**EVALUATION OF EX-REACTOR LOADING EVENT
ON HIGH-FLUENCE EBR-II CONTROL-ROD THIMBLE SE3**

by

J. E. Flinn, D. Krajcinovic,* R. D. Phipps,
D. G. Franklin, and S. C. Miller**

**EBR-II Project
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ABSTRACT

A Type 304 stainless steel EBR-II control-rod thimble (CRT 5E3) with high fluence was damaged while undergoing dimensional evaluation. The damage, which occurred when the thimble was inadvertently loaded in a bending mode, consisted of rather localized but extensive fracture.

An elastic stress analysis of the bending mode was done on the thimble, using semimembrane shell theory. The analysis disclosed several important aspects that the simpler and more commonly employed techniques do not disclose. The hoop stress was found to be the most probable to initiate failure in that crack initiation would most likely result from localized yielding from the hoop stress.

Structural assessment of the failure with the aid of scanning electron, transmission electron, and optical microscopy qualitatively supported the stress analysis in that the failure was associated with localized yielding and was accompanied by some, but limited, ductility. There was no evidence that a premature failure occurred (e.g., a failure at stresses below the yield stress of the material and which might be associated with grain-boundary embrittlement).

I. INTRODUCTION

A Type 304 stainless steel control-rod thimble (CRT 5E3) with high fluence ($\sim 1.7 \times 10^{23}$ nvt peak total fluence) was undergoing dimensional evaluation when it was inadvertently loaded in a bending mode. During the

course of obtaining the dimensional measurements, the thimble was pivoted from a horizontal to a vertical position by an electromechanical manipulator connected to a 1/16-in.-dia cable looped through a hole near the top end of the thimble. While being lifted off the examination table, the center portion of the thimble made contact (at approximately 1-1/2 in. above the spacer pads) with a rectangular bar suspended above the table. Before the lifting system could be stopped, the thimble was bent about the suspended bar. This produced localized fracture and expulsion of some metal fragments from around the region of contact. One of the fragments was recovered and structurally examined.

This evaluation of the loading event and resulting fracture of the thimble consists of two parts:

1. An elastic stress and deflection analysis of the loading mode; and
2. Structural examination of some of the fracture areas by scanning electron microscopy (SEM) and optical microscopy. In addition, one of the fracture fragments in a region close to a fracture surface was examined by transmission electron microscopy (TEM).

Structural examination of fracture areas complements an elastic stress analysis if plastic flow has occurred. An elastic analysis is applicable only up to the elastic limit of the material. Since the thimble, because of its high fluence, was expected to possess only a small amount of ductility before the onset of fracture, failure would be expected at stresses slightly above the elastic limit.

A significant facet of the evaluation was a good elastic stress analysis of the loading. The treatment takes into account the complicated geometry (long and slender hexagonal shell) of the thimble.

II. LOADING DESCRIPTION AND RESULTING FRACTURE PATTERNS

Figure 1 shows the loading mode for the thimble. In the freebody diagram (a), the line ABC represents the thimble, and F_A , F_B , and F_C are the forces exerted by the pulling (lifting) cable (A), the fulcrum (B) and the examination table (C), respectively. The forces f_B and f_C represent frictional forces imposed by the fulcrum and the table, respectively. The values for AB, BC, and α at the time of the loading of the thimble are given at the top of the figure.

(b) FRACTURE AREAS

Fig. 1. Loading and Resulting Fracture Areas on Control-rod Thimble (CRT) 5E3

The maximum of the force F_A that could be applied in pulling the thimble was determined to be 630 lb. In later testing, the cable broke when subjected to that force. Therefore, 630 lb was selected as the upper load limit. A moment and force balance for the freebody diagram shown in Fig. 1 yielded the following values: $F_A = 630$ lb; $F_B = 460$ lb; $F_C = 315$ lb; and $M_B = 19,800$ lb-in. The fracture occurred in the region of maximum dilation of the thimble approximately 2-1/2 in. above the reactor-core midplane. The fracture areas are schematically shown in (b) of Fig. 1. The cracks extended into four of the six flats of the thimble, and three small pieces were expelled from the fracture area. Only one of the expelled pieces was recovered. Figure 2 shows a series of photomacrographs of the fracture area. The first four--(a)-(d)--show the cracks on four of the six flats; no cracks were observed on flats No. 3 and No. 4. The recovered fragment is shown in (e) of Fig. 2. The fragment was almost entirely from flat No. 5, but it did contain a portion of the 5-6 node (corner between flats No. 5 and 6). This fragment was the object of the major portion of the structural evaluation, the results of which are given in Sec. V.

III. THIMBLE HISTORY

Control-rod thimble 5E3 was placed into EBR-II grid position 5E3 on February 14, 1963, and was removed more than eight years later, on June 18, 1971. During this long history of reactor service, the thimble accumulated 44,734 MWD and a calculated peak unperturbed total fluence of 1.7×10^{23} nvt while the reactor operated at power levels of 45, 50, and 62.5 MWt. This fluence was obtained from ^{235}U fission rates (based on a ^{235}U fission cross section of 1.4 b) published in the earlier editions as well as the present edition of the Guide for Irradiation Experiments in EBR-II.¹ Based on a "run-to-run" calculation, the results were summed for the entire residency of the thimble. This period of time also saw a change from the 14.2-in.-long fuel pin of the Mark-I type of driver fuel to the 13-1/2-in.-long fuel pin of the Mark-IA type of driver fuel. This change in the fuel-pin length lowered the horizontal core midplane from 1-3/16 in. below the buttons to 1-9/16 in. below the buttons.

Many changes in core loading occurred during the eight-year service of the thimble, and many of these changes had direct influence on the

(a) FLATS 1, 5, AND 6 (MAG 2/3X)

(b) FLATS 1, 2, AND 6 (MAG 2/3X)

Fig. 2. Extent of Cracking of CRT 5E3

(c) FLATS 2 AND 3 (MAG 2/3X)

(d) FLATS 4, 5, AND 6 (MAG 2/3X)

Fig. 2. Extent of Cracking of CRT SE3 (contd)

(e) EXPELLED FRAGMENT FROM FLAT NO. 5.
(MAG 4X)

Fig. 2. Extent of Cracking of CRT 5E3 (contd)

operating temperature of the thimble, because the temperature of the thimble is dependent upon that of its neighbors. This dependence is due to the fact that the thimble is cooled by bypass flow of about 9.4 gpm of sodium between the outside of the control rod and the inside of the thimble and leakage flow of sodium between the outside of the thimble and the adjacent subassemblies. The temperature of the thimble is, therefore, a function of the amount of heat being produced in the control rod and its six neighbors and the amount being conducted to the thimble walls. The operating-temperature range could be set between a low of 700°F, which is the inlet sodium temperature, and a high of 1003°F, which is the maximum calculated operating temperature of a neighbor.² In general, however, the maximum operating temperature of the thimble was between 850 and 925°F. These maximum temperatures occurred along an axial segment extending from the top end of the thimble to approximately 7 in. above the top of the core. The temperature increase is almost linear over a segment approximately 20 in. long, starting at the bottom end of the core (700°F) and increasing to the maximum temperature about 7 in. above the top of the core. The operating temperature in the region that fractured was about 775°F. Figure 3 shows seven plots, (a)-(g), of the calculated² outlet sodium-coolant temperature above the control-rod position (5E3) and the six adjacent positions. These values give an indication of how the maximum operating temperature of the thimble varied during operation. They also illustrate the temperature variation from one flat to another.

The thimble was transferred from the reactor to the HFEF (Hot Fuel Examination Facility) on June 18, 1971, in interbuilding coffin No. 1. Then it was cleaned by using the standard wash procedure for driver-fuel types of subassemblies. This procedure consists of two moist-air reaction cycles, one 25-gal rinse with demineralized water, and a 2-hr air drying cycle. No sodium residue was evident on the thimble surface after the cleaning.

The cleaned thimble was stored temporarily in the air cell and then given a preliminary examination that consisted of visual examination, measurement of straightness by TIR (total indicator runout), and a spot check of flat-to-flat measurements. The thimble was then returned to the air-cell storage pits before detailed examination could be made. The storage environment consisted of an air atmosphere with temperatures of 60-95°F and relative humidities of 50-65%. Total air-cell storage time before the fracturing of the thimble was 203 days.

Fig. 3. Coolant Temperatures above Position 5E3 (the Location of CRT 5E3) and the Six Adjacent Positions

Fig. 3. Coolant Temperatures above Position 5E3 (the Location of CRT 5E3) and the Six Adjacent Positions (contd)

Fig. 3. Coolant Temperatures above Position 5E3 (the Location of CRT 5E3) and the Six Adjacent Positions (contd)

Fig. 3. Coolant Temperatures above Position SE3 (the Location of CRT SE3) and the Six Adjacent Positions (contd)

On December 7, 1971, the thimble was removed from the pits for detailed examination. A complete series of flat-to-flat and corner-to-corner measurements was taken. The results are plotted in Fig. 4. The dimensional evaluation for a given flat-to-flat series involved measurements approximately 1/2 in. to the left and to the right of the center line of the flat (designated Edge A and Edge B, respectively, in Fig. 4) and also along the center line. The length of each flat also was measured. These measurements showed that the average length was $49-29/32 \pm 1/32$ in., or $13/32$ in. longer than the nominal as-fabricated length of $49-1/2$ in. Following these measurements, the thimble was being transferred from the vertical assembler-dismantler (VAD) to the storage area to await bow measurement when it was inadvertently fractured.

IV. STRESS AND DEFLECTION ANALYSIS

An elastic stress analysis and beam-deflection calculation have been made for a hex can to simulate the loading behavior illustrated in Fig. 1. The method is based on the semimembrane shell theory, which is expected to

Fig. 4. Flat-to-Flat and Corner-to-Corner Dimensions of CRT 5E3 (contd)

Fig. 4. Flat-to-Flat and Corner-to-Corner Dimensions of CRT 5E3 (contd)

be a good approximation of the exact theory for the geometries involved (long and slender shells). The physical model, shown in Fig. 5 and described by Krajcinovic,^{3,4} can be imagined as consisting of an infinite number of hexagonal frames interconnected with a lattice that transmits only normal and shearing forces. The principal advantages of using the analytical model instead of the beam approximation (commonly used in design stages) is not only an increase in accuracy, but even more important, the possibility of a hoop-stress determination (ignored by the beam model). Even though the developed analytical model is significantly more involved than the more simplified, commonly used methods, it still permits the derivation of formulas for stresses in closed form.

A brief review of the semimembrane approach is given here. This is followed by a stress analysis of the case where a long and thin hexagonal shell is subjected to a line load across one of its flats. This loading mode will yield the stress relations needed to analyze the bending of the thimble about a fulcrum.

A. Deformation Modes

The hexagonal shell that is to be analyzed (see Fig. 5) is composed of six identical planes rigidly joined together along the nodal lines (which correspond to the corners of the thimble). The stress-analysis approach is based on the semimembrane theory of Ref. 3. The coordinate description of our shell is shown in Fig. 6, in which an arbitrary point $N(z,s)$ on the surface on the middle of a flat is defined by axial and circumferential coordinates z and s , respectively. The displacements corresponding to these coordinates are $u(z,s)$ and $v(z,s)$, whose positive directions are those shown in Fig. 6.

The principal feature of the semimembrane approach is that the displacements u and v can be approximated by the series

$$u(z,s) = \sum_{i=1}^n U_i(z) \phi_i(s)$$

and

(1)

(a) HEXAGONAL SHELL

(b) LATTICE FRAME MODEL

Fig. 5. Description of Hexagonal Shell and Lattice Frame Model of It

Fig. 6. Hexagonal Shell, Showing the Non-vanishing Forces and the Two Displacement Components u and v

$$v(z,s) = \sum_{j=1}^n V_j(z) \psi_j(s),$$

where $U_i(z)$ and $V_j(z)$ are generalized coordinates that are to be determined, and $\phi_i(s)$ and $\psi_j(s)$ are deformation modes chosen *a priori*.

Five independent deformation modes for ϕ_i and ψ_j were rather arbitrarily selected. These are shown in Fig. 7. The modes are restricted to deformations symmetric with respect to the Y axis (see Fig. 6). The five modes shown in Fig. 7 illustrate the value of the analysis of the thimble. Modes ϕ_1 , ϕ_2 , and ψ_1 treat deformation in terms of conventional beam theory, i.e., the Euler-Bernoulli hypothesis is maintained in that cross sections of the entire shell remain in their original plane and do not distort during deformation. Modes ϕ_3 and ψ_2 represent deformation behavior where cross sections undergo distortions. These last two modes can be very important in describing the deformation of a hexagonal shell under externally applied loads.

B. Load Description

The analysis of the bending problem involves the application of rather concentrated forces to a portion of a thin, elastic hexagonal shell. No bracing support against cross-sectional distortion has been provided for the shell. The loading condition of interest is shown as (a) in Fig. 8. It consists of a line load across flat No. 6 of a hexagonal shell. The line load can be decomposed into a self-equilibrated load (b) and a system of resultant nodal forces (c). The self-equilibrated load bends the hexagonal frame without bending the shell as a beam (i.e., the axis, $z = 0$, of the shell remains unchanged). The load shown as (c) in Fig. 8 is associated with beam-like bending of the shell and with distortion of the cross section.

Each of the system stresses corresponding to the axial (z) and the hoop (s) directions consists of two terms:

$$\sigma_z = \sigma_z^{(b)} + \sigma_z^{(d)}$$

and

(2)

Fig. 7. Deformation Modes of the Analytical Model

Fig. 8. Line Load (p) across Flat No. 6 of the Hexagonal Shell, and Its Resolution into a Self-equilibrated Load and a Load with a Resultant

$$\sigma_s = \sigma_s^{(b)} + \sigma_s^{(d)},$$

where the superscripts (b) and (d) denote the contributions of bending and of cross-sectional distortions, respectively. An analysis of the self-equilibrated portion [(b) of Fig. 8] will yield the $\sigma_s^{(b)}$ portion and the axial stresses $\sigma_z^{(b)}$ and $\sigma_z^{(d)}$.

C. Hoop Stresses Due to Equilibrated Loading

The closed hexagonal frame can be easily analyzed using the standard force method commonly used in the analysis of structures. For the system shown in (b) of Fig. 8, there are three unknowns at any one section--two forces and a bending moment. One of the forces vanishes because of symmetry. The basic system is shown in (a) of Fig. 9. If the deformations due to normal and shear stresses in the basic system are neglected, the unknown (redundant) bending moment X_1 and the normal force X_2 in the upper flat are given by

(a) BASIC SYSTEM

(b)

(c)

(d) M_0

(e) M

Fig. 9. Basic System and Corresponding Moment Diagrams

$$X_1 = - \frac{\delta_{10}}{\delta_{11}}$$

and

(3)

$$X_2 = - \frac{\delta_{20}}{\delta_{22}},$$

where the subscripts 1 and 2 represent forces in the basic system, and 0 denotes external load application. Because of symmetry, the force X_3 is equal to zero. The terms δ_{10} , δ_{11} , δ_{20} , and δ_{22} for a frame of unit thickness are given by

$$\delta_{10} = \int \frac{M_1 M_0}{EI} ds,$$

$$\delta_{11} = \int \frac{M_1^2}{EI} ds,$$

$$\delta_{20} = \int \frac{M_2 M_0}{EI} ds, \tag{4}$$

and

$$\delta_{22} = \int \frac{M_2^2}{EI} ds,$$

where M is the bending moment, E is the modulus of elasticity, and I is the moment of inertia. The solution for Eqs. (3) and (4) can be obtained from (a) of Fig. 9, which represents the basic system of interest, and from the corresponding moment diagrams for X_1 , X_2 , and M_0 [(c) and (d) of Fig. 9]. For the basic system shown in Fig. 9, the unknowns are applied via a rigid arm ($EI = \infty$) at the center of the frame. This permits a decoupling of the equations, i.e.,

$$\int \frac{M_i M_j}{EI} = 0 \text{ for } i \neq j. \tag{5}$$

The moment diagram corresponding to the external loads shown in (b) of Fig. 8 is shown in (d) of Fig. 9.

The solutions per unit thickness for the basic system of Fig. 9 and Eq. (4) are:

$$i) \quad EI\delta_{11} = \int M_1^2 ds = 6\ell$$

and (6)

$$EI\delta_{22} = \int M_2^2 ds = \frac{5}{2} \ell^3;$$

ii) for the load,

$$EI\delta_{10} = \frac{2}{3} p\ell^3$$

and (7)

$$EI\delta_{20} = -\frac{1}{12} p\ell^3 h.$$

Therefore, the forces X_1 and X_2 are

$$X_1 = -\frac{p\ell^2}{9}$$

and (8)

$$X_2 = \frac{ph}{30}.$$

The final moment diagram due to self-equilibrated load for the load type shown as (b) in Fig. 8 is shown as (e) in Fig. 9.

D. Stresses Due to Load on the Shell

To compute the stresses in the shell due to the load component given in (c) of Fig. 8, we will employ the semimembrane theory as given in Ref. 3. The long shell, as described earlier, is completely free of any bracing against cross-sectional distortion. It is acted upon by a concentrated ring load of the type shown in (c) of Fig. 8. The analysis is divided into two independent stages: (1) bending of the shell as a beam (the Bernoulli-Euler hypothesis of planar cross section), and (2) analysis accounting for

the distortion of the cross section. Reference 3 shows that the load which bends the shell as a beam is

$$p_{s1} = \int p_s \psi_1 ds + \sum p_s(ij) \psi_1(ij), \quad (9)$$

where p_s is the load distributed in the plane of the flat, and ψ is the deformation mode as shown in Fig. 7. Reference 3 also shows that the load which distorts the cross section is

$$p_{s2} = p_k = \int p_s \psi_2 ds + \sum p_s(ij) \psi_2(ij), \quad (10)$$

where ψ_2 is the deformation mode shown in Fig. 7.

The distortion is due to the components of p_{s1} that are shown in Fig. 10. The forces shown are resolved as follows: $2R_1$ equals the resultant of the load distributed along flat No. 6 (i.e., $R_1 = 1/2 p\ell$), and p_2 equals the resultant of the distributed load over the projections of flats No. 5 and 1 (i.e., $p_2 = 1/2 p\ell$).

From the geometry, we see that

$$p_s = p_2 \cos 30^\circ = \frac{\sqrt{3}}{4} p\ell,$$

$$p_n = p_2 \sin 30^\circ = 1/4 p\ell,$$

$$R_2 = 1/2 p_n = 1/8 p\ell, \quad (11)$$

and

$$p_s = \frac{1}{\ell} p_5 = \frac{\sqrt{3}}{4} p,$$

where R_2 is applied at the 4-5, 5-6, 6-1, and 1-2 nodes normal to flats No. 5 and 1, and p_s is distributed along flats No. 5 and 1.

For the load distributed over the entire projection consisting of flats No. 5, 6, and 1, we have

$$p_2 = \frac{p\ell}{2},$$

Fig. 10. Decomposition of Lateral Load into Resultants

$$R_2 = \frac{p\ell}{8} ,$$

and

(12)

$$p_s = \frac{\sqrt{3}}{4} p .$$

From the geometry, we see that

$$p_s = p_1 = \frac{\sqrt{3} p\ell}{3} ,$$

$$p_4 = p_2 = \frac{\sqrt{3} p\ell}{12} ,$$

(13)

$$p_{s1} = 2 p\ell ,$$

and

$$p_{s2} = \frac{3}{2} p \ell h.$$

We note that the load p_{s1} equals the total vertical component, which is a good check of the load-decomposition procedure.

1. Stresses Due to the p_{s1} Component of the Load

As a result of the load component p_{s1} , the cross section does not distort, and the stresses determined are those for a beam. Hence, we have at $z = L/2$,

$$M_y = 1/4 p_{s1} L \quad (14)$$

and

$$\sigma_z = \pm \frac{M_y}{I_y} y, \quad (15)$$

where

$$I_y = \int y^2 dA = \frac{5}{2} d \ell^3 \quad (16)$$

and A is the cross-sectional area.

2. Stresses Due to the p_{s2} Component of the Load

To solve for p_{s2} requires the method of analysis used in Ref. 3. The analysis is very long and involved and will not be covered here. The results of the analysis yield the distortion contributions to the axial and hoop stresses. The stresses are written as follows (see Ref. 3):

$$\sigma_z^{(d)} = \pm \frac{M_\omega}{I_\omega} \Omega \quad (17)$$

and

$$\sigma_s^{(d)} = \pm 1/2 \frac{h^2 N_\kappa p \ell}{\ell L d^2}, \quad (18)$$

where M_ω is the bimoment, I_ω is the sectorial moment of inertia (in.⁶), Ω is the sectorial coordinate (in.²), the terms d , h , ℓ , and L are defined in Fig. 6, and the load, p , is shown in Fig. 8. Equation (17) was evaluated to be

$$\sigma_z^{(d)} = \pm \frac{8}{9} \frac{L h^3}{d \ell^5} N_m p \ell. \quad (19)$$

The terms N_κ and N_m were found to be

$$N_\kappa = \frac{L}{2\ell} \left(\frac{16d^2}{5\ell^2} \right)^{1/4} \quad (20)$$

and

$$N_m = - \frac{\ell}{4L} \left(\frac{5\ell^2}{16d^2} \right)^{1/4}. \quad (21)$$

When Eq. (20) is substituted into Eq. (18), we see that the distortion contribution $[\sigma_s^{(d)}]$ to the total hoop stress is independent of L , the length of the shell. Similarly, the distortion contribution $[\sigma_z^{(d)}]$ to total axial stress is also independent of L .

3. Description of Total Stress

It was stated earlier [see Eq. (2)] that the axial stress and the hoop stress each contains two parts--one due to bending and the other to cross-sectional distortion. For the hoop stress, σ_s , the bending moments due to the self-equilibrated load [(b) of Fig. 8] are shown in (e) of Fig. 9, i.e. (see Ref. 3),

$$\sigma_s^{(b)} = \pm \frac{31}{60} \frac{\ell}{d^2} p \ell. \quad (22)$$

Substituting Eq. (20) into Eq. (18) and combining the result with Eq. (22), we obtain for the total hoop stress the following:

$$\sigma_s = \pm \left[\frac{h^2}{4\ell^2 d^2} \left(\frac{16d^2}{5\ell^2} \right)^{1/4} + \frac{31}{60} \frac{\ell}{d^2} \right] p \ell. \quad (23)$$

From Eqs. (21), (19), and (15), the total axial stress is given as

$$\sigma_z = \pm \left[\frac{2}{9} \frac{h^3}{\ell^4 d} \left(\frac{5\ell^2}{16d^2} \right)^{1/4} p\ell + \frac{M_y}{I_y} y \right]. \quad (24)$$

The term $p\ell$ at the point of loading can be represented by

$$p\ell = P^* \left(\frac{31.5 + 56.4}{56.4} \right) = 1.550 P^*, \quad (25)$$

where P^* is the pulling force, $\left[F_A \text{ in (a) of Fig. 1} \right]$ provided by the cable on the thimble, and 31.5 and 56.4 are the distances AB and BC, in inches, given in (a) of Fig. 1.

The bending term for σ_z can be further reduced to the following from Fig. 1 and Eq. (16):

$$\sigma_z^{(b)} = \pm \frac{2(31.5)h}{5d\ell^3} P^*. \quad (26)$$

Substitution of Eq. (26) into Eq. (24) and use of the relationship given in Eq. (25) yields for the total axial stress the following:

$$\sigma_z = \pm \left[\frac{3.10}{9} \frac{h^3}{\ell^4 d} \left(\frac{5\ell^2}{16d^2} \right)^{1/4} + \frac{63}{5} \frac{h}{d\ell^3} \right] P^*. \quad (27)$$

Similarly, a substitution of Eq. (25) into Eq. (23) yields

$$\sigma_s = \pm 1.550 \left[\frac{h^2}{4\ell^2 d^2} \left(\frac{16d^2}{5\ell^2} \right)^{1/4} + \frac{31}{60} \frac{\ell}{d^2} \right] P^*. \quad (28)$$

The - and + signs for Eqs. (27) and (28) represent the state of stress of the outer and inner fibers of flat No. 6.

If the values $d = 0.040$ in., $\ell = 1.322$ in. and $h = 1.145$ in.--the nominal values for the thimble (see Fig. 6)-- are substituted into Eqs. (27) and (28), those equations are reduced, respectively, to the following:

$$\sigma_z = \pm [18.2 + 156.1] P^* = \pm 174.3 P^* \quad (29)$$

and

$$\sigma_s = \pm [42.3 + 661.7] P^* = \pm 704.0 P^*. \quad (30)$$

The hoop stress is about four times the axial stress for a given load p^* .

E. Buckling Stresses

In addition to estimates for the hoop and axial stresses, stress calculations for local buckling and for buckling of the entire beam are of interest. If the compressed flat (No. 6) is viewed as a panel hinged along the two edges, the local buckling stress for such a panel is⁵

$$\sigma_{cr} = \frac{4.0 \pi^2 E}{12 (1 - \nu^2)} \frac{d^2}{l^2}, \quad (31)$$

where ν is Poisson's ratio.

Buckling of the entire beam can be evaluated from Eq. (33) of Ref. 4. The critical moment for the global stability of the shell is

$$M_{cr} = \frac{m EI}{L}, \quad (32)$$

where

$$m = \frac{(1 + 2 \frac{r^2}{\pi^2} + \frac{s^4}{\pi^4})}{\left(\frac{I}{I_\omega} \frac{L^2}{\pi^4} + \frac{EI}{G \kappa \pi^2} \right)},$$

with

$$r^2 = \frac{32}{15} \left(\frac{d}{l} \right)^2 \left(\frac{L}{l} \right)^4,$$

$$s^4 = \frac{64}{5} \left(\frac{d}{l} \right)^2 \left(\frac{L}{l} \right)^4,$$

$$I_\omega = \frac{3}{8} d l^5,$$

and

$$\kappa = \frac{9}{4} d l^3.$$

G is the shear modulus.

For the thimble geometry, $m = 3.21$; for $L = 56.4$ in., the critical moment $M_{cr} = 713,000$ lb-in. This moment is considerably larger than M_B , the moment about point B in Fig. 1 (i.e., 19,800 lb-in.), so no global loss of stability would be expected.

F. Stress Computations and Conclusions for Bending of the Thimble

In the preceding sections, all the equations were given for the determination of the various stresses. For $F_A = P^* = 630$ lb, the resulting stresses for the outer fibers of flat No. 6 are given in Table I.

Table I. Calculated Stress Values for Thimble (ksi)

<u>Hoop Stress</u>			<u>Axial Stress</u>			<u>Buckling Stress</u>
$\sigma_s^{(d)}$	$\sigma_s^{(b)}$	$\sigma_s^{(T)}$	$\sigma_z^{(d)}$	$\sigma_z^{(b)}$	$\sigma_z^{(T)}$	σ_{cr}
-26.6	-416.9	-443.5	-11.5	-98.3	-109.8	-94.3

One can make the following interesting conclusions from the stress values shown in the table:

1. For an elastic-slightly plastic type of material, which the irradiated thimble could well be, yielding would first occur as a result of the hoop stress. For example, if the room-temperature yield stress of the material is 120,000 psi,^{6,7} yielding from the hoop stress would occur at a load $P^* = 170$ lb, whereas yielding of the inner and outer fibers from the axial stress may not have occurred at $P^* = 630$ lb.

2. The analysis of local buckling, although a somewhat rough analysis (i.e., it simplified treatment of adjoining flats and is not considered to be conservative), definitely indicates that such buckling could be a possible cause of failure. Although $\sigma_{cr} < \sigma_z^{(T)}$, a geometrically imperfect structure (the compressed thimble flat, even if initially perfect, is bent out of plane) is considered to buckle at 0.35-0.50 of the buckling load for a perfect structure. This would indicate that the force with which the thimble was pulled could be well below the maximum value of 630 lb and still cause buckling.

3. In terms of the axial stress, σ_z , beam theory tends to underestimate the fiber stress by nearly 10% by not taking into account the contribution from distortion.

It is postulated that failure was first initiated from cracks formed by the excessive hoop stress, and these cracks, coupled with other localized distortions across flat No. 6, would significantly lower the buckling strength. In summary, the stress calculations do disclose that yielding and failure would occur at much lower loads than that required for yielding in the axial fibers.

Postulation of the thimble failure from the above stress analysis necessarily restricts the thimble to an elastic-slightly plastic material, i.e., a material that displays a small amount of ductility. Such an analysis has no meaning for a premature failure, e.g., grain-boundary embrittlement in which the material might be expected to fail under a loading condition below that at which yielding would occur. The thimble after bending did display evidence of bulk plastic behavior in that a permanent set (bow) was measured after loading. Localized plastic flow was also observed (see Sec. V).

G. Bowing and Deflection Analysis

Just prior to the inadvertent loading of the thimble, flat-to-flat and corner-to-corner dimensional measurements were obtained. (These measurements were shown in Fig. 4.) The bowing due to irradiation is anticipated to be nearly the same as that measured for CRT 5F3, which had a similar irradiation history. The curvature of each thimble was toward the core center, and the maximum displacement of CRT 5F3 in reference to the thimble axis was 0.075 in. The ex-reactor loading of CRT 5E3 (see Fig. 1) bent the thimble opposite to the bow formed by irradiation. The bow, or permanent deflection, resulting from the loading event was measured; the maximum displacement was 0.16 in. Therefore, the total permanent bow as a result of the bending type of loading would be around 0.24 in.

An analysis of the elastic deflection that occurs at point A in Fig. 11 requires consideration of the geometry of the entire thimble. The thimble as shown in Fig. 11 consists of a thin hexagonal shell ($L_3 = 49.9$ in.), a hexagonal tube ($L_4 = 16$ in.), and a circular tube ($L_5 = 22.0$ in.). The cross-sectional dimensions of these geometries are shown at the bottom of the figure.

Fig. 11. Thimble Geometry and Description of Cross Sections

The corresponding moments of inertia for the three geometries are

(a) Hex shell: $I_o = \frac{5}{2} d\ell^3 = 0.231 \text{ in.},$

(b) Hex tube: $I_1 = \frac{\ell(2h)^3}{12} + \frac{4}{12} \frac{\ell}{2} h^3 - \frac{\pi d^4}{64} = 0.4605 \text{ in.},$

and

(c) Circular tube: $I_2 = \frac{\pi}{64} [d_o^4 - d_i^4] = 0.4705 \text{ in.}$

By normalizing the last two moment of inertias to that for the hexagonal shell, we obtain the following expression for describing the displacement, W_A , due to bending at point A:

$$\begin{aligned} EI_o W_A^{(b)} = & \frac{1}{3} L_1 P^* L_1^2 + \frac{1}{3} (L_3 - L_1) P^* [(L_1^2 + \lambda_1^2) + L_1 \lambda_1] \\ & + \frac{1}{3} L_4 P^* [(\lambda_1^2 + \lambda_2^2) + \lambda_1 \lambda_2] \frac{I_o}{I_1} + \frac{1}{3} L_5 P^* \lambda_2^2 \cdot \frac{I_o}{I_2}, \end{aligned} \quad (33)$$

where

$$\lambda_1 = L_1 \frac{L_4 + L_5}{L_2} = 21.22$$

and

$$\lambda_2 = L_1 \frac{L_5}{L_2} = 12.29.$$

With substitution of the appropriate values for length into Eq. (33), the displacement due to bending becomes

$$W_A^{(b)} = \frac{2.62 \times 10^4}{EI_o} P^* = 3.781 \times 10^{-3} P^*. \quad (34)$$

There is another contribution to the deflection at point A, and that is due to shear. The shear contribution is given as⁸

$$W_A^{(s)} = \alpha \frac{P^* L_1}{GA}, \quad (35)$$

where α (for an equivalent I-beam) is⁸

$$\alpha = \frac{A}{(2d)I} \left[\frac{1}{8} \ell (2h)^2 - \frac{1}{8} (2h - 2d)^2 (\ell - 2d) \right] = 1.860 \quad (36)$$

Since $A = 6d\ell = 0.317 \text{ in.}^2$ for the hexagonal shell and

$$G = \frac{E}{2(1 + \nu)} = 11.54 \times 10^6, \quad (37)$$

the shearing contribution to the deflection at point A becomes

$$W_A^{(s)} = 1.60 \times 10^{-5} P^*. \quad (38)$$

Therefore, from Eqs. (34) and (38), the total deflection at point A with respect to B is

$$W_A = 0.380 \times 10^{-2} P^*. \quad (39)$$

The maximum elastic deflection that could have occurred (i.e., for $P^* = 630 \text{ lb}$) would be around 2.4 in. However, for a load P^* equal to 170 lb, which is the load where localized yielding could occur due to the hoop stress, the deflection would be around 0.65 in.

The flattening (reduction in distance between opposite corners or flats) that could occur at B can also be estimated. It is described by the expression

$$\kappa_f = \frac{5}{108} \left(\frac{16d^2}{5\ell^2} \right)^{1/4} \frac{h}{d^3} \frac{1}{E} P^*, \quad (40)$$

which, with substitution of the appropriate values, becomes

$$\kappa_f = 2.55 \times 10^{-5} P^*. \quad (41)$$

For a load $P^* = 170 \text{ lb}$, the flattening is around $4.3 \times 10^{-3} \text{ in.}$

V. STRUCTURAL ASSESSMENT OF THE FRACTURE REGION

The structural evaluation of selected portions of the fracture region of the thimble was obtained through scanning electron microscopy (SEM), transmission electron microscopy (TEM), and optical microscopy. The intent of these observations was twofold: (1) to gain some knowledge of the material's microstructure after irradiation, and (2) to assess the fracture and microstructure resulting from the loading event. In both areas of evaluation, the structure study was intended to be qualitative rather than thorough.

The areas of the fracture region examined are shown in Fig. 12. The surface of the fragment expelled from flat No. 5 was examined by SEM, and the interior of the fragment was examined for voids, dislocations, etc., by TEM. The piece cut from flat No. 6 was cut into smaller pieces as shown at the bottom of Fig. 12. One of those pieces was metallographically prepared and viewed in a metallograph, and another was examined by SEM.

A. Fractography and Optical Microscopy

The two sections of the fracture region examined by SEM display two distinct types of fracture surface. One type was observed on a surface that ran parallel to a hoop direction on the expelled fragment. The other type of fracture was associated with an axially aligned crack from the load region section of flat No. 6.

The fracture observed along the hoop direction of the expelled fragment is shown in Fig. 13. The surface has three characteristic features:

1. It appears brittle in that essentially no reduction in area occurred.

2. The surface of the fracture appears to have plastically flowed over a very limited region along the fracture path.

3. The fracture path seems to change direction after traveling distances on the order of the grain dimensions, thereby indicating that the fracture may have followed grain boundaries. The grain size was measured by optical metallography on a section perpendicular to the fracture surface.

Our present interpretation of this fracture behavior is as follows. A narrow region along the grain boundaries is without radiation-produced

Fig. 12. Sections of Fracture Region Selected for Structural Examination

*Fig. 13. Fracture Surface along Hoop Direction of Expelled Fragment
(Mag 180X)*

voids and is thus softer (i.e., has a lower yield stress) than the matrix. The material along the grain boundary would flow plastically over a limited region, thus forcing the crack to propagate along the path outlined by the grains. This can occur only after high fluences have made the matrix very hard. The result is a low-ductility, high-strength failure.

The other surface examined, which runs parallel to the thimble axis, exhibits a fracture appearance (see Fig. 14) that has been attributed⁹ to channel fracture. The surface exhibits flat facets, which give the surface a cleavage appearance. It is difficult, however, to describe the fracture as cleavage, since the structure of the material is face-centered cubic. A similar type of fracture surface was observed by Fish *et al.*⁹ on a Type 304 stainless steel tensile sample from a hex-can flat irradiated to $\sim 1.0 \times 10^{23} \text{ n/cm}^2$ ($> 0.1 \text{ MeV}$) and tensile-tested at 700°F . Their explanation follows. At the yield stress, initial plastic deformation occurs randomly throughout the material. However, the passage of dislocations through a portion of material makes further deformation in that region easier (work softening) rather than more difficult (work hardening) so that further deformation is restricted to small regions. For example, sheared voids are evidence that plastic deformation has occurred locally. Continual deformation will eventually lead to separation along these narrow bands, thereby

Fig. 14. Fracture Surface along Axial Direction of Load Region Section of Flat No. 6, Near the 6-5 Node (Mag 560X)

leaving a flat surface. The result is again a high strength-low ductility type of failure.

It is difficult to associate the two distinct fracture surfaces with the stress analysis given earlier, since the stress state and the resulting fracture pattern were quite complicated. Also, all the analysis and evaluation was restricted to postloading behavior without the benefit of any intermittent examination during loading. For example, the fracture surface shown in Fig. 13 cannot be attributed to crack formation due to yielding in the hoop direction without subjecting another thimble to a controlled test, i.e., a test that loads the thimble above the yield stress in the hoop direction but is terminated before buckling occurs.

Optical-microscopy examination of some sections of the fracture region was intended for determining grain size as well as obtaining some insight on crack propagation within the hex-can wall. Figure 15 is a series of photographs taken for examining interior crack propagation in the piece shown in Fig. 12. Except for the small transgranular crack shown in (c) of Fig. 15, which terminates within the grain and at the fracture surface, the cracks appear to be fairly well restricted to the fracture surfaces.

(a) LOCATION NO. 1 (MAG 100X)

(b) LOCATION NO. 2 (MAG 100X)

Fig. 15. Photomicrographs of Structure across Thimble Wall. Approximate locations of areas are shown in Fig. 12

(c) LOCATION NO. 3 (MAG 250X)

(d) LOCATION NO. 4 (MAG 250X)

Fig. 15. Photomicrographs of Structure across Thimble Wall. Approximate locations of areas are shown in Fig. 12 (contd)

B. TEM Examination

TEM was performed only on the fracture fragment (see Fig. 12) expelled during loading. Prior to TEM examination, a small portion was cut from the fragment for SEM examination of the fracture surface. (This fracture surface was shown in Fig. 13.) An immersion-density measurement was obtained on the remaining piece. The volume increase based on this measurement was 9.0% $\Delta V/V$.

Before the disks suitable for thinning for TEM examination could be cut, the fragment had to be electro-thinned in a 50-50 solution of concentrated sulfuric and phosphoric acids. The thickness of the fragment was reduced from about 0.042 in. to 0.012 in. by that thinning. Disks suitable for foil preparation were then obtained by spark erosion of the residual fragment.

Several foils were examined from the thimble piece. Figures 16-22 show some of the results. The electron micrograph shown in Fig. 16 is typical of the void size, morphology, and distribution. Some void measurements were made from this figure; the results are shown in Table II. The average void size and the number density are in reasonable agreement with values for high-fluence control-rod thimbles reported by others.¹⁰ Figure 17 plots the void size distribution obtained from Fig. 16. Also shown in Fig. 16 is a residual hole left by a large precipitate or inclusion that was probably removed during the polishing step.

Considerable precipitation was observed along the grain boundaries, an example of which is shown in Fig. 18. The precipitation could not be retained during polishing, so it was not identified.

Attempts to evaluate the dislocation structure of the fragment were not completely successful. Figure 19 exemplifies the dislocation structure observed. The apparent density is so large that a number density cannot be measured. The large density is most likely associated with the long irradiation history. Any contribution from the loading event is beyond resolution.

There is evidence that plastic deformation has occurred at distances of up to about 3/16 in. from the fracture surfaces of the fragment. Figure 20 shows a network of intersecting slip bands and the sheared voids that

(Text continues on p. 57)

TABLE II. Void Measurements and Estimates of Associated Parameters in Fragment^a

Void Size, Å			Number Density (per cm ³)	$\Delta V/V$, %	
<u>Min</u>	<u>Max</u>	<u>Avg</u>		<u>From Immersion Density</u>	<u>From Void Volume</u>
70	460	230	$\times 10^{15}$	+9.0	+7.6

^aPeak total fluence, $1.2-1.7 \times 10^{23}$ nvt; irradiation temperature, 775-850°F; foil thickness, 900 Å.

Fig. 16. Typical Void Size, Morphology, and Distribution in Expelled Fragment. Hole left by large precipitate or inclusion is at upper right.

Fig. 17. Void Size Distribution in Expelled Fragment

Fig. 18. Residual Holes Left by Precipitates Removed from Grain Boundaries During Polishing of Expelled Fragment

Fig. 19. Dislocation Structure in Expelled Fragment

2000Å

Fig. 20. Intersecting Deformation Bands Approximately 3/16 in. from a Fracture Surface in Expelled Fragment

2000 Å

Fig. 21. Sheared Voids in Expelled Fragment

2000 Å

Fig. 22. Deformation Bands and Sheared Voids Adjacent to Polishing Perforation in Expelled Fragment

(text continued from p. 48)

lie in them. The width and the spacing of the bands shown are about $1000 \text{ \AA}$ and $7000 \text{ \AA}$, respectively. It would be expected that the slip bands are associated with low-temperature as opposed to high-temperature deformation, because (1) the bands are planar and not wavy, and (2) the voids are greatly sheared in the bands and show no evidence of shape recovery.

Figures 21 and 22 provide a closer look at the sheared voids. In Fig. 21, the band is out of contrast, but the sheared voids are quite evident. Some of these voids have undergone shearing strains as high as 100%.

In conclusion, the TEM results disclosed

1. void volume changes that agree with immersion-density values,
 2. void sizes and numbers that agree with those observed by others,
- and
3. evidence of plastic deformation in regions far removed from the original fracture surfaces.

The structural examination, in summary, showed evidence that failure of the thimble as a result of the bending mode of loading was characteristic of a high-strength, low-ductility material. Failure would, therefore, be associated with rather localized yielding. As a result, an elastic analysis (applicable to the elastic limit) such as the one presented in this report is very useful in describing the stress state where yielding would first occur.

There was no evidence in the structural examination to lead us to believe that failure could have been of a premature type, e.g., grain-boundary embrittlement. Therefore, it is concluded that localized yielding did occur, most likely due to the high hoop stresses. Because of the low ductility of the material, however, cracks were initiated and propagated to form the complex crack pattern, possibly in conjunction with ensuing buckling

VI. CONCLUSIONS

Several significant contributions resulted from the evaluation of the ex-reactor loading and resulting fracture that occurred in CRT 5E3. The most important aspect of the evaluation is the elastic stress analysis of the loading event. The stress analysis addressed the complicated geometry

afforded by the hex shell, as well as the deformation modes with both bending and distortion. The analysis disclosed the following:

1. Of all the stress components generated from the bending of the thimble, hoop stress is the most probable to initiate failure. Crack initiation would most likely occur due to localized yielding from the hoop stress.

2. Localized buckling is also a possible failure mode, but it would probably be preceded by yielding from the hoop stress.

3. Plastic yielding of the axial fibers from the axial stresses is less likely to be a failure mode when compared to the hoop and buckling stresses.

The elastic stress analysis used in this study is quite useful for application to thin-wall hexagonal shapes, especially when applied to materials that possess very low ductilities, i.e., materials in which the onset of failure occurs slightly above the yield stress. The thimble examined in this study can be described as such a material. Evidence to support the thimble as being a high strength-low ductility material was generated in the structure evaluation. Examinations of the fracture surfaces and nearby regions by SEM, TEM, and optical microscopy gave ample evidence of localized plastic flow. There was no structural evidence that the thimble could have failed prematurely, i.e., at stresses below the elastic limit.

VII. ADDITIONAL STUDIES

Further studies on the thimbles are under way. These will address analysis and evaluation of thimble behavior under in-reactor conditions and should eventually lead to quantitative guidelines for thimble service in EBR-II. The studies consist of: (1) elastic analysis (stress, strain, and deflection) of various loading modes on hex cans; (2) evaluation of all current and potential (e.g., transient) loading conditions in the reactor, including loads, hence stresses, that can arise during reactor operation as well as during handling and manipulation; (3) elastic stress analysis for all loading conditions considered; and (4) establishment of preliminary guidelines for thimble service in EBR-II, based on elastic considerations.

As this report is being written, controlled tests on strain-gauged unirradiated hex cans are under way to confirm the semimembrane stress analysis. In addition, stress analyses, deflection analyses, and formula tabulation are nearly completed for the following: bending, axial tension and compression, torsion, internal loading, transient loading, thermoelastic loading, frictional loading, point and localized distributed loads, combined loadings, various boundary conditions, and finite-element verification of analysis.

In-reactor fracture of thimbles and ducts is an important concern in all fast-reactor designs. The results obtained from the completed and ongoing studies described in this report should provide a basis for analyzing other systems employing the hex-can geometry.

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