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THERMAL FATIGUE AND OXIDATION DATA ON TAZ-8A, MAR-M 200, AND UDIMET 700 SUPERALLOYS

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16. Abstract

The fluidized bed technique has been used to determine the relative thermal fatigue and oxidation resistance of three superalloys--TAZ-8A, MAR-M 200, and Udimet 700. TAZ-8A and MAR-M 200 were also tested in the directionally-solidified form. For the 13 combinations of composition, solidification method, surface protection, and specimen geometry, the cycles to cracking varied from 1250 to 15,000. The alloy/coating having the best resistance to thermal fatigue cracking was coated directionally-solidified NASA TAZ-8A. This combination also had excellent oxidation resistance.

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FOREWORD

This report describes the final phase of the work performed under NASA Contract NAS3-17787 and is entitled "Thermal Fatigue and Oxiation Data on TAZ-8A, MAR-M 200, and Udimet 700 Superalloys." The report covers the period June 15, 1974 to January 15, 1975. Other fluidized bed thermal data of nickel- and cobalt-base alloys obtained between March 24, 1967, and February 28, 1973, are reported in NASA CR-72738, CR-121211, and CR-121212.

The NASA personnel assigned to the contract were:

John R. Danicic - Contract Specialist
Peter T. Bizon - Project Manager

The IITRI personnel who contributed to this project include Maurice Howes (Project Manager), John Andersen (Administrative Assistant), Harry Nichols, Arline Kerwin, and Violet Johnson.

Data are contained in Logbooks No. C21674. The IITRI internal designation for this report is IITRI-B6124-21.

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SUMMARY

This investigation is part of a general study of thermal fatigue conducted by the NASA-Lewis Research Center. The program used the fluidized bed heating and cooling technique to measure the relative thermal fatigue resistance of three superalloys. Earlier investigations are reported in NASA CR-72738, CR-121211, and CR-121212. The alloys in this investigation included MAR-M 200, Udimet 700, and TAZ-8A. Two types of surface protection were used on selected alloys. These were RT-XP and NiCrAlY. The resistance to cracking was measured by cycling specimens between fluidized beds at 1088°C (1990°F) and 316°C (600°F). The time of immersion in each bed was 3 minutes. The specimens were examined for cracks at intervals, and the lengths of the first three cracks were measured. When sufficient crack propagation data were obtained, the specimen was removed from test.

The alloy having the best resistance to thermal fatigue cracking was TAZ-8A DS, clad or coated. The number of cycles required to crack different alloys varied widely from over 15,000 cycles to 1250 cycles. This represents a 12:1 difference in behavior under identical severe testing conditions.

Oxidation occurs during thermal cycling, and some alloys experience considerable weight loss. The directionally solidified alloys are particularly susceptible and normally should be protected with a coating.

INTRODUCTION

The purpose of the reported work was to use the fluidized bed technique to measure the relative thermal fatigue cracking resistance of three high-temperature superalloys that could be used for advanced air-breathing engines. The work was carried out in a facility designed and built by IIT Research Institute.

This investigation is part of a general study of thermal fatigue being undertaken by the NASA-Lewis Research Center as described by Spera et al.[1] Some other parts of this general study were the previous fluidized bed thermal fatigue work by Howes[2,3] and the burner tests by Bizon et al.[4] An analytical life prediction to these data is given by Spera et al.[5] A description of the test method used in this investigation is given in detail by Howes.[6]

Thermal fatigue is a possible failure mechanism in any situation that involves fluctuating temperatures. If certain materials are heated or cooled rapidly and continuously, cracking sometimes occurs. This phenomenon, which is often called thermal shock, is caused by thermal gradients present during rapid temperature change. As a result, strain is produced which is related to the coefficient of expansion of the material. Failure occurs when thermally induced stresses exceed the strength of the material after starting as a crack in the most sensitive area. In metals, the thermal fatigue mechanism often results in the gradual formation of a network of cracks and is commonly referred to as craze cracking, heat cracking, or fire cracking. Any part which undergoes temperature cycling during service is likely to fail by this mechanism.

Failures due to thermal fatigue can be found in brake drums, turbine blades, internal combustion engine pistons, rolls for forming hot steel, forging dies, railway wheels, furnace components, and in molds used for glass and metal molding. Thermal fatigue can become the dominant failure mode in aircraft gas turbine engines as the operating temperature and thermal gradients become more severe and the expected service life becomes longer.

Many methods of heating and cooling have been used to simulate the thermal cycles experienced in actual applications. Some of the earliest work used direct flame impingement on a surface. However, unless carefully controlled, the combustion products and variation in temperature conditions will introduce an arbitrary environment which can influence the cracking mechanism.

High-frequency heating and electrical resistance heating systems can be used to establish simulated thermal cycling conditions; however, they are generally expensive to construct for the multistation test facilities which are needed to amass data quickly. In the consideration of thermal fatigue, the crack propagation rate is as important as the start of cracking. For instance, a material that cracks early might be satisfactory if the crack propagation rate is very slow. With high frequency and resistance heating, the formation of a crack alters the flux or current density in such a way that the crack is overheated and measurement of propagation rate becomes meaningless.

The fluidized bed heating system for thermal fatigue testing has many advantages and no significant disadvantages. The bed construction is simple and relatively inexpensive. The rate of heat transfer to a specimen or group of specimens is high. The heat content of a particulate solid fluidized media is also high, so that a large number of specimens or a large specimen can be rapidly and repeatedly heated without lowering the bed temperature significantly. The fluid bed system uses low-velocity air flows (on the order of 1 fps), and in this respect the high-velocity gas flows in a turbine engine are not simulated. The first reported use of fluidized beds for thermal fatigue testing was in 1958 by Glenny and co-workers.[7] Since that time there have been many reports of the use of this technique to evaluate thermal fatigue resistance, and a bibliography of the literature of thermal fatigue up to 1967 was compiled by Carden.[8]

The original high-temperature bed described by Glenny was 6 in. in diameter and was heated by wire-wound elements of 4 kw total input. For this program much heavier loads of test specimens had to be cycled, and a bed diameter of 11.5 in. with a power input of 55 kw was required. The low-temperature bed was controlled at an intermediate temperature instead of room temperature; thus the lower temperature beds were required to have provisions for both heating and cooling. These features are described in the section under Experimental Work which deals with the thermal fatigue facility.

EXPERIMENTAL WORK

Materials and Conditions

Thirteen variations of alloys and treatment were studied in this program. These are listed in Table 1. The three different alloy compositions along with their heat treatments which were used are shown in Table 2. The variables studied in this program included

1. Composition
2. Test piece shape (i.e., double or single edge wedges)

3. Solidification method

4. Surface protection

For the thermal fatigue testing two types of geometry were used (Figure 1). Most testing used the single-edge wedge type having a nominal edge radius of 0.030 in.

TAZ-8A and MAR-M 200 were used in the directionally solidified condition. Randomly solidified specimens of TAZ-8A and Udimet 700 were also tested.

Two types of surface protection were used as follows:

1. Coating: RT-XP--a coating containing an aluminide with a case depth of about 70 μm (2.7 mil) thick (Chromalloy American Corporation proprietary process).
2. Cladding: NiCrAlY--a commercial Ni-15.2Cr-12Al-0.33Y electron-beam vapor-deposited clad, about 135 μm (5.3 mils) thick (Pratt & Whitney Aircraft proprietary process specified as PWA 267).

Tensile properties at 760°C (1400°F) and stress-rupture properties at 982°C (1800°F) for TAZ-8A and Udimet 700 were obtained by NASA-Lewis using the uniaxial specimens (Figure 1). Specimens were made from the same heat of material as was used for fabricating the thermal fatigue specimens with about the same surface grain size (typically about 1/16 inch diameter). As specimens from the same heat for the directionally solidified MAR-M 200 were not available, nominal properties are presented. The results are given in Tables 3 and 4.

Thermal Fatigue Facility

A schematic drawing of the thermal fatigue testing facility is shown in Figure 2. It consists of a 11.0 in. diameter high-temperature bed situated between two 14 in. diameter intermediate-temperature beds.

The center high-temperature bed has either an Inconel retort or a silicon carbide retort (depending on the maximum temperature requirements), and a stainless steel air-diffuser box supplied with air from a low-pressure blower. The bed is heated by 12 silicon carbide elements with a total power of 55 kw. Heat insulation is provided by two layers of refractory insulating brick.

The intermediate beds are double-walled, with a stainless steel liner and a 1 in. insulation of Fiberfrax. Heating is provided by three Calrod elements (total power of 12 kw for each bed) situated above the stainless steel air box. For cooling, the heat exchanger can be either a multi-tube, water-cooled copper assembly (left bed, Figure 2) for bed temperatures up to 204°C (400°F) or an air-cooled stainless steel jacket (right bed, Figure 2) for bed temperatures above 204°C (400°F). These heat exchangers are interchangeable. For all work carried out on this program, the air-cooled heat exchanger was used.

The specimens are cycled by means of automatically controlled pneumatic cylinders which are sequenced by timers and limit switches. The facility will cycle automatically for the number of cycles selected.

The air supply for fluidization is controlled through flowmeters for each bed. The maximum fluidization air demand is about 3500 cu ft/sq ft/hr (3500 cfh) for each of the intermediate beds at 38°C (100°F) and 900 cu ft/sq ft/hr (600 cfh) for the high-temperature bed at 1204°C (2000°F). Less inlet air is required as the bed temperature is increased due to the expansion of the air as it passes through the bed. Tests show that the fluidization range is fairly narrow since the bed will rapidly empty if excessive air is used.

Each bed is fitted with four thermocouples for control, over-temperature protection, low-temperature test cutoff, and recording purposes.

Facility Performance

The high-temperature bed will operate at 1260°C (2300°F) using a silicon carbide retort and could be run at this temperature for testing small samples. However, as the specimen load in pounds per hour is increased, the maximum permissible bed temperature must be decreased. Otherwise the temperature of the heating elements would exceed the maximum permissible value of 1510°C (2750°F). With a specimen load of 15 lb every 4 min, the maximum bed temperature is about 1204°C (2000°F) with a constant input of about 45 kw. Below a 1204°C (2000°F) bed temperature, the Inconel retort may be used.

The intermediate beds will run at a maximum temperature of 427°C (800°F). When a 15 lb load is cooled from 1204°C (2000°F) every 4 min, the air-cooled and water-cooled heat exchangers will hold the bed temperatures at 204°C (400°F) and 83°C (200°F), respectively.

Thermal Fatigue Fixture

The fixture used for this program is shown in Figure 3. It consisted of three RA 333 vertical supports of the same section as the test pieces and tapered at the bottom to simulate test piece configuration. Specimens were bolted between supports using threaded 330 alloy. The fixture could be adjusted for different numbers of specimens by inserting different spacer blocks at the top of the fixture. This fixture had an average life of approximately 1000 cycles.

Test Conditions

All 19 specimens were cycled simultaneously. They were placed at random in the fixture as regards position from end and orientation.

The following fluidizing conditions were maintained constant through the entire test series:

	Air Flow Measured at 66°C (150°F)	
	$ft^3/ft^2/hr$	$m^3/m^2/hr$
Hot Bed	900	275
Intermediate Bed	2100	640

The fluidized media was 28-48 mesh tabular alumina.

The time of immersion in each bed was held constant at 3 min. The constant bed temperatures used for this series were as follows:

Series	Hot Bed °C	Hot Bed °F	Intermediate Bed °C	Intermediate Bed °F
4	1088	1990	316	600

For all of the alloys with the cladding, duplicate specimens were tested.

Inspection of Specimens During Testing

The specimens were removed at regular cycle intervals, and the test edges were examined for cracks using a 30X microscope. Inspections were made after 25, 50, 100, 200, 300, 500, 700, and

1000 cycles and every 1000 cycles thereafter to 15,000 cycles. When a crack was discovered, the length from crack tip to specimen edge was measured on both sides of the specimen and the average taken as the crack length. Measurement was made using a traveling microscope.

When sufficient crack data were obtained, the specimen was removed from the fixture and replaced by a stainless steel dummy specimen.

RESULTS

Thermal Fatigue Data

Complete crack propagation data are contained in Table 5. Data are given as crack length versus number of cycles for a maximum of three cracks in each edge. The appearance of all specimens before and after testing is shown in Figures 4 and 5, respectively.

The number of cycles required to initiate cracks was of primary interest in this study. There are several ways of determining this number, which cannot be measured directly. Glenny[7] used the procedure of averaging the cycles between the last inspection cycle to show no crack and the first inspection when the crack was observed. A refinement of this method is to plot crack length versus cycle number and extrapolate to zero crack length. This latter procedure is of particular value when the test section is of constant thickness and the crack length versus cycle number curves approximate straight lines. The wedge section specimen used in this investigation results in nonlinear crack propagation curves and makes it difficult to accurately extrapolate the curves to zero crack length. The averaging method of Glenny has been used in this investigation, and the cycles to initiate the first crack in each alloy are summarized in Table 6.

In some cases cracks initiated in the 0.040 in. test edge before the 0.025 in. edge. This was probably due to weaknesses in the 0.040 in. edge causing preferred initiation. Once a crack was well established, it is probable that the stresses were relieved sufficiently to delay crack initiation in the opposite edge. It was also noticeable that when several cracks propagated, they did so at regular intervals along the specimen. When one crack formed, it relieved the stresses locally and thus prevented another crack forming within the immediate neighborhood of the first crack.

Physical Changes During Testing

Weight changes during testing are given in Table 7. Dimensional changes are shown in Table 8. Specimens having the greatest weight loss after 7000 test cycles are:

MAR-M 200 DS	- 10.8%
TAZ-8A DS (single edge)	- 3.5%
TAZ-8A DS (double edge)	- 1.44%
Udimet 700 - clad	- 1.0%
TAZ-8A	- 0.97%

Figure 6 shows the weight changes of some Series 4 specimens during cycling. Some specimens showed slight weight gains before losing weight.

Ranking

If thermal fatigue cracking resistance is based upon the number of cycles required to form the first crack, then the alloys can be ranked as follows for Series 4, 1088/316°C (1990/600°F):

Rank	Alloy	Cycles to 1st Crack
	Double-Edge Wedge Specimens	
1 (highest)	TAZ-8A DS Coated	12,500
2-3	MAR-M 200 DS Clad, TAZ-8A DS Uncoated	6,500
4	TAZ-8A DS Clad	5,500
5	MAR-M 200 DS Uncoated	1,250
	Single-Edge Wedge Specimens	
1-4	TAZ-8A DS Uncoated, Coated, Clad, Composite and Clad	>15,000
5	TAZ-8A Coated	13,500
6	TAZ-8A Clad	12,000
7	Udimet 700 Clad	7,000
8	TAZ-8A Uncoated	4,500

CONCLUSIONS

The purpose of this investigation was to use the fluidized bed heating and cooling technique to measure the relative thermal fatigue cracking resistance of 13 combinations of superalloy composition, specimen design, casting technique, and coating.

The alloys showing the best resistance to thermal fatigue cracking were TAZ-8A DS clad and TAZ-8A DS coated. The number of cycles required to crack the various alloys varied widely from over 15,000 for the best materials to 1250 cycles for the worst. This represents a 12:1 difference in behavior under severe testing conditions.

Oxidation occurs during thermal cycling, and some alloys experience considerable weight loss. The directionally solidified alloys are particularly susceptible and normally should be protected with a coating.

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TABLE 1. ALLOYS AND CONDITIONS USED IN TEST PROGRAM

Alloy	Type of Wedge	Solidification Method	Surface Treatment	Specimen No.
TAZ-8A	Double	DS	-	1
TAZ-8A	Double	DS	Coated	2
TAZ-8A	Double	DS	Clad	3, 4
MAR-M 200	Double	DS	-	5
MAR-M 200	Double	DS	Clad	6, 7
TAZ-8A	Single	Random	-	9
TAZ-8A	Single	Random	Coated	10
TAZ-8A	Single	Random	Clad	11, 12
TAZ-8A	Single	DS	-	13
TAZ-8A	Single	DS	Coated	14
TAZ-8A	Single	DS	Clad	15, 16
TAZ-8A	Single	DS Composite	Clad	17, 18
Udimet 700	Single	Random	Clad	19, 20

TABLE 2. - COMPOSITIONS AND HEAT TREATMENTS

OF ALLOYS USED IN THE PROGRAM

	Composition, wt%		
Element	MAR-M 200 (Heat No. KD2012)	Udimet 700 (wrought) (Heat No. 6541)	TAZ-8A (Heat No. T24)
C	0.1[illegible]	0.113	0.10
Mn	<0.02	0.01	--
Si	0.080	0.02	--
Cr	9.20	14.85	5.85
Ni	Bal.	Bal.	Bal.
Co	10.25	17.50	--
Mo	--	5.10	5.41
W	12.55	--	3.90
Al	5.05	4.55	6.40
Ti	2.13	3.45	--
Zr	0.048	<0.02	0.52
B	0.017	0.013	39 ppm
Other	0.36Fe 0.96Cb <0.01V	0.85Fe	7.93Ta 2.44Cb
Solution Treatment	--	1121°C (2050°F) 4 hr	--
Intermediate Aging	--	843°C (1550°F) 24 hr	--
Final Aging	816°C (1500°F) 50 hr	760°C (1400°F) 16 hr	--

TABLE 3. - TENSILE PROPERTIES AT 760°C (1400°F)

Property	MAR-M 200 DS[a]	Udimet 700 (wrought)[b]	TAZ-8A DS[b]	[illegible]-8A[b]
Proportional Limit				
psi	126,000[c]	110,000	130,000	150,000
N/cm^2	86,900[c]	75,800	89,600	103,400
% of Nominal 0.2% YS	-	92	93	-
Ultimate Tensile Strength				
psi	152,000	143,000	171,400	174,000
N/cm^2	104,800	98,600	118,200	120,000
% of Nominal UTS	-	95	110	134
Reduction of Area, %	6	30	4.5	2

[a]Nominal properties (specimens not available).

[b]Each result is the average of two tests.

[c]0.2% yield stress.

TABLE 4. - STRESS-RUPTURE PROPERTIES AT 982°C (1800°F)

Property	MAR-M 200 DS[a]	Udimet 700 (wrought)	TAZ-8A DS	TAZ-8A
Stress				
psi	29,000	16,000	25,000	18,000
N/cm^2	20,000	11,000	17,200	12,400
Life (Nominal 100 hr)				
Hours	-	141	43.6	89
	-	133	147.9	79
% of Nominal	-	137	96	84
Reduction of Area, %	-	32	29.6	8

[a]Nominal properties (specimens not available).

TABLE 5. - SUMMARY OF CRACK PROPAGATION FOR TEST SERIES 4

CYCLED BETWEEN 1088°C (1990°F) AND 316°C (600°F)

(3 min dwell in each bed)

Edge Radius, in.	Cycles	Crack length, in.								
		First Crack			Second Crack			Third Crack		
		Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
					Specimen 1: TAZ-8A DS (DEW)					
0.025	Distance from bottom:			3.33 in.[a]			2.15 in.			2.47 in.
	6,000	Cracks not observed								
	7,000	.069	.079	.074	--	--	--	--	--	--
	8,000	.075	.079	.077	--	--	--	--	--	--
	9,000	.082	.080	.081	.050	.020	.035	--	--	--
	10,000	.100	.080	.090	.070	.030	.050	.050	.040	.045
0.040	Distance from bottom:			3.42 in.[a]			2.58 in.			2.87 in.
	6,000	Cracks not observed								
	7,000	.200	.144	.172	--	--	--	--	--	--
	8,000	.200	[illegible]	.178	--	--	--	--	--	--
	9,000	.200	.178	.189	.110	.120	.115	--	--	--
	10,000	.200	.190	.195	.150	.160	.155	.050	.060	.055
					Specimen 2: TAZ-8A DS Coated (DEW)					
0.025	Distance from bottom:			2.10 in.			1.7 in.			2.75 in.
	12,000	Small cracks in coating near fixing holes								
	13,000	.090	.060	.075	--	--	--	--	--	--
	14,000	.200	.190	.195	.140	.100	.120	0	.070	.035
0.040	14,000	Cracks not observed								
					Specimen 3: TAZ-8A DS Clad (DEW)					
0.025	Distance from bottom:			2.15 in.			3.30 in.[a]			
	5,000	Many small cracks in edge of cladding								
	6,000	No major cracks observed								
	7,000	.150	.146	.148	.227	.252	.240	--	--	--
0.040	7,000	Cracks not observed								
					Specimen 4: TAZ-8A DS Clad (DEW)					
0.025	Distance from bottom:			2.76 in.						
	4,000	Cracks not observed								
	5,000	.230	.140	.185						
	6,000	.236	.235	.236						
	7,000	.290	.261	.276						
0.040	7,000	Cracks not observed								
					Specimen 5: MAR-M 200 DS (DEW)					
0.025	Distance from bottom:			0.56 in.[a]			2.50 in.			2.80 in.
	1,000	Cracks not observed								
	1,500	.060	.060	.060						
	2,000	.095	.100	.098	0	0	0			
	2,500	.125	.125	.125	.030	.015	.023	0	0	0
	3,000	.135	.135	.135	.050	.050	.050	.040	.040	.040
	4,000	.200	.160	.180	.095	.080	.088	.090	.078	.084
	5,000	.200	.200	.200	.130	.150	.140	.120	.130	.125
	6,000	.205	.210	.208	.140	.180	.160	.150	.155	.153
	7,000	.224	.245	.235	.219	.210	.215	.194	.192	.193
0.040	7,000	Cracks not observed								
					Specimen 6: MAR-M 200 DS Clad (DEW)					
0.025	Distance from bottom:			2.73 in.			2.20 in.			3.10 in.[a]
	4,000	Cracks not observed								
	5,000	.098	.115	.107	0	0	0			
	6,000	.105	.140	.123	.060	0	.030	0	0	0
	7,000	.176	.204	.190	.113	.145	.129	.112	.109	.111
0.040	7,000	Cracks not observed								
					Specimen 7: MAR-M 200 DS Clad (DEW)					
0.025	Distance from bottom:			2.58 in.			1.67 in.			2.05 in.
	8,000	Cracks not observed								
	9,000	.080	.085	.083	--	--	--	--	--	--
	10,000	.140	.140	.140	.120	.100	.110	.090	.090	.090
0.040	Distance from bottom:			0.57 in.[a] (in line with fixing hole)						
	6,000	Cracks not observed								
	7,000	.107	.137	.122						
	8,000	.118	.140	.129						
	9,000	.134	.145	.140						
	10,000	.160	.150	.155						

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Edge Radius, in.	Cycles	Crack length, in. First Crack Front	First Crack Back	First Crack Avg	Second Crack Front	Second Crack Back	Second Crack Avg	Third Crack Front	Third Crack Back	Third Crack Avg
		Specimen 9: (No Specimen 8) TAZ-8A Random (SEW)								
0.030	Distance from bottom:	1.12 in.[a]			2.20 in.			1.57 in.		
	4,000	Cracks not observed								
	5,000	.140	.110	.125	.094	.075	.085			
	6,000	150	.160	.155	.140	.080	.110	0	0	0
	7,000	160	.170	.165	.127	.158	.143	.102	.100	.101
		Specimen 10: TAZ-8A Random, Coated (SEW)								
0.030	Distance from bottom:	2.43 in.								
	13,000	Cracks not observed								
	14,000	.060	.120	.090						
	15,000	.150	.170	.160						
		Specimen 11: TAZ-8A Random, Clad (SEW)								
0.030	Distance from bottom:	2.62 in.			1.30 in.					
	10,000	Cracks not observed in test section but commencing near fixing holes								
	13,000	.100	.090	.095	.040	.040	.040			
	14,000	.150	.170	.160	.040	.040	.040			
	15,000	.160	.170	.165	.170	.150	.160			
		Small glassy spots are exfoliating								
		Specimen 12: TAZ-8A Random, Clad (SEW)								
0.030	Distance from bottom:	2.78 in.			1.9 in.			2.5 in.		
	11,000	Cracks not observed								
	12,000	.010	.020	.015	--	--	--	--	--	--
	13,000	.040	.040	.040	.040	.050	.045	.090	.070	.080
	14,000	.150	.140	.145	.120	.120	.120	.110	.120	.115
	15,000	.170	.160	.165	.150	.140	.145	.120	.130	.125
		Specimen 13: TAZ-8A DS (SEW)								
0.030	15,000	Cracks not observed. Glassy scale is flaking off surface.								
		Specimen 14: TAZ-8A DS Coated (SEW)								
0.030	15,000	Cracks not observed								
		Specimens 15 and 16: TAZ-8A DS Clad (SEW)								
0.030	15,000	Minor cracks in cladding. Cladding has developed very rough surface.								
		Specimens 17 and 18: TAZ-8A DS Composite, Clad (SEW)								
0.030	200	3 out 4 welded ends became detached and identification was lost								
	3,000	Last welded end lost								
	15,000	Cracks not observed. Bushings are loose. Cladding has a very rough surface.								
		Specimen 19: Udimet 700 Random, Clad (SEW)								
0.030	Distance from bottom:	1.40 in.			2.65 in.					
	7,000	Cracks not observed								
	8,000	Small cracks commencing at inner edge of fixing holes								
	9,000	.140	.150	.145	--	--	--			
	10,000	.250	.260	.255	.100	.110	.105			
		Specimen 20: Udimet 700 Random, Clad (SEW)								
0.030	Distance from bottom:	1.2 in.[a]								
	500	Specimen started to deform like a banana. 0.030 in. out of line at 500 cycles increasing to 0.150 in. by 7000 cycles								
	5,000	Cracks not observed								
	6,000	.170	.150	.160	Cracks starting at fixing holes.					
	7,000	.300	.285	.293						

[a]Crack position is outside designated test section.

TABLE 6. - THERMAL CYCLES REQUIRED TO INITIATE THE FIRST CRACK IN EACH EDGE

Cycled 1088/316°C (1990/600°F), 3 min dwell in each bed

Alloy	Solidification Method	Condition	Type of Wedge	Specimen No.	.025 or .030 Edge	.040 Edge
TAZ-8A	Random	--	Double	--	600[a]	4,500[a]
				--	800[b]	>1,200[b]
	Random	--	Single	9	4,500	--
				--	800[b]	--
	Random	Coated	Single	10	13,500	--
	Random	Clad	Single	11	12,500	--
				12	11,500	--
	DS	--	Double	1	6,500	6,500
				--	4,350[b]	>6,250[b]
				--	4,350[b]	3,625[b]
	DS	--	Single	13	>15,000	--
	DS	Coated	Double	2	12,500	>14,000
	DS	Clad	Double	3	6,500	>7,000
				4	4,500	>7,000
	DS	Coated	Single	14	>15,000	--
	DS	Clad	Single	15	>15,000	--
				16	>15,000	--
	DS	Composite-Clad	Single	17	>15,000	--
				18	>15,000	--

TABLE 6 (cont.)

Alloy	Solidification Method	Condition	Type of Wedge	Specimen No.	.025 or .030 Edge	.040 Edge
MAR-M 200	Random	--	Double	--	13[a]	38[a]
	Random	Jocoat	Double	--	25[b]	>470[b]
	DS	--	Double	5	1,250	>7,000
				--	4,700[a]	>5,000[a]
				--	1,750[b]	>4,000[b]
	DS	Clad	Double	6	4,500	>7,000
				7	8,500	>10,000
Udimet 700	Random	Wrought	Double	--	13[a]	75[a]
	Random	Cast	Double	--	75[a]	150[a]
	Random	Wrought & Clad	Single	19	8,500	--
				20	5,500	--

[a]Results from CR-72738.

[b]Results from CR-121211.

TABLE 7. - WEIGHT CHANGES IN SERIES 4 SPECIMENS

Cycled 1088/316°C (1990/600°F), 3 min dwell in each bed

Spec. No.	Alloy and Condition	Original Weight, g	Weight Change after Given Cycles, %							
			500	1000	2000	3000	4000	5000	6000	7000
1	TAZ-8A DS	124.009	+.012	-.005	-.098	-.234	-.44	-.87	-1.15	-1.44
2	TAZ-8A DS Coated	124.682	+.014	+.016	+.014	+.014	+.007	-.008	-.012	-.015
3	TAZ-8A DS Clad	129.319	-.25	-.25	-.29	-.32	-.35	-.39	-.44	-.48
4	TAZ-8A DS Clad	130.940	+.011	+.013	0	-.025	-.050	-.10	-.16	-.20
5	MAR-M 200 DS	122.585	-.11	-.56	-2.86	-4.6	-6.1	-7.8	-9.8	-10.8
6	MAR-M 200 DS Clad	127.570	-.15	-.16	-.24	-.35	-.43	-.56	-.67	-.71
7	MAR-M 200 DS Clad	127.[illegible]	-.13	-.14	-.21	-.31	-.38	-.49	-.60	-.69
9	TAZ-8A Random	116.117	-.002	+.017	-.002	-.060	-.19	-.45	-.64	-.97
10	TAZ-8A Random Coated	110.804	+.013	+.016	+.013	+.011	+.009	+.007	+.006	+.004
11	TAZ-8A Random Clad	123.265	-.15	-.16	-.17	-.19	-.20	-.24	-.27	-.30
12	TAZ-8A Random Clad	117.326	+.02	+.01	-.0[illegible]	-.07	-.09	-.14	-.17	-.20
13	TAZ-8A DS	113.682	+.02	+.03	0	-.31	-.88	-2.0	-2.7	-3.5
14	TAZ-8A DS Coated	113.985	+.01	+.02	+.02	+.02	+.01	0	0	0
15	TAZ-8A DS Clad	116.385	-.12	-.12	-.14	-.16	-.18	-.22	-.26	-.30
16	TAZ-8A DS Clad	119.178	+.01	+.01	-.01	-.04	-.08	-.12	-.15	-.19
17	TAZ-8A DS Composite Clad	117.051	Ends detached from specimens							
18	[illegible]AZ-8A DS Composite Clad	116.197								
19	Udimet 700 Random Clad	112.217	-.09	-.11	-.22	-.36	-.50	-.72	-.88	-1.0
20	Udimet 700 Random Clad	112.617	-.11	-.12	-.18	-.23	-.27	-.35	-.49	-.64

TABLE 7 (cont.)

Spec. No.	Alloy and Condition	Original Weight, g	Weight Change after Given Cycles, % 8000	9000	10,000	11,000	12,000	13,000	14,000	15,000
1	TAZ-8A DS	124.009	-2.04	-2.27	-2.77					
2	TAZ-8A DS Coated	124.682	-0.019	-0.022	-0.023	-0.031	-0.038	-0.044	-0.052	
7	MAR-M 200 DS Clad	127.900	-0.85	-0.94	-1.10					
10	TAZ-8A Random Coated	110.804	+0.006	+0.006	+0.004	+0.003	-0.001	-0.001	-0.002	-0.003
11	TAZ-8A Random Clad	123.265	-0.032	-0.34	-0.39	-0.44	-0.43	-0.55	-0.62	-0.70
12	TAZ-8A Random Clad	117.326	-0.22	-0.25	-0.28	-0.31	-0.35	-0.41	-0.47	-0.53
13	TAZ-8A DS	113.682	-4.82	-5.0	-5.74	-6.93	-8.19	-9.64	-11.36	-13.39
14	TAZ-8A DS Coated	113.985	+0.01	+0.01	+0.01	+0.01	0	0	-0.003	-0.01
15	TAZ-8A DS Clad	116.385	-0.35	-0.39	-0.45	-0.50	-0.55	-0.63	-0.71	-0.82
16	TAZ-8A DS Clad	119.178	-0.23	-0.24	-0.34	-0.40	-0.46	-0.55	-0.63	-0.74
19	Udimet 700 Random Clad	112.217	-1.17	-1.30	-1.54					

NOTE: Specimens 6 and 7 may have lost less material due to oxidation because of the loss of a welded specimen support bar during cycling. See Figure 4.

TABLE 8. - DIMENSIONAL CHANGES IN SERIES 4 SPECIMENS

Cycled 1088/316°C (1990/600°F), 3 min dwell in each bed

Spec. No.	Alloy and Condition	Initial Dimensions, in.					Number of Cycles	Dimensions after Test, in.				
					Radius						Radius	
		Length	Width	Thickness	Nominal .040	Nominal .025 or .030		Length	Width	Thickness	Nominal .040	Nominal .025 or .030
1	TAZ-8A DS	3.985	1.248	.250	.040	.022	10,000	3.983	1.235	.252	.039	.017
2	TAZ-8A DS Coated	3.985	1.248	.253	.045	.025	14,000	3.990	1.250	.253	.044	.024
3	TAZ-8A DS Clad	3.980	1.249	.258	.047	.030	7,000	3.980	1.260	.259	.047	.028
4	TAZ-8A DS Clad	3.985	1.248	.262	.048	.030	7,000	3.984	1.260	.263	.046	.029
5	MAR-M 200 DS	4.006	1.248	.248	.039	.024	7,000	3.985	1.227	.238	.028	.011
6	MAR-M 200 DS Clad	3.975	1.265	.259	.046	.028	7,000	3.975	1.268	.261	.044	.027
7	MAR-M 200 DS Clad	3.990	1.265	.257	.046	.028	10,000	3.983	1.268	.258	.045	.025
9	TAZ-8A Random	3.980	1.002	.251	-	.028	15,000	3.983	1.004	.252	-	.024
10	TAZ-8A Random Coated	3.955	0.986	.248	-	.030	15,000	3.958	0.991	.249	-	.024
11	TAZ-8A Random Clad	3.980	1.008	.264	-	.036	15,000	3.984	1.020	.264	-	.036
12	TAZ-8A Random Clad	3.950	0.998	.252	-	.035	15,000	3.955	1.002	.254	-	.033
13	TAZ-8A DS	3.990	0.987	.242	-	.030	15,000	3.966	0.956	.228	-	.016
14	TAZ-8A DS Coated	3.990	0.990	.244	-	.032	15,000	3.997	0.991	.245	-	.028
15	TAZ-8A DS Clad	3.990	0.993	.248	-	.034	15,000	3.997	0.997	.251	-	.031
16	TAZ-8A DS Clad	3.985	1.000	.253	-	.035	15,000	3.986	1.005	.255	-	.032
17	TAZ-8A DS Composite Clad	3.990	1.000	.249	-	.032	15,000	(a)	1.005	.251	-	.030
18	TAZ-8A DS Composite Clad	4.005	0.999	.248	-	.033	15,000	(a)	1.004	.250	-	.032
19	Udimet 700 Random Clad	3.985	1.014	.259	-	.032	10,000	3.966	1.016	.260	-	.028
20	Udimet 700 Random Clad	3.995	1.013	.259	-	.036	7,000	(b)	1.038	.273	-	.034

[a]Ends detached during test.

[b]Severe distortion.

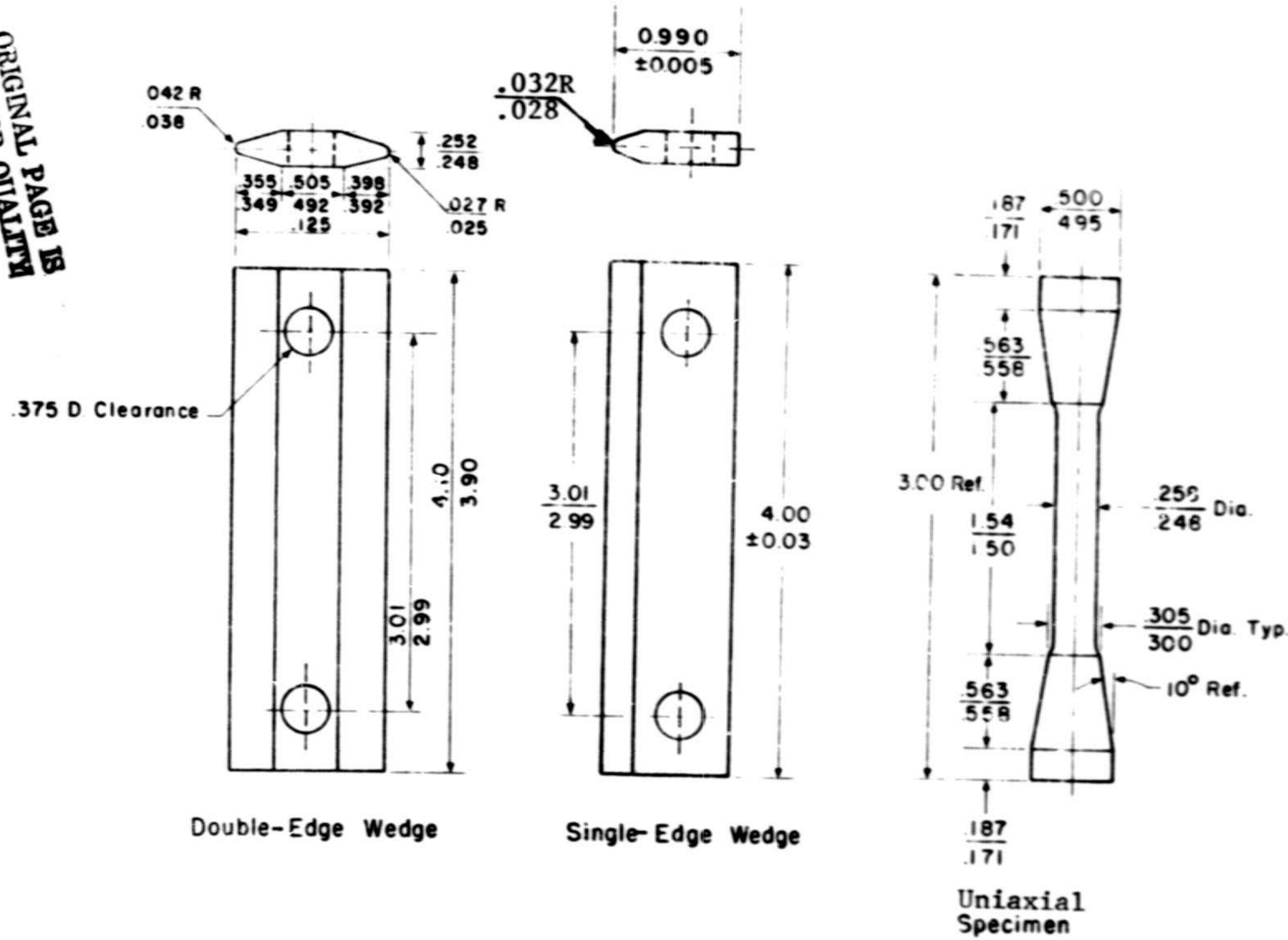


Figure 1

Dimensions of Test Specimens Used in the Program

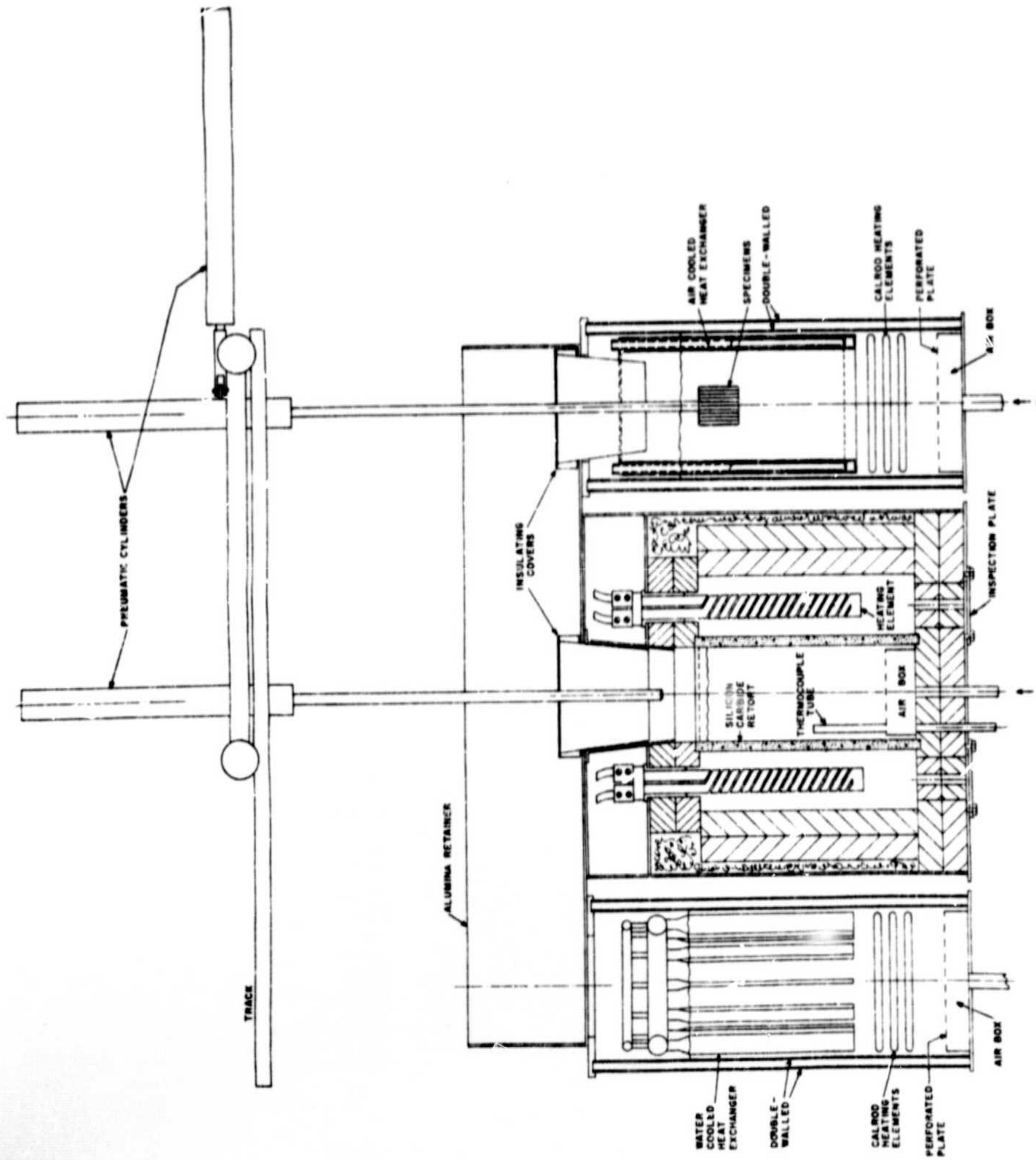


Figure 2
Thermal Fatigue Facility

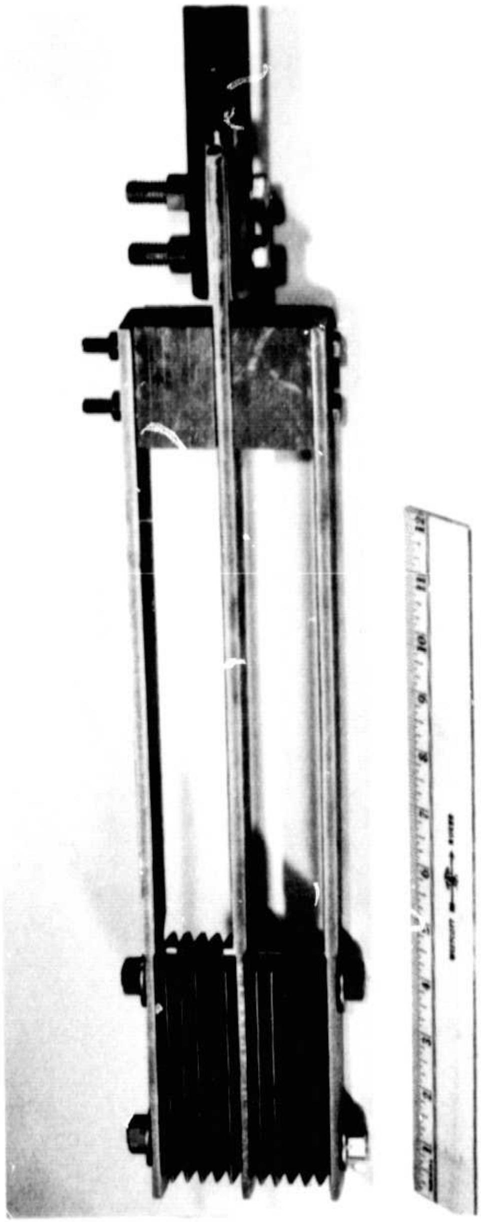
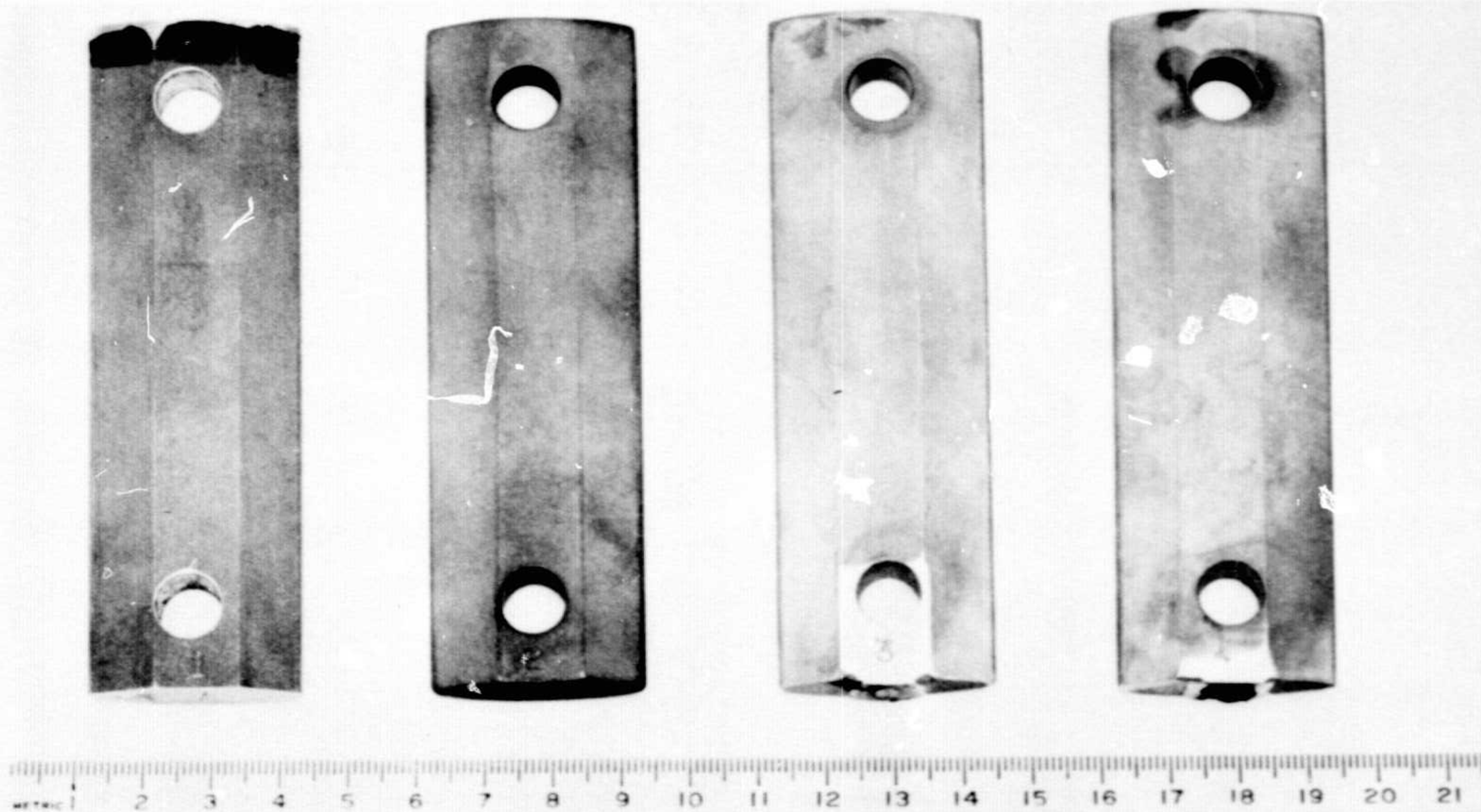


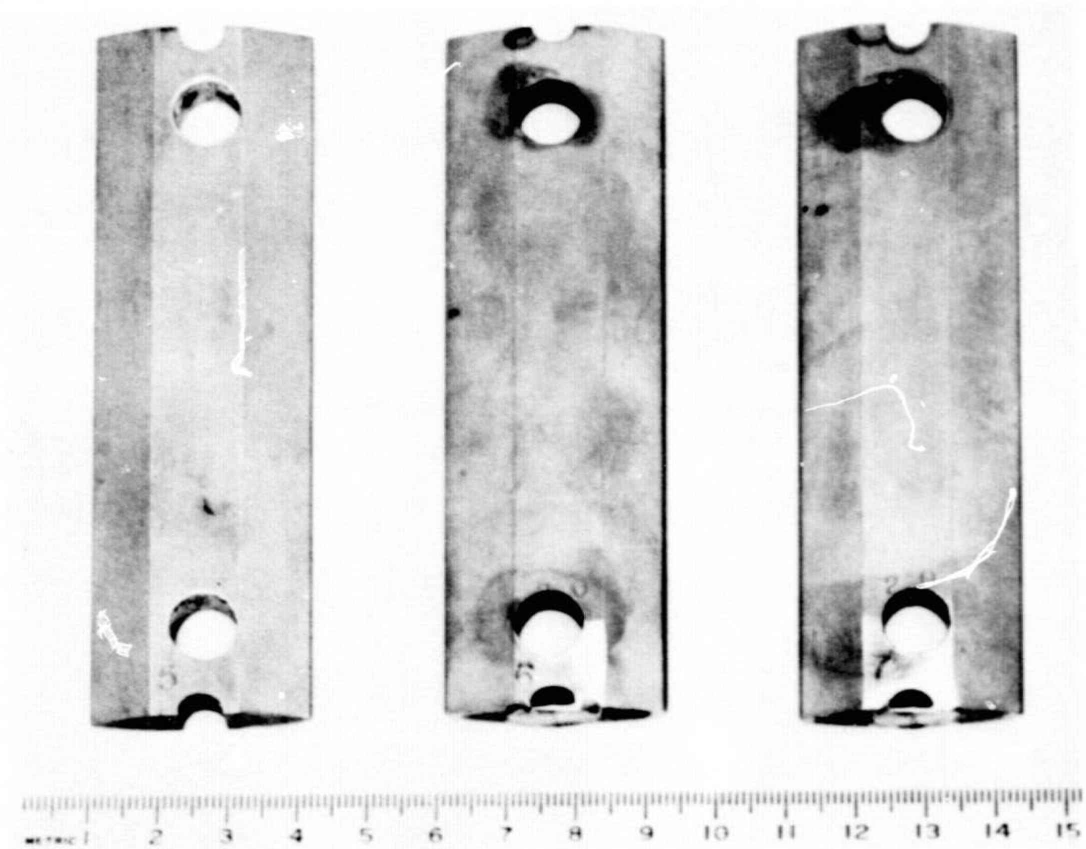
Figure 3
Thermal Fatigue Fixture



1	2	3	4
TAZ-8A DS	TAZ-8A DS (coated)	TAZ-8A DS (clad)	TAZ-8A DS (clad)

Figure 4

Appearance of Series 4 Specimens Before Testing

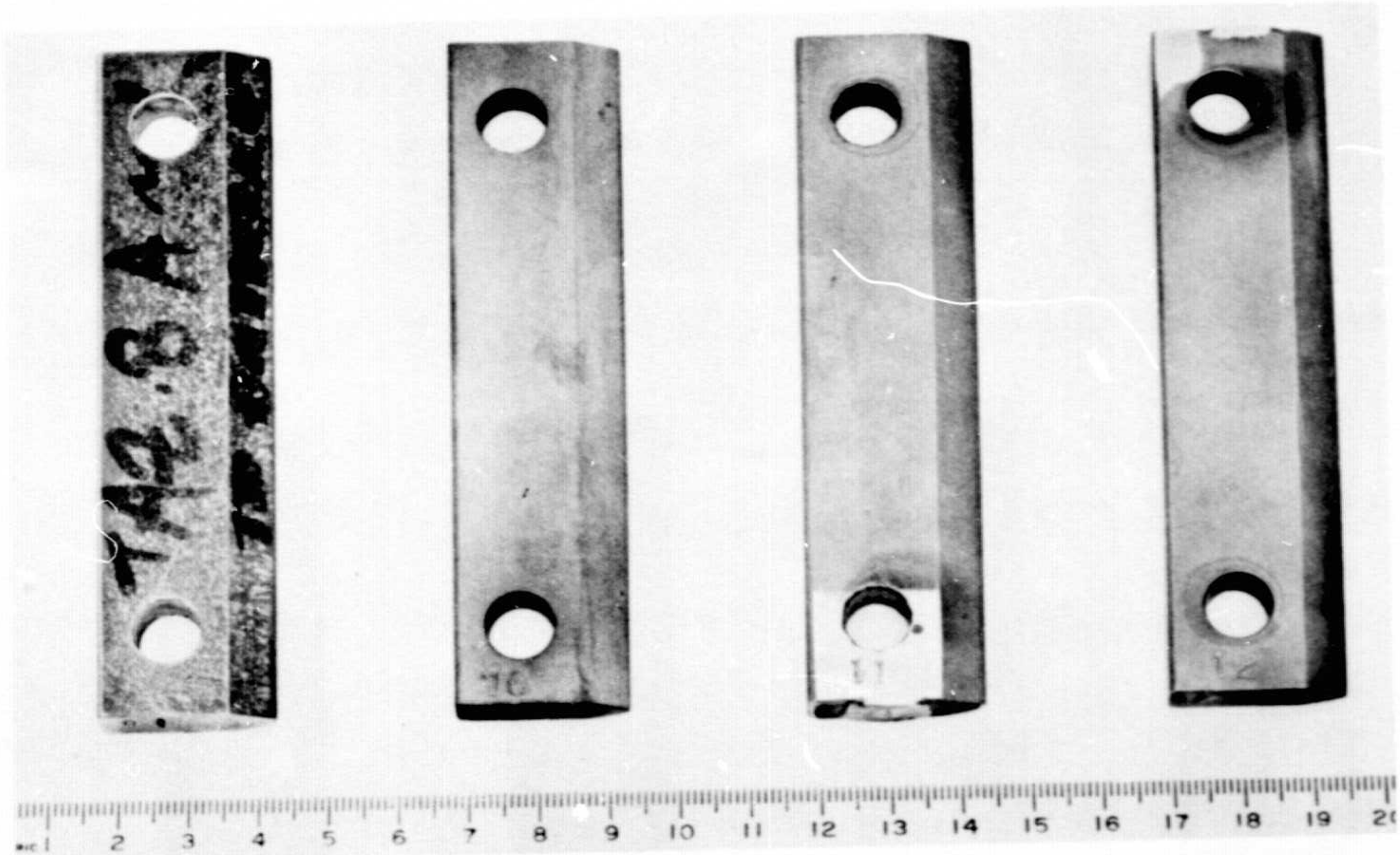


5 MAR-M 200 DS

6 MAR-M 200 DS (clad)

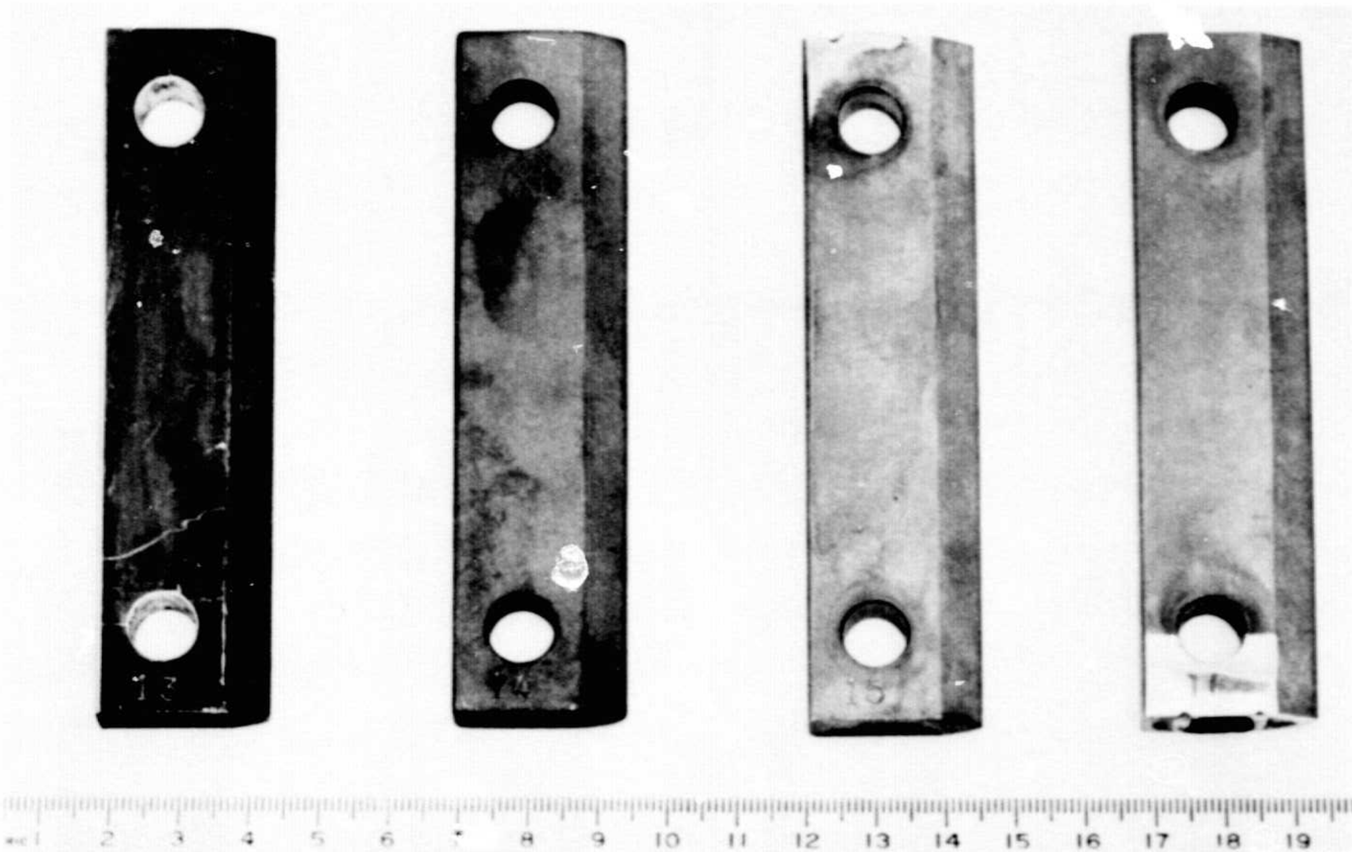
7 MAR-M 200 DS (clad)

Figure 4 (cont.)



9	10	11	12
TAZ-8A	TAZ-8A (coated)	TAZ-8A (clad)	TAZ-8A (clad)

Figure 4 (cont.)



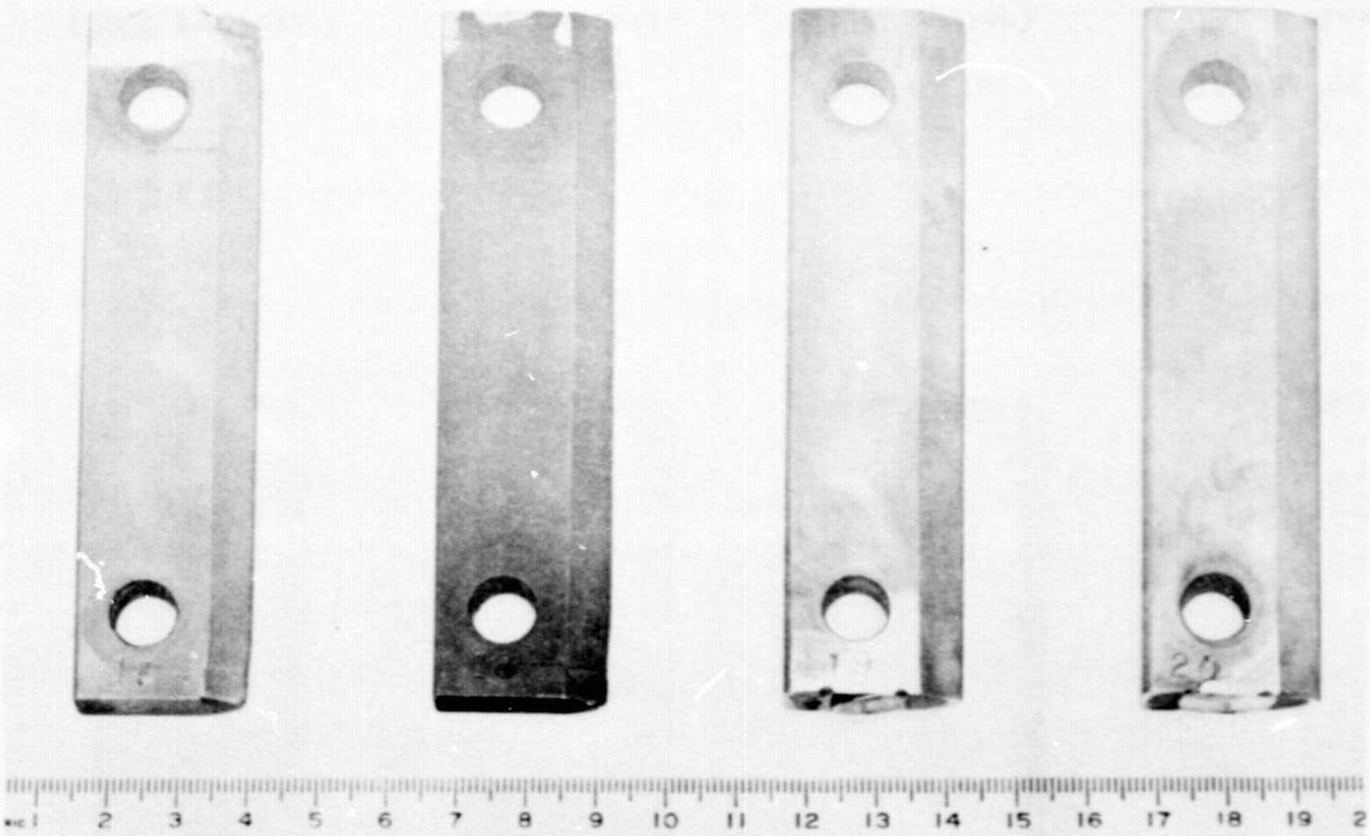
13
TAZ-8A DS

14
TAZ-8A DS
(coated)

15
TAZ-8A DS
(clad)

16
TAZ-8A DS
(clad)

Figure 4 (cont.)



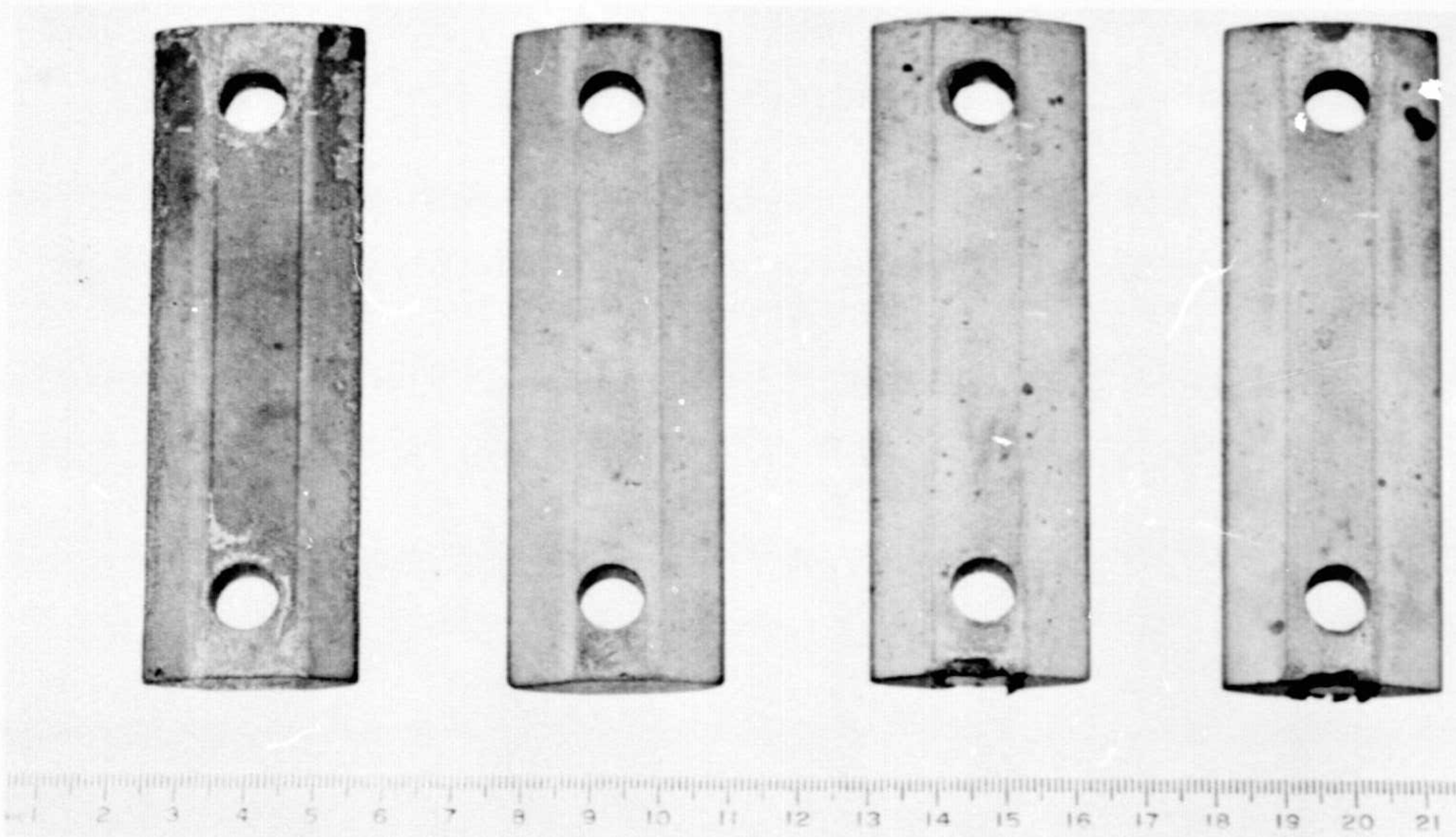
17 TAZ-8A DS Composite Clad

18 TAZ-8A DS Composite Clad

19 Udimet 700 (clad)

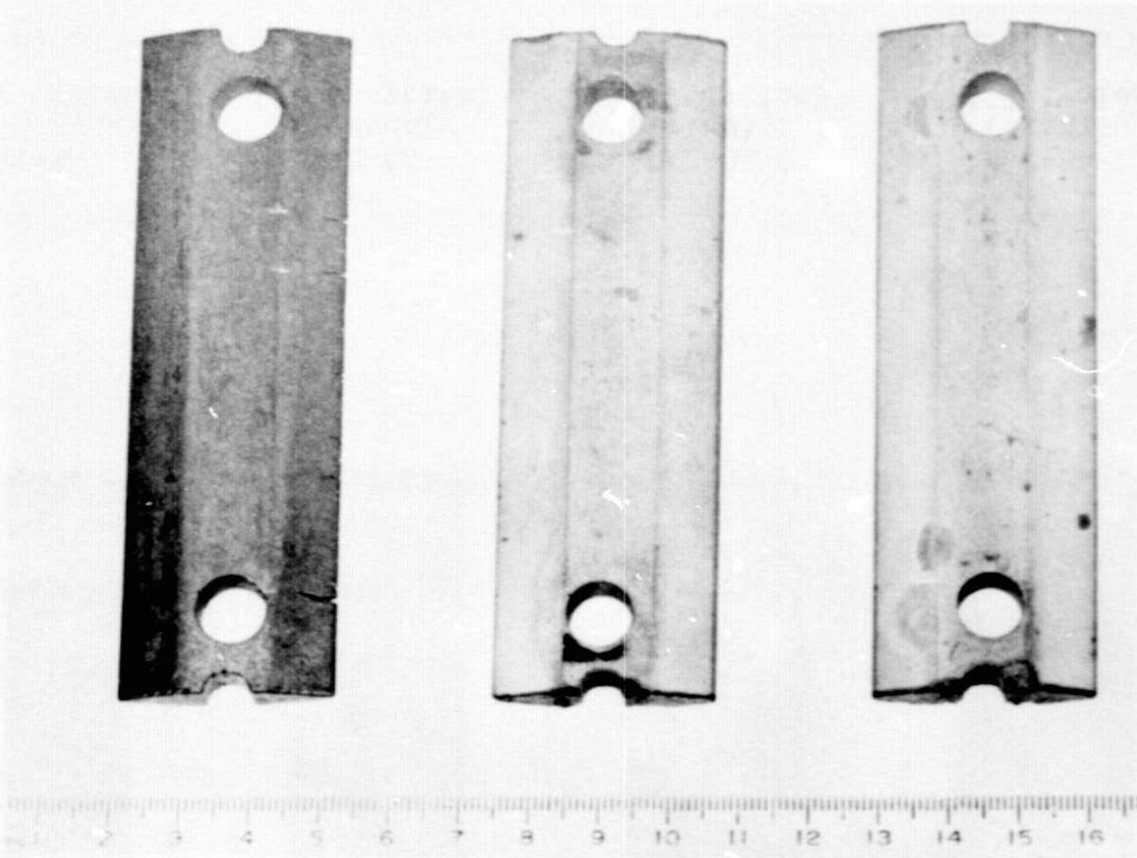
20 Udimet 700 (clad)

Figure 4 (cont.)



1	2	3	4
TAZ-8A DS	TAZ-8A DS	TAZ-8A DS	TAZ-8A DS
	(coated)	(clad)	(clad)
(7000 cycles)	(7000 cycles)	(7000 cycles)	(7000 cycles)

Figure 5
Appearance of Series 4 Specimens After Indicated Thermal Cycles

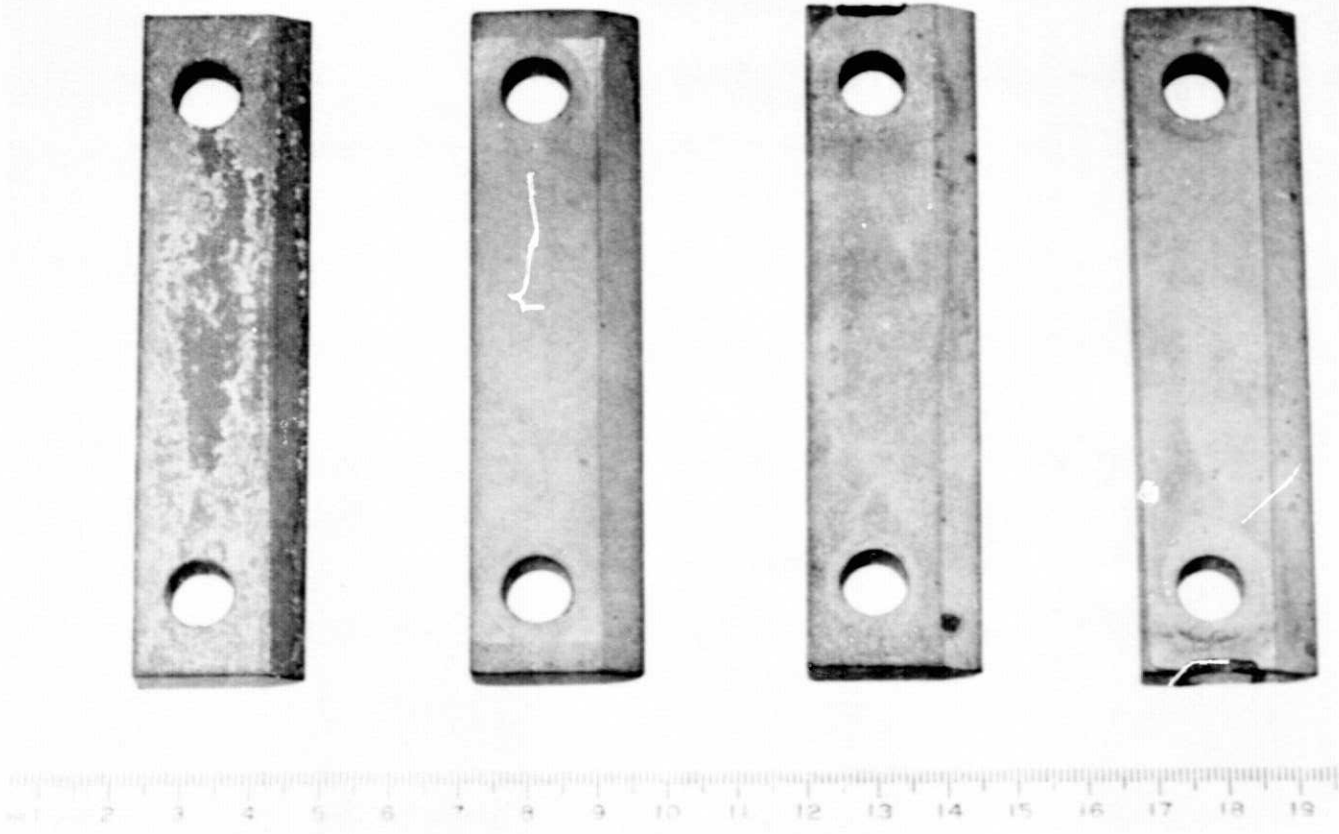


5
MAR-M 200 DS
(7000 cycles)

6
MAR-M 200 DS
(clad)
(7000 cycles)

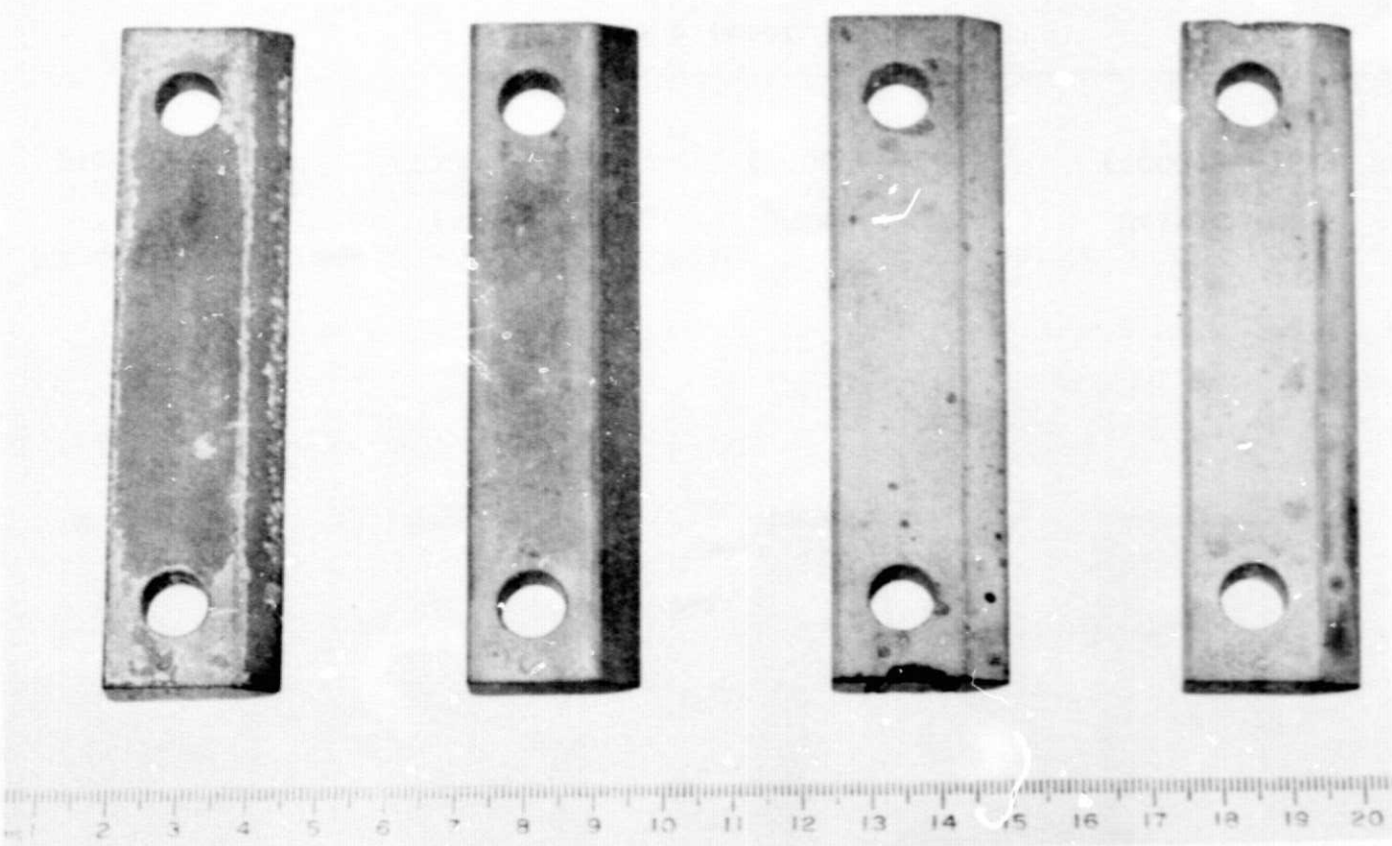
7
MAR-M 200 DS
(clad)
(7000 cycles)

Figure 5 (cont.)



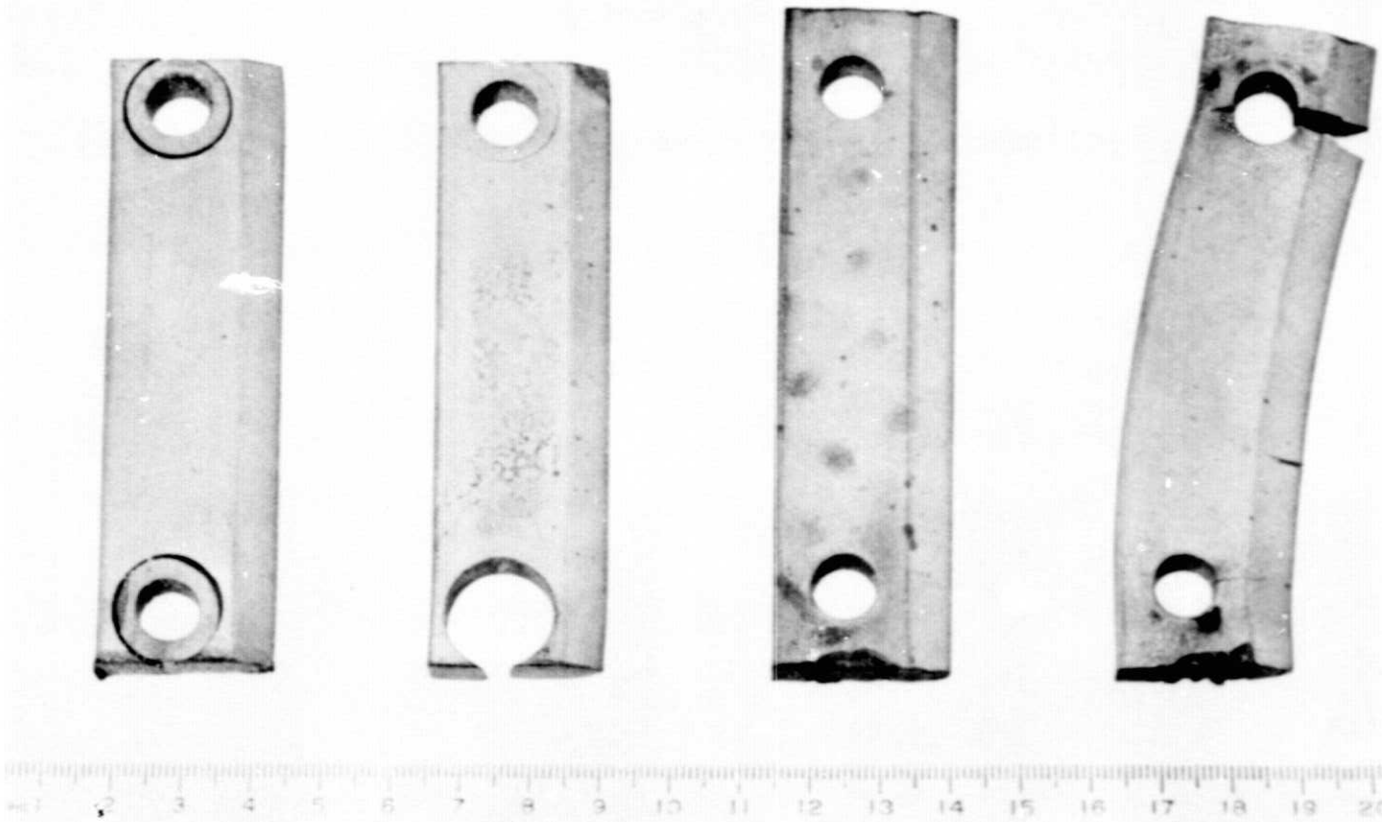
9	10	11	12
TAZ-8A	TAZ-8A (coated)	TAZ-8A (clad)	TAZ-8A (clad)
(7000 cycles)	(7000 cycles)	(7000 cycles)	(7000 cycles)

Figure 5 (cont.)



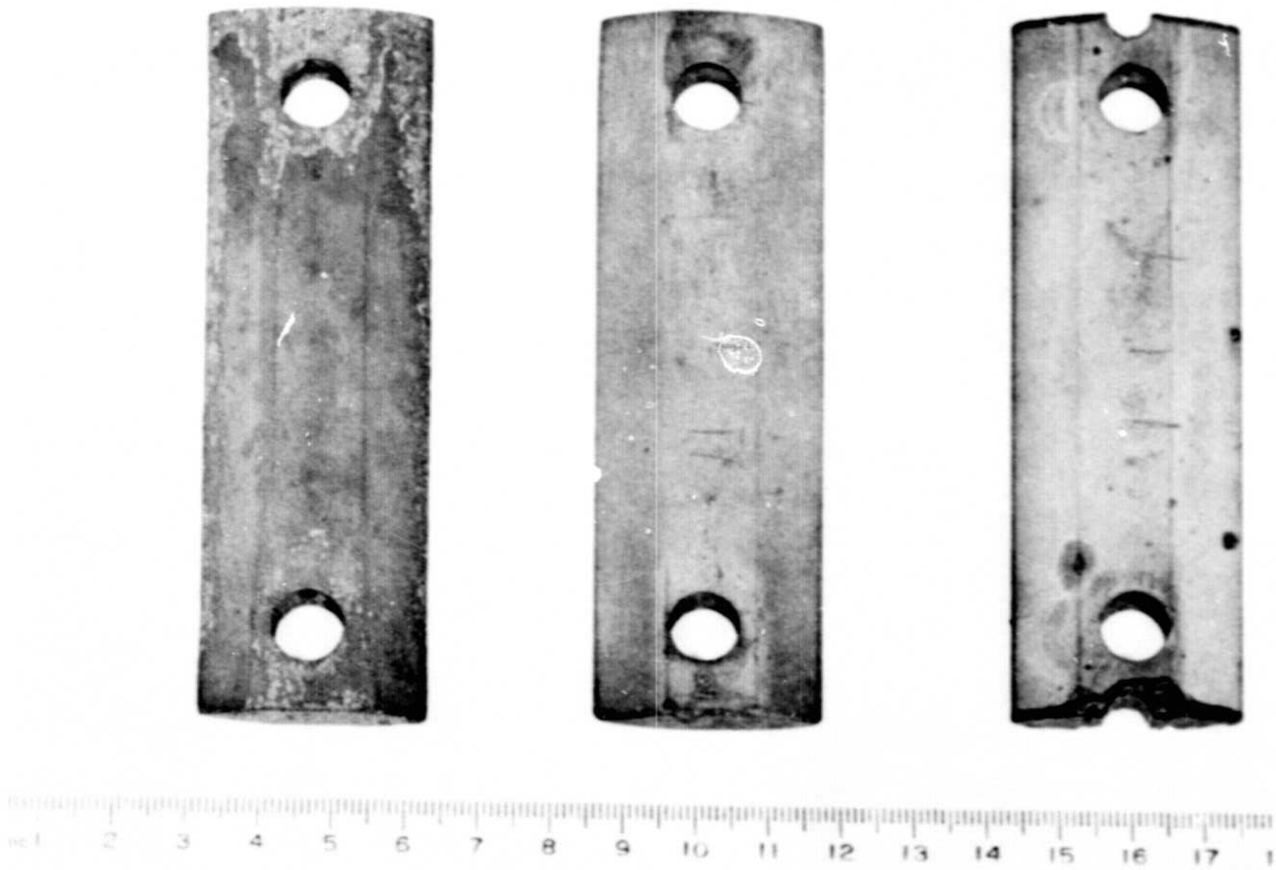
13	14	15	16
TAZ-8A DS	TAZ-8A DS (coated)	TAZ-8A DS (clad)	TAZ-8A DS (clad)
(7000 cycles)	(7000 cycles)	(7000 cycles)	(7000 cycles)

Figure 5 (cont.)



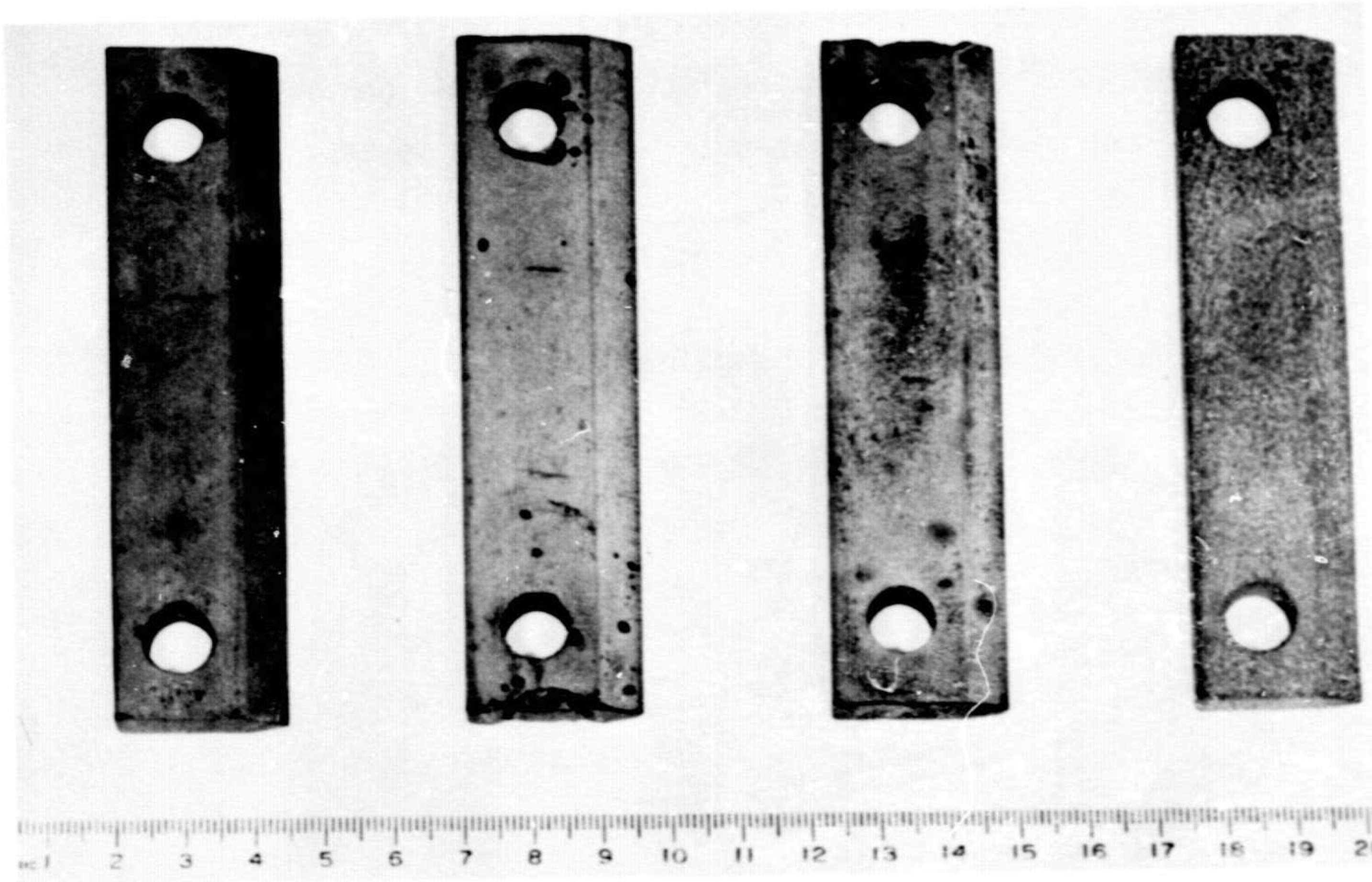
17	18	19	20
TAZ-8A DS Composite Clad (7000 cycles)	TAZ-8A DS Composite Clad (7000 cycles)	Udimet 700 (clad) (7000 cycles)	Udimet 700 (clad) (7000 cycles)

Figure 5 (cont.)



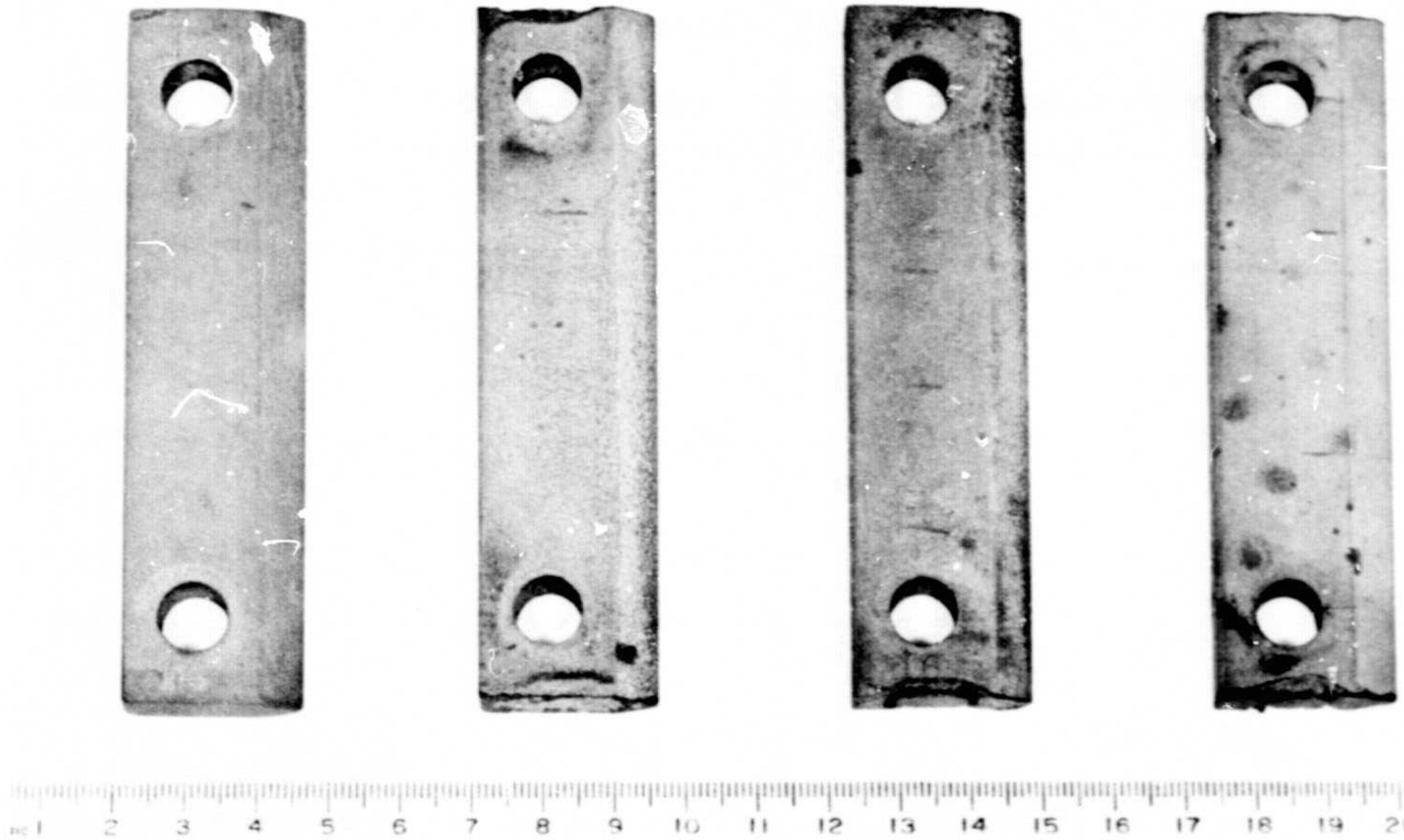
1	2	7
TAZ-8A DS	TAZ-8A DS (coated)	MAR-M 200 DS (clad)
(10,000 cycles)	(14,000 cycles)	(10,000 cycles)

Figure 5 (cont.)



10	11	12	13
TAZ-8A	TAZ-8A	TAZ-8A	TAZ-8A DS
(coated)	(clad)	(clad)	
(15,000 cycles)	(15,000 cycles)	(15,000 cycles)	(15,000 cycles)

Figure 5 (cont.)



14	15	16	19
TAZ-8A DS	TAZ-8A DS	TAZ-8A DS	Udimet 700
(coated)	(clad)	(clad)	(clad)
(15,000 cycles)	(15,000 cycles)	(15,000 cycles)	(10,000 cycles)

Figure 5 (cont.)

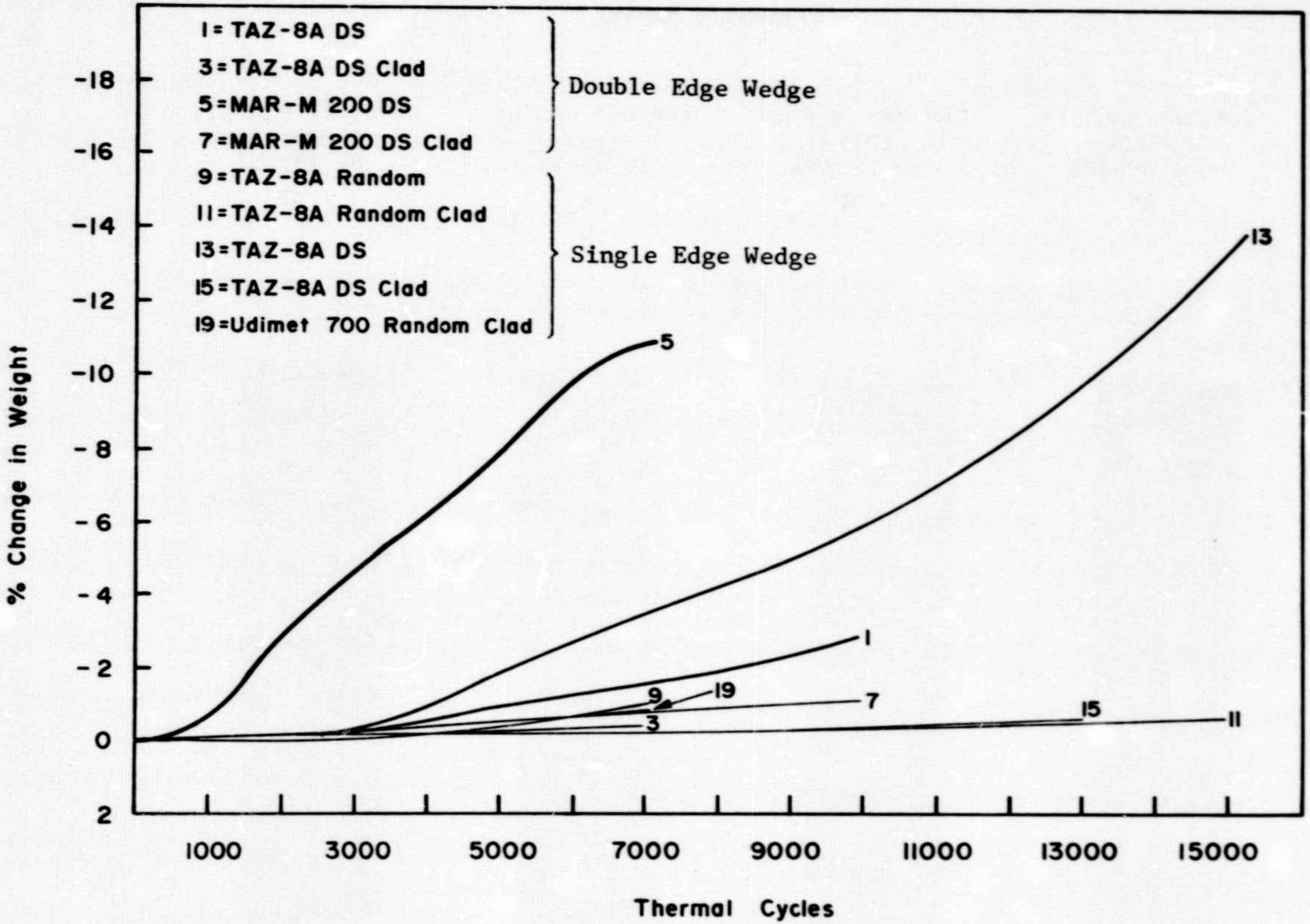


Figure 6

Weight Change of Some Series 4 Specimens