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**STRESSES IN ZIRCALOY-2 CLADDING
DURING VIBRATORY FUEL LOADING**

R. L. GIBBY and R. J. LOBSINGER

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DURING VIBRATORY FUEL LOADING

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February, 1966

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INTRODUCTION

Although high energy vibratory compaction has proven to be an excellent means of loading reactor fuel rods with sized ceramic fuel powder, severe stresses can be generated in the rods by this method, resulting in cladding failures. This report discusses the results of a vibration test program conducted to investigate fatigue failures in Zircaloy-2 tubes. A number of fuel tubes cracked at the ends attached to the vibrator unit during vibratory loading of fuel rods for the Plutonium Recycle Demonstration Experiment in the EBWR.

Although most of the affected tubes did not crack completely, ultrasonic inspection revealed cracks in and/or near the end caps. Exposure of the defective tubes to a simulated in-reactor environment (thermal cycling in an autoclave) caused crack propagation. This action prompted a study to determine the mechanisms of cladding failure and to establish or recommend modifications in fabrication methods which might eliminate the problem.

SUMMARY

The vibratory fuel loading test program produced fatigue failures in the experimental tubes, which appeared to be identical to the failures experienced during fabrication of EBWR fuel rods. Electrodynamic vibrators were used to apply various resonance frequencies to five empty fuel tubes. Held in vertical positions in four different end clamp arrangements, the tubes were subjected to longitudinal vibrations until they cracked.

Stress measurements indicated that the use of a modified tapered clamp would transfer severe stresses from the end-cap crevice (the failure site) to the heavier and stronger cladding wall, thereby eliminating fatigue failure.

EXPERIMENTAL PROCEDURE

Tube Clamp Arrangements

The test specimens used for stress measurements were standard Zircaloy-2 EBWR fuel tubes (143.51* cm by 0.945 ID by 0.069 cm wall thickness) with one end-cap in place. The tubes were vibrated in a vertical position after attachment to an electrodynamic vibrator (Figure 1). Three end-cap clamps (Figure 2) were used during the experiment. The clamps were either attached directly to the vibrator top (direct coupling) or to a "resonance" plate assembly mounted on the vibrator. Clamps already welded to plates were bolted as a unit to the resonance plate. This arrangement is referred to as a "reinforced resonance plate."

Electrodynamic Vibrators

Experiments were conducted with two different electrodynamic vibrators. A Calidyne vibrator was used for studying vibration of empty tubes directly coupled to the shaker, while a C-20 M-B shaker was used for studying cladding stresses generated during actual fuel loading. (The M-B shaker with resonance plate attached was used for production loading of the majority of EBWR fuel rods.) The Calidyne unit's frequency range of 0-2000 cps

*Length with end cap welded in place.

had to be scanned manually and the applied force level of the shaker was varied with a noncalibrated rheostat. With an established frequency range of 230-1600 cps, the M-B vibrator can be adjusted to scan either manually or at several fixed sweep rates from ~ 0.4 octaves/sec to ~ 0.06 octaves/sec. Monitored with an accelerometer arrangement, applied forces of 10, 20, 30, 40, and 50 g were used at various stages of the investigation.

Stress Measurements

Stress patterns and stress magnitudes were measured with "stress coat" brittle lacquer which was applied and cured in the immediate vicinity of the test. It was applied both on UO_2 -filled tubes and on empty tubes in order to analyze and compare stress patterns in each after vibratory treatment. After the stressing treatments, stress amplitudes were determined by measuring the number of cracks in the

*FIGURE 1. Vibration Test Apparatus
Resonance Plate Arrangement*

FIGURE 2. Configuration of End-Cap Clamps

brittle lacquer per unit length and comparing this with a coating on a standard test bar subjected to known stresses. Stress magnitudes determined by the brittle lacquer measurements were only semiquantitative because of the unknown effect of sustained vibration on the linear crack density.

In general, quantitative stress measurements were made with strain gauges. Metal film strain gauges (120 ohm resistance) were attached to the tubes with Eastman 910 adhesive. The soldered lead wire connections also had to be coated with cement to prevent fatiguing of gauge connections during vibration. Connected to a null balance circuit in an oscillograph, the strain gauges recorded the stresses directly on strip charts as a function of time and/or frequency. Stress values were calculated, assuming that the proportional limit was not exceeded during vibration. A room temperature value of 14×10^6 psi⁽¹⁾ for Young's modulus of Zircaloy-2 was used in the calculations.

Some heat was generated near the strain gauges during oscillation but was not great enough to affect overall strain measurements. A variety of strain gauges and mounting orientations were employed to determine regions of maximum stresses during vibration. As a result, during experimental runs, the gauges were mounted in the vicinity of the end clamp, since this region was demonstrated to be particularly susceptible to cracking. An empty fuel tube with a mounted strain gauge is shown in Figure 3.

FIGURE 3. Strain Gauge Mounted on Fuel Tube

Fuel Loading

A sized EBWR UO_2 - PuO_2 powder mixture consisting of 55 wt% (-6 +10 mesh), 25 wt% (-20 +65 mesh), and 20 wt% (-200 mesh) was used during fuel loading stress studies. To ensure similar stress conditions, a loading cycle similar to the EBWR loading cycle was followed. The rods were loaded for 1 min each at applied shaker forces of 20, 30, and 40 g. The shaker was automatically cycled in the frequency range 235-1600 cps at a sweep rate of 0.4 octaves/sec. After 3 min of loading, the rods were tamped for 1 min at an applied force of 50 g. The frequency range was manually swept by the operator.

Five empty rods were shaken on the Calidyne vibrator at various resonance frequencies until they cracked. The rods were subjected to metallographic examination, and the results were compared with rod failures that occurred during fuel loading.

RESULTS AND DISCUSSION

Longitudinal vibrations, imparted by an electrodynamic vibrator to the fixed end of a vertically held EBWR tube, excited natural transverse vibrational modes in the tube. At particular vibrator frequencies, transverse standing waves were established in the tubing. The standing waves were readily observed, since maximum tube deflections were normal to the tube axis and often exceeded 15 cm peak-to-peak. After vibration at resonance frequencies, stress coat crack patterns on empty and filled tubes consisted of circumferential stress bands spaced at intervals between unstressed bands or nodes. The number of nodes depended upon the frequency at which resonance occurred. The severest stresses occurred near the fixed end of the tubes, with the stresses greater for filled tubes than empty ones. Stresses as high as 45,000 psi were calculated from the crack densities measured in the brittle lacquer coatings on empty tubes.

In some cases, torsional or twisting vibrational modes were excited in conjunction with the transverse vibrations. Under ideal conditions, generation of transverse or torsional vibration by longitudinal excitation is impossible; however, in a real system it is difficult to obtain only pure longitudinal vibrations; consequently, transverse and torsional components are present, in some cases to a greater extent than others. At the natural transverse or torsional vibrational modes of a tube, the transverse or torsional vibration components are amplified in the resonating tube. Solution of the wave equation for transverse

vibration of a fixed-free tube gives the following equation for the allowed transverse vibration frequencies:

$$\nu_n = \frac{\pi}{2L^2} \sqrt{\frac{Ek^2}{\rho}} \beta_n^2 \quad (1)$$

where $\beta_n = (n-1/2)$, $n \geq 2$; $\beta_1 = 0.597$

ρ = density = 6.55 gm/cm³ for Zr-2

k = radius of gyration

$$= 1/2 \sqrt{r_1^2 + r_2^2} = 0.112 \text{ cm}$$

where r_1 = inside radius

r_2 = outside radius

L = tube length = 138.2 cm*.

Table I presents the calculated values for the first 13 transverse vibrational frequencies of an EBWR tube. The transverse vibrational modes observed for one tube, with the corresponding longitudinal excitation frequencies, are also shown. These preliminary data do not give a simple correlation between applied longitudinal frequency and excited transverse frequency. Transverse modes are excited at different longitudinal frequencies for each of the two electrodynamic vibrators.

The possibility of resonance at natural longitudinal vibration modes was also considered. Solution of the wave equation for longitudinal vibration of a fixed-free tube yields the following frequency equation:

$$\nu_n = \frac{(2n-1) \pi C}{2L} \quad (2)$$

where C = longitudinal wave velocity

$$= 4.65 \times 10^5 \text{ cm/sec}$$

L = tube length = 138.2 cm.

*Tube length for top of end cap clamp.

TABLE I
CALCULATED AND OBSERVED TRANSVERSE VIBRATION
FREQUENCIES OF EBWR TUBE WITH FIXED END*

<u>n</u>	<u>No. of Nodes (n-1)</u>	<u>Calculated v_n (cps)</u>	<u>Observed v_n (cps)</u>	<u>Longitudinal Excitation Frequency (cps)</u>
1	0	3.8	--	--
2	1	23.7	25	315
3	2	66.5	70	140 and 900
4	3	130	140	260
5	4	218	--	--
6	5	320	320	315
7	6	453	--	--
8	7	600	--	--
9	8	770	--	--
10	9	965	--	--
11	10	1180	--	--
12	11	1480	--	--
13	12	1680	--	--

**Mounted in tapered clamp (nylon insert) on resonance plate and vibrated with Calidyne unit.*

The calculated values for the first five natural longitudinal modes of an EBWR tube are given in Table II. The first natural mode at which resonance would occur is more than twice the highest frequency attained with either electrodynamic vibrator. Therefore, it was concluded that longitudinal resonance would not be expected unless the driving frequency was greatly increased.

Since flexing or bending stresses from transverse vibration were concluded to be the cause of fatigue failures, five empty tubes were vibrated at three resonating frequencies until failure occurred. With a standard clamp directly coupled to a Calidyne vibrator, the tube cracked in less than 10 min at a driving frequency of 600

cps. When a modified tapered clamp was substituted, tube life was extended to approximately 20 min. When MoS_2 powder was placed between tube and clamp, failure did not occur during 20 min of sustained vibration at a resonance frequency. The failed tubes were sectioned, and the cracked regions were subjected to metallographic examination. The fatigue failures in the experimental tubes appeared identical to the failures experienced during production of EBWR fuel rods, as illustrated in Figure 4.

By relocating severe stresses from the end-cap crevice region to the thicker tube wall, the modified tapered clamp was instrumental in extending tube life. Failures that did occur with the modified clamp were initiated

TABLE II
LONGITUDINAL VIBRATION FREQUENCIES OF EBWR TUBE WITH FIXED END

$\underline{n}$	Number of Nodes ($n-1$)	$\underline{v_n}$ (cps)
1	0	5,250
2	1	15,710
3	2	26,240
4	3	36,740
5	4	47,240

FIGURE 4. Fatigue Failures Produced Experimentally and during Fuel Loading of EBWR Rod

at clamp fretting marks on the tube. The MoS_2 powder was effective in reducing, temporarily, fretting action between tubing and clamp, thus further extending tube life during resonance vibration. Although the tapered clamp with nylon insert was not tested, it should be even more effective in reducing fatigue failures due to fretting.

Stress measurements were obtained for empty tubes with the following clamp arrangements:

- Standard clamp, resonance plate
- Standard clamp, reinforced resonance plate
- Modified tapered clamp, reinforced resonance plate
- Modified tapered clamp with nylon insert, reinforced resonance plate.

For comparison, some of these data are shown in oscillogram tracings in Figure 5. The frequency range was scanned at a sweep rate of about 0.1 octaves/sec. The ordinate has been converted to stress by multiplying strain values by Young's Modulus for Zircaloy-2. Since the scan speed of the oscillograph was much slower than the tube flexing frequency, a stress envelope was recorded. Both tensional and compressional stresses were measured with the gauges. The symmetry of the stress envelopes indicate strain gauge alignment with the bending direction. In most cases, the stress envelopes are very symmetrical.

Modifications of the end clamp do not affect the magnitude of maximum stress values, but the stress-frequency relationship is altered considerably. In other words, transverse vibrations are excited at different frequencies when different clamps and clamping arrangements are employed.

Rotational orientation of the standard end-cap clamp on the resonance plate did not affect the stress-frequency pattern (Figure 6). Reinforcement of the resonance plate, when using a standard clamp, increased the integrated stress level but did not increase maximum stress values (Figure 5). The additional stresses are generated in the low frequency range.

When loading an EBWR tube with sized PuO_2 - UO_2 powder, a design fatigue limit of 25,000 psi³ is not exceeded, at least in the vicinity of the strain gauge, until the vibrator force level reaches 40 g (Figures 7 and 8). Since tubes have failed at lower applied force levels, it is probable that stress raisers exist in the crevice region of the end cap. Zircaloy-2 weld metal is more notch-sensitive than the base metal⁽²⁾, and makes the weld area particularly susceptible to fatigue cracking. The use of the modified tapered clamp with nylon insert in production loading of EBWR fuel rod has eliminated fatigue failures by relocating severe stresses from the end-cap crevice to the heavier and stronger cladding wall.

The addition of oxide powder to a tube, as well as packing and densification of the powder in the tube, increases the magnitude of tube bending stresses. This is shown in the oscillogram in Figure 9, which displays successive frequency cycles at the same vibrator force level during fuel loading. The multitude of factors involved in the cracking process make it difficult to confirm this observation with simple bending stress calculations for empty and full tubes.

FIGURE 5. Stress Measurements of Empty Tubes with Different Clamps

FIGURE 6. Stress-Frequency Pattern after Rotational Orientation of the Standard End Clamp (Reinforced Resonance Plate) on the Resonance Plate

The greatest stresses were measured during tamping of a completely filled rod. At an applied force level of 50 g, stresses as high as 70,000 psi were recorded during manual sweeping of the entire frequency range. At this stress level, calculations indicate that less than 1000 cycles could cause fatigue cracking. Assuming that the transverse resonance frequency at which this stress occurred was approximately

70 cps, then only 14 sec at this frequency could result in cracking and failure.

The longitudinal excitation frequencies for transverse vibration shift to lower values as the tubes are filled with powder (Figure 8). According to equation (1), the natural frequencies of the rod should be expected to change inversely with its density. Since the UO_2 is present as an unbonded powder,

FIGURE 7. Stress-Frequency Patterns of Standard End Clamp (Reinforced Resonance Plate) at Different Applied Force Levels

and assuming that the modulus of elasticity for the UO_2 can be neglected, then the natural vibration modes of the fueled tube should occur at lower frequencies because of the increased density. This has not been confirmed experimentally, although it is strongly suggested by the observed shift in excitation frequency. Also shown in Figure 8 is the increase in number of excited bending modes at lower frequencies as the rods fill with fuel. The extra flexing action observed at low

frequencies should not contribute to fatiguing because the stresses encountered are below the design fatigue limit.

CONCLUSIONS

Longitudinal vibration of EBWR tubes excites transverse vibrational modes in the tube. The stresses, measured with strain gauges located near the end clamp, are great enough to cause fatiguing of the Zircaloy-2 during the final stages of fuel powder loading. With a standard clamp, the

FIGURE 8. Stress-Frequency Pattern of Standard End Clamp (Reinforced Resonance Plate) with Reinforced Resonance Plate at Different Applied Force Levels

FIGURE 9. Successive Frequency Cycles of Standard End Clamp (Reinforced Resonance Plate) with Reinforced Resonance Plate at Same Vibrator Force Level

end-cap crevice acts as a stress raiser and fatigue failure can occur at lower stress values. By relocating major stresses to the heavier cladding, a modified tapered end clamp with nylon insert is very effective in reducing fatigue failures. Reinforcement of the resonance plate is undesirable because it increases the integrated fatigue stress level.

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