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**HIGH-TEMPERATURE, LOW-CYCLE FATIGUE
BEHAVIOR OF TANTALUM**

by R. LaForce, R. F. Berning, and L. F. Coffin, Jr.

Prepared by

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16. Abstract <p>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^o 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.</p>			
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HIGH-TEMPERATURE, LOW-CYCLE FATIGUE BEHAVIOR OF TANTALUM

R. LaForce, R. F. Berning, and L. F. Coffin, Jr.

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

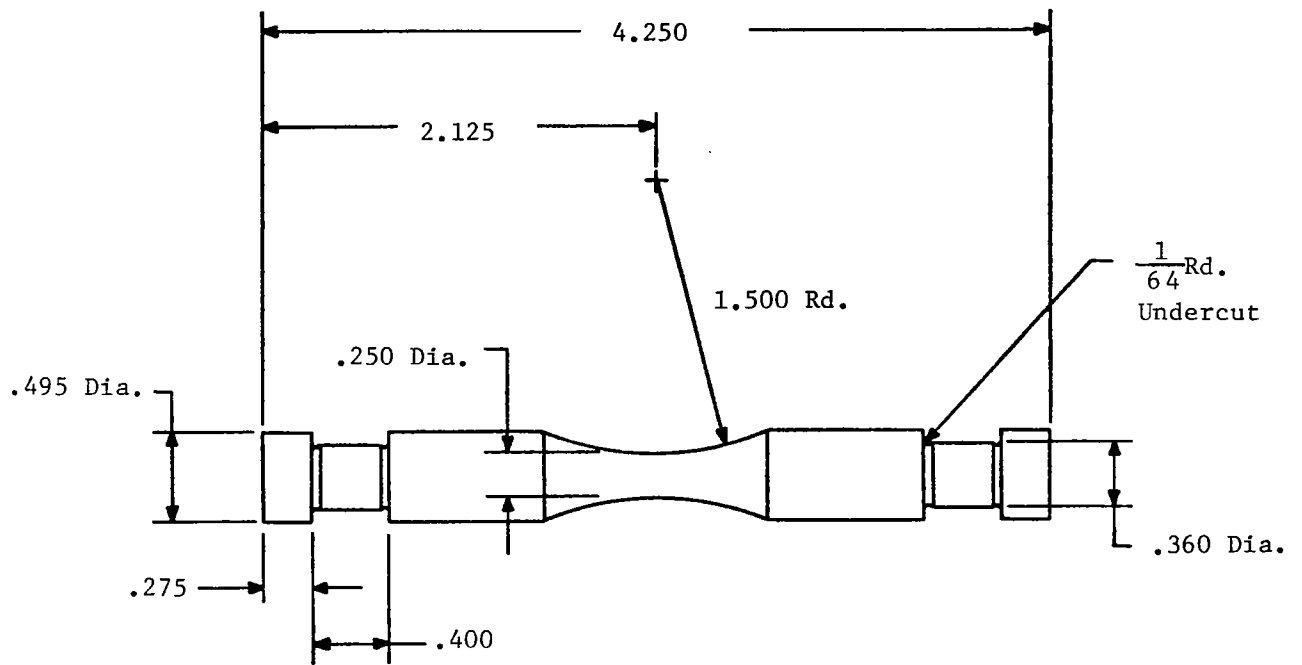


Figure 1. Low-Cycle Fatigue Test Specimen.

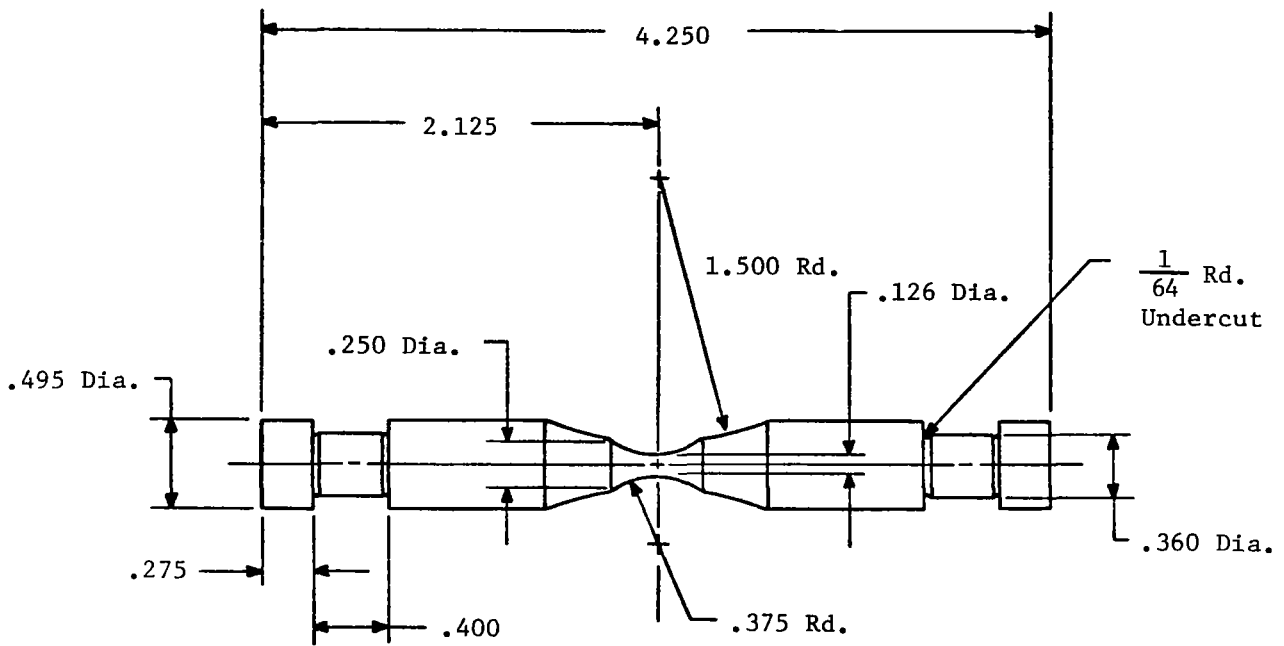


Figure 2. Modified Low-Cycle Fatigue Test Specimen.

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.

*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% H₂ 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 plexi-glass 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

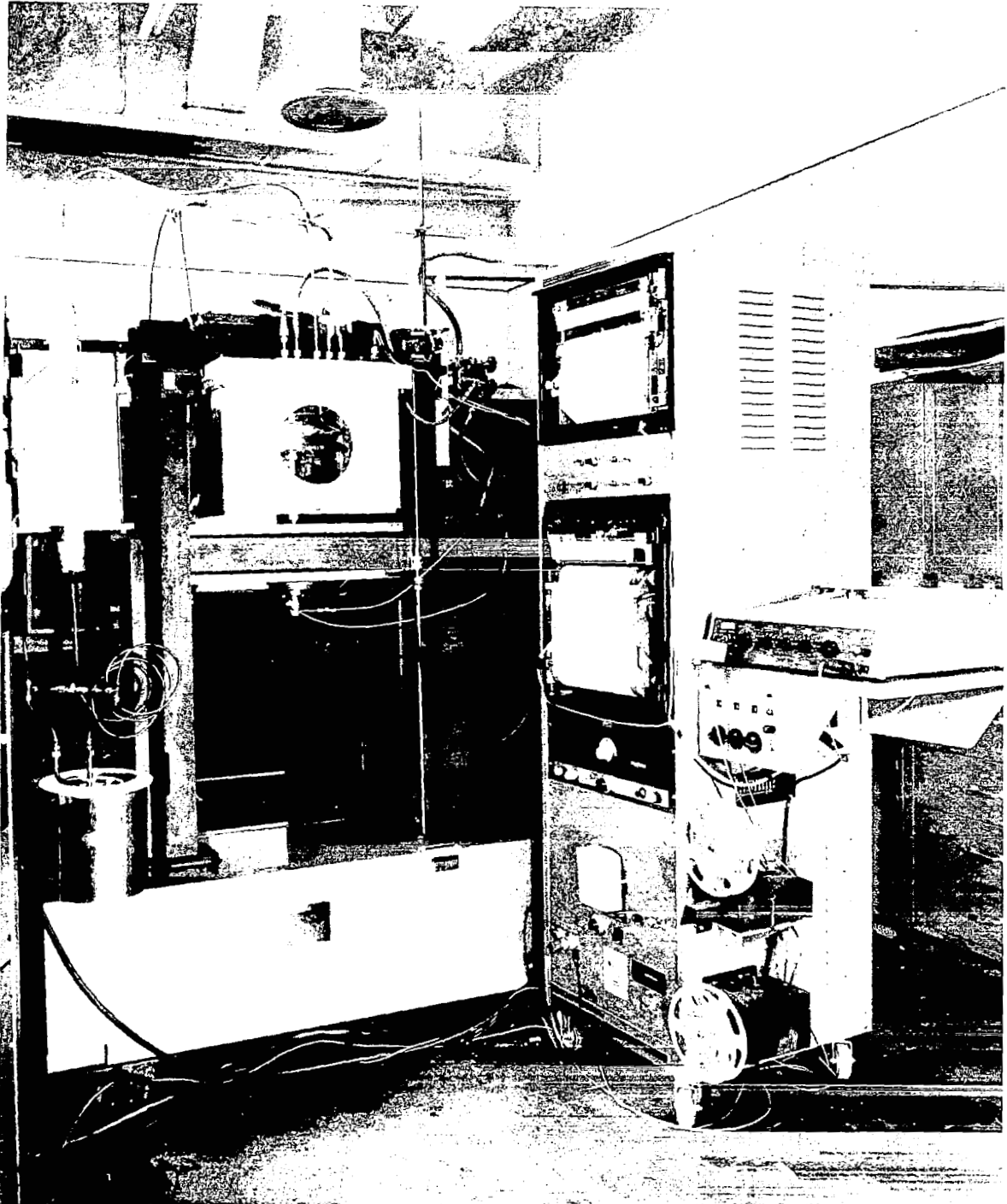


Figure 3. Experimental Facility.

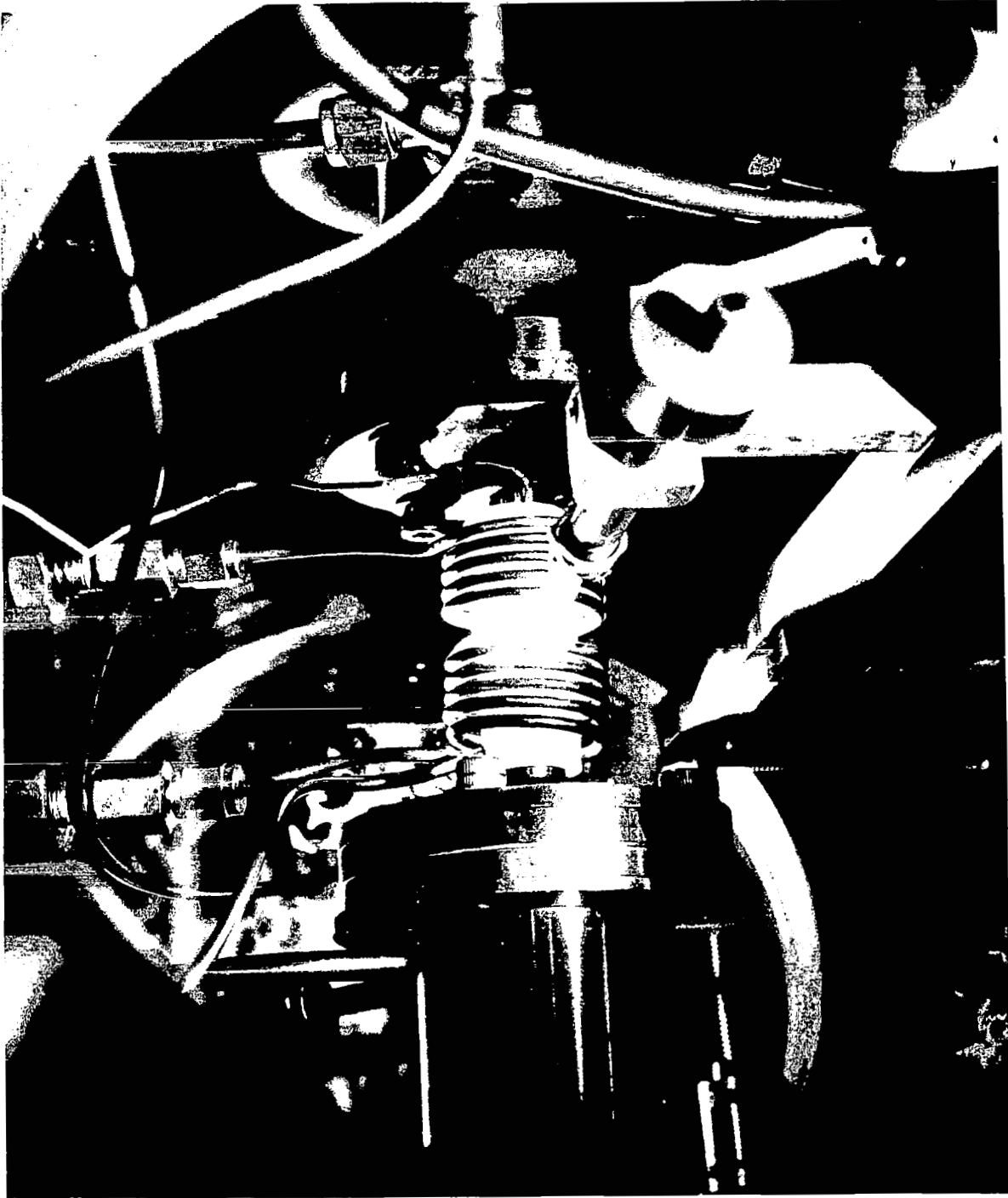


Figure 4. Close-up of Test.

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

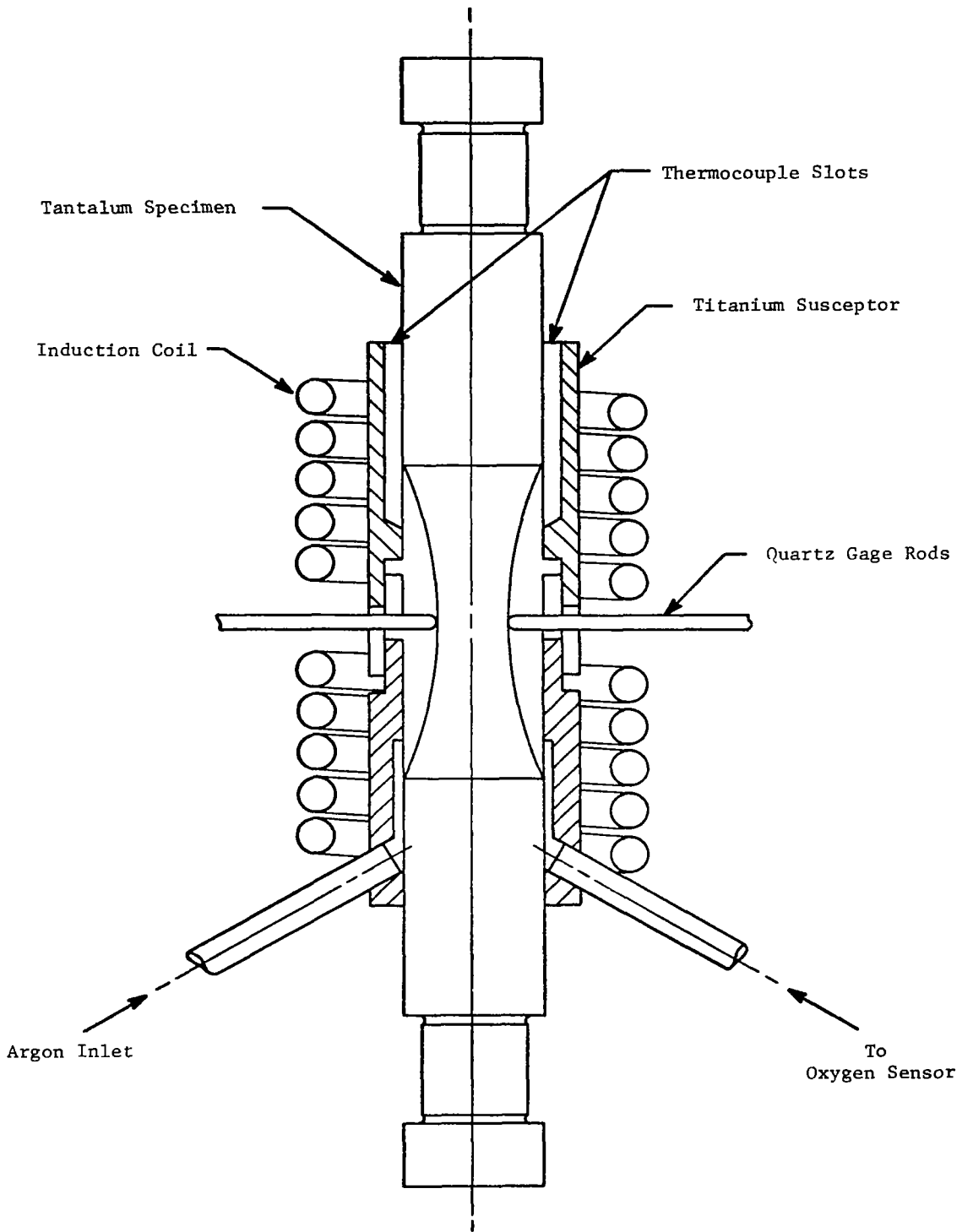


Figure 5. Details of Specimen-Susceptor-Induction Coil Design.

TABLE I

CONCENTRATION OF INTERSTITIALS IN TANTALUM SAMPLES*

<u>Sample No.</u>	<u>Test Temperature (°F)</u>	<u>Test Time (Hrs)</u>	<u>Carbon (ppm)</u>	<u>Oxygen (ppm)</u>	<u>Nitrogen (ppm)</u>	<u>Hydrogen (ppm)</u>
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	--	--

* 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.

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

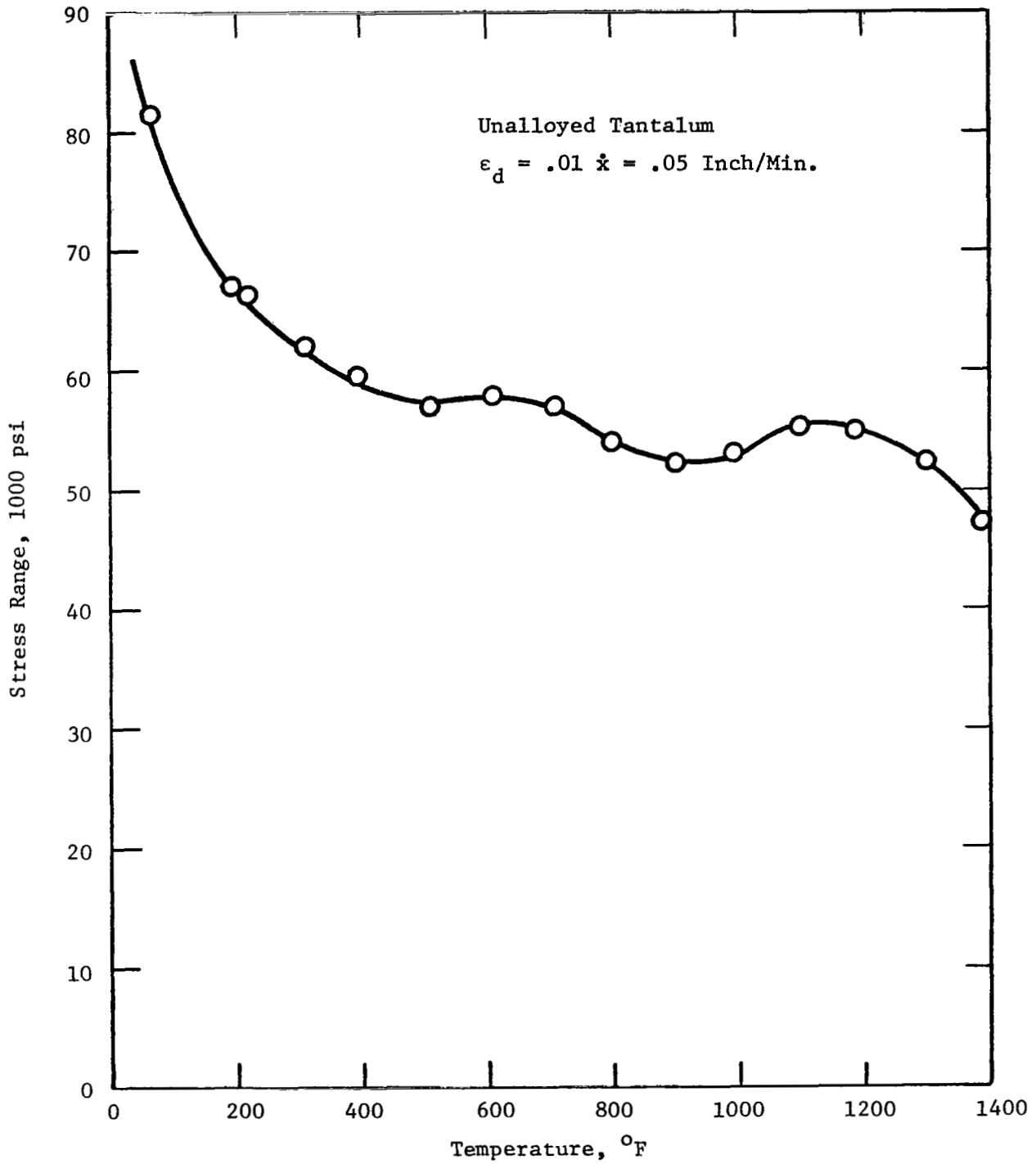


Figure 6. Stress Range Versus Temperature After Five Cycles -- Intermittent Temperature Strain Cycling Experiment.

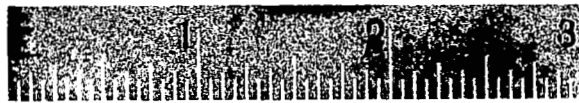
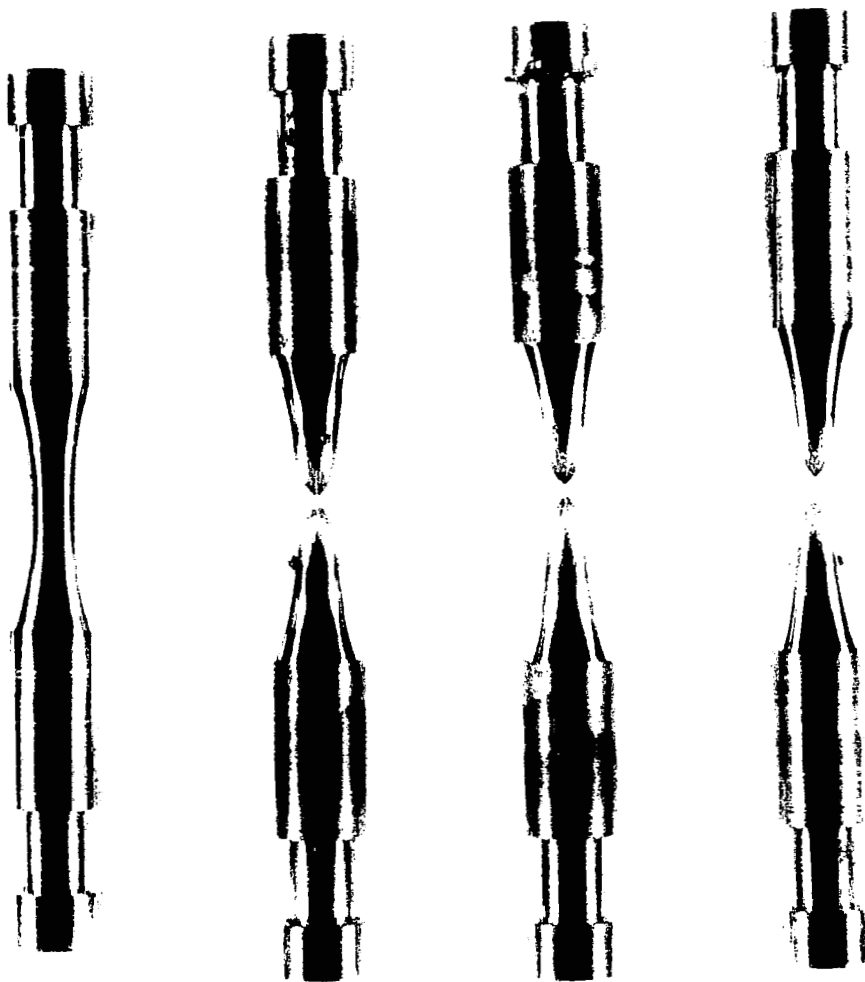


Figure 7. Necked Tensile Specimens.

TABLE II
SUMMARY OF TENSION TEST RESULTS

Temp., (°F)	$\dot{\lambda}$ ("/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

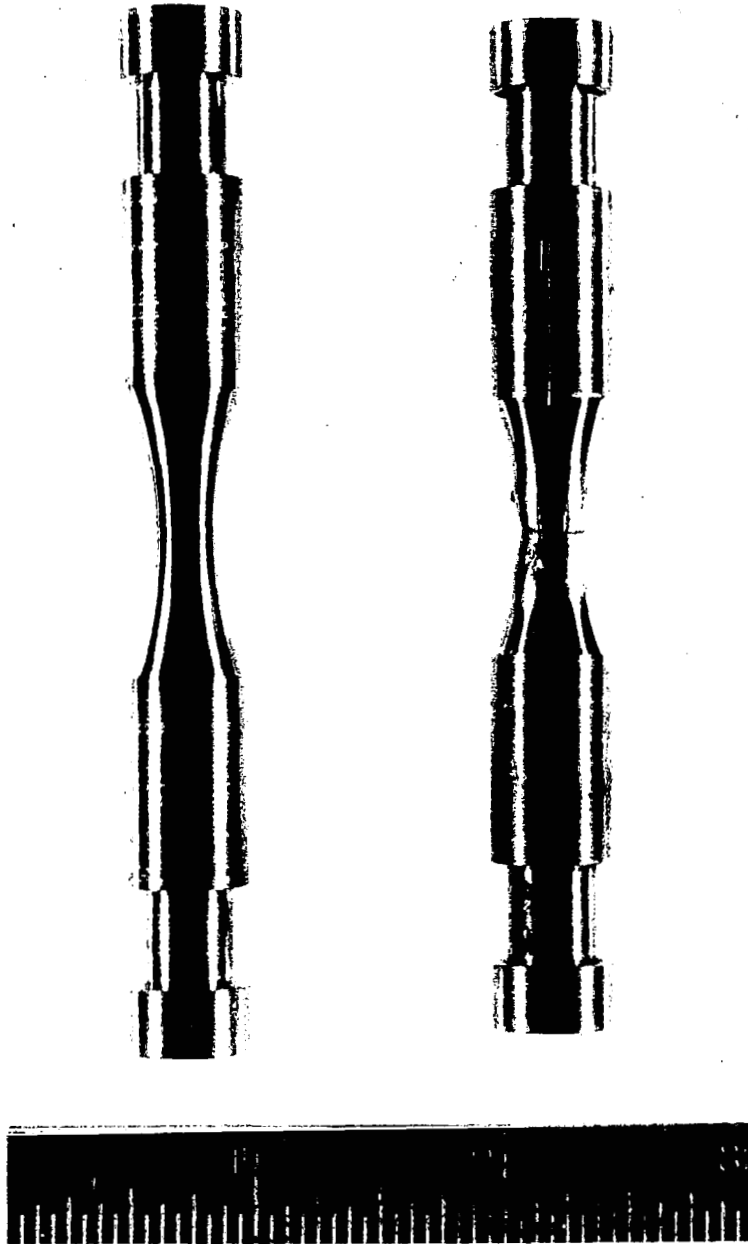


Figure 8. Shape Change in Specimen at Failure - $\epsilon_d = 0.01$, $T = 600^\circ\text{F}$.

TABLE III

SUMMARY OF FATIGUE TEST RESULTS

<u>Test No.</u>	<u>Temp., (°F)</u>	<u>Diametral Strain Amplitude (ϵ_d)</u>	<u>Plastic Strain Range ($\Delta\epsilon_p$)</u>	<u>Total Strain Range ($\Delta\epsilon$)</u>	<u>Stress Range ($\Delta\sigma$) (psi)</u>	<u>Frequency CPM (ν)</u>	<u>Cycles to Failure (N_f)</u>
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

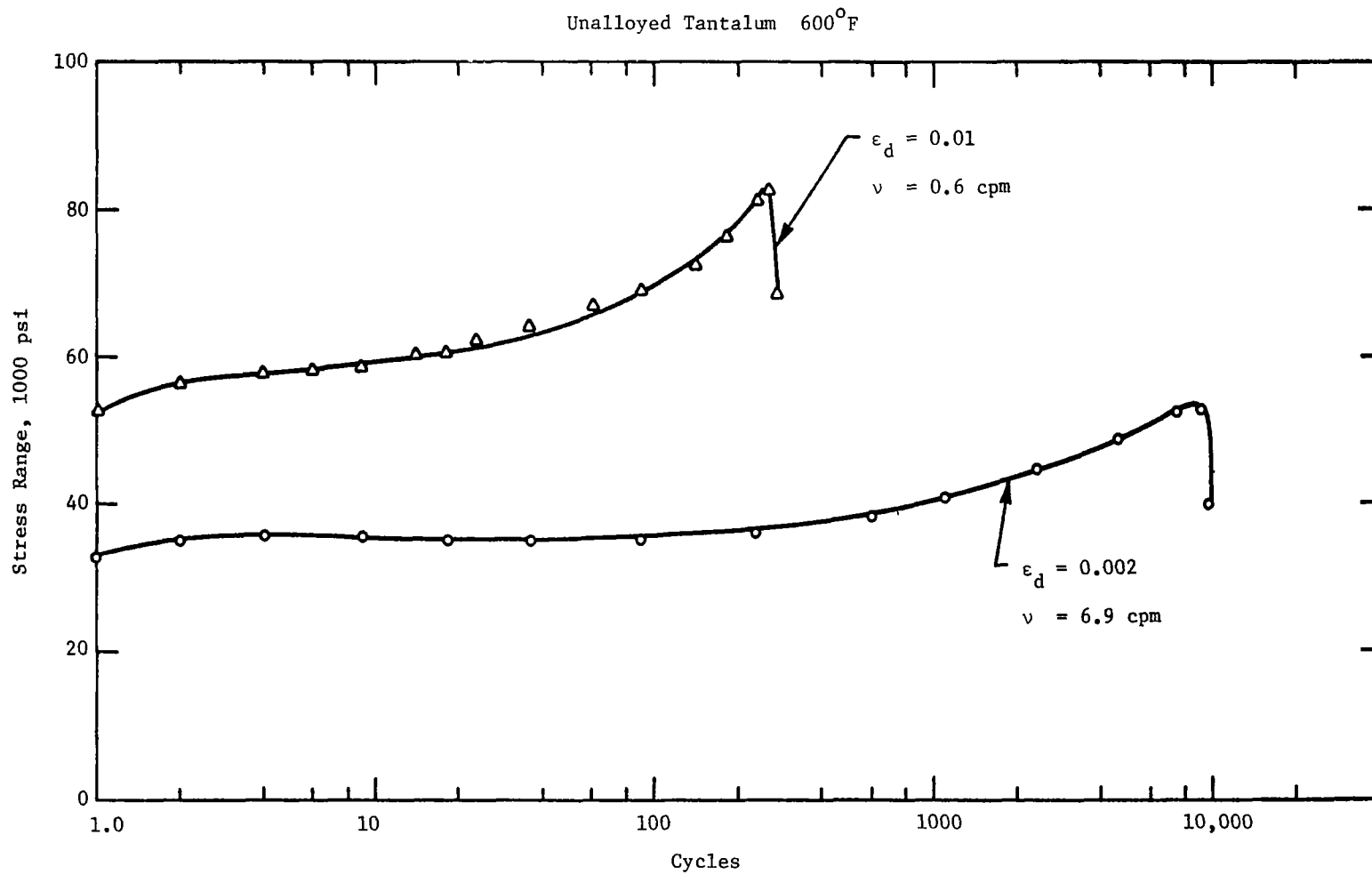


Figure 9. Stress Range Versus Cycles for Tantalum at 600°F.

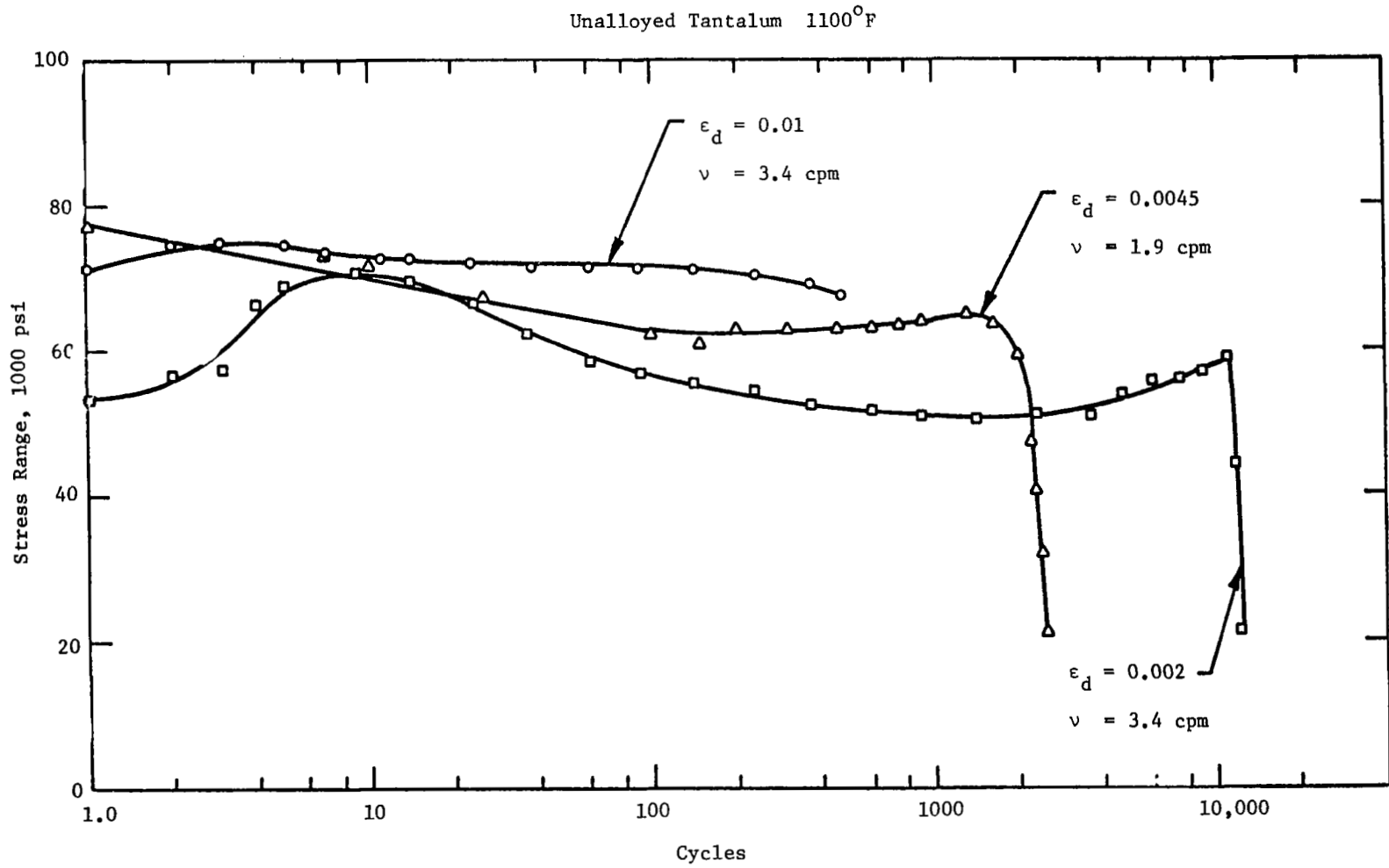


Figure 10. Stress Range Versus Cycles for Tantalum at 1100°F.

Unalloyed Tantalum 1350°F

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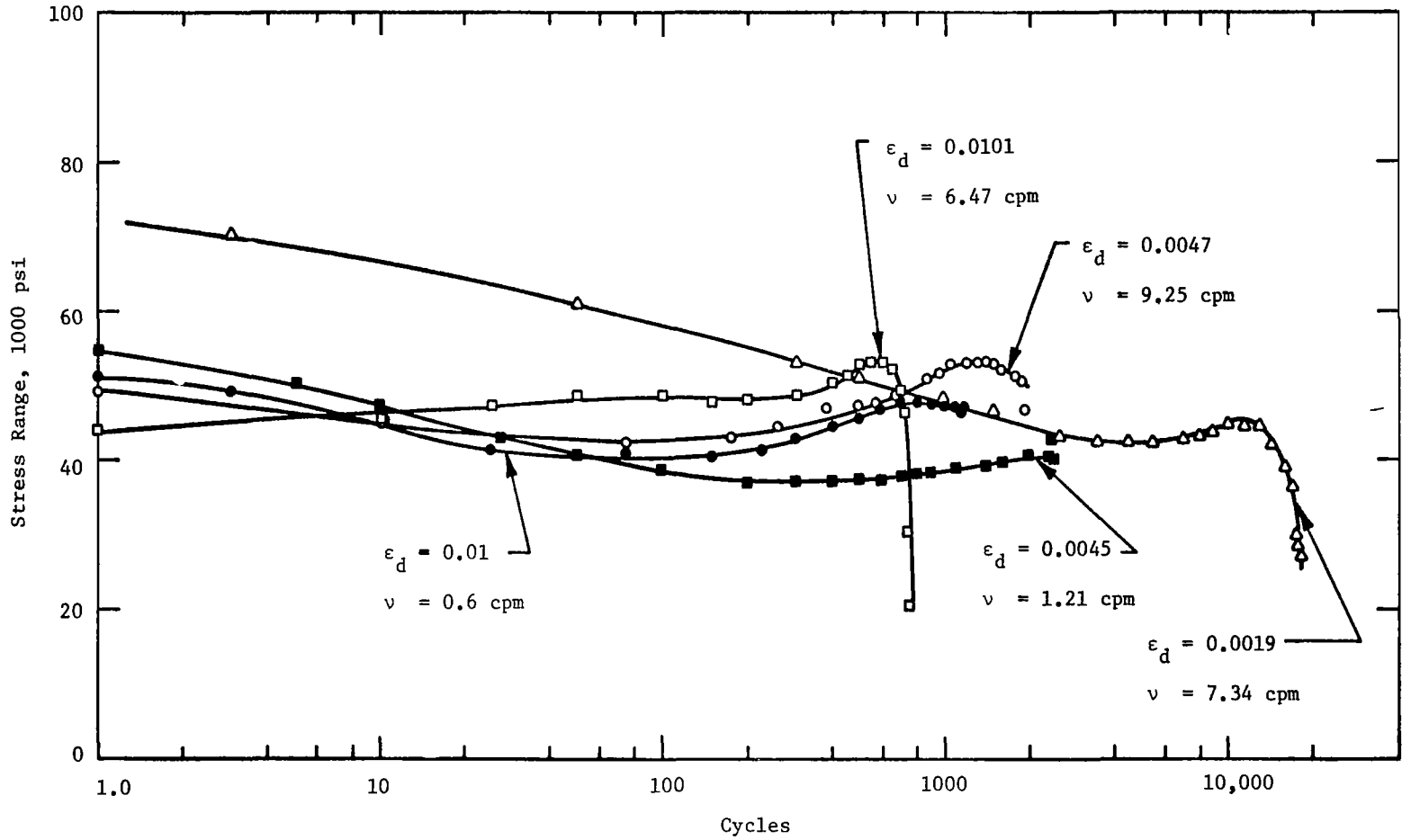


Figure 11. Stress Range Versus Cycles for Tantalum at 1350°F.

TABLE IV

CONSTANTS FOR TOTAL STRAIN-LIFE RELATIONSHIPS FOR UNALLOYED TANTALUM

<u>Temp., (°F)</u>	<u>C₂</u>	<u>β</u>	<u>k</u>	<u>A</u>	<u>n</u>	<u>k₁</u>	<u>ε_f</u>	<u>E</u>	<u>Applicable Equation</u>
600	2.13	0.5	1.0	22,400	0	0	4.27	26 X 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)

Unalloyed Tantalum 600°F

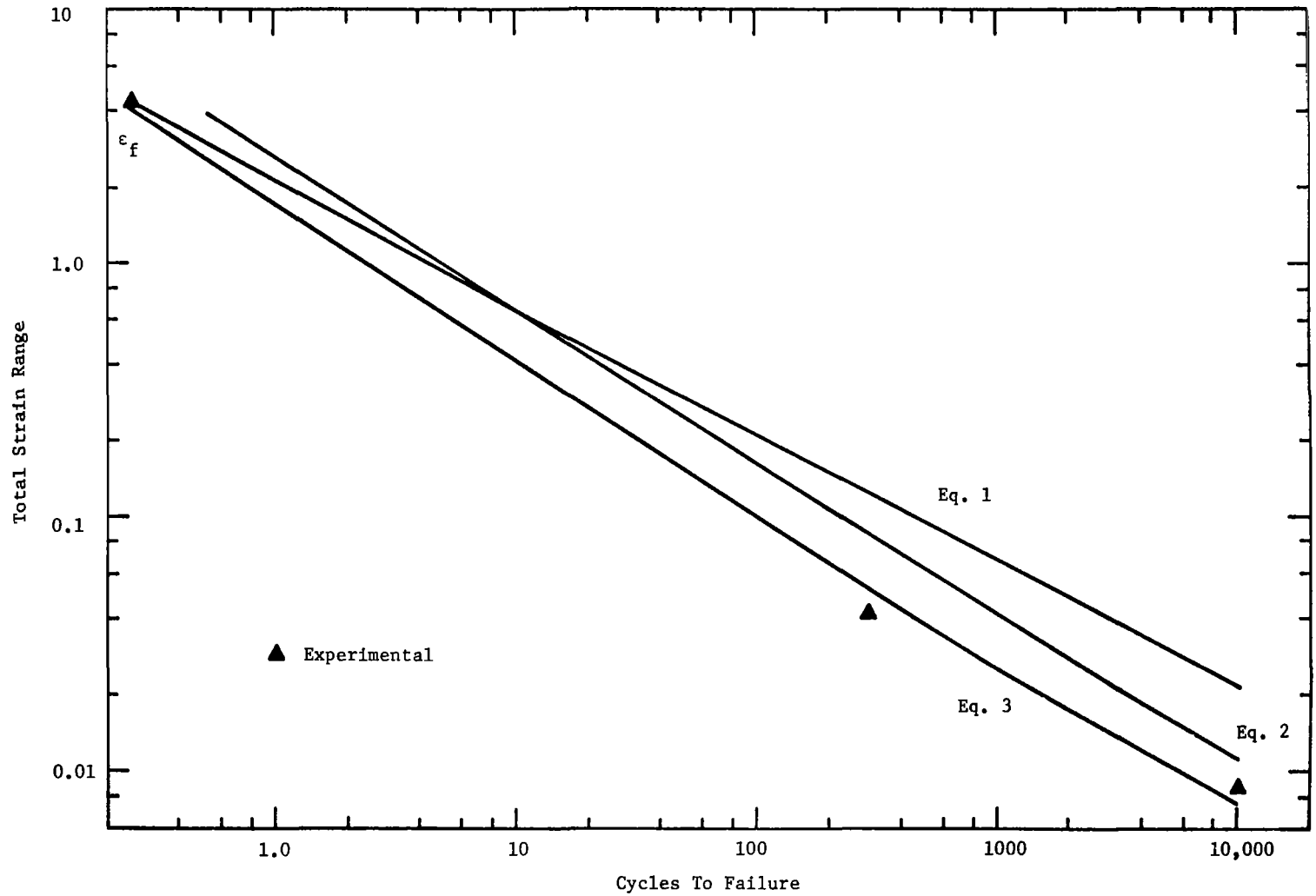


Figure 12. Total Strain Range Versus Fatigue Life of Tantalum at 600°F.

Unalloyed Tantalum 1100°F

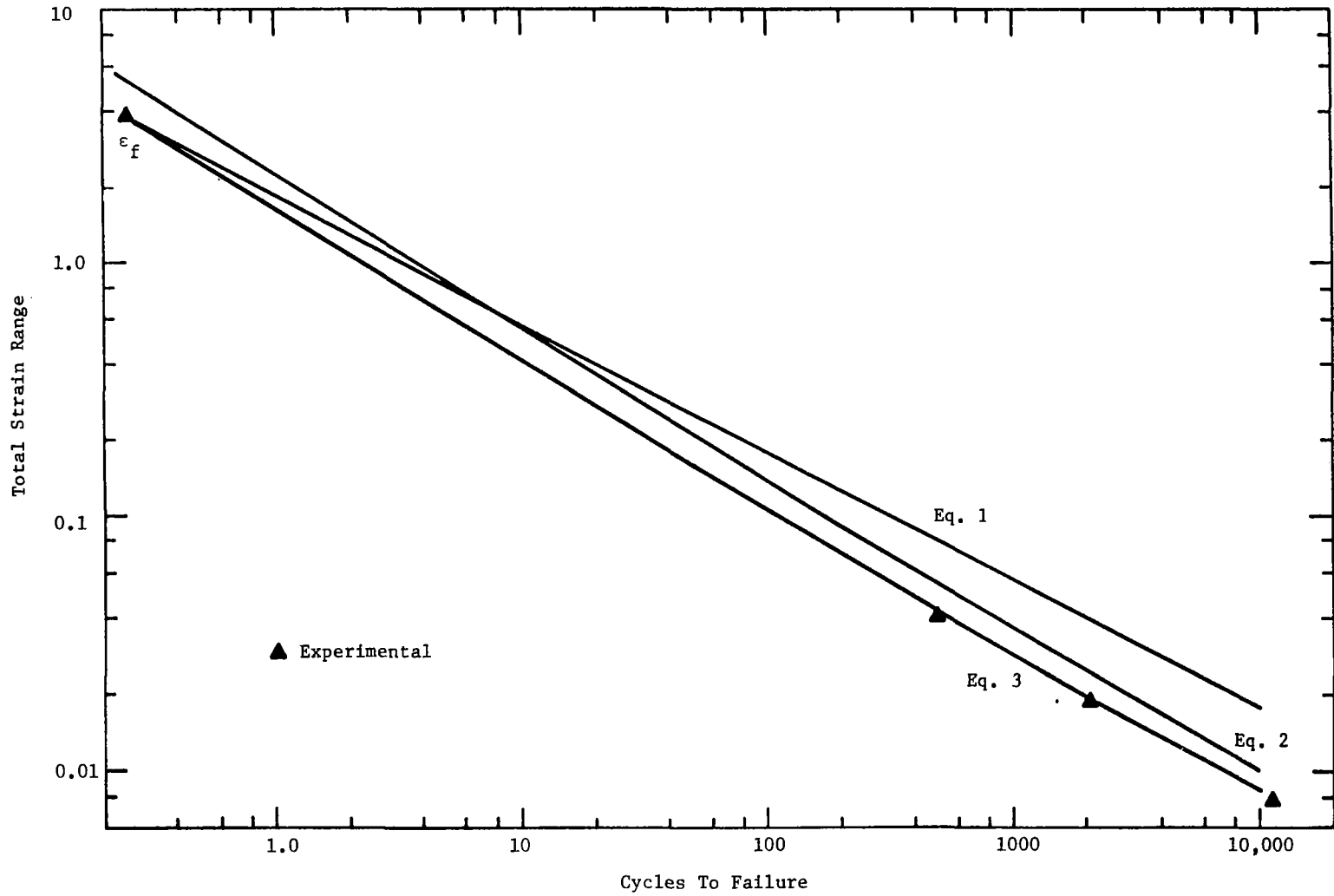


Figure 13. Total Strain Range Versus Fatigue Life of Tantalum at 1100°F.

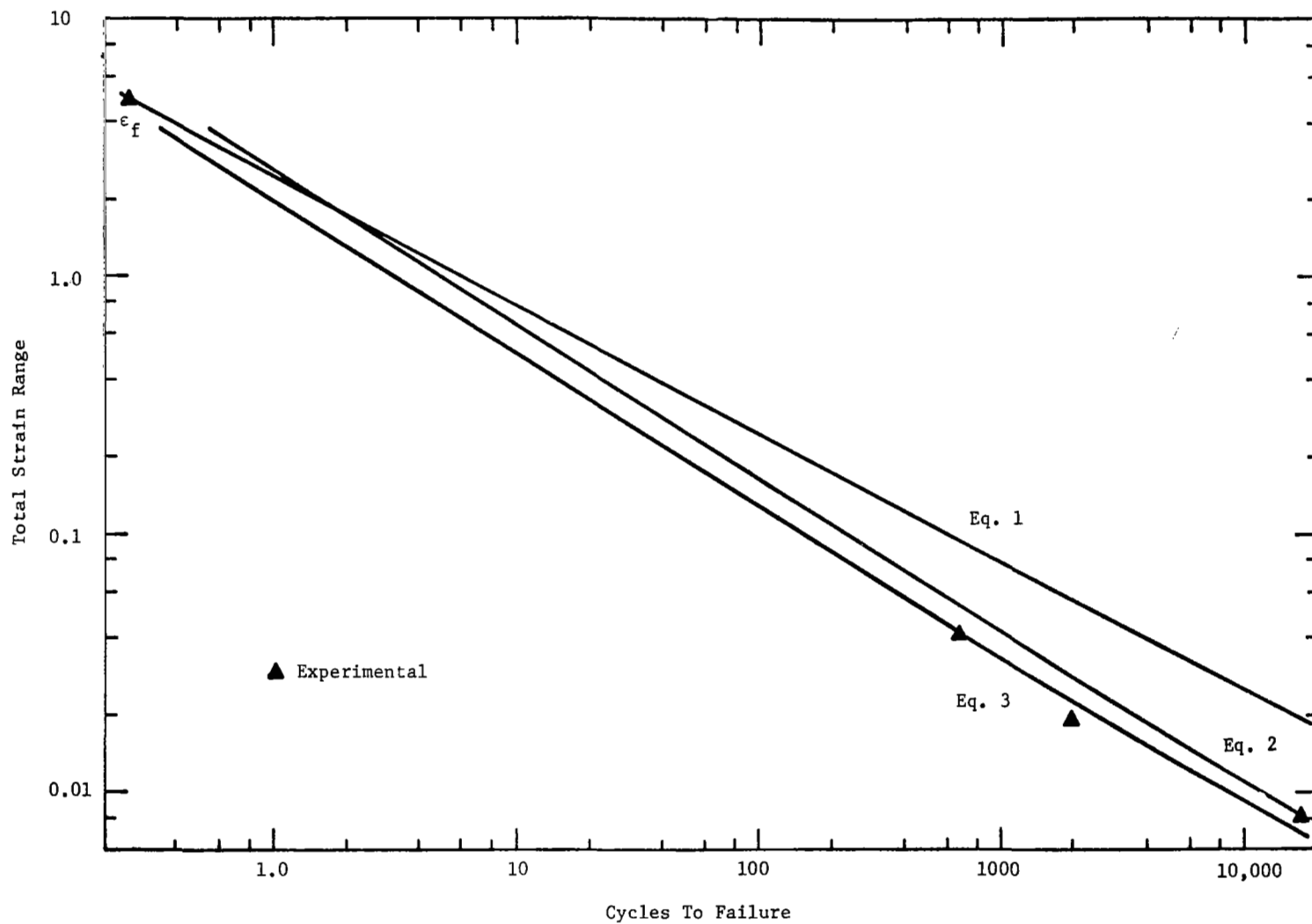


Figure 14. Total Strain Range Versus Fatigue Life of Tantalum at 1350°F for Equations (1) Through (3).

Unalloyed Tantalum 1350°F

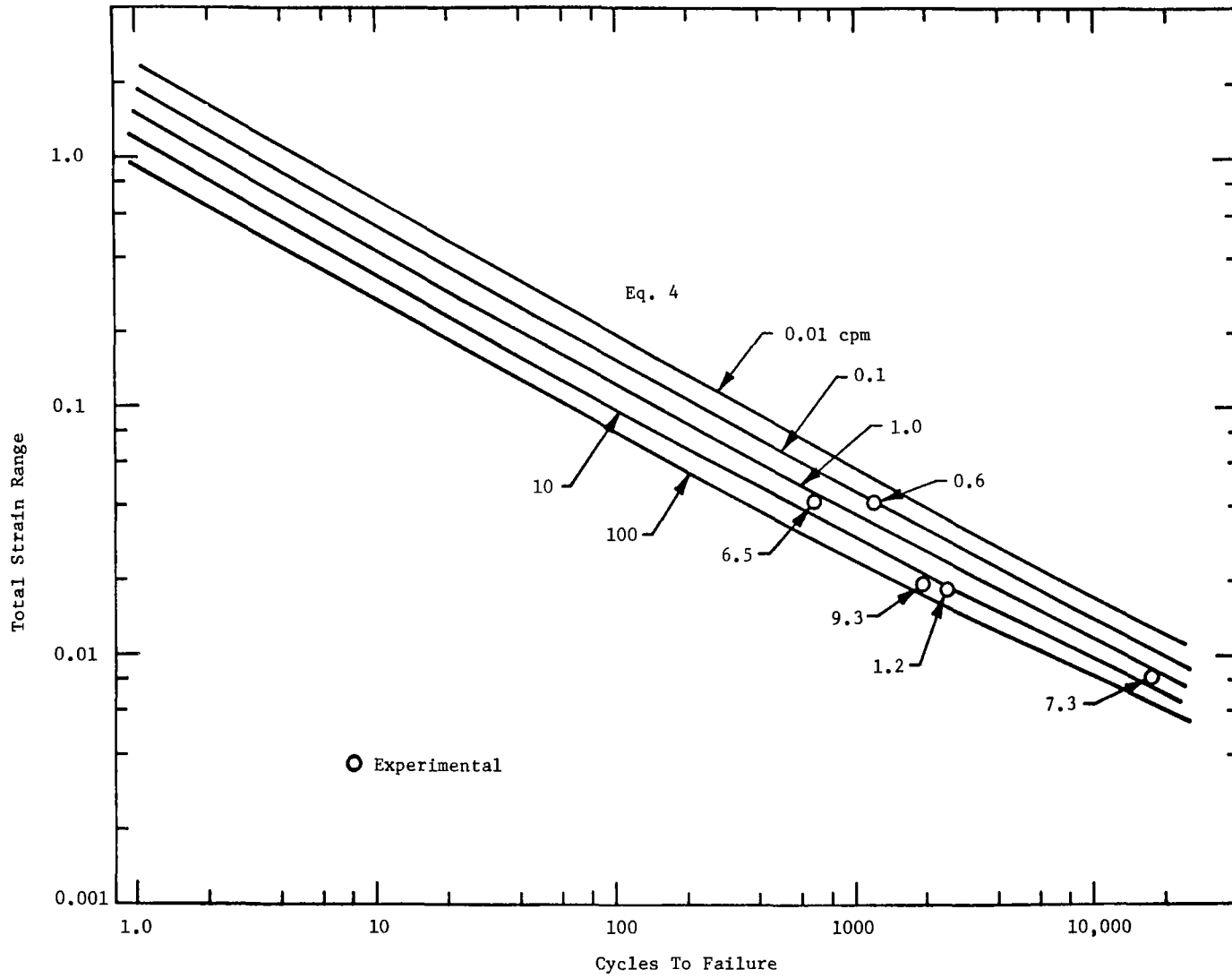


Figure 15. Total Strain Range Versus Fatigue Life of Tantalum at 1350°F for Equation 4.

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

$$\sigma_a = \frac{E \Delta \epsilon}{2} t \quad (6)$$

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

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

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.

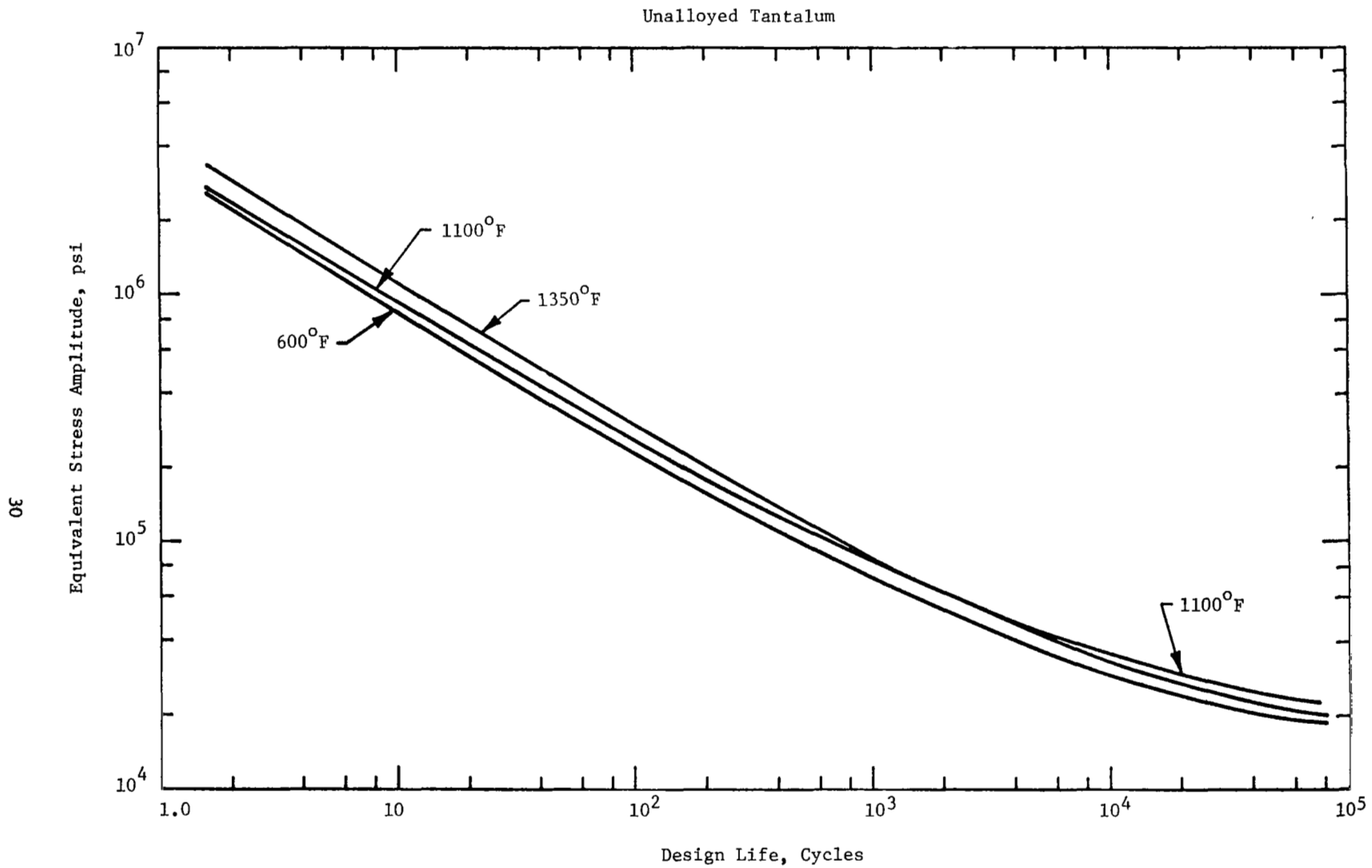


Figure 16. Equivalent Stress Amplitude Versus Design Life of Tantalum.

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

<u>Material</u>	<u>Temp.</u>	<u>Plastic Strain Range</u>
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

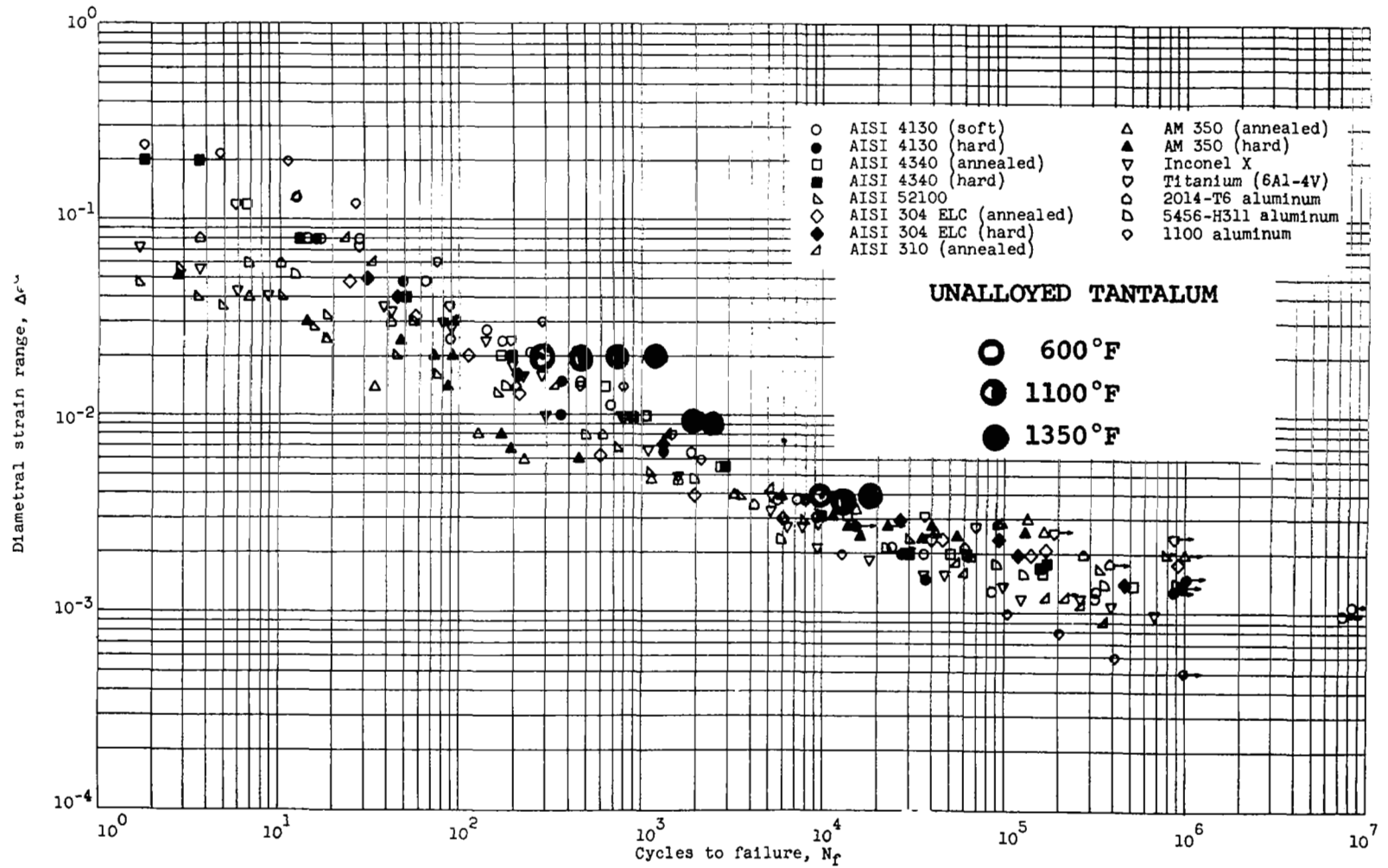


Figure 17. Summary of Diametral Strain Range vs Cycle to Failure for Several Materials.

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

*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.

REFERENCES

1. J.F. Tavernelli and L.F. Coffin, Jr., "Strain Cycling and Fatigue of Ductile Metals", Trans. AIME, 215, 794 (1959).
2. L.F. Coffin, Jr., "An Investigation of the Cyclic Strain and Fatigue Behavior of a Low Carbon Manganese Steel", Thermal and High Strain Fatigue, The Metals and Metallurgy Trust, London, 1967.
3. H.S. Spacil, "The Solid-Electrolyte Oxygen Sensor - I. Principles and Application", General Electric Research and Development Center Report 67-C-449, December 1967.
4. D.C. Lord and L.F. Coffin, Jr., "Manual for Low Cycle Fatigue Testing", General Electric Research and Development Center Report 68-C-373, October 1968.
5. L.F. Coffin, Jr., "The Effect of Quench Aging and Cyclic-Strain Aging on Low Carbon Steel", J. Basic Eng. Trans. ASME, 87D, 351 (1965).
6. J.W. Pugh, "Temperature Dependence of the Tensile Properties of Tantalum", Trans. ASM, 48, 677 (1956).
7. J. Glen, "Effect of Alloying Elements on the High Temperature Tensile Strength of Normalized Low-Carbon Steel", J. Iron and Steel Inst., 186, 21 (1957).
8. L.F. Coffin, Jr., "Cyclic Strain and Fatigue Behavior of Metals in the Creep Range", Proceedings First International Conference on Fracture, The Japanese Society for Strength and Fracture of Materials, Sendai, 1965.
9. L.F. Coffin, Jr., "Stability of Metals under Cyclic Plastic Strain", Trans. ASME, Journ. Basic Engineering, D82, 671, (1960).
10. J.F. Tavernelli and L.F. Coffin, Jr., "Experimental Support for a Generalized Equation Predicting Low Cycle Fatigue", J. Basic Eng. Trans. ASME, 84D, 533 (1962).
11. S.S. Manson, "Thermal Stress and Low Cycle Fatigue", McGraw-Hill, New York, 1966.
12. L.F. Coffin, Jr., "A Generalized Equation for Predicting High-Temperature, Low-Cycle Fatigue Including Hold Times", General Electric TIS Report 69-C-401, December 1969.
13. R.W. Smith, M.H. Hirschberg and S.S. Manson, "Fatigue Behavior of Materials under Strain Cycling in Low and Intermediate Life Range", NASA TN D-1574, April 1963.

14. L.F. Coffin, Jr., "The Effect of Vacuum on the High Temperature, Low-Cycle Fatigue Behavior of Structural Metals", International Conference on Corrosion Fatigue, University of Connecticut, June 1971.

APPENDIX A

TEST RESULTS

TEST NO 4A

TANTALUM AT 600 FAHR
 KI 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	29930	710	0.007156	0.008309
1	15020	17340	32360	-1160	0.007101	0.008346
2	17150	16080	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	35860	-330	0.00702	0.0084
9	17520	18270	35790	-370	0.007022	0.008399
11	17570	18220	35790	-350	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	18060	35510	-330	0.007029	0.008394
36	17380	18080	35460	-350	0.00703	0.008394
46	17430	18060	35510	-350	0.007029	0.008394
60	17430	18080	35510	-330	0.007029	0.008394
75	17430	18080	35510	-330	0.007029	0.008394
90	17430	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	36960	-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	0.008603
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	26660	53290	-10	0.006613	0.008662
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

CYC NO	TEN STRESS	COMP STRESS	STRESS RANGE	MEAN STRESS	PLASTIC STRAIN RANGE	TOTAL STRAIN RANGE
0	15710	23350	39060	-3820	0.038931	0.040433
1	25770	27280	53040	-760	0.038603	0.040648
2	28070	26130	56250	-60	0.038534	0.040697
3	28600	28690	57490	60	0.038505	0.040716
4	29120	28390	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	68560	170	0.038249	0.040887
90	34330	34730	69610	60	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	0.038269	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

CYC NO	TEN STRESS	COMP STRESS	STRESS RANGE	MEAN STRESS	PLASTIC	TOTAL
					STRAIN RANGE	STRAIN 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	36220	38350	74640	-1030	0.038115	0.040932
4	36200	38200	74400	-1000	0.038123	0.040935
5	36120	38040	74160	-960	0.038129	0.040931
6	35870	37880	73750	-1000	0.038133	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
13	35210	37170	72380	-980	0.03817	0.040954
23	34300	37170	71970	-1180	0.038179	0.040947
29	34720	37170	71830	-1220	0.038131	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	33980	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
467	26140	41600	67750	-7730	0.038277	0.040882

CYCLE NO AT MAX TEN 3

CYC NO AT .5 MAX TEN 487

TIME/CYCLE 0.351 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

CYC NO	TEN STRESS	COMP STRESS	STRESS RANGE	MEAN STRESS	PLASTIC STRAIN RANGE	TOTAL STRAIN 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	34980	69640	-160	0.005853	0.008531
18	34240	34070	68320	90	0.005833	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	27300	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	26430	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	50820	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	53950	-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	25030	44110	-3020	0.006442	0.008139
12230	10640	10720	21360	-40	0.006967	0.007759

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 2B

TANTALUM AT 1350 FAHR
 KI 0.0J4663
 X'HD RATE 0.1 IN/MIN
 ØRIG DIA 0.1233 IN
 ELASTIC MØDJULUS 26000000
 PØISSØN RATIO 0.3

CYC NO	TEN STRESS	CØMP STRESS	STRESS RANGE	MEAN STRESS	PLASTIC STRAIN RANGE	TØTAL STRAIN RANGE
0	22320	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	23930	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	22320	24390	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	23040	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 STØPPED AND CØOLED DØWN.
 NEW CØIL AND NEW SUSCEPTØR DESIGN. SPECIMEN
 REPØLISHED TO REMOVE GAGE MARKS. NEW DIA. .1259 IN.
 TEST RESUMED AT 281 CYCLES

TEST NO 36

TANTALUM AT 1350 FAHR
 K1 0.010135
 X'HD RATE 0.1 IN/MIN
 ØRIG DIA 0.1248 IN
 ELASTIC MØDULUS 26000000
 POISSØN RATIO 0.3

CYC NØ	TEN STRESS	COMP STRESS	STRESS RANGE	MEAN STRESS	PLASTIC STRAIN RANGE	TOTAL STRAIN 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	18130	30530	-2920	0.039335	0.04101
755	7760	12900	20660	-2570	0.040063	0.040858

CYCLE NØ 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 5B

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 NO 68

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

CYC NO	TEN STRESS	CØMP STRESS	STRESS RANGE	MEAN STRESS	PLASTIC STRAIN RANGE	TØTAL STRAIN 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	0.038903	0.040728
1150	22740	23730	46470	-500	0.038923	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 NØ 7B

TANTALUM AT 1350 FAHR
 K1 0.004477
 X'HD RATE 0.01 IN/MIN
 ØRIG DIA 0.1262 IN
 ELASTIC MØDULUS 26000000
 PØISSØN RATIO 0.3

CYC NØ	TEN STRESS	CØMP STRESS	STRESS RANGE	MEAN STRESS	PLASTIC STRAIN RANGE	TØTAL STRAIN 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	21030	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 NØ 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 NO 8 0

TANTALUM AT 1100 FAHR
 K1 0.004479
 X*HD RATE 0.02 IN/MIN
 ORIG DIA 0.1239 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	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	0.018948
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	0.018893
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	0.016314	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 NO 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 STOPPED AT 198 CYCLES AND 0 LOAD DUE TO WIDE
 TEMPERATURE FLUCTUATION AND ARCING. COIL 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)

UNALLOYED TANTALUM-600F

Equation (1)

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	836835	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	38390.	0.00213	2.99154 E-3

UNALLOYED TANTALUM-600F

Equation (2)

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

UNALLOYED TANTALUM-600F

Equation (3)

F	L	S	E2	E
K= 1	K1= 0	N= 0.169	C= 1.636	
A= 117400	M= 26000000	B= 0.615		
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

UNALLOYED TANTALUM-1100F

Equation (1)

F	L	S	E2	E
K= 1	K1= 0	N= 0	C= 1.82	
A= 20800	M= 26000000	B= 0.5		
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	0.132	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

UNALLOYED TANTALUM-1100F

Equation (2)

F	L	S	E2	E
K= 1	K1= 0	N= 0.2	C= 2.175	
A= 90790	M= 26000000	B= 0.6		
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

UNALLOYED TANTALUM-1100F

Equation (3)

F	L	S	E2	E
K=1.0	K1= 0	N= 0.155	C= 1.572	
A= 118400	M= 26000000	B= 0.594		
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

UNALLOYED TANTALUM-1350F

Equation (1)

F	L	S	E2	E
K= 0	K1= 0	N= 0	C= 2.48	
A= 10080	M= 26000000	B= 0.5		
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

UNALLOYED TANTALUM-1350F

Equation (2)

F	L	S	E2	E
K= 0	K1= 0	N= 0.2	C= 2.6139	
A= 51696.8	M= 26000000	B= 0.6		
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

UNALLOYED TANTALUM-1350F

Equation (3)

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	6.65393 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

UNALLOYED TANTALUM-1350F
A286-1100F

Equation (4)

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	2.94977 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	0.24852	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

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	2.67231	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

UNALLOYED TANTALUM-1350F-Equation (3)

F	L	S	E2	E
K= 1	K1= 0	N= 0.142	C= 2.049	
A= 87300	M= 26000000	B= 0.605		
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