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HIGH-TEMPERATURE, LOW-CYCLE FATIGUE BEHAVIOR OF TANTALUM

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16. Abstract

Elevated-temperature uniaxial, low-cycle fatigue tests are reported for unalloyed tantalum. Because of the extreme sensitivity of this metal to environmental contamination at high temperature, special techniques were developed to provide an inert argon atmosphere during the testing. The very high ductility of tantalum at the temperatures employed (up to 1350° F), coupled with its low strength, led to geometric instabilities in the high-strain, low-cycle regime and produced special testing problems. Results are compared to those of other structural metals and are presented in terms of equivalent stress-amplitude-fatigue design life for purposes of structural design. Tantalum was found to have high resistance to low-cycle fatigue, consistent with its high ductility.

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HIGH-TEMPERATURE, LOW-CYCLE FATIGUE BEHAVIOR OF TANTALUM

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INTRODUCTION

An investigation was undertaken of the low cycle fatigue behavior of unalloyed, annealed, arc-melted tantalum in the temperature range between room temperature and 1400°F. Although considerable experience has been developed at our laboratory in low cycle fatigue testing,(1,2) this study offered a particular challenge because of (a) the very high ductility of tantalum and (b) the extreme sensitivity of tantalum to atmospheric contamination and mechanical property deterioration in the temperature range of interest. In order to simplify the testing method, it was proposed that the investigation be conducted in an argon atmosphere which could be continuously monitored by means of an oxygen sensor(3) to ensure an oxygen level less than 1 ppm in argon.

As the program developed, it was found that the prevention of contamination became a major problem and some modifications in the original concept of specimen protection were found necessary. By the method which finally evolved, a sufficient number of tension and low cycle fatigue tests were conducted to determine low-cycle fatigue design curves at three elevated temperatures. Since the elevated temperature mechanical testing of tantalum has, in the past, been carried out in vacuums of 10^{-6} torr, the present procedure offers a considerable simplification in equipment and operation. The following report describes this method and the results obtained.

TEST PROCEDURE AND MATERIAL

Uniaxial cyclic and monotonic tests were performed in a 20,000 lb. capacity, reverse-loading Instron machine following procedures reported earlier.(4) All the tests were conducted in a purified argon atmosphere on test specimens shown in Figures 1 and 2. Induction heating was used in all experiments and temperature was controlled by means of a fine-wire thermocouple spot welded to the specimen surface about 1/4-inch from its minimum diameter. Two other thermocouples were used for temperature measurement. One was located 1/4-inch above the specimen's minimum diameter and the other 1/4-inch below. Load versus time (at

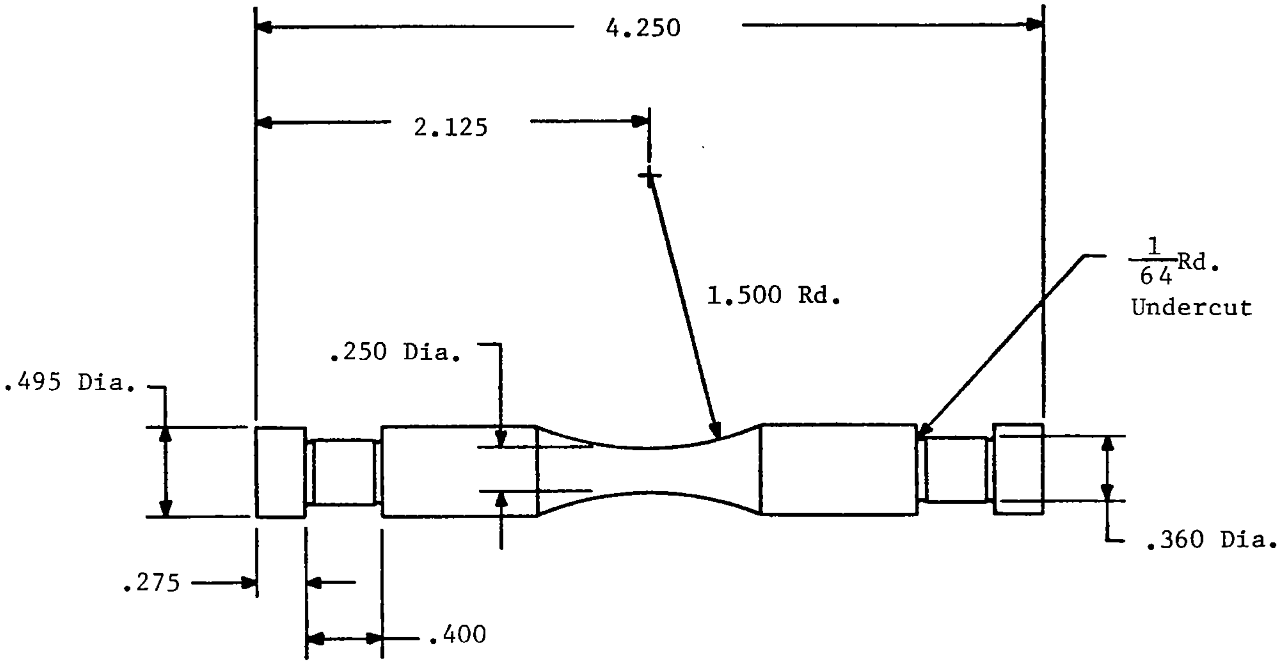

Figure 1. Low-Cycle Fatigue Test Specimen.

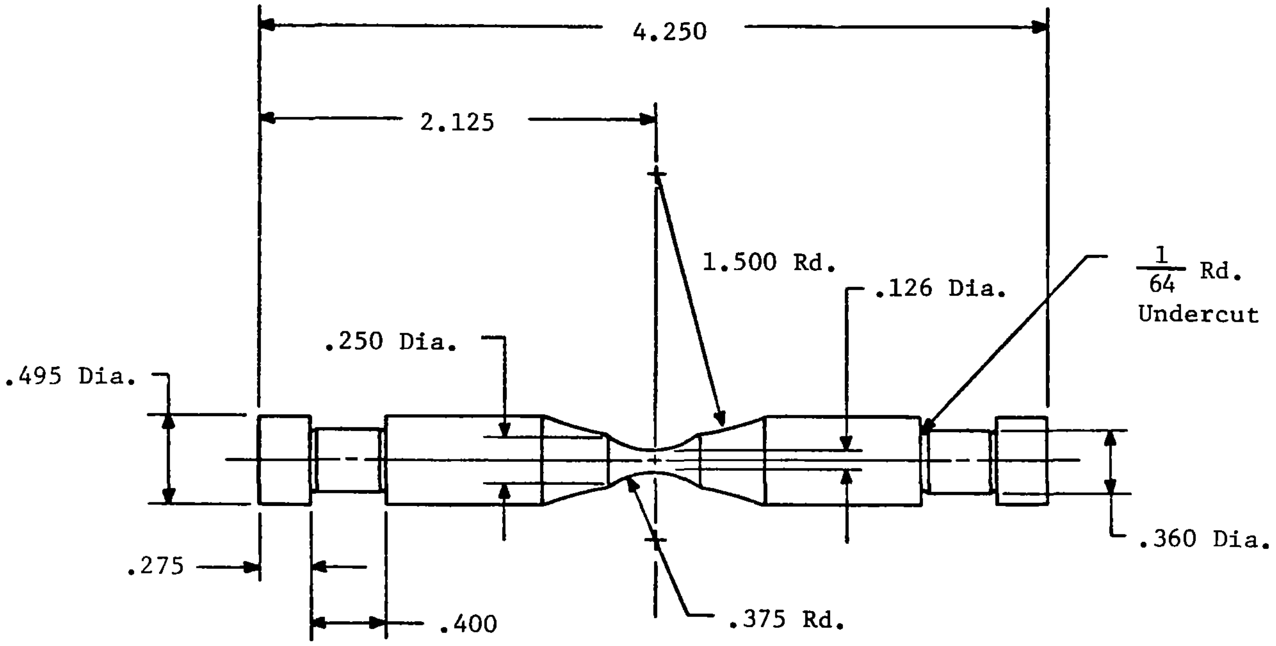

Figure 2. Modified Low-Cycle Fatigue Test Specimen.

constant crosshead rate) was recorded for the monotonic tests. For the cyclic tests, diametral strains were measured and recorded, and served as the basis for control of the test. The extensometer for these experiments has been described previously.(4) An X-Y instrument was used to record hysteresis loops of load and diameter change. Additionally both load and diameter were individually recorded as a function of time.

The material provided was annealed, unalloyed, arc-melted tantalum in the form of 5/8-inch-diameter rod. The rod satisfied ASTM specification B365-62T. Interstitial element analysis for this material was as follows: for carbon 29 ppm, for oxygen 18 ppm, for nitrogen 12 ppm, and for hydrogen 2 ppm.* The grain size of the rod was ASTM grain size number 5.

SPECIMEN PREPARATION

Cyclic strain test results are sensitive to the surface finish of the specimens. It was necessary to polish the reduced section portion of the specimens to less than a 4-microinch surface roughness to minimize this surface effect. Tantalum is a material that is difficult to machine to a smooth surface finish. The following method was worked out to achieve the necessary surface condition.

Two specimen geometries were machined. The first has a typical hourglass shape, a minimum diameter of .250" and an r/R** ratio of 12 as shown in Figure 1. The hourglass portion was plunge ground in a water-cooled, centerless grinder using a grinding wheel contoured to the required 1.5" radius of curvature and hand fed at a slow speed. The minimum diameter was ground .001" to .002 larger than the required size. The second type of specimen was a modification of the first and had a minimum diameter of .125" and an r/R ratio of 6 as shown in Figure 2. After a grinding operation identical with the first type specimen, a second grinding operation was performed. The specimen was mounted on centers in a cylindrical grinding machine and, using a wheel dressed to the proper contour, it was plunge ground to .001" over the required minimum diameter.

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*Material and chemical analyses performed by Nuclear Systems Programs Department. Each reported value is the average of two analyses.

**Where r is the hourglass radius of curvature and R is the specimen minimum radius.

Both types of specimens were then mounted in a lathe and the hourglass portion was polished by hand from this point on. The following grits were used to achieve the required finish:

1. 180 grit emery paper
2. 600 grit emery paper
3. 0 emery paper
4. 000 emery paper
5. 1 micron alumina powder and water on microcloth
6. 0.3 micron alumina powder and water on microcloth

If any tearing of the surface was noted at any stage of the polishing, the specimen was repolished from step 1. This procedure resulted in a surface considerably smoother than 4 microinches of roughness. Although the very fine remaining scratches were circumferential, they were not deemed to be detrimental to the tests.

TESTING ENVIRONMENT

In order to determine the appropriate atmosphere, some preliminary experiments were conducted on tantalum heated in pure argon, and argon with various additives including .5 and .05% CO, and .5 and .05% H_2 to provide a slightly reducing atmosphere. However, all but the pure argon showed contamination and it was decided to conduct the tests in argon only.

The problem of most concern was that of maintaining a purified argon atmosphere around the tantalum specimens while they were being tested at temperatures from 600°F to 1350°F. To accomplish this a cubical aluminum box approximately 18" on a side was constructed with the necessary seals top and bottom to allow connection to a fixed load cell on top and a moving crosshead below. This box also contained sight ports of plexiglass to allow observation of the experiments. Vacuum tight feedthroughs for water cooling lines, gas input and outlet lines, insulated R.F. lines, thermocouples, and extensometer leads were also necessary. Figures 3 and 4 show the experimental facility.

It was thought that the best way to maintain a good argon atmosphere was to purge the system with high purity argon and conduct the test under

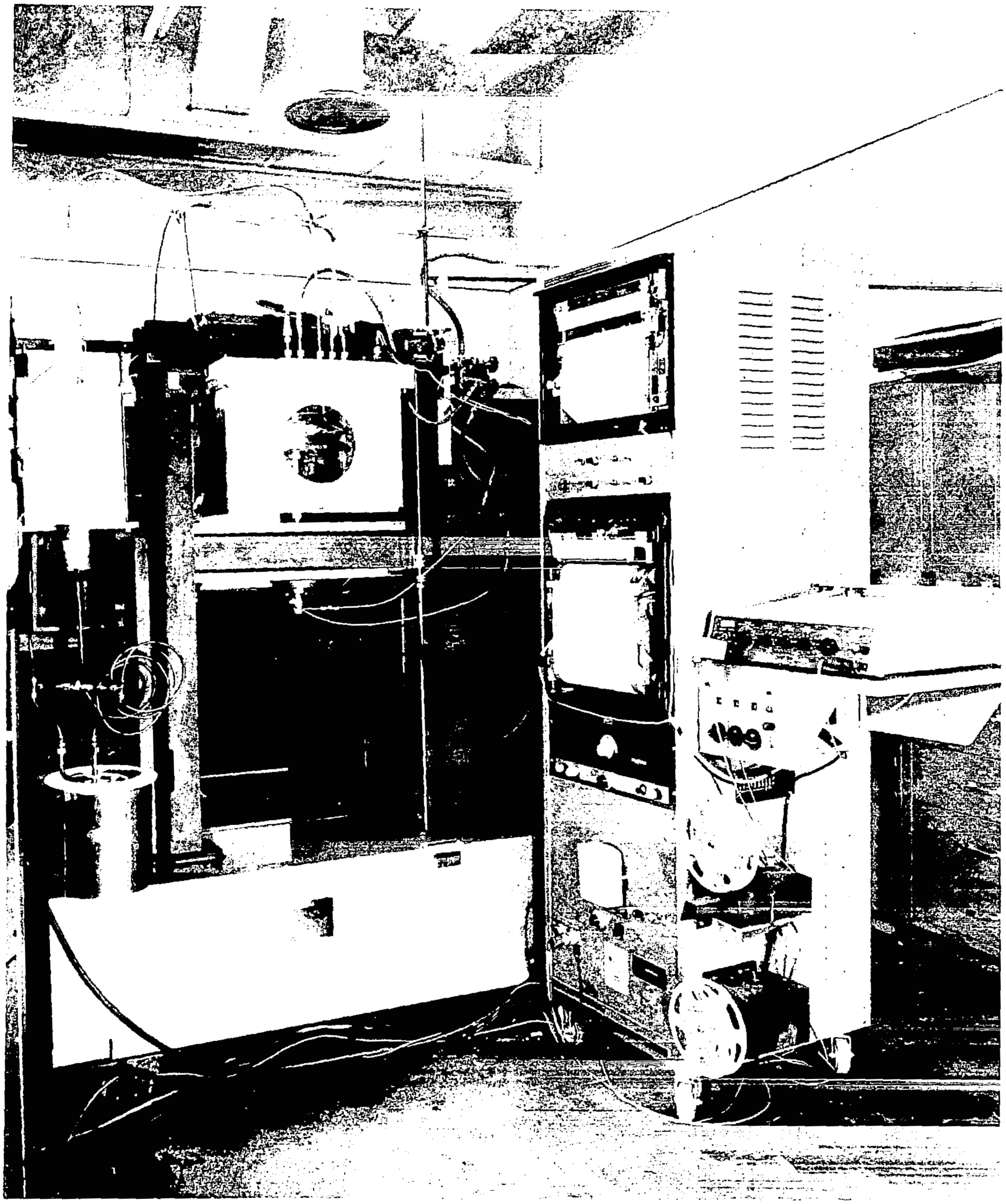

Figure 3. Experimental Facility.

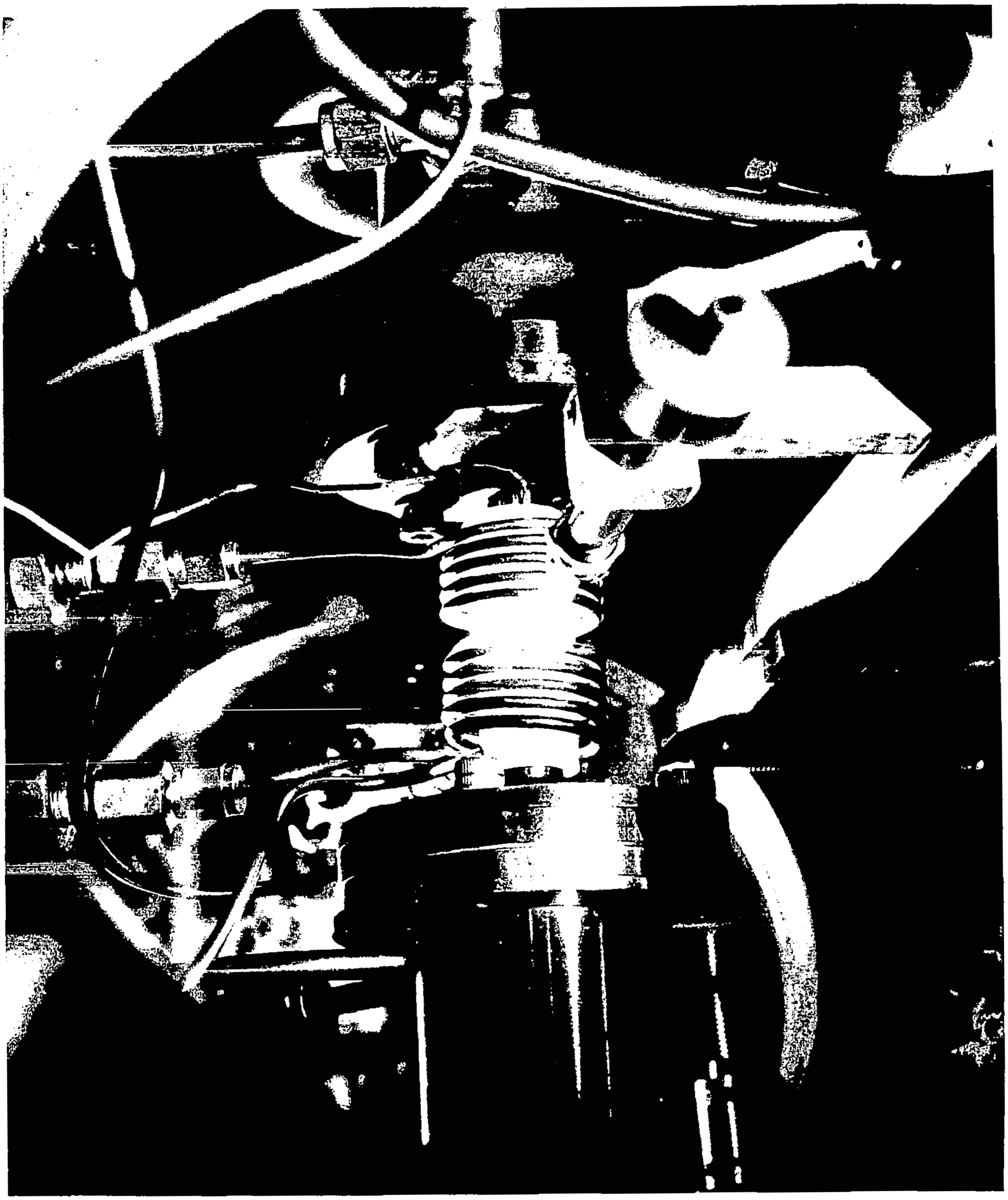

Figure 4. Close-up of Test.

a slight positive pressure (2 to 3 psi) and a flowing gas. Subsequent experiments indicated that slight contamination of the specimen occurred when tested in this fashion. A titanium "getter" was designed and installed to fit around the specimen and act as a susceptor for the high frequency heating coil (see Figure 5). This titanium susceptor had ports to accommodate the quartz gage rods of the extensometer as well as thermocouple holes and an entry hole through which the purified argon gas passed. This gas was allowed to leak into the aluminum box through the spaces around the quartz gage rods. A new titanium susceptor was used for each test. This system prevented oxidation of the specimen as determined by subsequent surface examination, microhardness traverses on transverse sections through the gage section and chemical analysis. For example, in Table I, the post-test concentration of interstitials, particularly, oxygen, is compared with that for the pretest material for a number of fatigue samples. For the monotonic tensile test experiments the only change made was the elimination of the gage rod holes from the susceptor.

For the higher temperature (1350°F) tests, a serious arcing problem developed between the high frequency induction coil and the specimen susceptor. After many attempts at correcting the situation by insulation and increased spacing, a simple solution was achieved by slitting each susceptor to within 1/8" of the end engaging the specimen. By this means the central temperature of the susceptor was lowered appreciably, decreasing the ionizing tendency of the argon gas.

Tank argon was used as the starting gas with typical analysis as follows:

Argon	99.998%
Oxygen	0.0015%
Hydrogen	0.0001%
Nitrogen	0.0002%
Carbon Dioxide	0.0001%
Hydrocarbons	0.0001%
Dew Point	-73°F

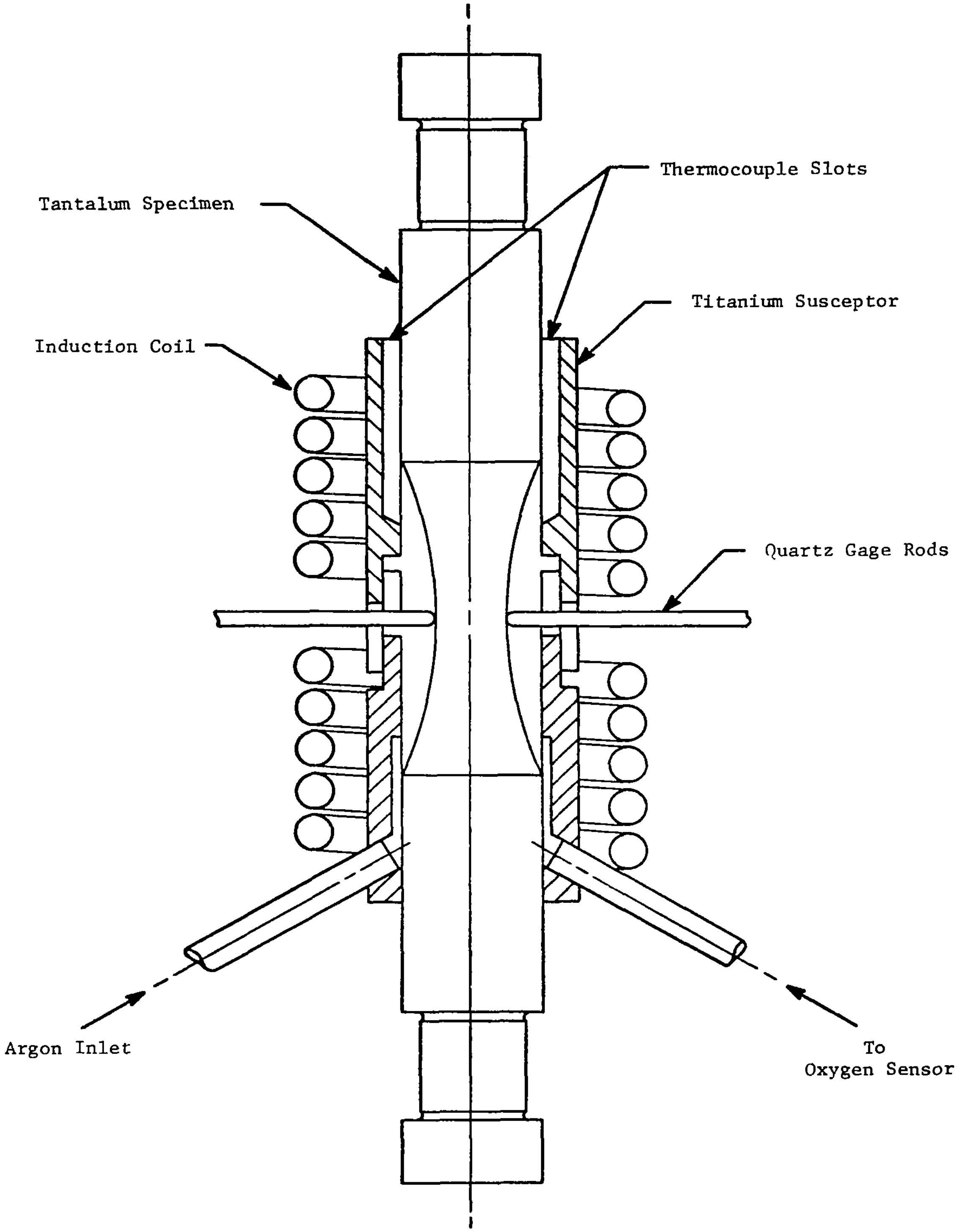

Figure 5. Details of Specimen-Susceptor-Induction Coil Design.

TABLE I

CONCENTRATION OF INTERSTITIALS IN TANTALUM SAMPLES*

Sample No.	Test Temperature (°F)	Test Time (Hrs)	Carbon (ppm)	Oxygen (ppm)	Nitrogen (ppm)	Hydrogen (ppm)
Pretest Material	-	-	25, 32	20, 16	12, 11	3, 2
4A	600	24.6	31, 47	19, 8	2, 2	2, 2
9A	1100	3.1	24, 48	36, 25	1, 3	1, 1
8B	1100	22.1	-	28	--	--
2B	1350	3.45	-	18	--	--
3B	1350	1.95	-	7	--	--
5B	1350	41.4	-	9	--	--
6B	1350	32.7	11	10	6	5
7B	1350	32.8	-	18	--	--

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* Chemical analyses performed by the Nuclear Systems Programs Department.

This gas was treated by passing it through copper tubing at approximately 10 standard cubic feet per hour to a molecular sieve that was maintained in a mixture of alcohol and dry ice. From there it flowed through an Inconel tube 2-1/4" diameter by 24" long enclosed in a furnace with a hot zone 8" long. This tube was filled with small lathe turnings of titanium. The furnace was maintained at a temperature of 1500°F.

The gas then passed through copper tubing from the chip furnace into the aluminum box, and finally emerged inside the titanium susceptor. An oxygen sensor(3) was used to determine the amount of oxygen present in the purified argon. The hydrocarbons present in the gas impaired the operation of the sensor to prevent an exact measurement at very low concentrations, but indication was that less than 1 ppm oxygen was present in the purified gas.

INTERMITTENT TEMPERATURE STRAIN CYCLING

Early in the program an intermittent temperature strain cycling test was conducted to determine the stress response of the material at different temperatures. This follows the procedure outlined earlier(5) in an investigation of cyclic strain aging in low carbon steels at elevated temperatures. The purpose of this test was to determine the sensitivity of tantalum of this purity to strain aging. It is well known that body-centered cubic metals will undergo hardening with strain at specific elevated temperatures as a consequence of the pinning action of interstitial elements, principally carbon and nitrogen. Evidence for this in tantalum has been reported by several investigators.(6) It has also been shown by Glen(7) that other alloying or impurity elements can cause strain-induced hardening at specified temperatures. It is reasonable to expect similar effects to occur in tantalum, the degree of which would depend on its purity.

Relating this behavior to strain induced by cyclic means, it was shown(8) that strain-induced hardening led to cyclic strengthening and a corresponding decrease in controlled-strain fatigue life. Thus for a material for which little is known concerning its low cycle fatigue resistance at elevated temperature, and for which only a limited exploratory program was contemplated, an intermittent-temperature strain-cycling investigation on a single specimen could be very useful. Specifically, by identifying temperatures where strain aging peaks occurred, these temperatures could be selected for low-cycle fatigue tests with some confidence that these temperatures would represent the least favorable fatigue resistance over a broad temperature spectrum.*

The specifics of this test involved subjecting the specimen to five complete strain cycles starting at room temperature, stopping the test, and raising the temperature to 200°F, applying five strain cycles, and repeating the sequence, raising the temperature 100°F for each step. The value of ε_d (the diametral strain amplitude) was .01 and the crosshead rate was .05"/min.

With reference to Figure 6 the stress range is shown after five cycles at each temperature. It will be noted that, in addition to the normal decrease in strength with temperature, two specific temperatures, namely 600°F and 1100°F are identified where aging peaks have occurred. Neither peak is particularly pronounced, indicating the material to be of high purity. The 600°F peak was expected in view of the strain-aging literature;(6) the 1100°F peak was unexpected and unidentified as to mechanism. However, the effect is real, as indicated by the stress range-cycles of strain data subsequently obtained. In fact it was observed in later tests that for the same controlled diametral strain range, the material is stronger at 1100°F than at 600°.

On the basis of this test, these two temperatures were selected for low-cycle fatigue evaluation. Additionally, tests at 1350°F were conducted since the SNAP-8 tantalum boiler would experience this maximum temperature in service.

TENSION TESTS

Prior to low-cycle fatigue testing, constant crosshead rate tension tests were conducted at 600, 1100 and 1350°F. Results are shown in Table II. As seen this material is highly ductile. Figure 7 shows the severely necked specimens. Based on these high ductilities, it would be expected that this material should be highly resistant to low-cycle fatigue.

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*This assumption presumes that failure will not be a consequence of high temperature, intergranular fracture.

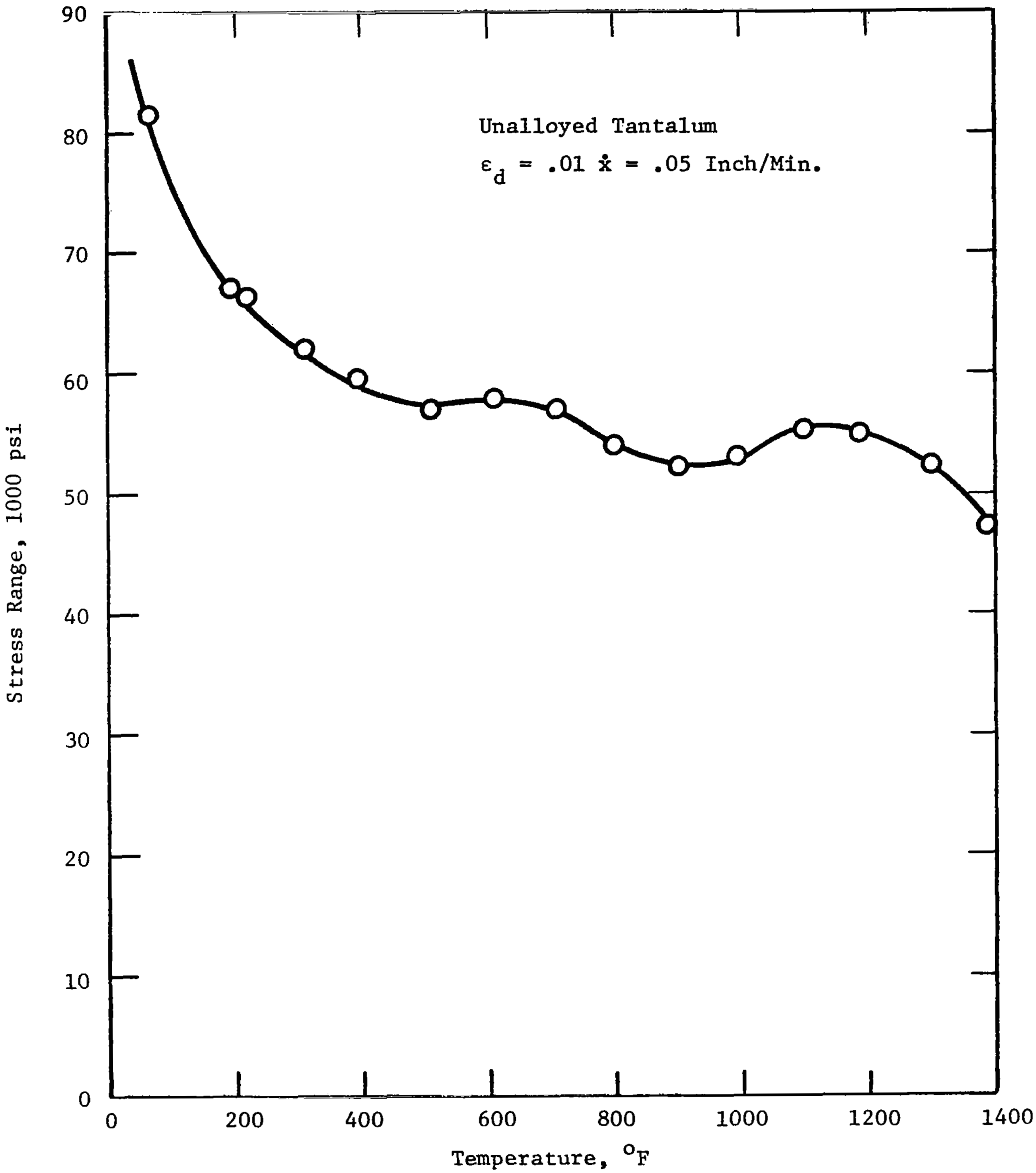


Figure 6. Stress Range Versus Temperature After Five Cycles -- Intermittent Temperature Strain Cycling Experiment.

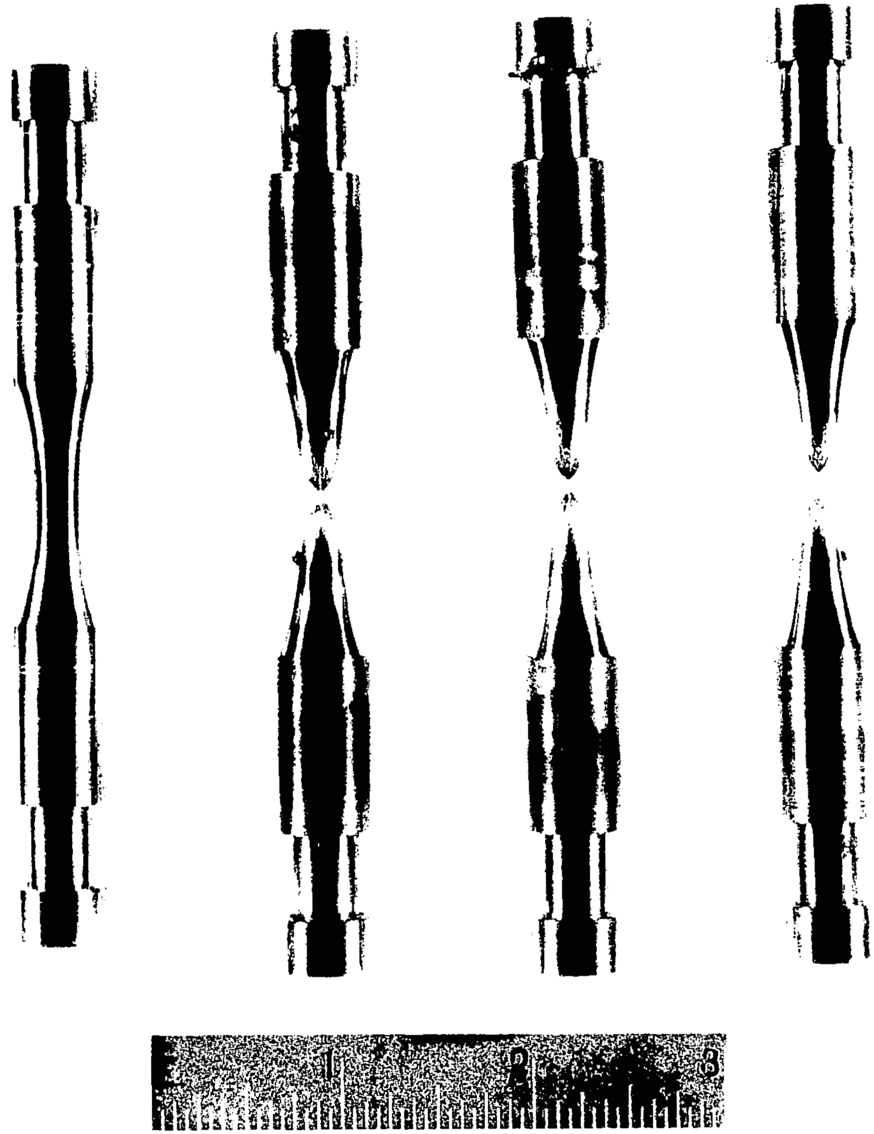


Figure 7. Necked Tensile Specimens.

TABLE II

SUMMARY OF TENSION TEST RESULTS

Temp., (°F)	$\dot{X}$ ("/min)	Yield Strength (psi)	Ultimate Strength (psi)	Reduction of Area-(%)	True Strain at Fracture (in/in)
600	.005	11,200	29,100	98.6	4.27
1100	.002	10,400	30,300	97.4	3.65
1350	.005	5,040	17,900	99.3	4.96

LOW-CYCLE FATIGUE TESTS

Aside from the problem of maintaining a high purity argon atmosphere throughout the test, the soft, ductile characteristics of the tantalum at elevated temperatures introduced stability problems in those tests where fatigue lives of less than 1000 cycles were required. The form of the instability is exhibited in Figure 8. Here the specimen has shortened considerably, and bulged at either side of the minimum diameter, while maintaining its minimum diameter constant. This type of instability has been discussed earlier(9) and relates to the magnitude of cyclic strain hardening. The higher the temperatures the more pronounced is the phenomenon.

The pronounced shortening of the specimen caused a problem in the accommodation of the susceptor, and necessitated a two-piece overlapping arrangement. After considerable experimentation, a satisfactorily designed susceptor evolved, and this is shown in Figure 5. A further step was taken to reduce the specimen shape change by a modification of the hourglass shape. Previous experience has shown that greater specimen stability can be achieved in high-strain, push-pull fatigue testing if the ratio of hourglass radius of curvature to specimen radius is about six or less. Figure 2 shows the modified shape to achieve this condition.

In addition to the shape change resulting from cyclic straining, a very pronounced surface roughening of the material was observed, as a consequence of the large number of slip steps formed at the surface. This behavior is characteristic of high ductility materials subjected to large amounts of cyclic plastic strain.

A total of ten low-cycle fatigue tests were carried out and the test conditions and results are included in Table III. Stress range vs. life results are shown in Figures 9 through 11. Of interest here is the increasing stress range with cycling at 600°F indicating cyclic strain aging. At 1100°F the results show no clear trend (Figure 10). There is, however, an increased strength of the material at 1100°F over 600°F for each diametral strain range. Note also, as expected, the increased stress range for increasing levels of strain range. At 1350°F various frequencies and strain ranges are employed as seen in Figure 11. Here

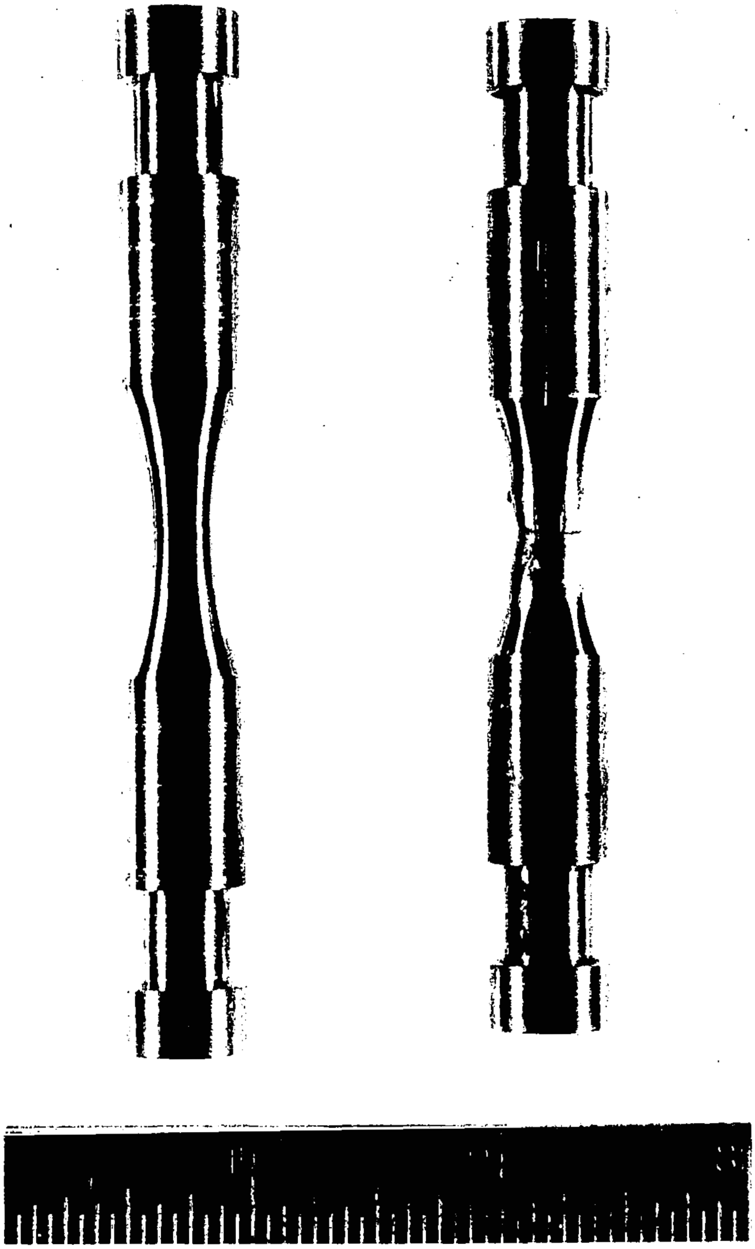


Figure 8. Shape Change in Specimen at Failure - $\varepsilon_d = 0.01$, $T = 600^{\circ}F$.

TABLE III

SUMMARY OF FATIGUE TEST RESULTS

Test No.	Temp., (°F)	Diametral Strain Amplitude (ε_d)	Plastic Strain Range ($\Delta\varepsilon_p$)	Total Strain Range ($\Delta\varepsilon$)	Stress Range ($\Delta\sigma$ psi)	Frequency CPM (ν)	Cycles to Failure (N_f)
4A	600	0.002	0.0069	0.0085	49,000	6.94	10,001
8A	600	0.01	0.0038	0.0409	70,000	.64	273
10A	1100	0.00187	0.0062	0.0083	53,900	3.40	12,230
9A	1100	0.01	0.00382	0.0409	70,400	2.62	487
8B	1100	0.00448	0.0165	0.0189	63,500	1.88	2,355
2B	1350	0.00466	0.0175	0.0195	52,000	9.25	1,912
3B	1350	0.01014	0.0393	0.0413	51,000	6.47	740
5B	1350	0.00194	0.00672	0.0084	43,500	7.34	17,500
6B	1350	0.01	0.0389	0.0407	47,000	0.60	1,177
7B	1350	0.00448	0.0170	0.0185	40,000	1.88	2,387

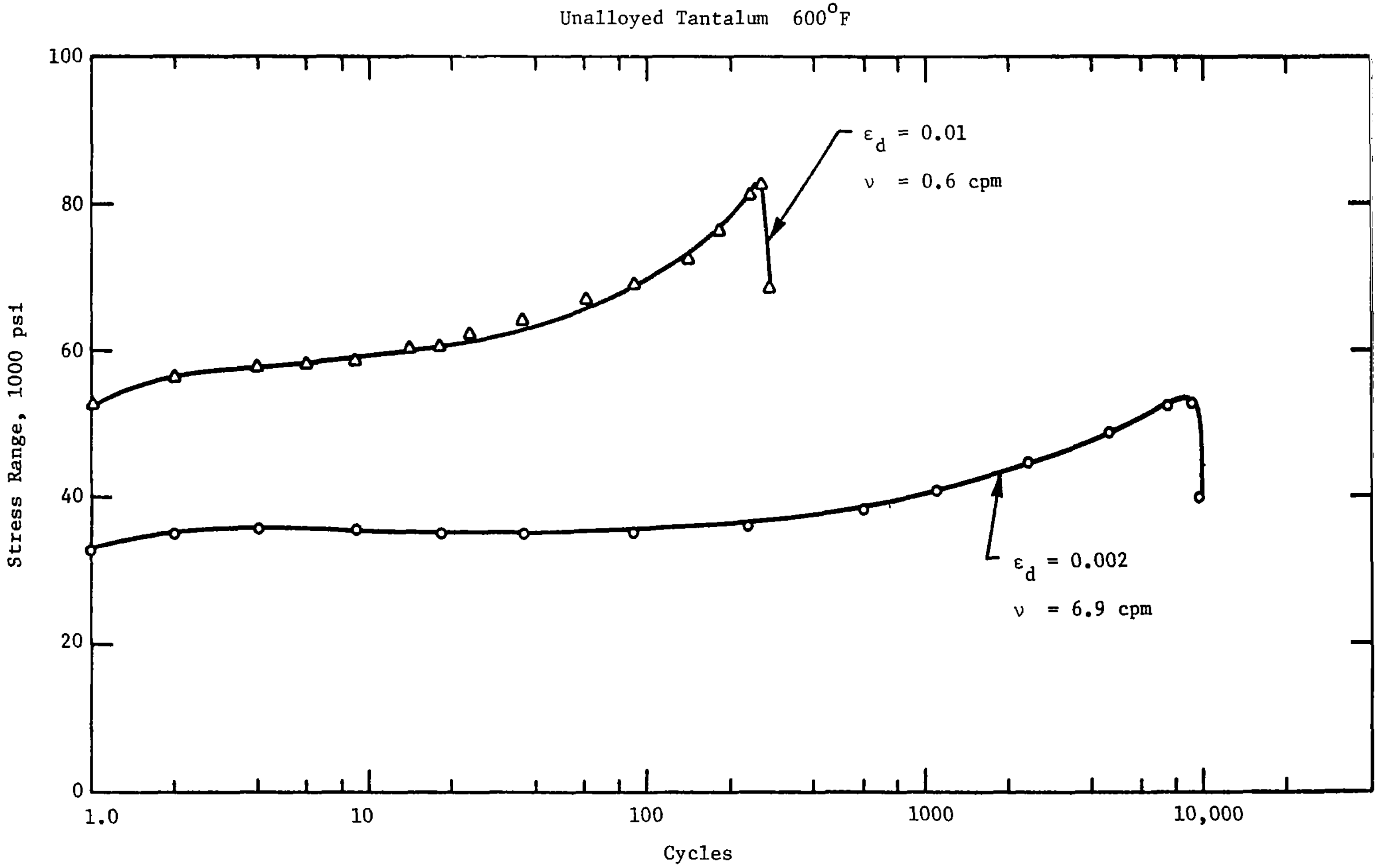


Figure 9. Stress Range Versus Cycles for Tantalum at 600°F.

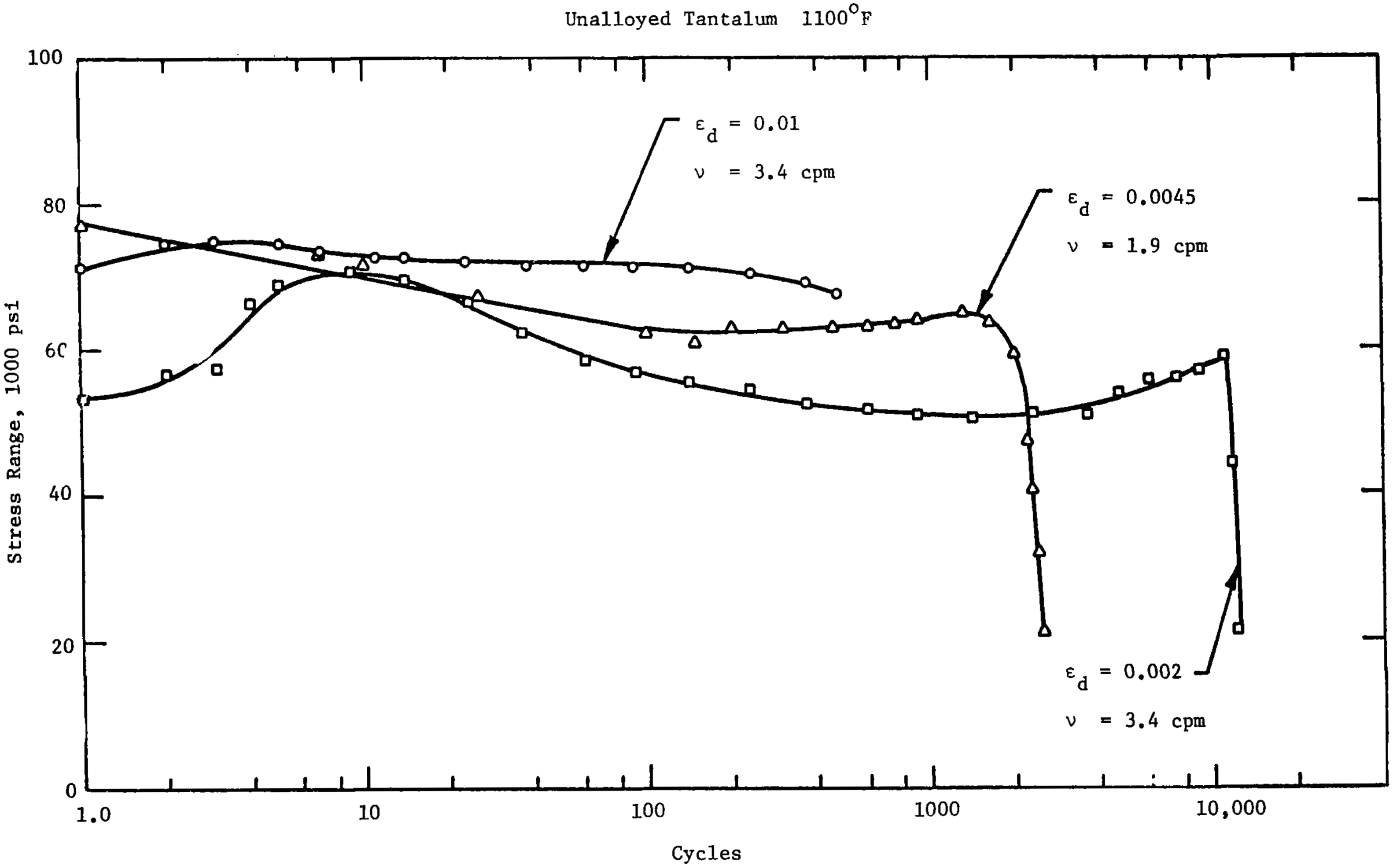


Figure 10. Stress Range Versus Cycles for Tantalum at 1100°F.

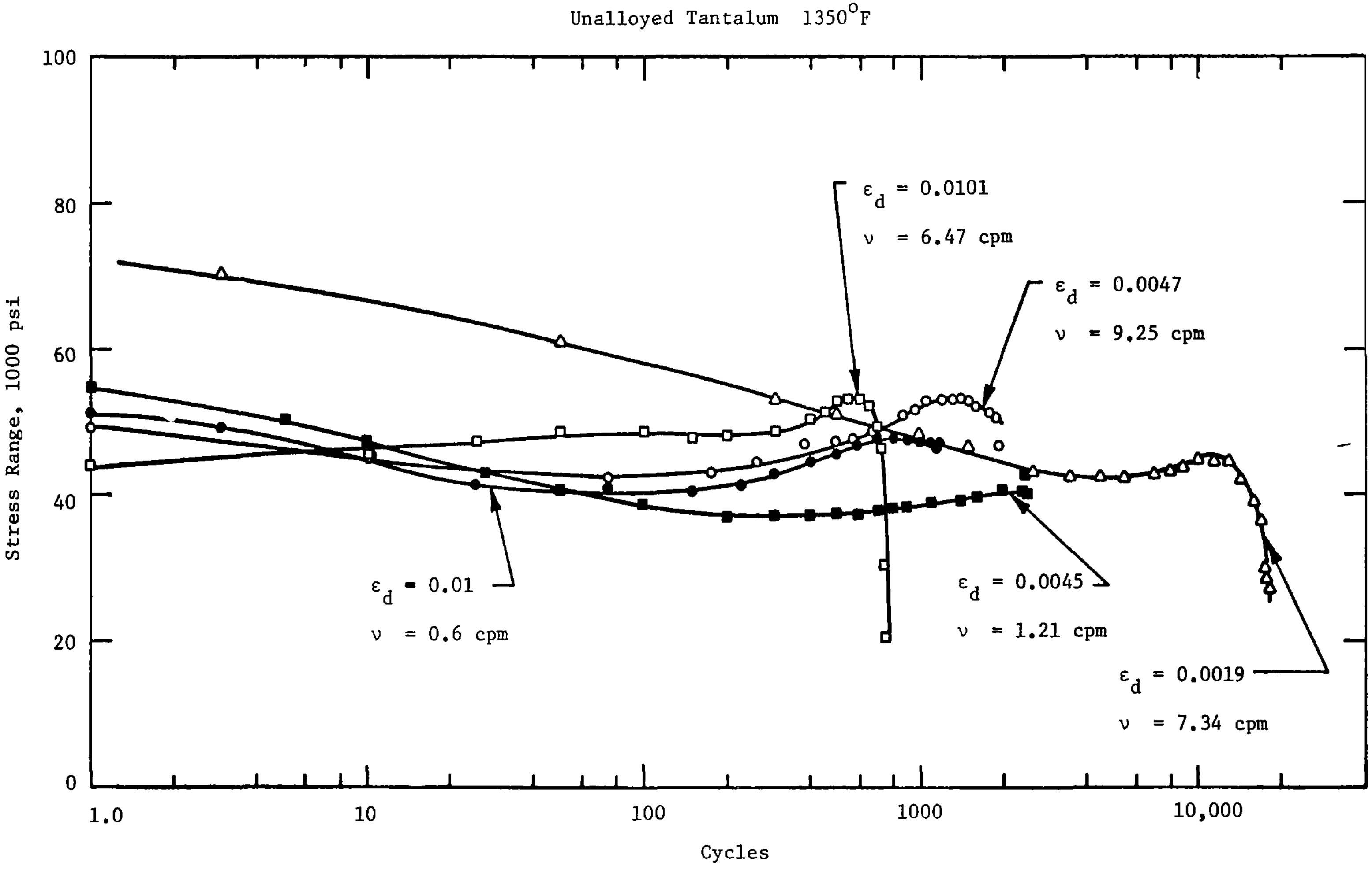


Figure 11. Stress Range Versus Cycles for Tantalum at 1350°F.

TABLE IV

CONSTANTS FOR TOTAL STRAIN-LIFE RELATIONSHIPS FOR UNALLOYED TANTALUM

Temp., (°F)	C_2	β	k	A	n	k_1	ε_f	E	Applicable Equation
600	2.13	0.5	1.0	22,400	0	0	4.27	26×10^6	(1)
600	2.389	0.6	1.0	85,570	0.2	0	4.27	26	(2)
600	1.636	0.615	1.0	117,400	0.169	0	4.27	26	(3)
1100	1.82	0.5	1.0	20,800	0	0	3.65	26	(1)
1100	2.175	0.6	1.0	90,790	0.2	0	3.65	26	(2)
1100	1.572	0.594	1.0	118,400	0.155	0	3.65	26	(3)
1350	2.48	0.5	1.0	10,800	0	0	4.96	26	(1)
1350	2.614	0.6	1.0	51,700	0.2	0	4.96	26	(2)
1350	2.049	0.605	1.0	87,300	0.142	0	4.96	26	(3)
1350	1.481	0.543	1.189	69,413	0.124	0.0736	4.96	26	(4)

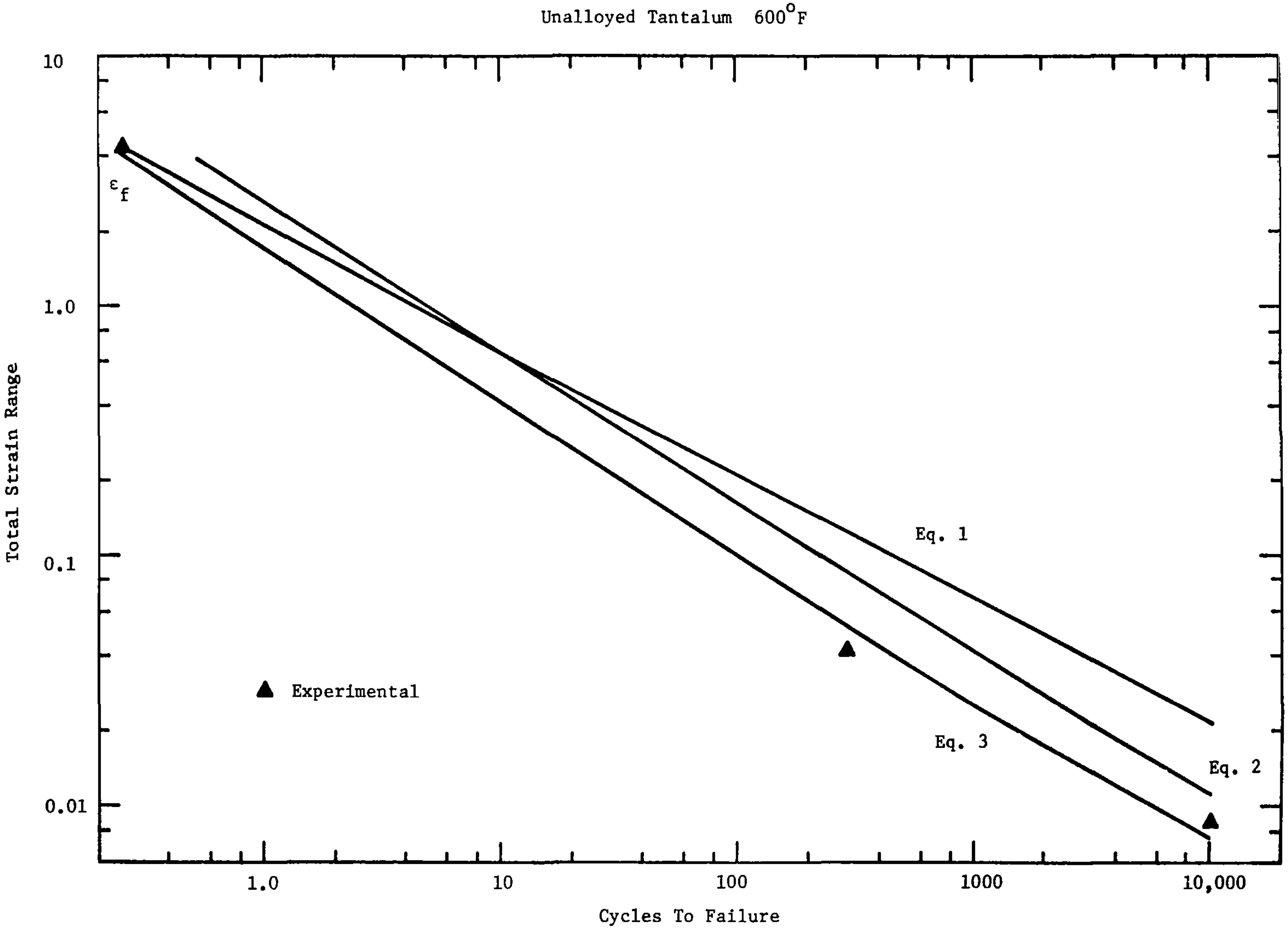


Figure 12. Total Strain Range Versus Fatigue Life of Tantalum at 600°F.

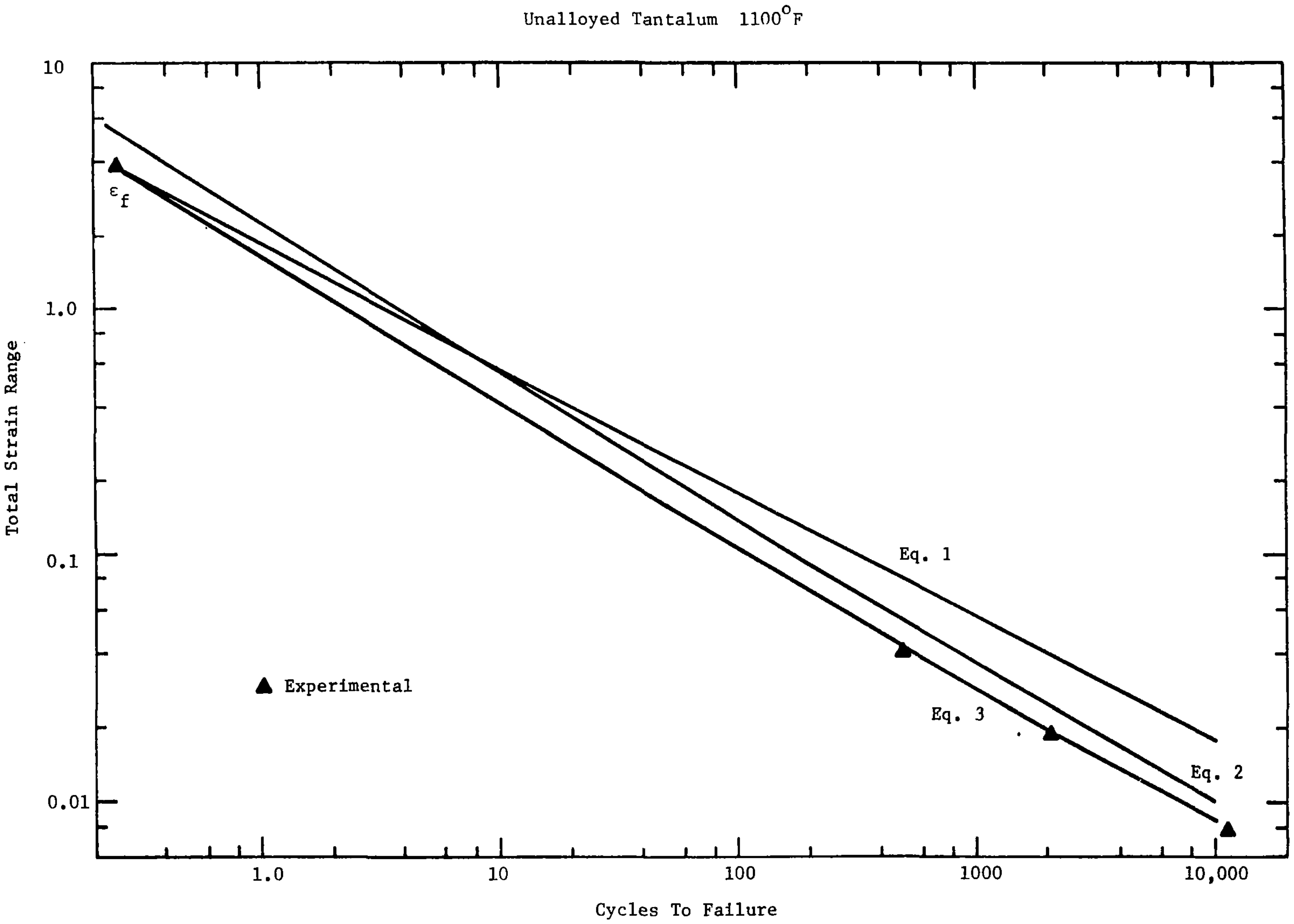
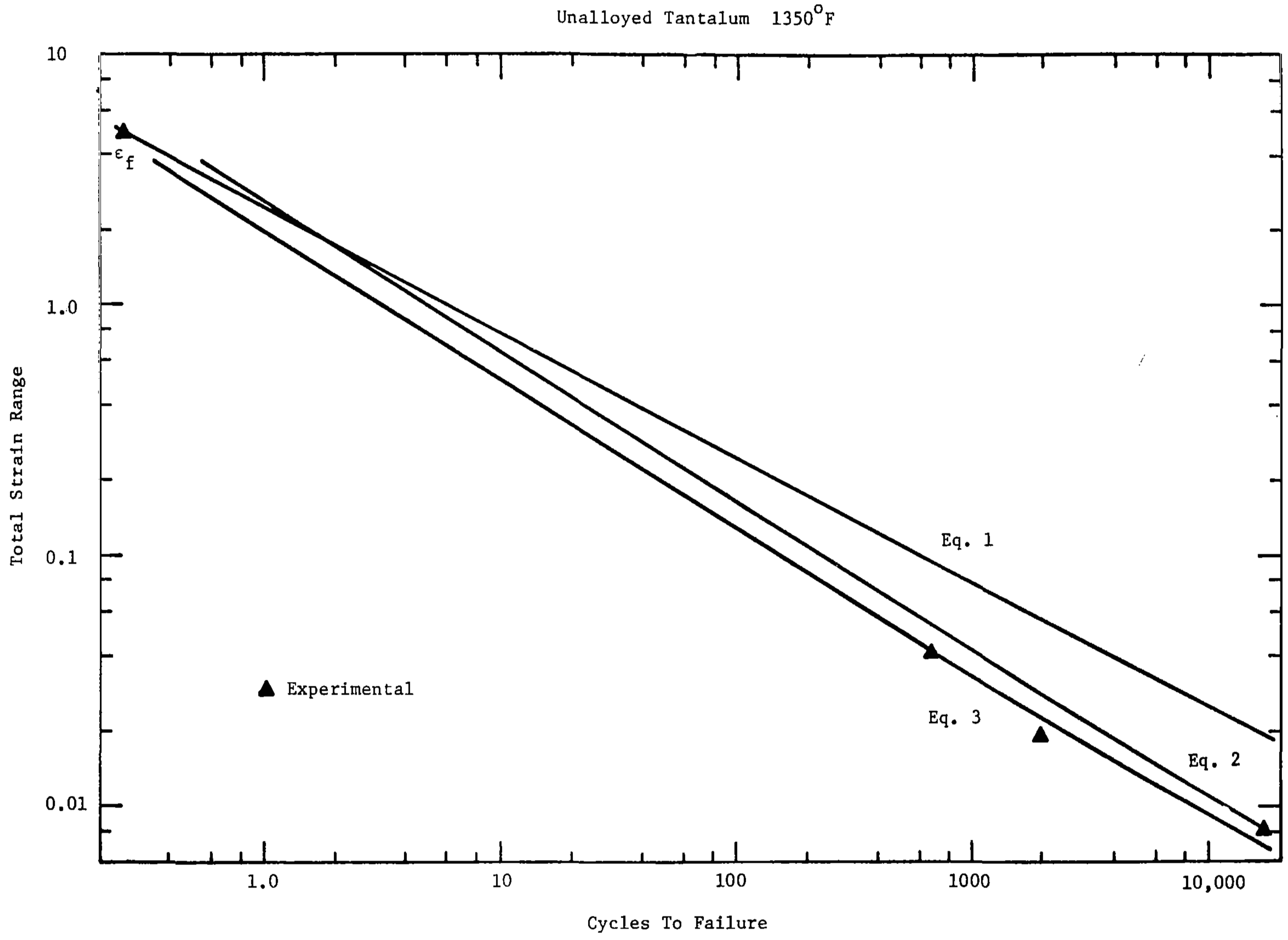


Figure 13. Total Strain Range Versus Fatigue Life of Tantalum at 1100°F.



Unalloyed Tantalum 1350°F

Figure 14. Total Strain Range Versus Fatigue Life of Tantalum at 1350°F for Equations (1) Through (3).

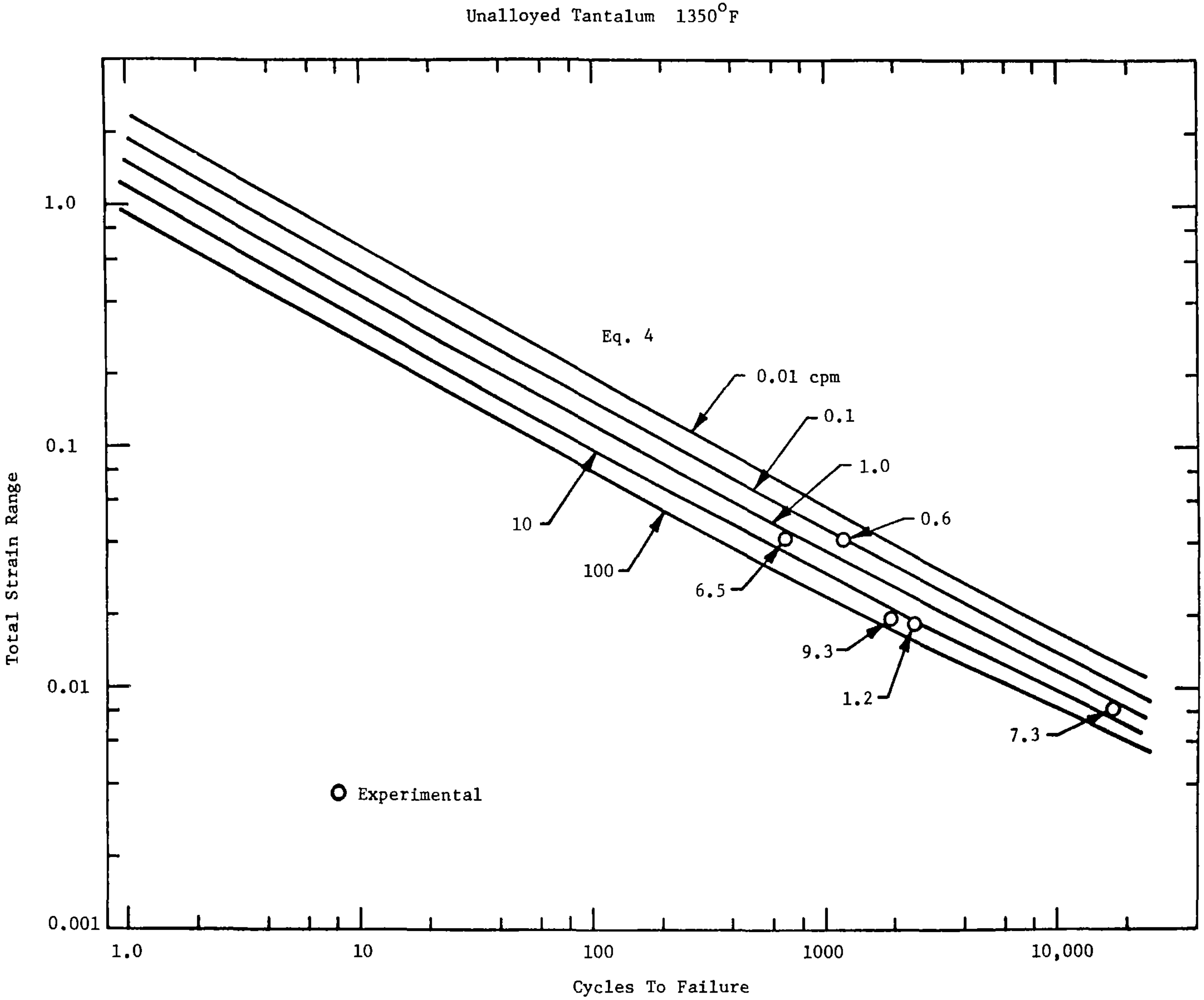


Figure 15. Total Strain Range Versus Fatigue Life of Tantalum at 1350°F for Equation 4.

EQUIVALENT STRESS AMPLITUDE - DESIGN LIFE CURVES

Since the original purpose of the study was to obtain data useful for design purposes, the procedures adopted in generating equivalent stress amplitude curves for materials in Section III of the ASME Nuclear Pressure Vessel Code will be followed. This requires the conversion of the strain range data to equivalent stress amplitude or

$$\sigma_a = \frac{E\ \Delta\varepsilon_t}{2} \tag{6}$$

and introducing a safety factor of either 2 on stress amplitude or 20 on life, whichever gives the lower life. It is apparent from Figures 12 through 15 that the factor of 20 on life is the more conservative.

In the construction of these design curves, the best fit to the actual fatigue results, equation (3), is employed. By employing Eq. (3) and the appropriate constants of Table IV, the equivalent stress amplitude can be calculated. Analytically, this relation is

$$S_a = \frac{A}{2}\ (20N_f')^{-\beta n} + \frac{EC_2}{2}\ (20N_f')^{-\beta} \tag{7}$$

where S_a is the design stress amplitude and N_f' the design life. A plot of S_a vs. N_f' is included as Figure 16 for the three test temperatures. At 1350° where a frequency effect has been observed, Eq. (6) can be considered as conservative since decreasing the frequency (in the direction of the actual service situation) is found to increase the fatigue life. Tabulation of the calculations for S_a are included as Appendix C. Here S is the equivalent stress amplitude and L is the design life.

It should be pointed out that the high values of the equivalent stress does not in fact mean that the material is capable of supporting those stresses. Rather they are the elastic equivalent of strains, which are obtained through elastic thermal stress analysis and apply only for fatigue life prediction.

Unalloyed Tantalum

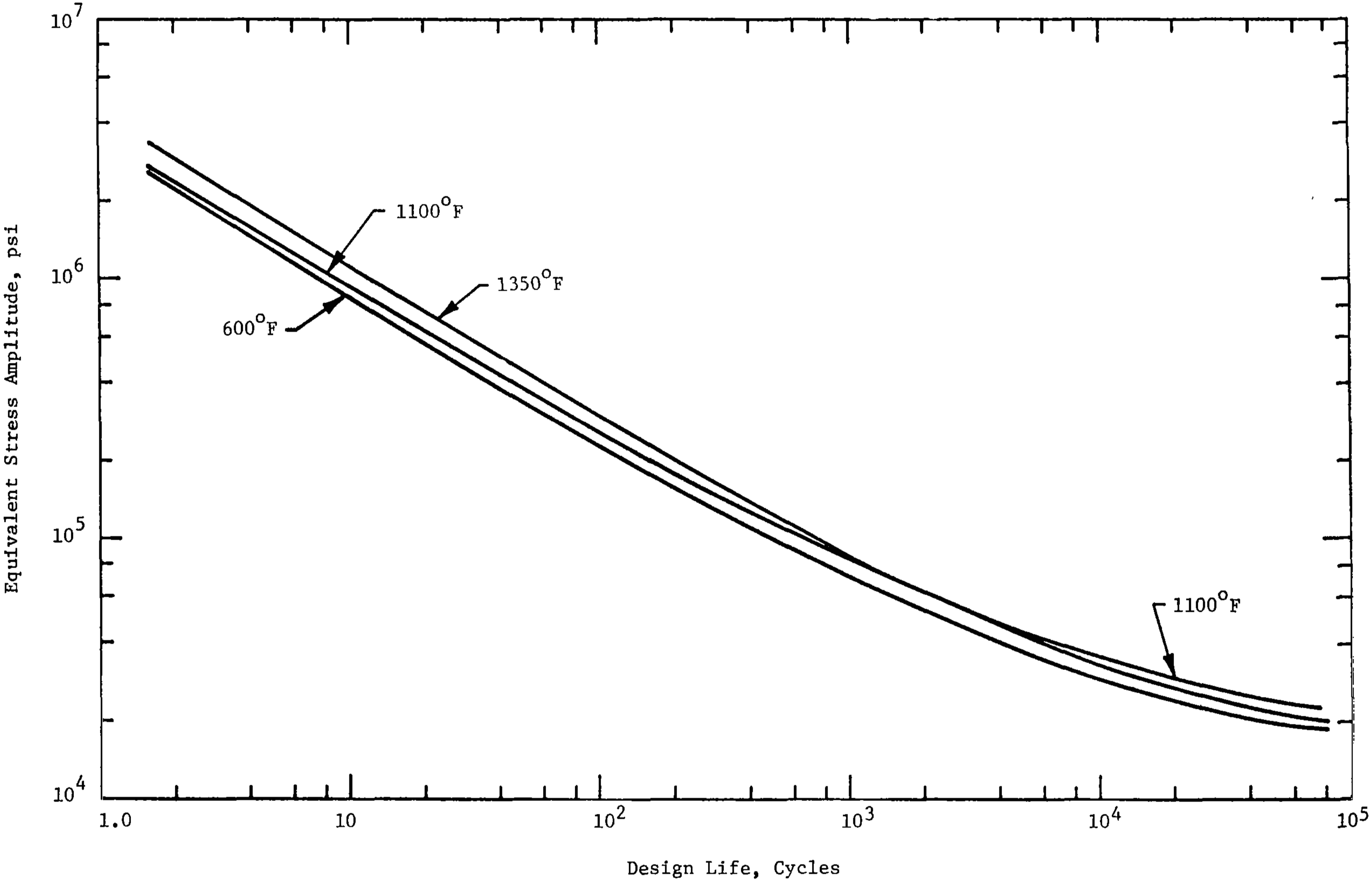


Figure 16. Equivalent Stress Amplitude Versus Design Life of Tantalum.

DISCUSSION

Although only three tension tests and ten fatigue tests were conducted in this investigation, enough information has been developed to provide reasonable equivalent stress amplitude - design life curves. This statement is supported by the following facts:

(a) over the temperature range of 70° to 1400°F, intermittent temperature strain cycling experiments identified aging peaks at two temperatures. From past experience, at those temperatures where aging peaks occur (when the stress range is a maximum), the low-cycle fatigue resistance is reduced.

(b) At these temperatures it was determined that the tensile ductility of the material is very high (>95%). Therefore, since low-cycle fatigue behavior generally relates to tensile ductility below the creep range, as expressed in equations (1) and (2), the low-cycle fatigue resistance of unalloyed tantalum can be expected to equal any metallic material currently being employed in engineering structures.

(c) Although the fatigue tests do not agree closely with those relationships based on tensile data equations (1) and (2), they do indicate a high resistance to low-cycle fatigue. For example, in Table V some typical plastic strain ranges are given to produce failure in 1000 cycles, as obtained for a variety of materials from our earlier investigations plus those for the pure Ta. Additionally in Figure 17 diametral strain range values are compared with those taken from Reference 13. This is a summary plot of many materials strain cycled at room temperature. Note that for the most part, the tantalum results fall above any of the other materials.

In applying these test results to design, it should be remembered that tantalum is highly susceptible to impurity pickup which can embrittle the material significantly. Thus the present results apply to tantalum

TABLE V

COMPARISON OF 1000-CYCLE-LIFE PLASTIC STRAIN RANGE FOR SEVERAL MATERIALS

Material	Temp.	Plastic Strain Range
Unalloyed Tantalum	600°F	.023
Unalloyed Tantalum	1100°F	.026
Unalloyed Tantalum	1350°F	.032
1100 Aluminum	RT	.0174
"A" Nickel	RT	.018
AISI 347 Stainless Steel	RT	.023
AISI 347 Stainless Steel	1112°F	.013
2024-T4 Aluminum	RT	.014
OFHC Copper	RT	.018

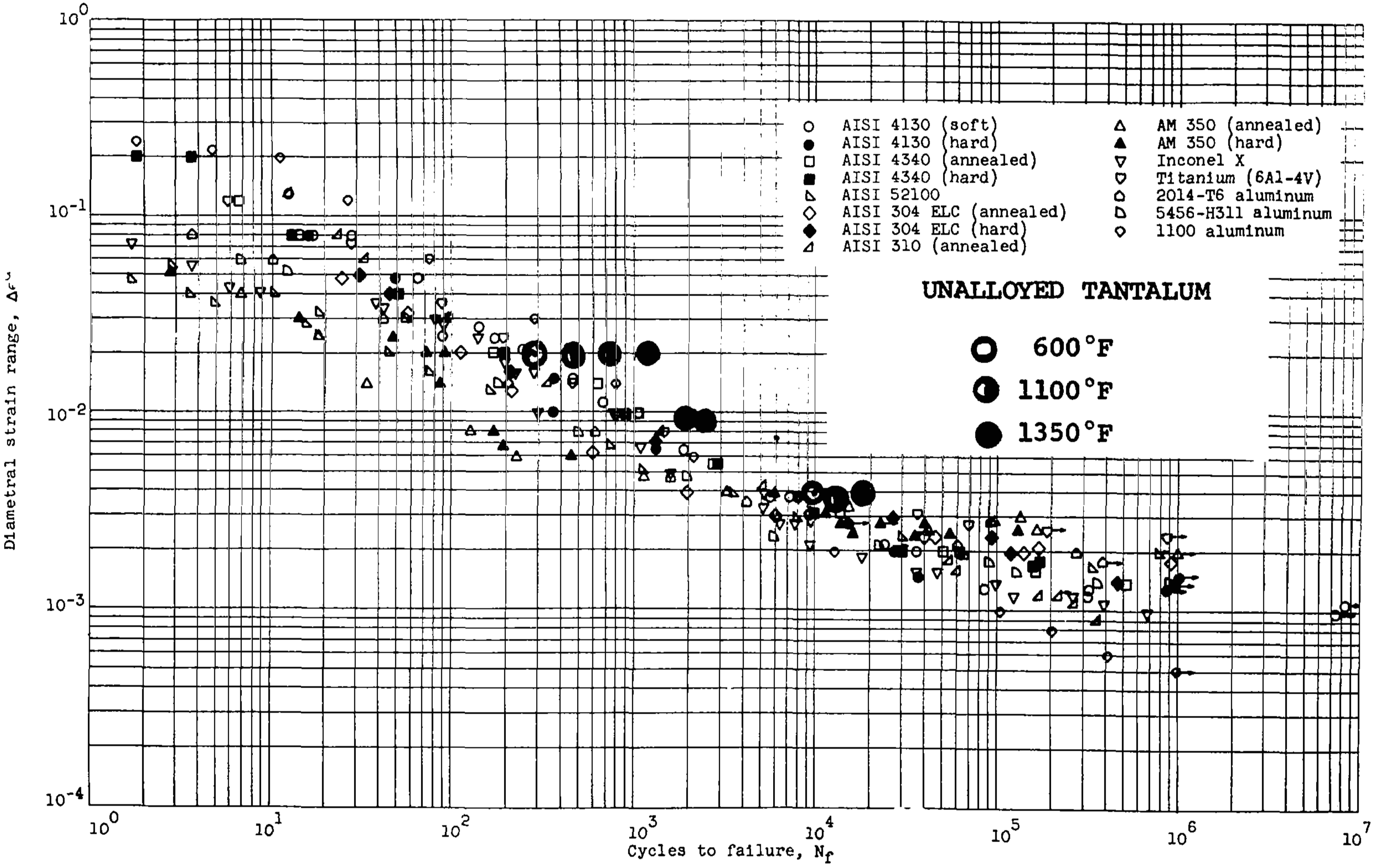


Figure 17. Summary of Diametral Strain Range vs Cycle to Failure for Several Materials.

containing relatively low interstitial element contents as a result of environmental exposure.

An interesting feature of the test results is the frequency effect obtained at 1350°F. By contrast to the present results which show an increased life with decreasing frequency, most materials exhibit a decreased life at elevated temperature. Two explanations for this anomalous effect seem reasonable. The first is that, at 1350°F, the material is still below the creep range. At this temperature the tensile ductility is increasing with increasing temperature (Table I). Following the argument that the ductility can be represented more generally by some temperature - strain rate parameter, a decreasing strain rate or decreasing frequency at a fixed temperature is comparable to an increasing temperature at a fixed strain rate. Hence, lowering the frequency at 1350°F reduces the strain rate which is equivalent to raising the temperature and increasing the related tensile ductility. This is reflected in increased life. The second explanation is less direct. At elevated temperature the atmosphere plays an important role in decreasing the fatigue life. If other materials were tested in the inert atmosphere of the present tests, they also might show a behavior similar to that of tantalum. In air, however, decreasing the frequency increases the exposure time that the crack tip must endure in the air environment and increases the rate of crack propagation, shortening the life. Unfortunately, there is no experimental information on the effect of frequency on high-temperature fatigue in inert environments.*

SUMMARY

Uniaxial low-cycle fatigue tests of unalloyed recrystallized tantalum were conducted. Tests were conducted in a temperature range from 70° to 1400°F with the emphasis on tests at 600°, 1100°, and 1350°F. Specimens were protected from contamination during testing by a purified flowing argon gas and titanium susceptors.

Tantalum exhibited a high resistance to low-cycle fatigue failure at the temperatures employed, which is consistent with its high tensile ductility at these test temperatures. Contrary to most materials, tantalum

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*Note added in proof: In recent low-cycle fatigue tests on A-286 alloy at 1100°F and cast Udimet 500 alloy at 1500°F conducted in high vacuum,(14) it was found that the pronounced frequency effect which had occurred in air was completely removed.

exhibited an increased fatigue life with decreasing frequency at 1350°F. This behavior may be attributed to the absence of oxidation in the tantalum tests or the increasing ductility of tantalum at that temperature.

Results did not agree closely with total strain-fatigue life relationships based on tensile data; however, the results for tantalum compared very favorably to those for other common structural metals. The results were also presented in terms of equivalent stress amplitude - fatigue design life for purposes of structural design.

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APPENDIX A

TEST RESULTS

TEST NO 4A

TANTALUM AT 600 FAHR
K1 0.001962
X'HD RATE 0.2 IN/MIN
ORIG DIA 0.2339 IN
ELASTIC MODULUS 26000000
POISSON RATIO 0.3

CYC NO	TEN STRESS	COMP STRESS	STRESS RANGE	MEAN STRESS	PLASTIC STRAIN RANGE	TOTAL STRAIN RANGE
0	15700	14280	29980	710	0.007156	0.008309
1	15020	17340	32360	-1160	0.007101	0.008346
2	17150	18080	35230	-470	0.007035	0.00839
3	17380	18270	35650	-440	0.007025	0.008396
4	17620	18310	35930	-350	0.007019	0.008401
5	17660	18410	36070	-370	0.007016	0.008403
6	17710	18310	36020	-300	0.007017	0.008402
7	17620	18270	35880	-330	0.00702	0.0084
9	17520	18270	35790	-370	0.007022	0.008399
11	17570	18220	35790	-330	0.007022	0.008399
14	17430	18080	35510	-330	0.007029	0.008394
18	17430	18080	35510	-330	0.007029	0.008394
23	17380	18040	35420	-330	0.007031	0.008393
29	17430	18080	35510	-330	0.007029	0.008394
36	17380	18080	35460	-350	0.00703	0.008394
46	17430	18080	35510	-330	0.007029	0.008394
60	17430	18080	35510	-330	0.007029	0.008394
75	17430	18080	35510	-330	0.007029	0.008394
90	17480	18080	35560	-300	0.007027	0.008395
110	17520	18080	35600	-280	0.007026	0.008396
140	17620	18170	35790	-280	0.007022	0.008399
180	17760	18410	36160	-320	0.007013	0.008404
230	17850	18550	36400	-350	0.007008	0.008408
290	18180	18780	36950	-300	0.006995	0.008417
360	18550	19060	37610	-250	0.00698	0.008427
460	18690	19380	38070	-340	0.006969	0.008434
600	19110	19520	38630	-200	0.006957	0.008442
750	19490	19890	39380	-200	0.006939	0.008454
900	19810	20260	40070	-220	0.006923	0.008465
1100	20420	20770	41190	-180	0.006897	0.008482
1400	21030	21370	42400	-170	0.00687	0.0085
1800	21590	22020	43610	-220	0.006842	0.008519
2300	22480	22720	45190	-120	0.006805	0.008543
2900	23130	23180	46310	-30	0.006779	0.00856
3600	23600	23990	47590	-200	0.00675	0.00858
4600	24420	24690	49100	-140	0.006715	0.008605
6000	25350	25620	50970	-130	0.006672	0.008632
7500	26170	26430	52600	-130	0.006634	0.008657
8840	26750	26660	53410	50	0.006615	0.00867
9000	26640	26650	53290	-10	0.006618	0.008668
9560	15890	24110	40000	-4110	0.006925	0.008463
10140	12150	25960	38110	-6910	0.006968	0.008434

CYCLE NO AT MAX TEN 8840
CYC NO AT .5 MAX TEN 10001
TIME/CYCLE 0.1439 MIN
CYCLES/MIN 6.94927
PLASTIC STRAIN RATE 0.091945 IN/IN/MIN
CALC TIME TO .5 MAX TEN 1439.14 MIN

```
TEST NO 6A

TANTALUM AT  600  FAHR
 K1 0.009958
 X'HD RATE 0.05 IN/MIN
 ORIG DIA 0.249 IN
 ELASTIC MODULUS 26000000
 POISSON RATIO 0.3

                                                        PLASTIC       TOTAL
CYC     TEN          COMP         STRESS     MEAN       STRAIN        STRAIN
NO      STRESS       STRESS       RANGE      STRESS     RANGE         RANGE

 0      15710        23350        39060      -3820      0.038931       0.040433
 1      25770        27280        53040      -760      0.038603      0.040648
 2      28070        28180        56250      -60      0.038534     0.040697
 3      28600        28690        57490       60      0.038505     0.040716
 4      29120        28890        58010       120      0.038493      0.040724
 5      29220        28990        58210       120      0.038489      0.040728
 6      29330        29090        58420       120      0.038484      0.040731
 7      29330        29090        58420       120      0.038484      0.040731
 9      29640        29290        58930       180      0.038472      0.040739
 11       30060        29390        59450      340      0.03846       0.040747
 14       30270        29990        60270      140      0.038441       0.040759
 18       30690        30200        60890      250      0.038427       0.040769
 23       31420        31000        62420      210      0.038391       0.040792
 29       32260        31400        63670      430      0.038363       0.040811
 36       32470        32010        64480      230      0.038344       0.040824
 46       33310        32510        65820      400      0.038313       0.040845
 60       34250        33320        67570      470      0.038273       0.040872
 75       34460        34120        68580      170      0.038249       0.040887
 90       34880        34730        69610      80     0.038226      0.040903
 110        35610        35230        70840      190      0.038197      0.040922
 140        36660        36340        73000      160      0.038147      0.040955
 180        38020        38250        76270     -110      0.038072      0.041005
 230        39490        42270        81760     -1390      0.037945      0.04109
 252        38020        44990        83010     -3490      0.037916      0.041109
 273        20530        48520        69050     -13990      0.038239      0.040894


 CYCLE NO AT MAX TEN 230
 CYC NO AT .5 MAX TEN 273
 TIME/CYCLE 1.567 MIN
 CYCLES/MIN 0.638162
 PLASTIC STRAIN RATE 0.04843 IN/IN/MIN
 CALC TIME TO .5 MAX TEN 427.791 MIN
```

```
TEST NO 9A

TANTALUM AT  1100  FAHR
 K1 0.00996
 X'HD RATE 0.05 IN/MIN
 ORIG DIA 0.1255 IN
 ELASTIC MODULUS 26000000
 POISSON RATIO 0.3


                                         PLASTIC TOTAL
CYC  TEN     COMP    STRESS MEAN     STRAIN  STRAIN
NO  STRESS STRESS   RANGE  STRESS   RANGE   RANGE

 0  23920   33280   57200 -4680   0.03852   0.04072
 1  34970   36450   71420 -740  0.038192   0.040939
 2  36120   38200   74320 -1040   0.038125   0.040933
 3  36280   38350   74640 -1030   0.038116   0.040988
 4  36200   38200   74400 -1000   0.038123   0.040985
 5  36120   38040   74160 -960  0.038129   0.040981
 6  35870   37880   73750 -1000   0.038138   0.040975
 7  35790   37880   73670 -1040   0.03814   0.040973
 9  35460   37720   73180 -1130   0.038151   0.040966
 11   35380   37480   72860 -1050   0.038159   0.040961
 14   35300   37400   72700 -1050   0.038162   0.040958
 18   35210   37170   72380 -980   0.03817   0.040954
 23   34800   37170   71970 -1180   0.038179   0.040947
 29   34720   37170   71830 -1220   0.038181   0.040946
 36   34640   37170   71800 -1270   0.038183   0.040945
 46   34640   37170   71800 -1270   0.038183   0.040945
 60   34640   37170   71800 -1270   0.038183   0.040945
 75   34550   37170   71720 -1310   0.038185   0.040943
 90   34550   37170   71720 -1310   0.038185   0.040943
 110   34550   37250   71800 -1350   0.038183   0.040945
 140   34470   37320   71790 -1430   0.038183   0.040945
 180   33960   37090   71060 -1560   0.0382   0.040933
 230   33560   36850   70410 -1640   0.038215   0.040923
 290   32900   36610   69510 -1850   0.038236   0.040909
 360   32160   37170   69330 -2500   0.03824   0.040907
 460   29850   38040   67890 -4090   0.038273   0.040884
 487   26140   41600   67750 -7730   0.038277   0.040882


 CYCLE NO AT MAX TEN 3
 CYC NO AT .5 MAX TEN 487
 TIME/CYCLE 0.381 MIN
 CYCLES/MIN 2.62467
 PLASTIC STRAIN RATE 0.200092 IN/IN/MIN
 CALC TIME TO .5 MAX TEN 185.547 MIN
```

```
TEST NO 10A

TANTALUM AT  1100  FAHR
 K1 0.001865
 X'HD RATE 0.1 IN/MIN
 ORIG DIA 0.124 IN
 ELASTIC MODULUS 26000000
 POISSON RATIO 0.3


                                          PLASTIC TOTAL
CYC  TEN     COMP    STRESS MEAN    STRAIN  STRAIN
NO  STRESS STRESS  RANGE  STRESS  RANGE   RANGE

 0  25770  24010  49770  880   0.006311   0.008226
 1  27430  25820  53250  800   0.006231   0.008279
 2  28840  27550  56400  640   0.006159   0.008328
 3  29260  28380  57640  440   0.00613  0.008347
 4  33330  33000  66330  170   0.005929   0.00848
 5  34830  34070  68900  380   0.00587  0.00852
 6  33750  33820  67570 -40  0.005901  0.0085
 7  35740  37120  72860 -690   0.005779   0.008581
 9  35660  35560  71210  50  0.005817  0.008556
 11  34740  35060  69800 -160  0.005849  0.008534
 14  34660  34960  69640 -160  0.005853  0.008531
 18  34240  34070  68320  90  0.005883  0.008511
 23  33580  33080  66660  250  0.005922  0.008486
 29  32330  32260  64590  40  0.005969  0.008454
 36  31000  31270  62270 -130  0.006023  0.008418
 46  30170  30690  60860 -260  0.006056  0.008396
 60  29340  29950  59290 -300  0.006092  0.008372
 75  28510  29450  57960 -470  0.006122  0.008352
 90  28260  28870  57130 -310  0.006142  0.008339
 110  27430  28300  55730 -430  0.006174  0.008317
 140  27430  28300  55730 -430  0.006174  0.008317
 180  27010  27800  54810 -390  0.006195  0.008303
 230  26850  27720  54570 -440  0.006201  0.008299
 290  26350  27060  53410 -360  0.006228  0.008282
 360  26180  26480  52660 -150  0.006245  0.00827
 460  25930  26400  52330 -230  0.006252  0.008265
 600  25770  25990  51750 -110  0.006266  0.008256
 750  25520  25570  51090 -30  0.006281  0.008246
 900  25600  25570  51170  10  0.006279  0.008247
 1100  25350  25330  50680  10  0.006291  0.00824
 1400  25350  25160  50510  90  0.006294  0.008237
 1800  25100  24910  50020  90  0.006306  0.008229
 2300  25520  25570  51090 -30  0.006281  0.008246
 2900  25430  26230  51670 -400  0.006263  0.008255
 3600  25100  26230  51340 -570  0.006275  0.00825
 4600  26350  27640  53930 -640  0.006214  0.008291
 6000  27180  28630  55810 -720  0.006172  0.008319
 7500  27350  28710  56050 -680  0.006166  0.008322
 9000  28180  29040  57220 -430  0.00614  0.00834
 11000  29170  29700  58870 -260  0.006101  0.008366
 11946  19030  25080  44110 -3020  0.006442  0.008139
 12230  10640  10720  21360 -40  0.006967  0.007789

 CYCLE NO AT MAX TEN 7
 CYC NO AT .5 MAX TEN 12230
 TIME/CYCLE 0.294 MIN
 CYCLES/MIN 3.40136
 PLASTIC STRAIN RATE 0.03931 IN/IN/MIN
 CALC TIME TO .5 MAX TEN 3595.62 MIN
```

```
TEST NO 28

TANTALUM AT  1350  FAHR
 K1 0.034663
 X'HD RATE 0.1 IN/MIN
 ORIG DIA 0.1233 IN
 ELASTIC MODULUS 26000000
 POISSON RATIO 0.3

                                                         PLASTIC       TOTAL
CYC     TEN         COMP        STRESS     MEAN          STRAIN        STRAIN
NO      STRESS      STRESS      RANGE      STRESS        RANGE         RANGE

 0      22820       26720       49540      -1950         0.017509      0.019414
 1      23250       25890       49130      -1320         0.017518      0.019408
 10      21300       24230       45530      -1460         0.017601      0.019352
 75      19610       22900       42510      -1640         0.017671      0.019306
 175       19870       23230       43100      -1680         0.017657      0.019315
 260       20370       23980       44350      -1800         0.017628      0.019334
 380       22660       24230       46880      -790         0.01757       0.019373
 500       22740       24560       47300      -910         0.01756       0.01938
 575       22830       24890       47720      -1030         0.017551      0.019386
 675       22990       25060       48050      -1030         0.017543      0.019391
 780       23500       25640       49140      -1070         0.017518      0.019408
 875       23840       26550       50390      -1360         0.017439      0.019427
 955       24510       27380       51900      -1430         0.017454      0.01945
 1050        25110       27380       52490      -1140         0.017441      0.01946
 1125        25190       27380       52570      -1090         0.017439      0.019461
 1200        25190       27460       52660      -1140         0.017437      0.019462
 1300        25190       27550       52740      -1180         0.017435      0.019463
 1400        25110       27710       52820      -1300         0.017433      0.019465
 1500        24850       27880       52730      -1510         0.017435      0.019463
 1600        24430       27630       52060      -1600         0.017451      0.019453
 1700        24180       28040       52220      -1930         0.017447      0.019455
 1800        23670       27800       51470      -2060         0.017464      0.019444
 1900        22990       27800       50790      -2400         0.01748      0.019433
 1911        22910       28870       51780      -2980         0.017457      0.019449
 1912        23330       23230       46560       50        0.017577      0.019368

 CYCLE NO AT MAX TEN 1125
 CYC NO AT .5 MAX TEN 1912
 TIME/CYCLE 0.1081 MIN
 CYCLES/MIN 9.25069
 PLASTIC STRAIN RATE 0.322642 IN/IN/MIN
 CALC TIME TO .5 MAX TEN 206.687 MIN
ARCED AT 280 CYCLES. TEST STOPPED AND COOLED DOWN.
NEW COIL AND NEW SUSCEPTOR DESIGN. SPECIMEN
REPOLISHED TO REMOVE GAGE MARKS. NEW DIA. .1259 IN.
TEST RESUMED AT 281 CYCLES
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TEST NO 3B

TANTALUM AT  1350  FAHR
 K1 0.010135
 X'HD RATE 0.1 IN/MIN
 ORIG DIA 0.1248 IN
 ELASTIC MODULUS 26000000
 POISSON RATIO 0.3

                                                        PLASTIC      TOTAL
CYC     TEN        COMP       STRESS     MEAN          STRAIN       STRAIN
NO      STRESS     STRESS     RANGE      STRESS        RANGE        RANGE

 0      21690      24350      46040      -1330         0.039477      0.041248
 1      20860      23150      44010      -1150         0.039524      0.041217
 10      21520      24110      45640      -1290         0.039487      0.041242
 25      22520      25150      47680      -1310         0.03944      0.041274
 50      23110      25790      48900      -1340         0.039411      0.041292
 100       22860      25790      48650      -1470         0.039417      0.041289
 150       22520      25630      48160      -1560         0.039429      0.041281
 200       22520      25630      48160      -1560         0.039429      0.041281
 300       22690      26040      48730      -1670         0.039416      0.04129
 400       23530      26920      50440      -1700         0.039376      0.041316
 450       24190      27400      51590      -1600         0.039349      0.041334
 500       24780      28040      52810      -1630         0.039321      0.041353
 550       24860      28280      53140      -1710         0.039314      0.041358
 600       24860      28440      53300      -1790         0.03931      0.04136
 630       24360      28120      52480      -1880         0.039329      0.041347
 660       24030      28120      52140      -2050         0.039337      0.041342
 700       21690      28120      49810      -3210         0.039391      0.041306
 716       18690      27400      46080      -4360         0.039477      0.041249
 740       12350      18180      30530      -2920         0.039835      0.04101
 755       7760      12900      20660      -2570         0.040063      0.040858

 CYCLE NO AT MAX TEN 600
 CYC NO AT .5 MAX TEN 740
 TIME/CYCLE 0.15449 MIN
 CYCLES/MIN 6.47291
 PLASTIC STRAIN RATE 0.508901 IN/IN/MIN
 CALC TIME TO .5 MAX TEN 114.323 MIN
```

TEST NO 5[illegible]

TANTALUM AT 1350 FAHR
K1 0.001935
X'HD RATE 0.05 IN/MIN
ORIG DIA 0.1253 IN
ELASTIC MODULUS 26000000
POISSON RATIO 0.3

CYC NO	TEN STRESS	COMP STRESS	STRESS RANGE	MEAN STRESS	PLASTIC STRAIN RANGE	TOTAL STRAIN RANGE
0	30940	37480	68420	-3270	0.006161	0.008793
3	32560	37970	70530	-2700	0.006112	0.008825
50	28330	32960	61290	-2310	0.006326	0.008683
300	24420	29080	53510	-2330	0.006505	0.008563
500	23530	28190	51720	-2330	0.006546	0.008536
1000	21820	26500	48320	-2340	0.006625	0.008433
1500	20840	25690	46530	-2420	0.006666	0.008456
2500	19290	24320	43610	-2510	0.006734	0.008411
3500	18720	24070	42800	-2670	0.006752	0.008398
4500	18560	24070	42640	-2760	0.006756	0.008396
5500	18560	23910	42470	-2680	0.00676	0.008393
7000	18720	24150	42880	-2710	0.00675	0.0084
8000	18720	24240	42960	-2760	0.006749	0.008401
9000	18890	24400	43280	-2750	0.006741	0.008406
10000	19460	24880	44340	-2710	0.006717	0.008422
11500	19860	25040	44910	-2590	0.006704	0.008431
13000	19540	24960	44500	-2710	0.006713	0.008425
14500	19130	22780	41910	-1820	0.006773	0.008385
16000	18810	20760	39570	-980	0.006827	0.008349
17000	17500	19310	36810	-900	0.006891	0.008306
17500	16280	13810	30100	1230	0.007045	0.008203
17750	15880	13890	29770	990	0.007053	0.008198
18000	14570	14140	28710	220	0.007077	0.008182
18194	13680	14060	27730	-190	0.0071	0.008167

CYCLE NO AT MAX TEN 3
CYC NO AT .5 MAX TEN 17500
TIME/CYCLE 0.13625 MIN
CYCLES/MIN 7.33945
PLASTIC STRAIN RATE 0.089722 IN/IN/MIN
CALC TIME TO .5 MAX TEN 2384.37 MIN

```
TEST NØ 6[illegible]

TANTALUM AT  1350  FAHR
 K1 0.01
 X'HD RATE 0.01 IN/MIN
 ØRIG DIA 0.1235 IN
 ELASTIC MØDULUS 26000000
 PØISSØN RATIØ 0.3


                                                        PLASTIC       TØTAL
CYC     TEN         CØMP        STRESS      MEAN        STRAIN        STRAIN
NØ      STRESS      STRESS      RANGE       STRESS      RANGE         RANGE

 0      26060       25200       51260        430       0.038817      0.040789
 1      26150       24870       51020        640       0.038823      0.040785
 3      25290       24060       49350        620       0.038861      0.040759
 25       19160       22420       41580      -1630       0.03904       0.04064
 75      20870       20130       40990       370       0.039054      0.040631
 150      20180       20130       40310       30       0.03907      0.04062
 225      20780       20870       41650      -40       0.039039      0.040641
 300      21380       21520       42900      -70       0.03901      0.04066
 400      21890       22340       44230      -230       0.038979      0.04068
 500      22650       23160       45810      -250       0.038943      0.040705
 600      23420       23650       47070      -110       0.038914      0.040724
 700      23590       23970       47570      -190       0.038902      0.040732
 800      23680       24140       47810      -230       0.038897      0.040736
 900      23590       24140       47730      -270       0.038899      0.040734
 1000      23420       23970       47400      -280       0.038906      0.040729
 1100      23340       23970       47310      -320       0.038908      0.040728
 1150      22740       23730       46470      -500       0.038928      0.040715
 1177      22820       24140       46960      -660       0.038916      0.040723


 CYCLE NO AT MAX TEN 1
 CYC NO AT .5 MAX TEN 1177
 TIME/CYCLE 1.6733 MIN
 CYCLES/MIN 0.597621
 PLASTIC STRAIN RATE 0.046402 IN/IN/MIN
 CALC TIME TO .5 MAX TEN 1969.47 MIN
```

```
TEST NO 7B

TANTALUM AT  1350  FAHR
 K1 0.004477
 X'HD RATE 0.01 IN/MIN
 ORIG DIA 0.1262 IN
 ELASTIC MODULUS 26000000
 POISSON RATIO 0.3

                                                      PLASTIC     TOTAL
CYC     TEN        COMP       STRESS     MEAN        STRAIN      STRAIN
NO      STRESS     STRESS     RANGE      STRESS      RANGE       RANGE

 0      24760      30660      55430      -2950       0.016629     0.018761
 1      25330      29710      55040      -2190       0.016638     0.018755
 5      22990      27340      50320      -2170       0.016747     0.018682
 10      21620      25910      47530      -2150       0.016811     0.018639
 27      19520      24090      43610      -2280       0.016902     0.018579
 50      18310      22820      41130      -2250       0.016959     0.018541
 100       17340      21790      39130      -2220       0.017005     0.01851
 200       16460      20840      37290      -2190       0.017047     0.018482
 300       16130      21080      37210      -2470       0.017049     0.01848
 400       16130      21000      37130      -2430       0.017051     0.018479
 500       16210      21080      37290      -2430       0.017047     0.018482
 600       16290      21230      37530      -2470       0.017042     0.018485
 700       16370      21470      37850      -2550       0.017035     0.01849
 800       16460      21630      38090      -2590       0.017029     0.018494
 900       15730      22580      38310      -3430       0.017024     0.018497
 1100        16540      22500      39040      -2980       0.017007     0.018509
 1200        16620      22500      39120      -2940       0.017005     0.01851
 1400        16860      22660      39520      -2900       0.016996     0.018516
 1600        17180      22740      39920      -2780       0.016987     0.018522
 1800        17340      22900      40240      -2780       0.016979     0.018527
 2000        17340      23220      40560      -2940       0.016972     0.018532
 2100        17340      23220      40560      -2940       0.016972     0.018532
 2300        17260      23220      40480      -2980       0.016974     0.018531
 2380        18150      24640      42790      -3250       0.016921     0.018566
 2387        18150      23530      41680      -2690       0.016946     0.018549

 CYCLE NO AT MAX TEN 1
 CYC NO AT .5 MAX TEN 2387
 TIME/CYCLE 0.8244 MIN
 CYCLES/MIN 1.213
 PLASTIC STRAIN RATE 0.040363 IN/IN/MIN
 CALC TIME TO .5 MAX TEN 1967.84 MIN
```

```
TEST NØ 80

TANTALUM AT  1100  FAHR
 K1 0.004479
 X'HD RATE 0.02 IN/MIN
 ØRIG DIA 0.1239 IN
 ELASTIC MØDULUS 26000000
 PØISSØN RATIØ 0.3


                                                        PLASTIC       TØTAL
CYC     TEN        CØMP       STRESS    MEAN        STRAIN        STRAIN
NØ      STRESS     STRESS     RANGE     STRESS      RANGE         RANGE

 0      32140      42330      74470     -5100       0.016197      0.019062
 1      34060      42990      77050     -4470       0.016138      0.019101
 10      32220      39460      71680     -3620       0.016262      0.019019
 25      29710      37400      67110     -3850       0.016367      0.018943
 100      27200      34940      62130     -3870       0.016482      0.018872
 147      26030      34940      60960     -4450       0.016509      0.018854
 200      31550      31650      63200     -50       0.016458       0.018888
 300      31470      31570      63030     -50       0.016461       0.018886
 450      31300      31570      62860     -130      0.016465       0.018883
 600      31330      31810      63190     -210      0.016453       0.018888
 750      31330      32140      63520     -380      0.01645       0.018393
 900      31630      32300      63940     -340      0.01644       0.0189
 1100      31720      32550      64270     -420      0.016433      0.018905
 1300      31880      32800      64680     -460      0.016423      0.018911
 1600      31380      32550      63930     -530      0.016441      0.0189
 1700      31300      32470      63770     -590      0.016444      0.018897
 1800      30630      32060      62690     -710      0.016469      0.01888
 2000      28700      30500      59200     -900      0.01655      0.018827
 2100      26280      28360      54640     -1040      0.016655      0.018757
 2200      22680      25070      47750     -1200      0.016814      0.018651
 2300      18830      21370      40200     -1270      0.016988      0.018534
 2400      15400      16690      32090     -640      0.017176      0.01841
 2450      12970      14390      27360     -710      0.017285      0.018337
 2475      11470      12740      24210     -640      0.017357      0.018288
 2499      10130      11430      21550     -650      0.017419      0.018248

 CYCLE NØ AT MAX TEN 1
 CYC NO AT .5 MAX TEN 2355
 TIME/CYCLE 0.5316 MIN
 CYCLES/MIN 1.88111
 PLASTIC STRAIN RATE 0.060714 IN/IN/MIN
 CALC TIME TO .5 MAX TEN 1251.92 MIN
TEST STØPPED AT 198 CYCLES AND 0 LØAD DUE TØ WIDE
TEMPERATURE FLUCTUATIØN AND ARCING. CØIL REINSULATED
AND TEST RESUMED AT 199 CYCLES.
```

APPENDIX B

TABULATION OF PSEUDO-STRESS AMPLITUDE, PLASTIC STRAIN RANGE AND TOTAL STRAIN RANGE VERSUS FATIGUE LIFE FOR UNALLOYED TANTALUM EQUATIONS (1) TO (4)

Equation (1)

```
UNALLØYED TANTALUM-600F

K= 1              K1= 0              N= 0                C= 2.13

A= 22400          M= 26000000        B= 0.5

F                 L                  S                   E2                 E

 1                 1                  2.77012 E+7         2.13               2.13086
 1                 3.16228            1.55824 E+7         1.19779            1.19865
 1                 10                 8.76755 E+6         0.673565           0.674427
 1                 31.6228            4.93526 E+6         0.378774           0.379635
 1                 100                2.7802  E+6         0.213              0.213862
1                 316.228            1.56832 E+6         0.119779           0.12064
 1                 1000               886835              6.73565 E-2        6.82181 E-2
1                 3162.28            503606              3.78774 E-2        3.87389 E-2
1                 10000              288100              0.0213             2.21615 E-2
 1                 31622.8            166912              1.19779 E-2        1.28394 E-2
1                 100000             98763.5             6.73565 E-3        7.59719 E-3
1                 316228             60440.6             3.78774 E-3        4.64927 E-3
1                 1000000            38890.              0.00213            2.99154 E-3
```

Equation (2)

```
UNALLØYED TANTALUM-600F

K= 1              K1= 0              N= 0.2              C= 2.389

A= 85570          M= 26000000        B= 0.6

F                 L                  S                   E2                 E

 1                 1                  3.11079 E+7         2.389              2.39292
 1                 3.16228            1.56097 E+7         1.19734            1.20075
 1                 10                 7.8398  E+6         0.60009            0.603061
 1                 31.6228            3.94349 E+6         0.300757           0.303345
 1                 100                1.98887 E+6         0.150736           0.15299
 1                 316.228            1.00763 E+6         7.55468 E-2        7.75101 E-2
 1                 1000               514450              3.78631 E-2        3.95731 E-2
 1                 3162.28            266056              1.89765 E-2        2.04658 E-2
1                 10000              140503              9.51078 E-3        1.08079 E-2
 1                 31622.8            76653.9             4.76668 E-3        5.89646 E-3
1                 100000             43848.9             0.002389           3.37299 E-3
 1                 316228             26706.6             1.19734 E-3        2.05436 E-3
 1                 1000000            17504.8             6.0009 E-4         1.34652 E-3
```

Equation (3)

```
UNALLØYED TANTALUM-600F

K= 1               K1= 0              N= 0.169           C= 1.636

A= 117400          M= 26000000        B= 0.615

F                  L                  S                  E2                 E

 1                  1                  2.13318 E+7        1.636              1.64091
 1                  3.16228            1.05333 E+7        0.805904           0.810258
 1                  10                 5.21113 E+6        0.396993           0.400856
 1                  31.6228            2.58685 E+6        0.195561           0.198989
 1                  100                1.29188 E+6        9.63348 E-2        9.93754 E-2
 1                  316.228            651986             4.74551 E-2        5.01528 E-2
 1                  1000               335012             2.33767 E-2        2.57701 E-2
 1                  3162.28            177307             1.15155 E-2        0.013639
 1                  10000              98236.2            5.67262 E-3        7.55663 E-3
 1                  31622.8            58056.8            2.79437 E-3        4.46591 E-3
 1                  100000             37174.1            1.37652 E-3        2.85955 E-3
 1                  316228             25920.2            6.78084 E-4        1.99386 E-3
 1                  1000000            19518.4            3.34028 E-4        1.50141 E-3
```

Equation (1)

```
UNALLØYED TANTALUM-1100F

K= 1               K1= 0              N= 0               C= 1.82

A= 20800           M= 26000000        B= 0.5

F                  L                  S                  E2                 E

 1                  1                  2.36704 E+7        1.82               1.8208
 1                  3.16228            1.33154 E+7        1.02346            1.02426
 1                  10                 7.49235 E+6        0.575535           0.576335
 1                  31.6228            4.21781 E+6        0.323647           0.324447
 1                  100                2.3764 E+6         0.182              0.1828
 1                  316.228            1.3409 E+6         0.102346           0.103146
 1                  1000               758595             5.75535 E-2        5.83535 E-2
 1                  3162.28            431141             3.23647 E-2        3.31647 E-2
 1                  10000              247000             0.0182             0.019
 1                  31622.8            143450             1.02346 E-2        1.10346 E-2
 1                  100000             85219.5            5.75535 E-3        6.55535 E-3
 1                  316228             52474.1            3.23647 E-3        4.03647 E-3
 1                  1000000            34060.             0.00182            0.00262
```

Equation (2)

```
UNALLOYED  TANTALUM-1100F

K= 1               K1= 0              N= 0.2             C= 2.175

A= 90790           M= 26000000        B= 0.6

F                  L                  S                  E2                 E

 1                  1                  2.8328 E+7         2.175              2.17908
 1                  3.16228            1.42173 E+7        1.09008            1.09363
 1                  10                 7.14258 E+6        0.546335           0.54943
 1                  31.6228            3.59465 E+6        0.273816           0.276511
 1                  100                1.81455 E+6        0.137233           0.13958
 1                  316.228            920711             6.87795 E-2        7.08239 E-2
 1                  1000               471276             3.44714 E-2        0.036252
 1                  3162.28            244757             1.72766 E-2        1.88274 E-2
 1                  10000              130124             8.65883 E-3        1.00095 E-2
 1                  31622.8            71709.3            4.3397 E-3         5.5161 E-3
 1                  100000             41594.9            0.002175           3.19961 E-3
 1                  316228             25772.2            1.09008 E-3        1.98248 E-3
 1                  1000000            17206.5            5.46335 E-4        1.32358 E-3
```

Equation (3)

```
UNALLOYED  TANTALUM-1100F

K=1.0              K1= 0              N= 0.155           C= 1.572

A= 118400          M= 26000000        B= 0.594

F                  L                  S                  E2                 E

 1                  1                  2.04995 E+7        1.572              1.57688
 1                  3.16228            1.03704 E+7        0.793328           0.797721
 1                  10                 5.25607 E+6        0.400362           0.404313
 1                  31.6228            2.67281 E+6        0.202047           0.205601
 1                  100                1.36711 E+6        0.101965           0.105162
 1                  316.228            706330             0.051458           5.43331 E-2
 1                  1000               371212             2.59688 E-2        2.85548 E-2
 1                  3162.28            200607             1.31055 E-2        1.54313 E-2
 1                  10000              113175             6.61382 E-3        8.70576 E-3
 1                  31622.8            67850.6            3.33774 E-3        5.21928 E-3
 1                  100000             43897.5            1.68443 E-3        3.37673 E-3
 1                  316228             30838.2            8.50066 E-4        2.37217 E-3
 1                  1000000            23374.1            4.28995 E-4        1.79801 E-3
```

Equation (1)

```
UNALLOYED TANTALUM-1350F

K= 0               K1= 0               N= 0               C= 2.48

A= 10080           M= 26000000         B= 0.5

F                  L                   S                  E2                 E

 1                  1                   3.2245 E+7         2.48               2.48039
 1                  3.16228             1.81349 E+7        1.39461            1.39499
 1                  10                  1.02002 E+7        0.784245           0.784633
 1                  31.6228             5.73821 E+6        0.441013           0.441401
 1                  100                 3.22904 E+6        0.248              0.248388
 1                  316.228             1.81803 E+6        0.139461           0.139848
 1                  1000                1.02456 E+6        7.84245 E-2        7.88122 E-2
 1                  3162.28             578357             4.41013 E-2        0.044489
 1                  10000               327440             0.0248             2.51877 E-2
 1                  31622.8             186339             1.39461 E-2        1.43338 E-2
 1                  100000              106992             7.84245 E-3        8.23014 E-3
 1                  316228              62371.7            4.41013 E-3        4.79783 E-3
 1                  1000000             37280.             0.00248            2.86769 E-3
```

Equation (2)

```
UNALLOYED TANTALUM-1350F

K= 0               K1= 0               N= 0.2             C= 2.6139

A= 51696.8         M= 26000000         B= 0.6

F                  L                   S                  E2                 E

 1                  1                   3.4012 E+7         2.6139             2.61631
 1                  3.16228             1.7058 E+7         1.31005            1.31215
 1                  10                  8.55933 E+6        0.656582           0.65841
 1                  31.6228             4.29861 E+6        0.329071           0.330663
 1                  100                 2.16206 E+6        0.164926           0.166313
 1                  316.228             1.09026 E+6        8.26588 E-2        8.38665 E-2
 1                  1000                552232             4.14275 E-2        4.24794 E-2
 1                  3162.28             281828             2.07629 E-2        2.16791 E-2
 1                  10000               145652             1.04061 E-2        0.011204
 1                  31622.8             76834.6            5.21542 E-3        5.91036 E-3
 1                  100000              41849.2            2.6139 E-3         3.21917 E-3
 1                  316228              23883.9            1.31005 E-3        1.83722 E-3
 1                  1000000             14504.4            6.56582 E-4        1.11572 E-3
```

Equation (3)

```
UNALLØYED TANTALUM-1350F

K=1.0               K1= 0               N= 0.142            C= 2.049

A= 87300            M= 26000000         B= 0.605

F                   L                   S                   E2                  E

 1                   1                   2.66853 E+7         2.049               2.05272
 1                   3.16228             1.33173 E+7         1.02104             1.02441
 1                   10                  6.65398 E+6         0.508794            0.511844
 1                   31.6228             3.33191 E+6         0.253537            0.256301
 1                   100                 1.67496 E+6         0.12634             0.128843
 1                   316.228             847912              6.29567 E-2         0.065224
 1                   1000                434535              0.031372            3.34257 E-2
 1                   3162.28             227413              0.015633            1.74933 E-2
 1                   10000               123178              7.79008 E-3         9.47524 E-3
 1                   31622.8             70308.4             3.88188 E-3         5.40834 E-3
 1                   100000              43122.1             1.93438 E-3         3.31709 E-3
 1                   316228              28813.4             9.63922 E-4         2.21641 E-3
 1                   1000000             20993.3             4.80332 E-4         1.61487 E-3
```

Equation (4)

```
UNALLOYED TANTALUM-1350F
A286-1100F

K= 1.139            K1= 0.0736          N= 0.124            C= 1.481

A= 69413            M= 26000000         B= 0.543

F                   L                   S                   S1                  E

  100                 1                   1.205  E+7          0.923211            0.926921
  100                 3.16228             6.46773 E+6         0.494084            0.497518
  100                 10                  3.47882 E+6         0.264424            0.267601
  100                 31.6228             1.87791 E+6         0.141515            0.144455
  100                 100                 1.01994 E+6         7.57358 E-2         7.84566 E-2
  100                 316.228             559652              4.05323 E-2         4.30502 E-2
  100                 1000                312288              2.16921 E-2         2.40221 E-2
  100                 3162.28             178951              1.16092 E-2         1.37654 E-2
  100                 10000               106710              0.006213            8.20843 E-3
  100                 31622.8             67231.6             3.32507 E-3         5.17166 E-3
  100                 100000              45348.8             1.77951 E-3         3.48837 E-3
  100                 316228              32938.7             9.5236 E-4          2.53375 E-3
  100                 1000000             25650.5             5.09684 E-4         1.97312 E-3

  10.                 1                   1.52429 E+7         1.16931             1.17253
  10.                 3.16228             8.17405 E+6         0.625789            0.628773
  10.                 10                  4.38973 E+6         0.33491             0.337672
  10.                 31.6228             2.36331 E+6         0.179237            0.181793
  10.                 100                 1.27776 E+6         9.59242 E-2         9.82891 E-2
  10.                 316.228             695829              5.13367 E-2         5.35253 E-2
  10.                 1000                383496              2.74744 E-2         2.94997 E-2
 10.                 3162.28             215514              1.47037 E-2         0.016578
  10.                 10000               124847              7.86915 E-3         9.60361 E-3
  10.                 31622.8             75614.4             4.21142 E-3         5.81649 E-3
 10.                 100000              48609.9             2.25387 E-3         3.73922 E-3
  10.                 316228              33550.2             1.20622 E-3         2.58079 E-3
  10.                 1000000             24928.6             6.45547 E-4         1.91758 E-3

 1                   1                   1.92894 E+7         1.481               1.4838
 1                   3.16228             1.03375 E+7         0.792602            0.795196
 1                   10                  5.54561 E+6         0.424185            0.426585
 1                   31.6228             2.98008 E+6         0.227015            0.229237
 1                   100                 1.60615 E+6         0.121494            0.12355
 1                   316.228             870006              6.50212 E-2         6.69235 E-2
 1                   1000                475260              3.47981 E-2         3.65585 E-2
 1                   3162.28             263281              1.86232 E-2         2.02524 E-2
 1                   10000               149167              9.96678 E-3         1.14744 E-2
 1                   31622.8             87479.3             5.33403 E-3         6.72918 E-3
 1                   100000              53894.8             2.85466 E-3         4.14575 E-3
 1                   316228              35393.1             1.52776 E-3         2.72255 E-3
 1                   1000000             25002.8             8.17627 E-4         1.92329 E-3

 0.1                 1                   2.44168 E+7         1.87578             1.87822
 0.1                 3.16228             1.30798 E+7         1.00388             1.00614
 0.1                 10                  7.01146 E+6         0.537257            0.539343
 0.1                 31.6228             3.76298 E+6         0.287529            0.28946
 0.1                 100                 2.02367 E+6         0.15388             0.155667
 0.1                 316.228             1.09209 E+6         8.23535 E-2         0.084007
 0.1                 1000                592854              0.044074            4.56042 E-2
 0.1                 3162.28             325046              2.35875 E-2         2.50036 E-2
 0.1                 10000               181142              1.26236 E-2         0.013934
 0.1                 31622.8             103591              6.75588 E-3         7.96857 E-3
 0.1                 100000              61592.              3.61561 E-3         4.73784 E-3
 0.1                 316228              38655.9             0.001935            2.97353 E-3
 0.1                 1000000             25956.3             1.03558 E-3         1.99664 E-3
```

0.01	1	3.09129 E+7	2.3758	2.37791
0.01	3.16228	1.65547 E+7	1.27148	1.27344
0.01	10	8.86969 E+6	0.68047	0.682284
0.01	31.6228	4.75608 E+6	0.364174	0.365852
0.01	100	2.55387 E+6	0.194899	0.196452
0.01	316.228	1.37466 E+6	0.104306	0.105743
0.01	1000	742983	5.58225 E-2	5.71525 E-2
0.01	3162.28	404377	2.98751 E-2	3.11059 E-2
0.01	10000	222659	1.59885 E-2	1.71276 E-2
0.01	31622.8	124941	8.55675 E-3	9.61083 E-3
0.01	100000	72213.2	4.57941 E-3	5.55486 E-3
0.01	316228	43595.5	2.45081 E-3	3.3535 E-3
0.01	1000000	27910.8	1.31162 E-3	2.14699 E-3
0.001	1	3.91422 E+7	3.0091	3.01094
0.001	3.16228	2.09575 E+7	1.61041	1.61211
0.001	10	1.12247 E+7	0.861859	0.863435
0.001	31.6228	6.01521 E+6	0.46125	0.462708
0.001	100	3.22662 E+6	0.246852	0.248202
0.001	316.228	1.73367 E+6	0.13211	0.133359
0.001	1000	934165	7.07027 E-2	7.18588 E-2
0.001	3162.28	505811	3.78387 E-2	3.89086 E-2
0.001	10000	276128	2.02505 E-2	2.12406 E-2
0.001	31622.8	152801	1.08377 E-2	1.17539 E-2
0.001	100000	86423.8	5.80011 E-3	6.64799 E-3
0.001	316228	50553.6	3.1041 E-3	3.88874 E-3
0.001	1000000	31035.7	1.66125 E-3	2.38736 E-3
0.0001	1	4.95665 E+7	3.81121	3.81281
0.0001	3.16228	2.65351 E+7	2.03968	2.04117
0.0001	10	1.42086 E+7	1.0916	1.09297
0.0001	31.6228	7.61111 E+6	0.584202	0.58547
0.0001	100	4.07975 E+6	0.312653	0.313827
0.0001	316.228	2.18935 E+6	0.167326	0.168412
0.0001	1000	1.17721 E+6	8.95495 E-2	9.05544 E-2
0.0001	3162.28	635116	4.79251 E-2	0.048855
0.0001	10000	344619	2.56486 E-2	2.65091 E-2
0.0001	31622.8	188799	1.37266 E-2	0.014523
0.0001	100000	105081	7.34621 E-3	8.08319 E-3
0.0001	316228	59976.2	3.93154 E-3	4.61356 E-3
0.0001	1000000	35557.9	2.10408 E-3	2.73523 E-3
0.00001	1	6.27709 E+7	4.82714	4.82853
0.00001	3.16228	3.36008 E+7	2.58339	2.58468
0.00001	10	1.7989 E+7	1.38258	1.38377
0.00001	31.6228	9.63341 E+6	0.739929	0.741031
0.00001	100	5.1612 E+6	0.395995	0.397015
0.00001	316.228	2.76735 E+6	0.211929	0.212873
0.00001	1000	1.48582 E+6	0.11342	0.114294
0.00001	3162.28	799611	6.07002 E-2	6.15085 E-2
0.00001	10000	432036	3.24855 E-2	3.32336 E-2
0.00001	31622.8	235012	1.73856 E-2	1.80778 E-2
0.00001	100000	129285	9.30444 E-3	9.94503 E-3
0.00001	316228	72440.7	4.97955 E-3	5.57236 E-3
0.00001	1000000	41776.2	2.66496 E-3	3.21355 E-3

APPENDIX C

TABULATION OF EQUIVALENT STRESS AMPLITUDE VERSUS DESIGN FATIGUE LIFE FOR UNALLOYED TANTALUM

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UNALLOYED TANTALUM-600F- Equation (3)

K= 1              K1= 0             N= 0.169          C= 1.636

A= 117400         M= 26000000       B= 0.615

F                 L                 S                 E2                E

 1                 0.05              2.13318 E+7       1.636             1.64091
 1                 0.158114          1.05333 E+7       0.805904          0.810258
 1                 0.5               5.21113 E+6       0.396993          0.400856
 1                 1.58114           2.58685 E+6       0.195561          0.198989
 1                 5                 1.29188 E+6       9.63348 E-2       9.93754 E-2
 1                 15.8114           651986            4.74551 E-2       5.01528 E-2
 1                 50                335012            2.33767 E-2       2.57701 E-2
 1                 158.114           177307            1.15155 E-2       0.013639
 1                 500               98236.2           5.67262 E-3       7.55663 E-3
 1                 1581.14           58056.8           2.79437 E-3       4.46591 E-3
 1                 5000              37174.1           1.37652 E-3       2.85955 E-3
 1                 15811.4           25920.2           6.78084 E-4       1.99386 E-3
 1                 50000             19518.4           3.34028 E-4       1.50141 E-3
```

```
UNALLOYED TANTALUM-1100F- Equation (3)

K= 1              K1= 0             N= 0.155          C= 1.572

A= 118400         M= 26000000       B= 0.594

F                 L                 S                 E2                E

 1                 0.05              2.04995 E+7       1.572             1.57688
 1                 0.158114          1.03704 E+7       0.793328          0.797721
 1                 0.5               5.25607 E+6       0.400362          0.404313
 1                 1.58114           2.67281 E+6       0.202047          0.205601
 1                 5                 1.36711 E+6       0.101965          0.105162
 1                 15.8114           706330            0.051458          5.43331 E-2
 1                 50                371212            2.59688 E-2       2.85548 E-2
 1                 158.114           200607            1.31055 E-2       1.54313 E-2
 1                 500               113175            6.61382 E-3       8.70576 E-3
 1                 1581.14           67850.6           3.33774 E-3       5.21928 E-3
 1                 5000              43897.5           1.68443 E-3       3.37673 E-3
 1                 15811.4           30838.2           8.50066 E-4       2.37217 E-3
 1                 50000             23374.1           4.28995 E-4       1.79801 E-3
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```
UNALLOYED TANTALUM-1350F-Equation (3)

K= 1                K1= 0               N= 0.142            C= 2.049

A= 87300            M= 26000000         B= 0.605

F                   L                   S                   E2                  E

 1                   0.05                2.66853 E+7         2.049               2.05272
 1                   0.158114            1.33173 E+7         1.02104             1.02441
 1                   0.5                 6.65398 E+6         0.508794            0.511844
 1                   1.58114             3.33191 E+6         0.253537            0.256301
 1                   5                   1.67496 E+6         0.12634             0.128843
 1                   15.8114             847912              6.29567 E-2         0.065224
 1                   50                  434535              0.031372            3.34257 E-2
 1                   158.114             227413              0.015633            1.74933 E-2
 1                   500                 123178              7.79008 E-3         9.47524 E-3
 1                   1581.14             70308.4             3.88188 E-3         5.40834 E-3
 1                   5000                43122.1             1.93438 E-3         3.31709 E-3
 1                   15811.4             28813.4             9.63922 E-4         2.21641 E-3
 1                   50000               20993.3             4.80332 E-4         1.61487 E-3
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