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DETERMINATION OF ELEVATED-TEMPERATURE FATIGUE DATA ON REFRACTORY ALLOYS IN ULTRA-HIGH VACUUM

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FOREWORD

The work described herein is being performed by TRW Inc. under the sponsorship of the National Aeronautics and Space Administration under Contract NAS 3-6010. The purpose of this study is to obtain fatigue life data on refractory metal alloys for use in designing space power systems.

The program is administered for TRW Inc. by E. A. Steigerwald, Program Manager. C. R. Honeycutt and J. C. Sawyer are the Principal Investigators.

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I. INTRODUCTION

The purpose of this investigation is to generate fatigue data for refractory alloys at elevated temperatures in ultra-high vacuum environments. The ultimate objective is to determine whether fatigue life or creep is the limiting design parameter in turbine applications involving space electric-power systems.

During this report period, the cathetometer for measuring specimen displacement was received and strain measurements on vibrated specimens were obtained. Tests conducted on 1/4 inch diameter (6.35×10^{-3}m) smooth specimens of TZM stressed to 25,600 psi (1.76×10^{8}N/m^2) did not produce failures either at ambient temperatures of 72°F (22°C) or 1000°F (538°C) after approximately 2×10^7 cycles.* The introduction of a notch having a theoretical stress concentration factor of 3, however, resulted in extremely rapid failure of TZM at an ambient temperature of 1840°F (1003°C) in tension-compression loading where the maximum stress on the unnotched cross-sectional area was calculated as 16,800 psi (1.16×10^{8}N/m^2).

II. VACUUM SYSTEM INSTALLATION

The fourth and final vacuum chamber has been received and installed in the laboratory. Initial tests have indicated that a slight leak exists in one feed through; however, the repairs can be performed without returning the unit to the vendor. The bake-out oven has also been received and adapted for use on the vacuum systems.

III. DISPLACEMENT MEASUREMENTS

A formidable problem in determining the elevated temperature fatigue properties using ultrasonic methods is the measurement of the dynamic stress applied to the specimen. Although a capacitive pick-up is employed outside the furnace section to quantitatively monitor deflection of the loading train and control resonance, the actual stress in the specimen is determined from displacement measurements made on the gauge section with a cathetometer. This technique eliminates errors that may be introduced by calculating stress for a specimen located in the hot zone from measurements of displacement made by a pick-up located outside the furnace.

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* Unless otherwise noted the temperatures reported represent the ambient temperatures at which the tests were conducted. When pertinent to the test results the increase in temperature produced in the specimen by the introduction of the ultrasonic energy will also be presented.

The optical cathetometer (see Figure 1) consists of a 100X filar eyepiece microscope mounted on a slide micrometer having a travel of 3 inches (7.61×10^{-2} m). The components include an illuminator and a cathetometer supporting stand mounted on a portable cabinet. The design of the microscope is such that the working distance is 14-1/2 inches (3.68×10^{-1}m) which allows the specimen to be viewed from outside of the vacuum chamber while still maintaining a relatively high magnification.

The method of converting specimen deflection into strain measurements has been described in detail by Neppiras(1)*. The deflection in the specimen gauge section is assumed to follow the relationship:

$$\delta = \delta_o \sin \frac{2\pi X}{\lambda} \qquad (1)$$

where: δ is the deflection along any point on the gauge section,

δ_o is a constant (the maximum deflection in a $\lambda/4$ resonator),

λ is the wave length of the vibrating wave, and

X is the distance from the center of the specimen.

By definition, the strain (ϵ) is equal to $\partial\delta / \partial X$, therefore:

$$\epsilon = \frac{\partial \delta}{\partial X} = \delta_o \frac{2\pi}{\lambda} \cos \frac{2\pi X}{\lambda} \qquad (2)$$

and ϵ max occurs at the center of the specimen (X = 0).

$$\epsilon_{max} = \delta_o \frac{2\pi}{\lambda} \qquad (3)$$

From measurements of the deflection (δ) at a known distance (X) from the specimen midpoint, the constant (δ_o) can be determined from Equation 1. With this constant, the maximum strain can be determined from Equation 3 and the stress can be calculated by multiplying the strain by the modulus of elasticity.

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* Numbers in parentheses pertain to references in the Bibliography.

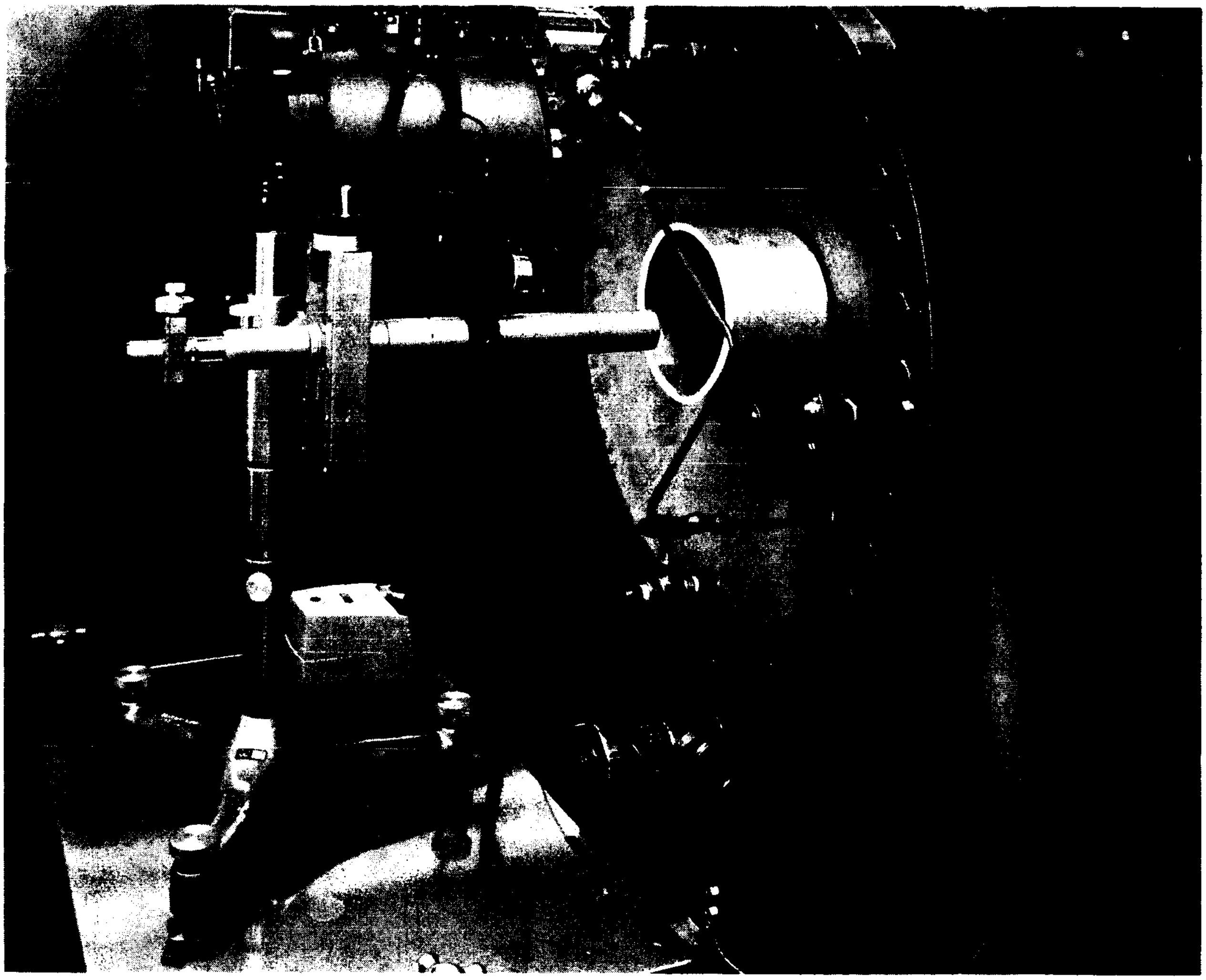


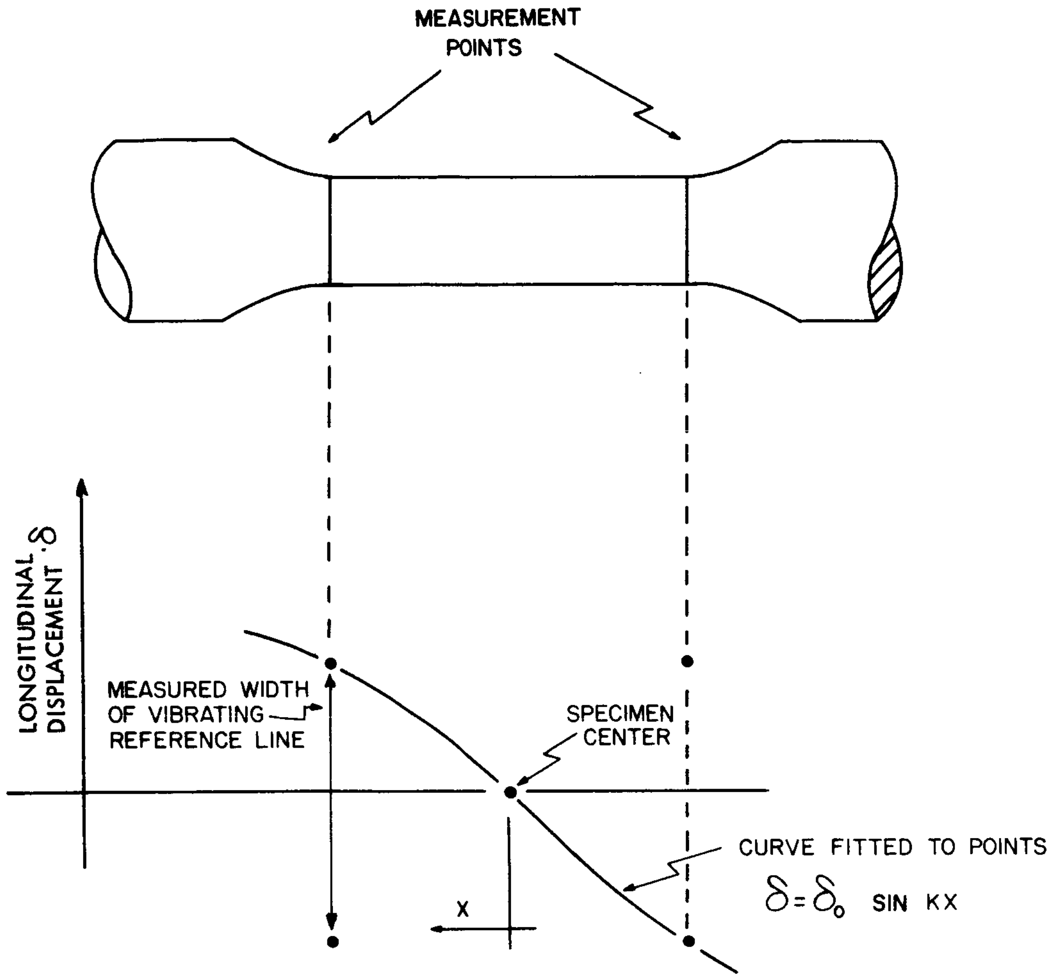
FIGURE 1. CATHETOMETER IN POSITION TO OBSERVE SPECIMEN

The actual experimental technique is schematically shown in Figure 2. The cathetometer is used to measure the width of characteristic marks on the specimen at a known distance from each of the specimen shoulders. The difference between the width of the marks before and during vibration represents the sum of the positive and negative deflection produced by the vibratory wave (2δ). A comparison of the deflection values at points equidistant from the specimen midpoint provides a measure of whether the maximum strain point is truly located in the center of the specimen gauge section.

Measurements were taken at an ambient temperature of 72°F (22°C) at various points along the gauge section of a TZM specimen. In addition, deflection values were also obtained at points on the specimen shoulders and ends to determine whether the theoretical stress amplification produced by the specimen design was actually obtained. The results of the measurements are presented in Figure 3. Considering initially the gauge section, the measurements were taken at the points designated (a) and (a'), which are located 0.350 inches from the specimen midpoint. An average value of 375μ-inches deflection (2δ) was obtained at these points, and this value of deflection was used to calculate the solid deflection curve shown in Figure 3. The measured values of deflection in the gauge section were somewhat below the predicted values. The calculated deflection at the specimen ends and at the shoulder are also compared with the measured deflection. The displacement measured at the shoulders compared reasonably well with predictions based on the calculations.

The strain values calculated from Equation 2 are also shown as the dotted line curve in Figure 3. A marked strain concentration occurs at the shoulder due to the reduced cross-section. The strain along the gauge length is reasonably uniform varying from 5.39×10^{-4} at the midpoint to 5.14×10^{-4} at the radius. Using the measured modulus of 47.6×10^6 psi (3.28×10^{11} N/m^2), the stress at the midpoint of the TZM specimen tested was 25,600 psi (1.76×10^8 N/m^2) with 200 volts applied to the crystal.

The deflection present in each component of the vibrating train was measured with the cathetometer and compared to the predicted deflection to determine if any areas existed where excessive energy losses were experienced. The results obtained in these series of tests, conducted at room temperature, are shown in Figure 4. The largest degree of energy loss apparently occurred in the mounting flange where the observed 1.13 amplification of deflection was considerably below the theoretical amplification of 4. The lack of strain amplification in this component can be attributed to the fact that the mounting flange weld, although located at the deflection node, occupies a finite area which unavoidably causes a loss in amplification.



STRAIN (ϵ) DETERMINED BY DIFFERENTIATING EQUATION OBTAINED FOR DISPLACEMENT CURVE

$$\epsilon = \frac{\partial \delta}{\partial x} = -K\,\delta_0 \cos KX$$

AT SPECIMEN CENTER $\epsilon = -K\delta_0$

FIGURE 2. SCHEMATIC ILLUSTRATION OF METHOD FOR DETERMINING SPECIMEN STRAIN IN HIGH FREQUENCY TESTS

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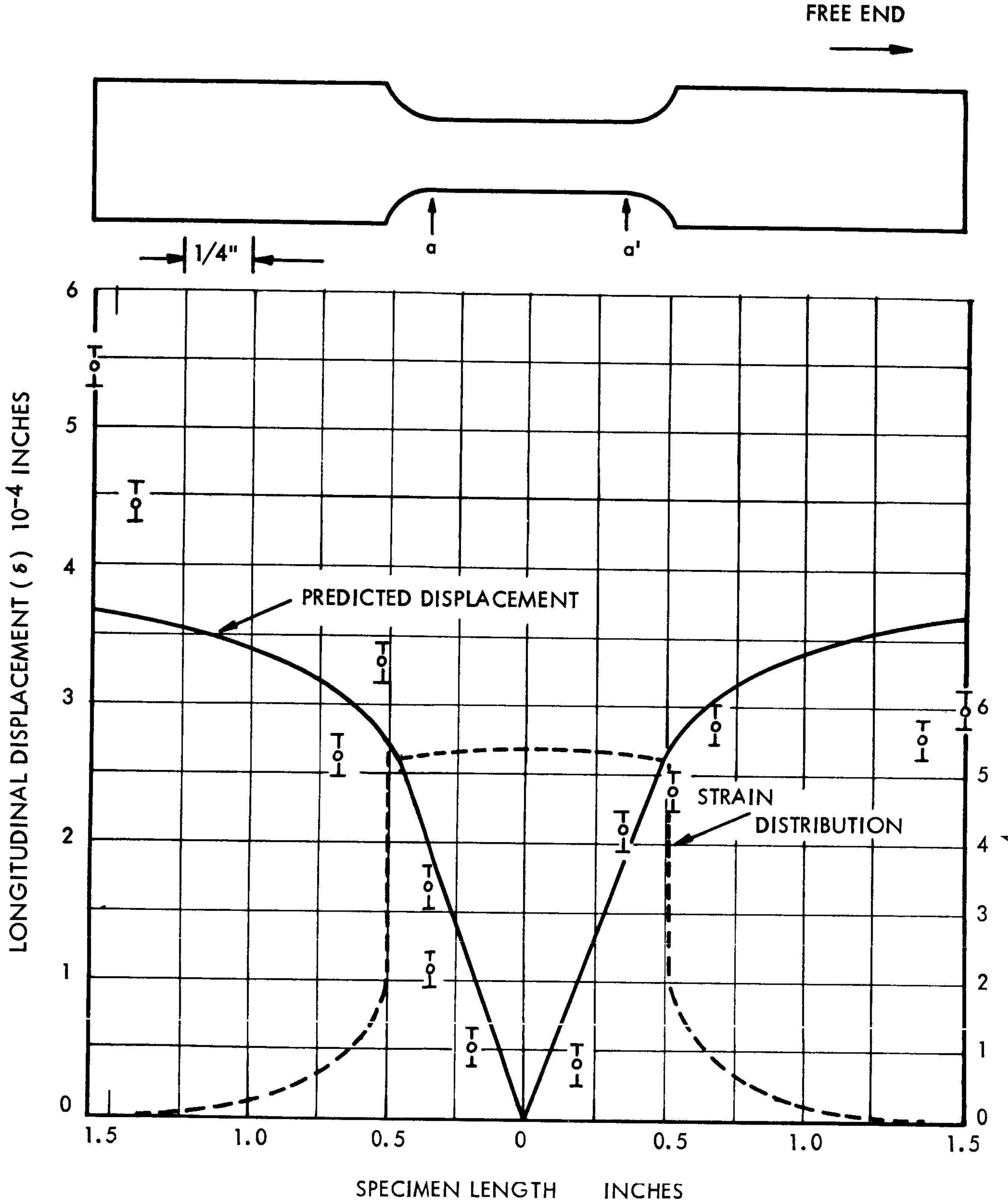

FIGURE 3. COMPARISON OF OBSERVED AND CALCULATED DISPLACEMENT IN TZM SPECIMEN TESTED AT 20 KHZ, 180 VOLTS

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Amplification		Displacement	
Actual	Predicted	2δ (μ- inches)	Position
			A
		168	B
	--	129	C
1.13	4	146	D
7.25	16	940	E

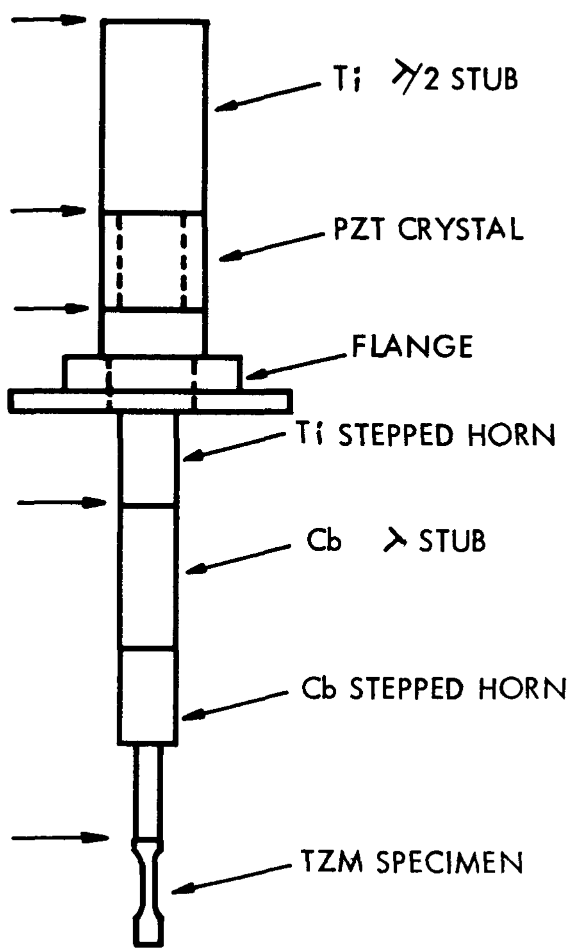

FIGURE 4. COMPARISON BETWEEN PREDICTED AND OBSERVED DISPLACEMENTS IN VIBRATION TRAIN, 180 VOLTS APPLIED TO CRYSTAL, 20 KHZ FREQUENCY, ROOM TEMPERATURE MEASUREMENTS

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The apparent loss through the flange, however, may not be real but merely a reflection in the uncertainity in measuring low values of deflection directly by optical means. For example, the measured amplification from points D to E is 6.3 which is not possible, since the value can never exceed 4.0. This discrepancy can be rationalized on the basis that actual uncertainties of ±50μ-inches are present in the displacement measurements so that the measured values at C or D, where small displacements are involved, can be considerably in error. The capactive pick-up will be used to obtain more accurate values of displacement at points A, B, and D to determine the effectiveness of the flange mounting. Additional flange mounting designs will also be evaluated in an effort to improve the efficiency of energy transfer through the flange.

IV. TEST RESULTS

Although the test materials - TZC and Cb132M - have not been recieved from the vendors, preliminary tests on both smooth and notch specimens were conducted in an effort to evaluate the test techniques and determine whether sufficient power is available to fracture 1/4 inch (6.35×10^{-3}m) diameter specimens. The initial tests were performed at room temperature on TZM specimens to determine the variation in strain produced by a given increase in applied voltage. The results shown in Figure 5 indicate that the maximum strain developed in the specimen was directly proportional to the applied voltage over the range evaluated. In the case where an actual flange was mounted to the vacuum seal there was some indication that the strain developed in the specimen was below the value predicted by the linear relationship shown in Figure 5. Considerable internal heating of the specimen also occurred at the higher voltages, and this factor may have contributed to the observed deviation.

The results of tests conducted on the 1/4 inch (6.35×10^{-3}m) diameter TZM specimens are summarized in Table 1. These tests were conducted before the cathetometer was received from the vendor, so that no direct measurement of strain in the specimen was obtained. A maximum drive of 200 to 250 volts was employed to determine whether specimen failure would occur and to identify possible problems in the load train. In cases where static loads were required the columbium horns had to be replaced by TZM to eliminate excessive creep during the test. No failures were experienced in the 1/4 inch (6.35×10^{-3}m) diameter specimen at any of the test conditions. The specimen is currently being redesigned to a 1/8 inch (3.17×10^{-3}m) diameter in an effort to increase the applied stress level.

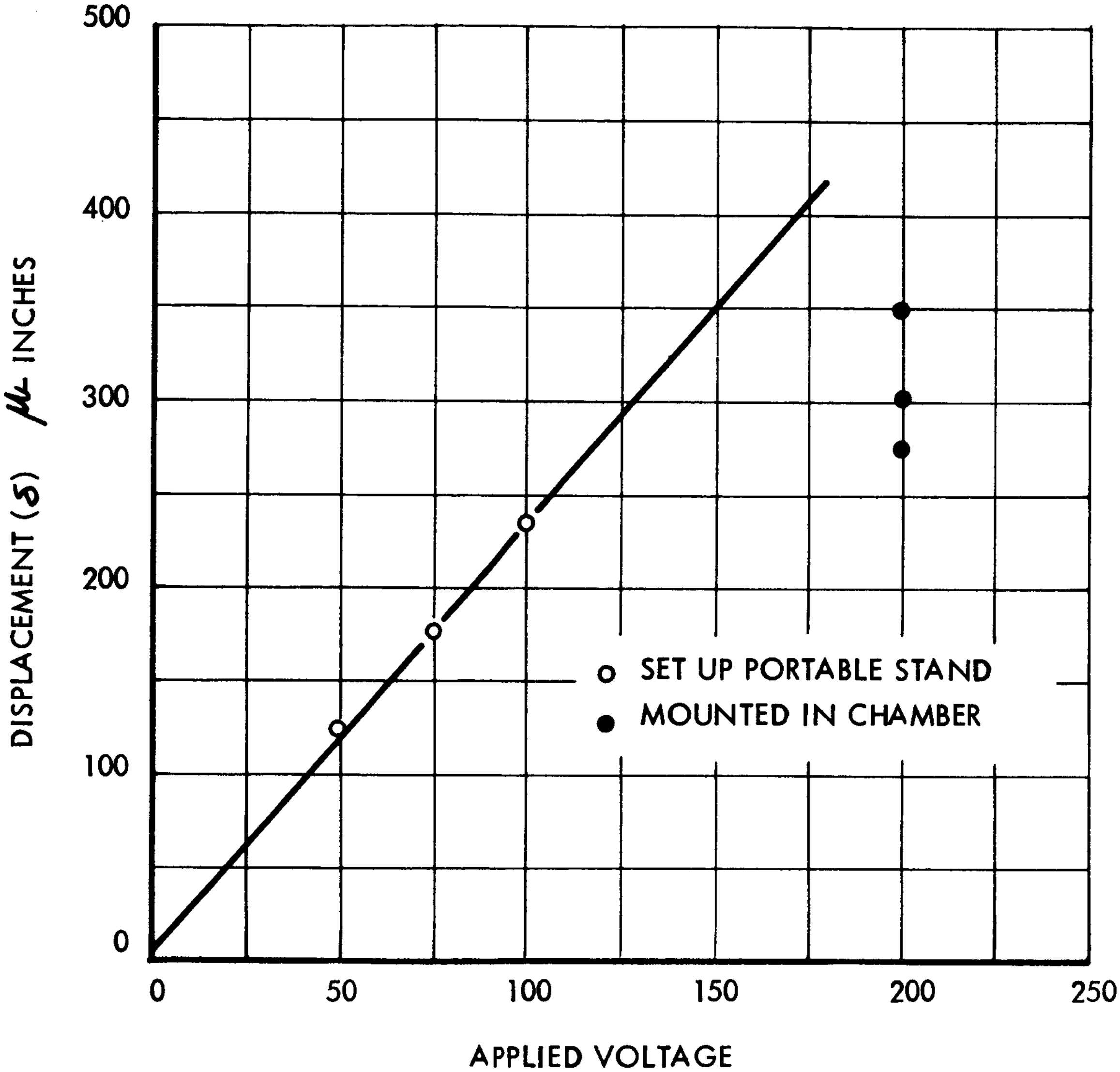

FIGURE 5. RELATIONSHIP BETWEEN VOLTAGE APPLIED TO THE CRYSTAL AND THE DISPLACEMENT AS MEASURED WITH A CATHETOMETER

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TABLE I

Vacuum Fatigue Tests On Smooth Specimens

Maximum Applied Voltage, Specimen Diameter 1/4 Inch (6.34×10^{-3} m)

Material	Description	Cause of Failure
TZM	Heated in vacuum to an ambient temperature of 1640°F (893°C); driven at 19.7 kHz;(Kcps) static load of 16,000 psi (1.10×10^8 N/m^2.)	Threaded coupling between bottom Cb horn and $\lambda/2$ stub failed during heatup; joint subsequently eliminated.
TZM	Heated in vacuum to an ambient temperature of 1520°F (827°C); driven at 19.3 kHz(Kcps); static load of 16,000 psi (1.10×10^8 N/m^2.)	Bottom Cb horn showed creep at the base of threaded coupling during heatup.
TZM	Ambient Temperature, 72°F (22°C) in vacuum at static loads of 16,000 psi (1.10×10^8 N/m^2); 23,600 psi (1.63×10^8 N/m^2); 30,100 psi (2.07×10^8 N/m^2); 38,900 psi (2.68×10^8 N/m^2); 44,500 psi (3.07×10^8 N/m^2); driven for 3 hours at each load at 19.7 kHz(Kcps); total number of cycles = 1.06×10^9	No fatigue failures.
TZM	Heated in vacuum to ambient temperatures of 500°F (260°C), 850°F (454°C), and 1000°F(538°C); static load 44,500 psi (3.07×10^8 N/m^2); driven 19.6 kHz (Kcps) for 3 hours at each temperature, total number of cycles = 2.12×10^8.	No fatigue failures.

Notch fatigue tests were also conducted on a TZM specimen at an ambient temperature of 1840°F (1003°C). The specimen geometry is shown in Figure 6. This geometry was selected to produce a theoretical stress concentration factor of three ($K_T = 3$).[2] Fatigue tests have indicated that the effective stress concentration factor (K_f) is usually less than theoretical value and the relationship can be expressed as follows (3):

K_f = effective stress concentration factor

$$K_f = \frac{\text{stress to failure of unnotched part}}{\text{nominal stress to failure of notched part}}$$

$$K_f = \frac{K_T}{1 + 2\sqrt{A/r}\left(\frac{K_T - 1}{K_T}\right)}$$

where: r is the notch radius,

A is an experimentally determined constant, and

K_T stress concentration factor.

Since no data for TZM are available which would allow the determination of the constant A, the value of 0.002 was arbitrarily selected. This figure is representative of the A value for high-strength steels which have a relative notch sensitivity in static tests that appears to be comparable to TZM. The effective stress concentration factor (K_f) was then calculated as 1.75. The total stress magnification produced by the notch was considered as the product of K_f and the ultrasonic stress amplification produced by the decreased area at the notch[4]:

$$\text{Stress amplification} = K_F\left[\frac{D}{d}\right]^2 = 1.75\ (4) = 7.0$$

where D and d are defined as the major and minor diameters of the notch specimen (see Figure 6).

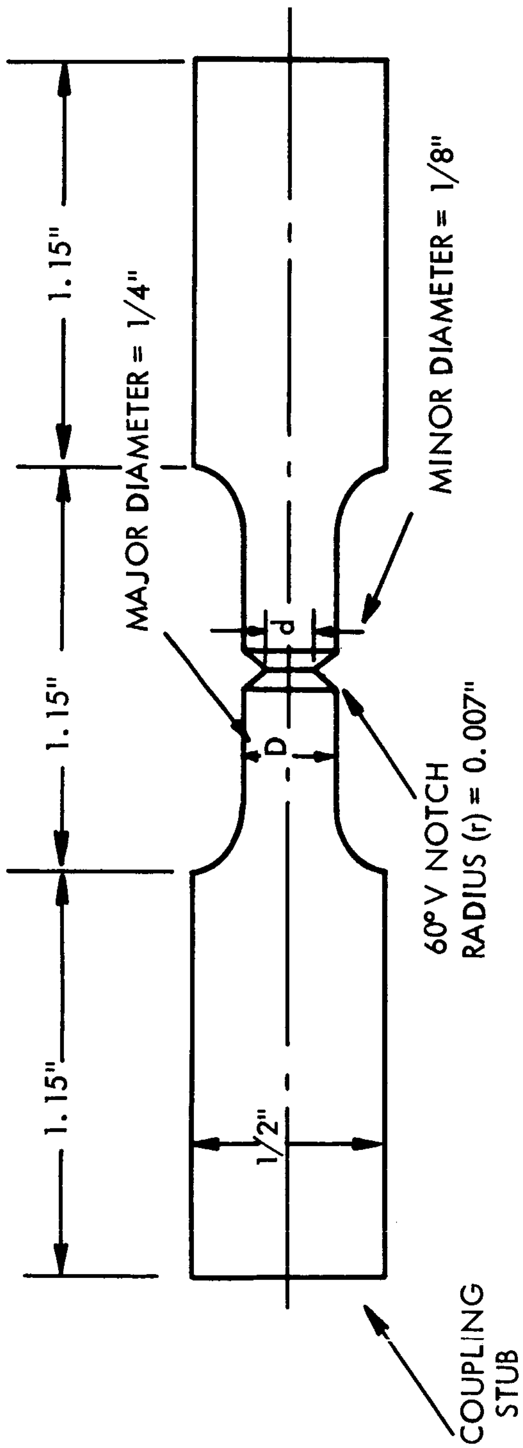

FIGURE 6. GEOMETRY OF NOTCH TENSILE SPECIMEN

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The test plan for evaluating the notched specimen at elevated temperatures involved measuring the specimen deflection on the major diameter to obtain a value of the nominal stress and then increasing the voltage in discrete increments until failure occurred. Specimen fracture and loss of resonance took place at an ambient temperature of 1840°F (1003°C) approximately 18 minutes (20×10^6 cycles) after the application of the lowest applied voltage (78 volts). Optical pyrometer measurements indicated that the application of the ultrasonic energy increased the temperature of the specimen at the base of the notch by 54°F (30°C). Using the applied voltage-displacement curves obtained for notch specimens a strain of 60×10^{-6} in/in was determined as being present in the major diameter section. Applying an elastic modulus of 40×10^6 psi ($2.76 \times 10^{11} N/m^2$) and an effective stress concentration (K_f) of 7.0 the maximum stress at the notch was calculated as 16,800 psi ($1.16 \times 10^8 N/m^2$). The appearance of the fracture surface is shown in Figure 7. A fatigue crack with noticeable "beach" marks was apparent across approximately one-half the cross-sectional area. Additional tests will be conducted with specimens having less severe stress concentration factors in an effort to define the variation in fatigue properties with notch geometry.

V. FUTURE WORK

Delivery of both the TZC and Cb132M has been scheduled for July. A smooth specimen geometry will be defined which is capable of undergoing fatigue cracking at 2000°F (1093°C). Elevated temperature tests will be initiated with both smooth and notch specimens of TZC to define representative S-N curves.

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FIGURE 7. APPEARANCE OF FRACTURE SURFACE OF NOTCHED TZM SPECIMAN (K_T = 3), TESTED AT AN AMBIENT TEMPERATURE OF 1840°F (1003°C), 78 VOLTS, 18.6 KHz, TOTAL TEST TIME 18 MINUTES (2.0 X 10^7 CYCLES)

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