.1 cm (1.5 by 2.0 in.), the peripheral fillet constitutes roughly 60 percent of the total braze (there is considerable variation depending upon the relationship between the edge of the specimen and the core nodes). This condition makes the test hypersensitive to corrosion or other (mechanical) damage to the peripheral core.

The faying-surface specimens were pulled to failure in tension (single lap shear).

The strength values obtained were logged against the total exposure time since installation. The tabulated data are shown in tables I through V in the appendix. Each set of data was subjected to a statistical regression analysis. These analyses are shown in tables VI through X in the appendix.

STRESS RUPTURE

HONEYCOMB SANDWICH TESTS

Flatwise tension stress-rupture tests were conducted using single-cell tube specimens and honeycomb sandwich specimens. The honeycomb specimens were made with 2.54-cm-deep (1.0-in.) SC4-20N Ti-3Al-2.5V core. Since adhesives were inadequate for attaching the specimens to the loading blocks, the sandwich was made with 6.35-mm-thick (0.25-in.) skins that were drilled and tapped for attachment to the loading blocks with cap screws. Testing was conducted at 230°, 320°, and 425°C (450°, 600°, and 800°F). Specimens that did not fail in 50,000 hours (5.7 years) were unloaded and pulled to failure at room temperature.

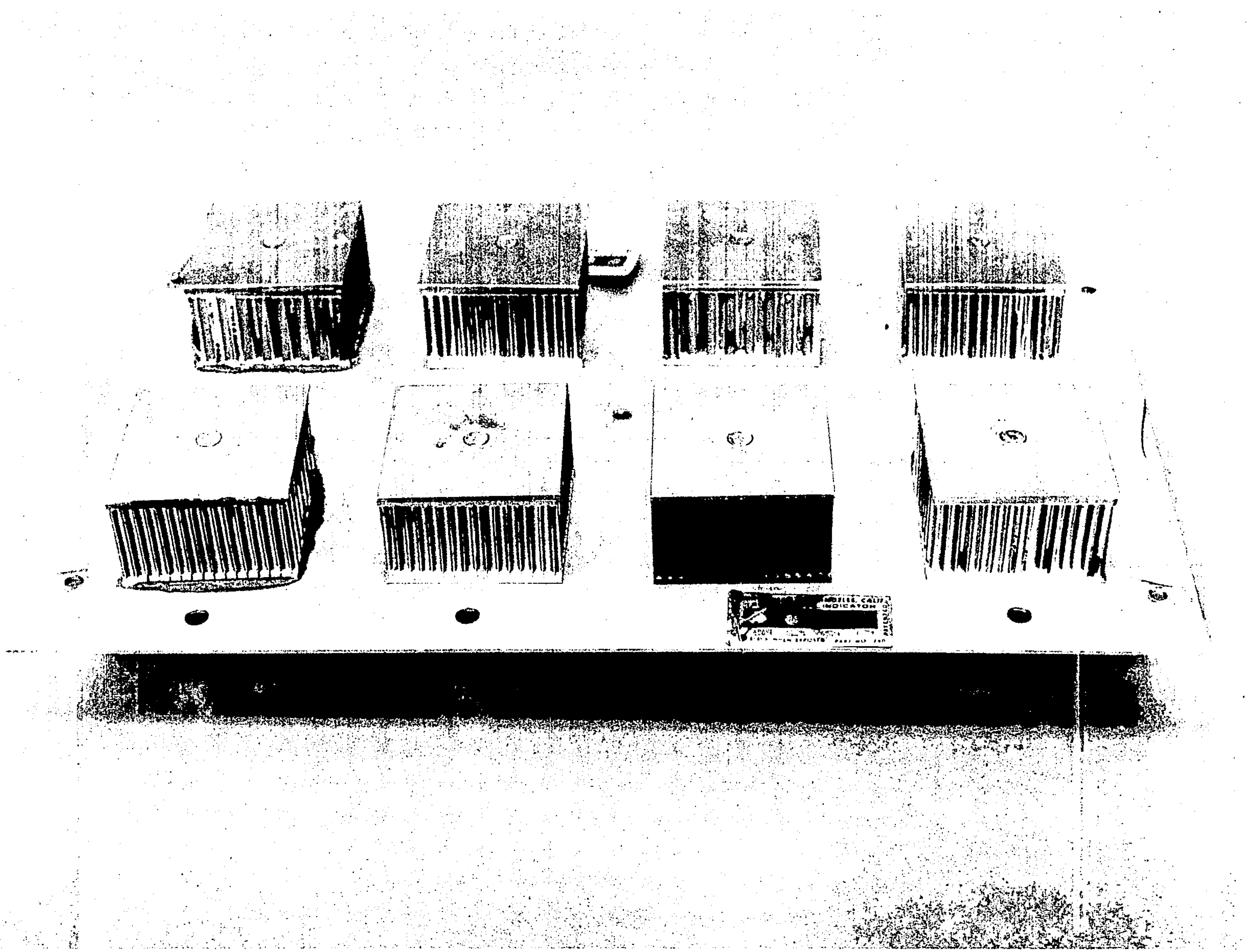


Figure 7.— Supersonic YF-12A Test Specimens

FAYING-SURFACE TESTS

Two double-shear lap joint specimens, as depicted in figure 8, were loaded in tandem at 230°C (450°F) at an applied shear stress of 13.8×10^6 Pa (2000 psi) (33 percent of USS). Lines scribed across the joint were examined periodically with a microscope to measure creep.

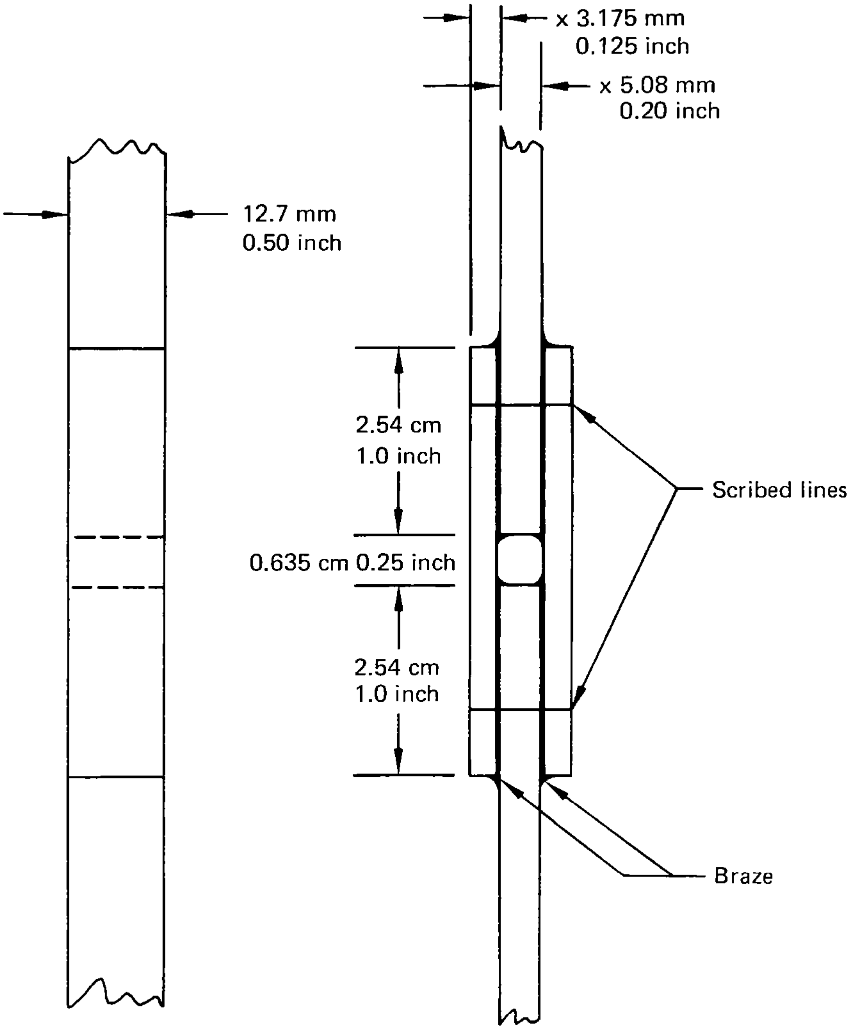


Figure 8.— Faying Surface Braze Stress-Rupture Test Specimen

5.0 RESULTS

The cooperation of the participating airlines, engine manufacturers, and NASA was excellent. With the exception of the Libyan Arab airplane, which was destroyed before any specimens were returned, over 80 percent of the originally installed specimens were returned for evaluation.

727 AIRPLANE LANDING GEAR

The specimens, as returned, were coated with a heavy black layer of adherent reverted rubber and other soil that effectively masked any evidence of corrosion attack. Cleaning methods that would remove the soil also removed any corrosion deposits. After flatwise tensile testing (sandwich specimens), the characteristics of corrosion attack could be examined (see Discussion).

STRUCTURAL SPECIMENS

The composite core (part SS2-20N and part SC4-20N) in these specimens produced a large inherent variation in the flatwise tensile strength. The statistical analysis showed a small decrease in the strength of the specimens with exposure time.

ACOUSTIC SPECIMENS

Both visual examination and statistical analysis showed the acoustic specimens to be considerably degraded with increased exposure time.

FAYING-SURFACE SPECIMENS

Neither visual examination nor statistical analysis showed any degradation in the strength of the faying-surface joints.

JET ENGINE EXHAUST

The tests conducted in indoor test cells at both General Electric and Pratt & Whitney produced essentially the same results. There was no evidence of braze degradation in either the structural or acoustic specimens by either visual examination or statistical analysis.

The tests in the Pratt & Whitney outdoor test cell in Florida were too limited to provide conclusive results. The specimen fixture in this installation was located in an extremely high sonic environment, which caused loss of the entire fixture before representative testing had been accomplished. Visual examination of the specimen with the longest test time accumulated (16 months) showed light surface corrosion on an acoustic specimen. The flatwise tensile strength was lower than would be predicted from the visual corrosion damage. The low strength could have been caused by mechanical damage from the high sonic environment.

YF-12A AIRPLANE

The specimens were installed in the YF-12A airplane for a total time of 75 months. During that time, a total of 193.4 flight hours was logged, of which 56.8 hours were above Mach 2.6 and 21.5 hours were above Mach 3. Temperature indicators mounted on the test panel showed that the parts reached a maximum temperature close to 260°C (500°F).

There was no visible change in any of the specimens since the original installation. Flatwise tensile strength could not be determined. The specimens were fabricated using SS2-20N core throughout. Such a construction has a flatwise tensile strength of approximately 34.5×10^6 Pa (5000 psi), which is greater than can be achieved by adhesive bonding loading blocks. All tests resulted in the failure of the adhesive at stress levels between 27.6×10^6 and 34.5×10^6 Pa (4000 and 5000 psi).

STRESS RUPTURE

HONEYCOMB SANDWICH TESTS

The results of the honeycomb sandwich stress-rupture tests are shown in figure 9. This figure contains data generated on the SST and DOT follow-on programs as well as the current contract. Failure in all cases occurred in the braze but was attributed to prior creep of the core that relaxed the triaxial stresses at the root of the braze.

The data show that the flatwise tensile strength of ABTi sandwich is time dependent, with a leveling phenomenon analogous to a fatigue endurance limit. This limit is approximately 40 percent of the static strength sustained load, 4.1×10^6 Pa (600 psi) at 230°C (450°F). At 316° and 425°C (600° and 800°F), the limits are approximately 30 percent and 20 percent sustained load, 2.8×10^6 and 1.4×10^6 Pa (400 and 200 psi), respectively.

FAYING-SURFACE TESTS

The two double-shear lap joint specimens neither failed nor showed detectable creep after 51,117 hours at 230°C (450°F) under a sustained load of 13.8×10^6 Pa (2000 psi). Room-temperature static shear strengths after this exposure were 68.6×10^6 and 58.6×10^6 Pa (9950 and 8500 psi) for the two specimens. These values fall within the range of unexposed room-temperature strengths, demonstrating that the exposure caused no degradation in properties.

METALLURGICAL STABILITY

Specimens from this contract, prior DOT programs (FAA-SS-72-03, ref. 3), and unpublished Boeing R&D programs were sectioned after thermal exposure and the thicknesses of the titanium aluminide ($TiAl_3$) interface layers were measured for growth during the thermal exposure. If no significant growth of the aluminide layer occurred, the braze was considered metallurgically stable at that exposure. Figure 10 is a plot of combined data showing the time/temperature limits. These data reveal that the braze joint has long term metallurgical stability at temperatures up to 425°C (800°F) and is usable at higher temperatures for shorter times.

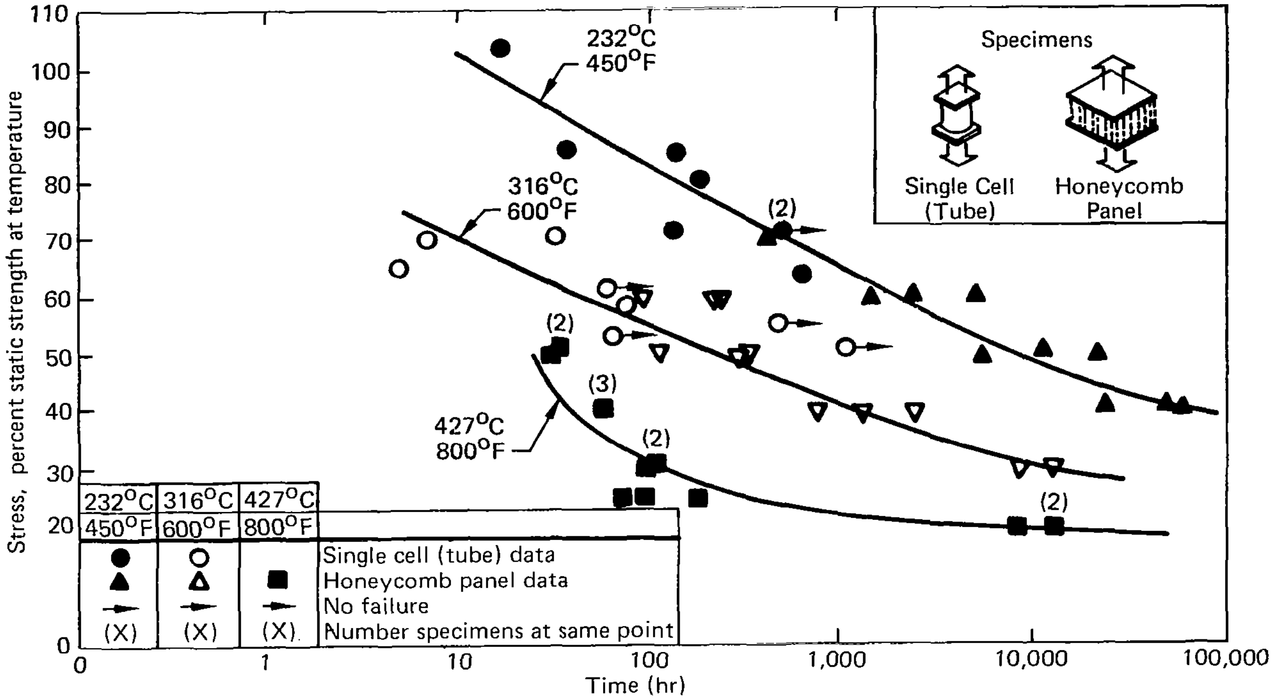
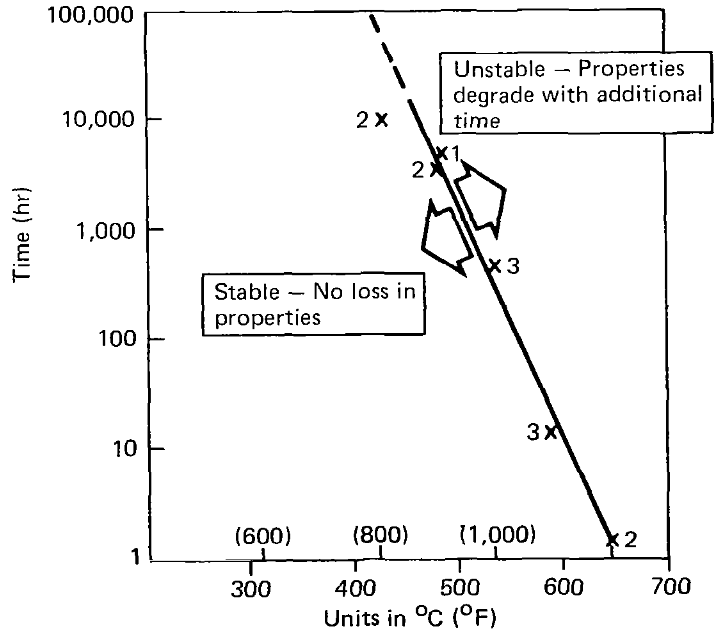


Figure 9.— Summary of Creep-Rupture Data



Data from:

1. This Contract
2. Unpublished Boeing R&D
3. FAA-SS-72-03

Figure 10.— Metallurgical Stability of ABTi

6.0 DISCUSSION

Previous testing (ref. 1) developed three primary factors in ABTi corrosion:

1. The 3003 aluminum alloy used for brazing has a high intrinsic corrosion resistance.
2. The aluminum corrodes only when in contact with liquid water.
3. Under severe (liquid) environments, the aluminum corrosion can be prevented by an appropriate protective finish.

The corrosion of ABTi is limited to attack on the aluminum braze alloy. In the presence of liquid water, corrosion initiates as pitting attack at the intersection of grain boundaries. Further attack progresses along the grain boundaries until the entire braze fillet is affected. This progression, together with environmental factors that control the rate, can be illustrated with a brazed specimen from the 727 airplane landing gear exposure test.

The corrosion morphology on a specimen from the 727 airplane landing gear test is representative, in kind, of all types of specimens and aircraft applications. Figure 11 illustrates salient features. This photo shows the entire 3.8- by 5.1-cm (1.5- by 2.0-in.) face skin removed from a 727 landing gear test specimen. Sides marked A and B were painted with a corrosion protective primer; sides C and D were left bare. G is the attachment hole and E is the cell with a vent hole in one skin. Neither E nor G (on this specimen) received any protective finish (see fig. 1). This particular specimen had been on the airplane for approximately 5 years.

Cells marked H, I, and J had open nodes at the outside edge. Cell F had a small slit at the bottom of a cell wall (see fig. 12). This slit permitted some moisture to enter but also provided a drain such that water could not accumulate. Cell E contained the vent hole in the upper skin that would permit moisture to enter and accumulate without draining. The fastener hole G was not sealed (slip-fit fastener), but was shielded from liquid water by the fastener head. (The deposits around the hole are residual adhesive from bonding loading blocks for the flatwise tensile test.) The fillets marked 1 through 4 are the locations of scanning electron photomicrographs (SEM) discussed later. The various areas illustrate the corrosive behavior of ABTi.

Sides A and B, which were coated with a chromate-inhibited epoxy primer, are representative of any exposed aluminum that has been given an appropriate protective finish. The SEM photograph at cell wall 2, figure 13, shows the surface of the fillet to be smooth with no evidence of corrosive attack. The results confirm prior testing (ref. 1) that an appropriate protective finish prevents corrosion.

Cell F experienced a minimum exposure to moisture because of the small opening into the cell. The resulting corrosion within the cell was also minimal. The SEM photo of fillet 1, figure 14, shows the initiation of corrosion pits and the start of intergranular attack.

Call J was completely open to moisture. The SEM photo of fillet 3, figure 15, shows that corrosion has progressed along grain boundaries over the entire fillet surface; however, after 5 years, the basic structure of the fillet is still intact and able to sustain load.

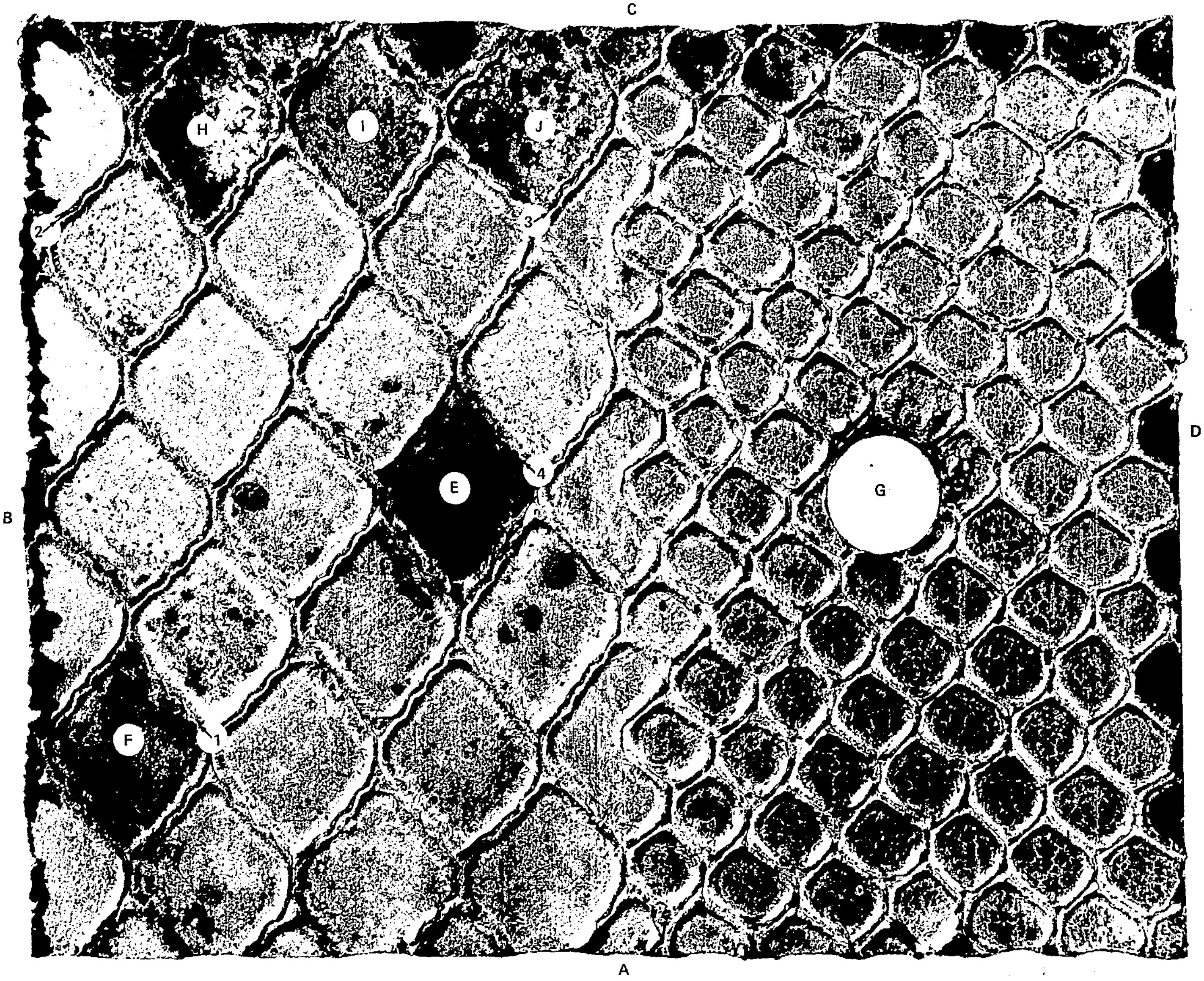


Figure 11.— Face Skin From 727 Landing Gear Structural Specimen

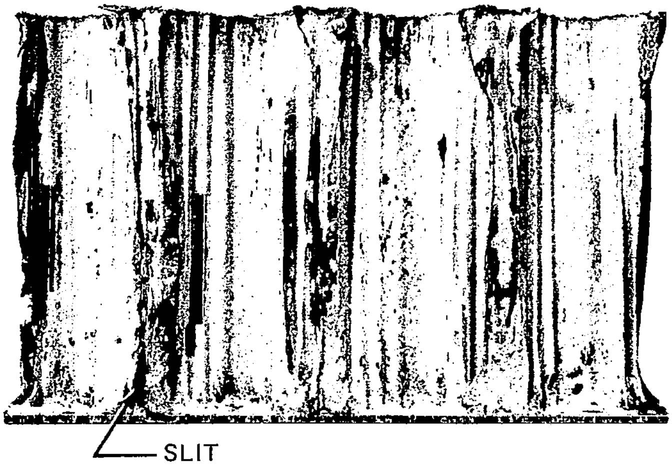


Figure 12.– Side View of Specimen Showing Slit In Wall of Cell F

Cell E, with an exposed vent hole, which can accumulate liquid water, represents the worst condition. (Acoustic sandwich that has more and/or larger holes is worse than this specimen because water can enter more readily, but the difference is in amount, not kind.) The entrapped water dries more slowly than an exposed surface, which increases the time the aluminum is wet and, hence, the amount of corrosion. The SEM photograph of fillet 4, figure 16, shows that the exposed side of the fillet is almost completely gone and corrosion has penetrated beyond the cell wall to the inner side of the fillet.

An area such as the fastener hole, G, that is accessible to water vapor but not to liquid water, does not corrode.

The small degradation in the structural specimens revealed by statistical analysis would not occur if (1) all of the edges had been painted and (2) there had been no vent hole. If a crack should develop in service, it would be expected to act similar to the fastener hole (with regard to corrosion), as there would not be sufficient opening to permit ingress of liquid water.

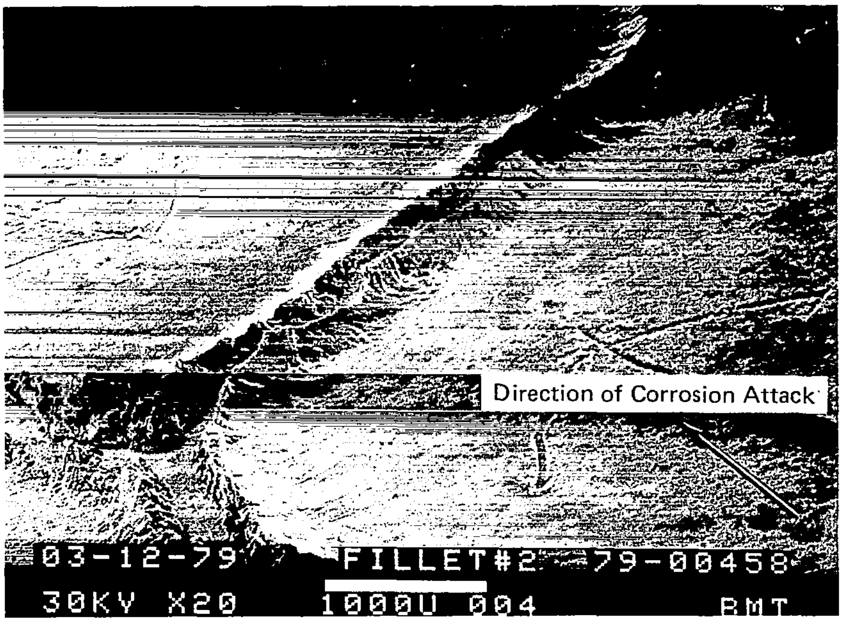


Figure 13.—SEM Photograph of Fillet Number 2 Showing No Evidence of Corrosion Attack

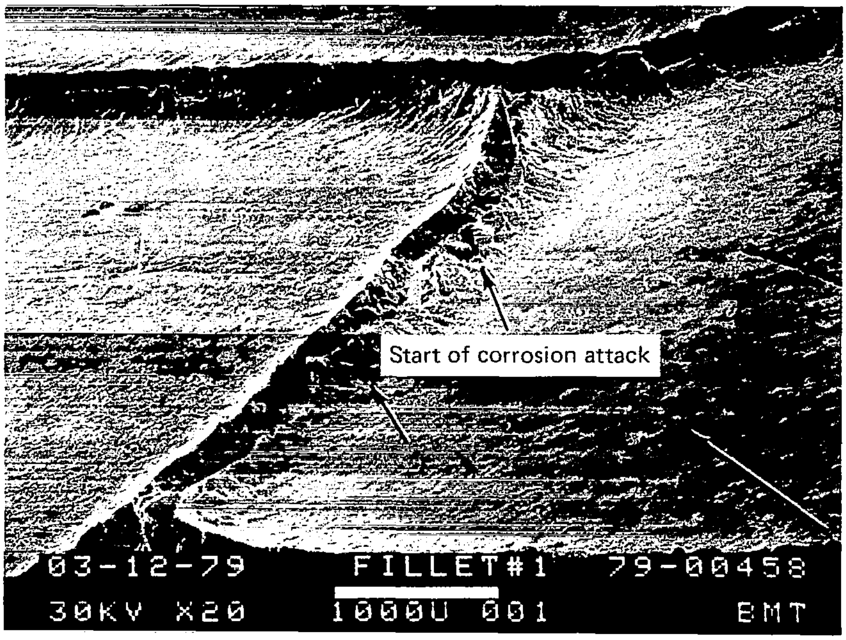


Figure 14.— SEM Photograph of Fillet Number 1

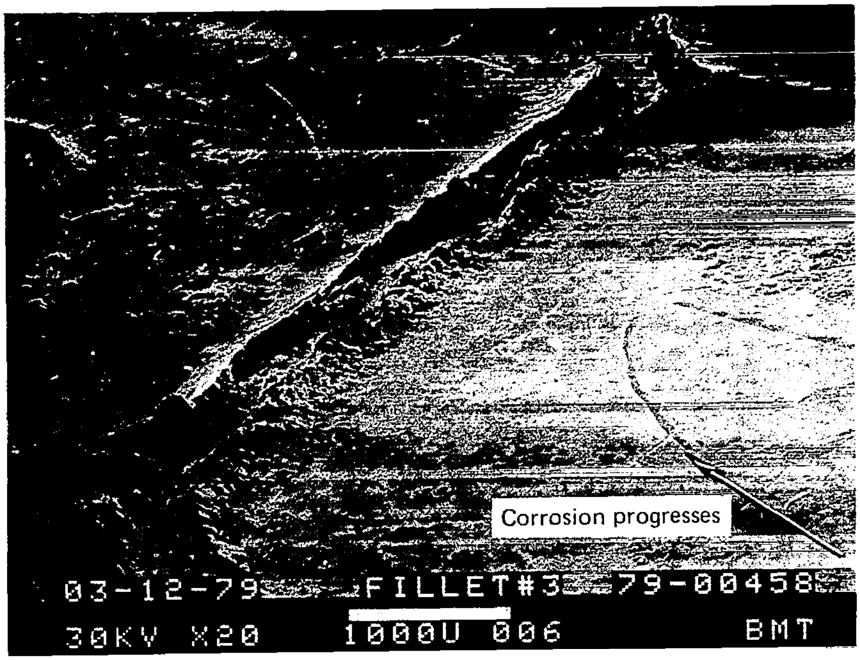

Corrosion progresses

Figure 15.— SEM Photograph of Fillet Number 3

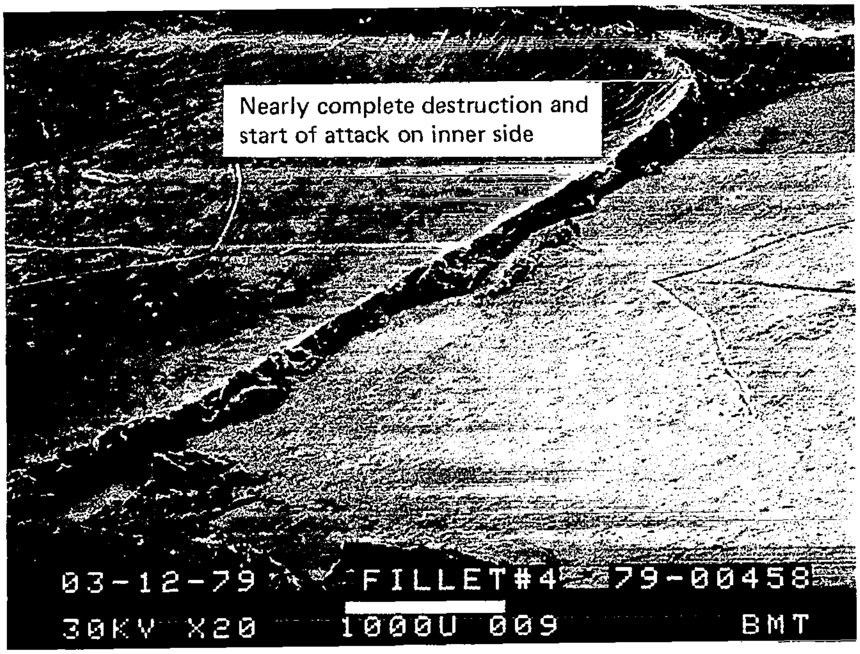

Nearly complete destruction and start of attack on inner side

Figure 16.— SEM Photograph of Fillet Number 4

7.0 CONCLUSIONS

1. Aluminum-brazed titanium (ABTi) structures that do not incorporate features that will trap water (such as noise attenuation panels with perforated skins) have excellent corrosion resistance in aircraft service environments.
2. For extended or severe service applications, the corrosion resistance of ABTi can be further enhanced by appropriate protective finishes.
3. ABTi structures, such as acoustic panels, that can trap water must be protected from corrosion. This protection can be achieved either by a protective finish or by heating (to drive off moisture) such as air in an engine exhaust.
4. Thermal exposure for up to 50,000 hours at 425°C (800°F) is not deleterious to the properties of the brazement. Higher temperatures up to 650°C (1200°F) can be sustained for progressively shorter times.
5. The ABTi system has useful flatwise tension stress-rupture strength up to at least 425°C (800°F).
6. Lap shear joints neither creep nor rupture in 50,000 hours at 230°C (450°F) when loaded at one-third the ultimate shear strength.

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APPENDIX

Table I.—Controls (No Exposure)

Specimen	Strength, psi	MPa
Structural	18.4	2 667
	11.1	1 617
	10.9	1 583
	16.4	2 383
	13.1	1 900
	15.1	2 183
Acoustic	11.5	1 667
	12.9	1 867
	12.8	1 850
	11.4	1 650
	11.8	1 717
	11.7	1 700
	12.3	1 783
	12.2	1 773
Faying surface	78.4	11 364
	49.7	7 208
	57.8	8 377
	54.9	7 959
	55.7	8 078
	62.2	9 026

Table II.–Structural Honeycomb

Months exposure	Flatwise strength, MPa (psi)							
	Air France	All Nippon	Braniff	Continental	Lutthansa	Northwest	Trans World	Western
6					14.7(2136) 10.6(1540)			
10					13.7(1981) 14.2(2060)			
11						10.5(1528) 12.3(1788)		
13	14.6(2119) 11.4(1650)	13.0(1885) 12.4(1796)	13.4(1937) 16.5(2389)				12.0(1736) 14.7(2138)	
14								15.7(2281) 13.9(2009)
15				15.7(2275) 14.1(2038)	11.7(1690) 12.8(1861)			
17						9.5(1382) 12.6(1826)		
18	13.6(1978) 15.0(2182)						14.3(2070) 16.5(2390)	
21					7.4 (1068) 13.7 (1983)			
22			14.1(2046) 13.2(1910)					
23						12.6(1832) 12.6(1824)		
24			15.1(2193)					
25		2042(14.1) 1859(12.8)						
27	13.8(2000) 16.3(2369)							
30							12.5(1809) 14.3(2079)	14.1(2043) 15.0(2171) 12.5(1809) 14.1(2042)
31			13.0(1892) 10.4(1509)					
32				14.9(2163) 14.8(2149) 14.5(2098) 12.7(1842) 14.8(2142) 13.9(2018)				
33					12.9(1869) 12.8(1857)			

d = minor damage to specimen D = specimen badly damaged

Table II.— (Concluded)

Months exposure	Flatwise strength, MPa (psi)							
	Air France	All Nippon	Braniff	Continental	Lufthansa	Northwest	Trans World	Western
34						12.4(1805) 9.8(1421)		
37		10.0(1453) 12.9(1876)	11.8(1712) 14.8(2151) 12.9(1865)					
42					12.3(1778) 11.8(1709) 12.4(1793) 12.8(1854)			
43								13.2(1921) 11.7(1608)
45			13.0(1883) 10.5(1522)					
46	10.4(1506) 13.6(1973)				14.1(2038) 10.6(1542)	12.5(1815) 6.4(926)		
49	10.4(1513) 11.5(1661)	11.5(1661) 11.2(1621)						
50			14.2(2062)					
51				15.8(2296) 11.8(1708)				12.1(1750) 12.2(1776)
53							9.9(1437) 10.6(1536)	
58					1378d(9.5) 1931(13.3)	1424(9.8) 1584(10.9)		
61		10.0(1444d) 7.8(1129d)						
62	D D							
63								12.2(1770) 13.6(1967)
64							1267d(8.7) 1847(12.7)	
69								13.0(1892) 12.4(1800)
70					8.7(1267) 12.7(1847)			
73		11.0(1600)						

d = minor damage to specimen, D = specimen badly damaged

Table III.— Acoustic Honeycomb

Months exposure	Flatwise strength, MPa (psi)						
	Air France	All Nippon	Braniff	Lufthansa	Northwest	Trans World	Western
6				6.4(924)	9.1(1322)		
7	11.7(1699)						
8						5.2(759)	
12		9.0(1308)		10.6(1543)	4.0(577)		
13	7.6(1098)						7.1(1028) 8.0(1162)
16							7.9(1147) 8.1(1180) 7.7(1124)
18		6.9(1004)					
19						7.6(1103)	6.0(864)
20	10.9(1588)						
24		7.7(1122)		6.5(939)	6.6(956)		
26							7.4(1072) 6.3(916)
29							8.0(1164) 6.0(877)
30		5.5(803)					
32						2.6(378)	
35							5.8(841)
36		D			3.1(447) 6.2(899)		8.1(1172)
38			11.1(1608)				
39							4.8(693)
41		D					
43			4.6(670)				7.2(1038) 4.4(642)
48		D	7.1(1036)		4.7(676)		
49				5.2(750) 9.3(1354) 12.6(1824)			11.9(1733)
50						5.7(833)	
57			2.6(377)				
62			0 0 1.2(167) 1.9(273) 3.3(483)				

D = specimen badly damaged

Table IV.— Faying-Surface Joints

Months exposure	Flatwise strength, MPa (psi)						
	Air France	All Nippon	Braniff	Lufthansa	Northwest	Trans World	Western
6				56.0(8120)	59.1(8570)		
7	51.9(7530)						
8						29.3(4250)	
12		62.5(9060)		49.4(7160)	52.8(7660)		
13	64.9(9420)						58.2(8440) 54.6(7920)
16							55.3(8020) 49.9(7240)
19						44.7(6480)	
24		55.0(7984)		53.8(7810)	51.4(7460)		
26							48.9(7097)
29							58.6(8506)
35							55.5(8051)
36							38.6(5599) 45.5(6596)
43			52.8(7660)				79.1(11477)
47			51.1(7405)				
48		52.2(7564)			41.5(6025)		
49				56.7(8228)			
50						37.6(5452)	
57			55.4(8039)				
60				47.0(6820)			51.6(7487)
62			51.3(7436) 79.6(11550)	54.1(7843)*			

*Adjusted for approximately 8.9 by 19.8 mm (0.35 in. by 0.78 in.) as brazed void.

Table V.— Jet Engine Exhaust

Months exposure[a]	Time, hours[b]	General Electric		Pratt & Whitney			
				Hartford		Florida	
		Structural	Acoustic	Structural	Acoustic	Structural	Acoustic
3	136	13.8(2003)	15.5(2241)				
4	328				12.3(1780)		
	40						10.7(1549)
6	7						12.9(1875)
8	1114				10.9(1583)		
9	787	11.6 (1679)	1880(13.0)				
10	206					10.2(1482)	
	324						9.2(1339)
13	897	12.8 (1857)	14.1(2044)				
14	2227			15.9(2310)	12.4(1792)		
16	507					D	6.9(1000) 5.4(783d)
20	2668			12.5(1819)	13.7(1996)		
23	1180	15.0(2170)	13.4(1944)				
24	3091			12.8(1851)	12.4(1794)		
36	3508			11.4(1650)	12.7(1838)		
47	1993	15.6(2260)	12.5(1819)				
49	—			11.8(1712)	12.4(1794)		
59	2208	16.7(2428)	10.4(1515)				
60	6010			D	7.1(1024d)		
70	2592	10.5(1527d)					

Notes:

[a] Months = Total elapsed time installed

[b] Hours = Time at temperature during engine run:

General Electric: 62.2° to 113°C
(144° to 236°F)

Pratt & Whitney:
Hartford: 427° to 482°C
(800° to 900°F)
Florida: 85° to 427°C
(185° to 800°F)

d = minor damage, D = major damage

Table VI.— 727 Landing Gear — Structural

```
  REGRESSION TITLE  . . . . . . . . . . . . . . . .STRUCTURAL HONEYCOMB STRENGTH VS TIME
  DEPENDENT VARIABLE  . . . . . . . . . . . . . .       2 STRENGTH
  TOLERANCE . . . . . . . . . . . . . . . . . . .   .0100
ALL DATA CONSIDERED AS A SINGLE GROUP

MULTIPLE R              .2994          STD. ERROR OF EST.       269.7654
MULTIPLE R-SQUARE       .0897

ANALYSIS OF VARIANCE
                      SUM OF SQUARES     DF    MEAN SQUARE       F RATIO    P(TAIL)
         REGRESSION      709596.661       1     709596.661         9.751     .00235
         RESIDUAL       7204563.636      99      72773.370

                                                STD. REG
   VARIABLE     COEFFICIENT STD. ERROR            COEFF         T   P(2 TAIL)

    (CONSTANT   2015.2498 )
TIME         1      -4.658       1.492            -.299    -3.123      .002

THE FOLLOWING COMPUTER PROGRAM WAS USED FOR ALL STATISTICAL ANALYSES:

BMDPIR - MULTIPLE LINEAR REGRESSION
HEALTH SCIENCES COMPUTING FACILITY                              PROGRAM REVISED OCTOBER 7, 1974
UNIVERSITY OF CALIFORNIA, LOS ANGELES                           WRITEUP REVISED APRIL, 1974
```

Table VII.— 727 Landing Gear — Acoustic

```
  REGRESSION TITLE . . . . . . . . . . . . . . . . . .ACOUSTICAL HONEYCOMB STRENGTH VS TIME
  DEPENDENT VARIABLE . . . . . . . . . . . . . . . .       2 STRENGTH
  TOLERANCE . . . . . . . . . . . . . . . . . . . .    .0100
ALL DATA CONSIDERED AS A SINGLE GROUP

MULTIPLE R               .6381           STD. ERROR OF EST.       365.3273
MULTIPLE R-SQUARE        .4072

ANALYSIS OF VARIANCE
                        SUM OF SQUARES     DF    MEAN SQUARE       F RATIO    P(TAIL)
         REGRESSION      4859094.703       1    4859094.708        36.408     .00000
         RESIDUAL        7073595.220      53     133464.061

                                                STD. REG
  VARIABLE      COEFFICIENT STD. ERROR           COEFF          T   P(2 TAIL)

   (CONSTANT     1492.4343 )
TIME        1      -15.622       2.589          -.638     -6.034     -.000
```

Table VIII.— 727 Landing Gear — Faying Surface

```
  REGRESSION TITLE . . . . . . . . . . . . . . . .FAYING STRENGTH VS TIME
  DEPENDENT VARIABLE . . . . . . . . . . . . . .       2 STRENGTH
  TOLERANCE . . . . . . . . . . . . . . . . . . .   .0100
ALL DATA CONSIDERED AS A SINGLE GROUP

MULTIPLE R              .2406          STD. ERROR OF EST.      1322.0675
MULTIPLE R-SQUARE       .0579

ANALYSIS OF VARIANCE
                      SUM OF SQUARES     DF     MEAN SQUARE        F RATIO    P(TAIL)
         REGRESSION     3866785.711       1     3866785.711          2.212     .14562
         RESIDUAL      62923052.183      35     1747862.561

                                                STD. REG
  VARIABLE       COEFFICIENT STD. ERROR           COEFF         T    P(2 TAIL)

   (CONSTANT     8157.8521 )
TIME        1      -16.046       10.788            -.241    -1.487     .146
```

Table IX A.— Jet Engine **Exhaust** *— Structural Vs Total Installed Time*

```
  REGRESSION TITLE . . . . . . . . . . . . . . . . . .STRUCTURAL HONEYCOMB STRENGTH VS TIME
  DEPENDENT VARIABLE . . . . . . . . . . . . . . . .       5 STRENGTH
  TOLERANCE . . . . . . . . . . . . . . . . . . . .    .0100
ALL DATA CONSIDERED AS A SINGLE GROUP

MULTIPLE R               .1714          STD. ERROR OF EST.       335.5750
MULTIPLE R-SQUARE        .0294

ANALYSIS OF VARIANCE
                      SUM OF SQUARES     DF    MEAN SQUARE       F RATIO    P(TAIL)
         REGRESSION      47741.758       1      47741.758           .424     .52551
         RESIDUAL      1576548.242      14     112610.589

                                                STD. REG
  VARIABLE      COEFFICIENT STD. ERROR          COEFF           T    P(2 TAIL)

   (CONSTANT    1975.0856 )
TIME        3        3.059        4.698          .171       .651        .526
```

Table IX B.– Jet Engine Exhaust – Structural Vs Engine Operating Hours

```
IN THIS VERSION OF BMDPIR
   -- WHEN ZERO INTERCEPT IS USED, SUBPROBLEMS GIVE BAD RESULTS.
  REGRESSION TITLE . . . . . . . . . . . . . . . .STRUCTURAL HONEYCOMB STRENGTH VS HOURS
  DEPENDENT VARIABLE . . . . . . . . . . . . . .        5 STRENGTH
  TOLERANCE . . . . . . . . . . . . . . . . . . .    .0100
ALL DATA CONSIDERED AS A SINGLE GROUP

MULTIPLE R              .0995           STD. ERROR OF EST.       338.9285
MULTIPLE R-SQUARE       .0099

ANALYSIS OF VARIANCE
                      SUM OF SQUARES     DF    MEAN SQUARE       F RATIO    P(TAIL)
         REGRESSION       16074.656       1       16074.656         .140     .71395
         RESIDUAL       1608215.344      14      114872.525

                                                STD. REG
  VARIABLE      COEFFICIENT STD. ERROR            COEFF          T   P(2 TAIL)

   (CONSTANT    2052.8811 )
HOURS      4        -.026        .070            -.099     -.374      .714
```

Table IX C.— Jet Engine Exhaust — Structural Vs Combined Installed Time and Engine Hours

```
IN THIS VERSION OF BMDPIR
   -- WHEN ZERO INTERCEPT IS USED, SUBPROBLEMS GIVE BAD RESULTS.
  REGRESSION TITLE . . . . . . . . . . . . . . . .STRUCTURAL HONEYCOMB STRENGTH VS TIME & HOURS
  DEPENDENT VARIABLE . . . . . . . . . . . . . .       5 STRENGTH
  TOLERANCE . . . . . . . . . . . . . . . . . . .   .0100
ALL DATA CONSIDERED AS A SINGLE GROUP

MULTIPLE R              .3947          STD. ERROR OF EST.       324.7736
MULTIPLE R-SQUARE       .1558

ANALYSIS OF VARIANCE
                      SUM OF SQUARES     DF    MEAN SQUARE       F RATIO    P(TAIL)
         REGRESSION      253077.119       2     126538.559         1.200     .33256
         RESIDUAL       1371212.881      13     105477.914

                                               STD. REG
  VARIABLE       COEFFICIENT STD. ERROR         COEFF          T   P(2 TAIL)

   (CONSTANT     2027.0440 )
TIME        3      10.529        7.024           .590      1.499       .158
HOURS       4       -.144         .103          -.549     -1.395       .186
```

Table X A.— Jet Engine Exhaust — Acoustic Vs Total Installed Time

```
  REGRESSION TITLE . . . . . . . . . . . . . . .ACOUSTICAL HONEYCOMB STRENGTH VS TIME
  DEPENDENT VARIABLE . . . . . . . . . . . . . .       5 STRENGTH
  TOLERANCE . . . . . . . . . . . . . . . . . . .   .0100
ALL DATA CONSIDERED AS A SINGLE GROUP

MULTIPLE R            .1340             STD. ERROR OF EST.       167.2251
MULTIPLE R-SQUARE     .0180

ANALYSIS OF VARIANCE
                      SUM OF SQUARES     DF    MEAN SQUARE       F RATIO    P(TAIL)
         REGRESSION        9202.137       1       9202.137          .329     .57331
         RESIDUAL        503356.413      18      27964.245

                                           STD. REG
  VARIABLE      COEFFICIENT STD. ERROR       COEFF         T   P(2 TAIL)

   (CONSTANT    1828.2465 )
TIME       3       -1.277       2.226         -.134     -.574      .573
```

Table X B.— Jet Engine Exhaust — Acoustic Vs Engine Operating Hours

```
IN THIS VERSION OF BMDPIR
   -- WHEN ZERO INTERCEPT IS USED, SUBPROBLEMS GIVE BAD RESULTS.
  REGRESSION TITLE . . . . . . . . . . . . . . . . .ACOUSTICAL HONEYCOMB STRENGTH VS HOURS
  DEPENDENT VARIABLE  . . . . . . . . . . . . . . .       5 STRENGTH
  TOLERANCE . . . . . . . . . . . . . . . . . . . .   .0100
ALL DATA CONSIDERED AS A SINGLE GROUP

MULTIPLE R                .0155           STD. ERROR OF EST.       168.7265
MULTIPLE R-SQUARE         .0002

ANALYSIS OF VARIANCE
                      SUM OF SQUARES     DF    MEAN SQUARE       F RATIO    P(TAIL)
         REGRESSION         122.942       1        122.942          .004     .94833
         RESIDUAL        512435.608      18      28468.645

                                                  STD. REG
  VARIABLE      COEFFICIENT STD. ERROR          COEFF          T   P(2 TAIL)

   (CONSTANT    1809.4892 )
HOURS      4          .002        .033           .015      .066     .948
```

Table X C.— Jet Engine Exhaust — Acoustic Vs Combined Installed Time and Engine Hours

```
IN THIS VERSION OF BMDPIR
   -- WHEN ZERO INTERCEPT IS USED, SUBPROBLEMS GIVE BAD RESULTS.
   REGRESSION TITLE . . . . . . . . . . . . . . . .ACOUSTICAL HONEYCOMB STRENGTH VS TIME & HOURS
   DEPENDENT VARIABLE . . . . . . . . . . . . . . .        5 STRENGTH
   TOLERANCE. . . . . . . . . . . . . . . . . . . .    .0100
ALL DATA CONSIDERED AS A SINGLE GROUP

MULTIPLE R             .2350           STD. ERROR OF EST.       168.7743
MULTIPLE R-SQUARE      .0552

ANALYSIS OF VARIANCE
                      SUM OF SQUARES     DF    MEAN SQUARE       F RATIO    P(TAIL)
         REGRESSION       28317.489       2      14158.744          .497     .61688
         RESIDUAL        484241.061      17      28484.768

                                              STD. REG
   VARIABLE      COEFFICIENT STD. ERROR        COEFF           T    P(2 TAIL)

    (CONSTANT    1815.0329 )
TIME         3      -3.587       3.606         -.376       -.995       .334
HOURS        4        .043        .052          .310        .819       .424
```

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Topical Report

16 Abstract

This program completed long term creep-rupture, flight service and jet engine exhaust tests on aluminum-brazed titanium (ABTi) originally initiated under the DOT/SST follow-on program. The program included exposure to natural airline service environments for up to 6 years.

The results showed that ABTi has adequate corrosion resistance for long time commercial airplane structural applications. Special precautions are required for those sandwich structures designed for sound attenuation that utilize perforated skins. ABTi was also shown to have usable creep-rupture strength and to be metallurgically stable at temperatures up to 425°C (800°F).

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