MASTER

EXTERNAL DISTRIBUTION AUTHORIZED

ORNL
Central Files Number
61-3-69

113

EGCR CORE STRUCTURAL ANALYSIS

The Effects of Fast-Neutron Irradiation and the
Bowing Characteristics of the Graphite Columns

S. E. Moore
W. A. Shaw

NOTICE

This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report. The information is not to be abstracted, reprinted or otherwise given public dissemination without the approval of the ORNL patent branch, Legal and Information Control Department.

OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for the

U.S. ATOMIC ENERGY COMMISSION

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

External Distribution Authorized

ORNL

Central Files Number

61-3-69

EGCR CORE STRUCTURAL ANALYSIS

The Effects of Fast-Neutron Irradiation and the Bowing
Characteristics of the Graphite Columns

S. E. Moore

W. A. Shaw

DATE ISSUED

APR 14 1961

OAK RIDGE NATIONAL LABORATORY

Oak Ridge, Tennessee

operated by

UNION CARBIDE CORPORATION

for the

U. S. ATOMIC ENERGY COMMISSION

ABSTRACT

An analysis of the EGCR core structure was made to determine the lateral deflections (bowing) of the graphite columns resulting from shrinkage caused by fast-neutron irradiation, the life expectancy of each column due to restraints imposed on the bowing, and the reaction forces induced in the supporting structures. Based on currently available data for EGCR type graphite shrinkage and assuming experimental loop operation, a maximum bowing potential of 3.61 in. was calculated for an interior column. It was found that strains equivalent to the rupture strains observed from tensile tests could be expected after 4 to 6 years of full-power operation. Over half of the columns will reach these strains before the 20-yr reactor design life has been reached.

TABLE OF CONTENTS

	<u>Page No.</u>
SUMMARY	4
NOMENCLATURE.	5
AN ESTIMATE OF THE BOWING OF GRAPHITE COLUMNS DUE TO IRRADIATION.	6
Approximating Planes	7
Radius of Curvature.	9
Unrestrained Bowing.	11
Restrained Bowing.	15
COLUMN LIFE	21
FORCES ON SUPPORT LATTICE	26
Lattice Force History.	26
Maximum Deformation of Members	27
LEAST SQUARES FIT OF FAST-NEUTRON EXPOSURE DATA	29
HOOR GLASS SHRINKAGE.	30

SUMMARY

The fast-neutron exposure in the EGCR graphite core leads to column bowing. Steel bands around the periphery of the core limit the lateral deflection so that stresses are set up in the graphite columns and lateral forces are exerted on the structural members at the top and bottom of the core. These stresses and forces may lead to column failures during the design life of the reactor which will result in operation difficulties.

The amount of bowing depends on the fast-neutron flux distributions in both the radial and axial directions. Mathematically, the problem is similar to a thermoelastic problem. The complicated nature of the radial flux distribution makes an exact analysis of the bowing prohibitive. However, if the lateral deflection is small relative to the length of the column, a good estimate can be obtained by assuming that the strains in the axial directions are unaffected by the transverse stresses and that plane cross-sections remain plane during deformation. Expressions are developed for calculating the lateral deflection, bending strains, end reaction forces, and the life expectancy of the columns. Since the physical properties, the irradiation induced shrinkage rate, and the maximum strain which graphite can accommodate before failure vary widely for different types of graphite, the resulting formulas were developed so that changes in these numbers can be evaluated easily.

Using recommended values, the analysis of the EGCR core shows that based on irradiation induced shrinkage data alone over half of the columns will undergo strains equivalent to those experienced at rupture before the end of the 20-yr design life, and the first failure from this source may occur after 4 to 6 yr of full-power operation.

NOMENCLATURE

- ϵ_z = axial strain, in./in.
 $\epsilon_z(x)$ = ϵ_x axial strain caused by deflection in x direction
 $\epsilon_z(y)$ = ϵ_y axial strain caused by deflection in y direction
 γ = coefficient of irradiation growth (negative for shrinkage),
in./in./1000 Mwd/AT
D = fast-neutron exposure, 1000 Mwd/AT
 Ψ = fast-neutron exposure at reactor mid-plane, Mwd/AT
(i,j) = coordinate positions of exposure
L = half column height
 ℓ = length of 1/4 period of $\cos \frac{\pi z}{2\ell}$
w = a geometric constant, $w = \frac{2\ell}{\pi^2} [2\ell + \pi (L-\ell)]$
 ζ, ξ, η = cartesian coordinates of a generic slide of the column
x = deflection of the column in the x direction
y = deflection of the column in the y direction
z = axial position
A,B,C = coefficients of the approximating plane
 ℓ, m, n = direction cosines of the approximating plane
 ρ = radius of curvature of the column
 Θ = angle between the tilted top surface of the element Δz relative
to the bottom surface
 Δ = the distance a column may bow before contact with the adjacent
column
 t_o = the time of initial contact, yr
T = the life of a column, yr
 c_x, c_y = the maximum distance of a fiber from the centroid of the column,
in.
 R_e, R_L = the rate of application $\frac{d(\dots)}{dt}$

AN ESTIMATE OF THE BOWING OF GRAPHITE COLUMNS DUE TO IRRADIATION

The graphite core of the EGCR¹ consists of 120 columns 232 in. long. The basic geometry of the cross section of the columns is a square 16 in. x 16 in. This geometry is modified for the outer columns so that the entire core is circular. Most of the inner columns have from two to four 5 1/4-in. full length channels for housing the fuel elements. In addition, there are four 6 1/4-in. diameter channels and four 11-in. diameter channels for test loops (see Fig. 1). Each column is restrained at the bottom support plate by a square pin inset into the bottom of the column and at the top by a lattice of steel beams. The columns are closely packed and three steel bands surround the periphery of the core near the mid-plane so that the lateral deflections (bowing) will be limited.

The effect of neutron irradiation on the deformation of a solid resembles closely the effect of temperature. Consequently, any distribution of neutron flux nonlinear in the space coordinates x , y , z will cause stresses as well as deformation in the body. The evaluation of these effects would constitute a problem analogous to a problem in thermoelasticity.

The fast-neutron flux exposure for the graphite moderator columns of the EGCR is essentially sinusoidal in the axial direction. Normal to the axis it is considerably more irregular. Data for the exposure at the reactor mid-plane (horizontal) have been computed by numerical techniques and given in tabular form.² The exposure pattern is identical in each quadrant of the core. In addition, the exposure is symmetrical about the 45° lines through the experimental loops; hence, the transposed numbering system was used in Fig. 1. Exposure lines for a typical column cross

¹"Experimental Gas-Cooled Reactor Preliminary Hazards Summary Report," ORO-196 (May 1959), pp 36-39.

²Personal communication with C. A. Preskitt, Reactor Division, ORNL.

section at the mid-plane are shown in Fig. 2. The complicated nature of the flux makes an exact analysis of the problem prohibitive. However, an estimate of the bowing of the column can be made by assuming the strain in the axial direction is unaffected by the transverse stresses, that is

$$\epsilon_z = \gamma D + C$$

where ϵ_z is the normal strain component in the axial direction, D is the neutron exposure (time dependent), and γ is the coefficient of irradiation growth. C is a constant (different for each fiber) such that plane cross sections remain plane.

The additional inplane stresses caused by flux and temperature gradients around the fuel channels are considered in separate studies. The general effect of the plane stresses would be to decrease the column life and reduce the lattice structure forces but would not change the bowing rate.

Consider a generic slice of a column of length Δz . According to the assumption, each unrestrained fiber (that is, $C = 0$) will elongate a length

$$\epsilon_z \Delta z = \gamma D \Delta z \quad . \quad (1)$$

If the base plane of the slice is taken as a reference, then the top plane will become a warped irregular surface corresponding to the irregularity of the flux (see Fig. 3). The assumption that plane sections remain plane requires that the warped surface be approximated by a plane. The new configuration of the slice is equivalent to a uniform extension plus a rotation of the top plane relative to the base plane. Only the latter contributes to the bowing of the column.

Approximating Planes

The neutron exposure of each graphite column is a function of time t as well as space. It is approximately of the form

$$D(x,y,z,t) = \begin{cases} \psi(x,y,t) \cos \frac{\pi z}{2l} & ; 0 \leq z \leq l \\ 0 & ; l < z \leq L \end{cases} \quad (2)$$

where l is the length corresponding to the intersection of the cosine curve and the horizontal axis in Fig. 4, and L is one-half of the column length (116 in.). The length l was taken as 100 in. in all cases even though it varies slightly from column to column.

The unrestrained elongations of a longitudinal fiber of a generic slice of a column (see Fig. 5) of length Δz is

$$\delta(\Delta z) = \epsilon_z \Delta z \quad .$$

The new position (see Fig. 6) of each cross point of the grid relative to the original position of the top surface is given by

$$\zeta_{ij} = r \psi_{ij} \cos \frac{\pi}{l} z \Delta z \quad ; \quad 0 \leq z \leq l \quad (3)$$

where ψ_{ij} is the tabulated exposure value for $x = i$ and $y = j$. The equation of the approximately plane relative to the original position of the top surface, without subscripts, may be written in the general form

$$\bar{\zeta} = A\bar{\xi} + B\bar{\eta} + C \quad (4)$$

where $\bar{\zeta} = \zeta/\Delta z$ is now dimensionless. The coefficients can be determined by the method of least squares using the computed data points ζ_{ij} for any value of z and Δz . For convenience, let

$$\bar{\zeta}_{ij} = \frac{\zeta_{ij}}{r \Delta z \cos \frac{\pi}{2l} z} \quad (= \bar{\psi}_{ij}) \quad . \quad (5)$$

Then

$$\bar{\zeta} = \bar{A}\xi + \bar{B}\eta + \bar{C} \quad . \quad (6)$$

The coefficients $\bar{A}$, $\bar{B}$, and $\bar{C}$ have been computed by the method of least squares for the numbered columns in Fig. 1.

Since the exposure is time dependent, it will be useful to have $\bar{\zeta}$ as a time dependent quantity. The total exposure was calculated for 20 years; therefore, let $\bar{A}_0 = 1/20 \bar{A}$, $\bar{B}_0 = 1/20 \bar{B}$, and $\bar{C}_0 = 1/20 \bar{C}$. Equation (6) can then be written as

$$\bar{\zeta} = \bar{A}_0 t \xi + \bar{B}_0 t \eta + \bar{C}_0 t \quad . \quad (7)$$

The values of the constants are given in Table 1.

Radius of Curvature

The direction cosines of the normal to the plane

$$\zeta = A\xi + B\eta + C \quad (8)$$

are given by

$$\ell = \frac{-A}{\sqrt{A^2 + B^2 + 1}} \quad m = \frac{-B}{\sqrt{A^2 + B^2 + 1}} \quad n = \frac{1}{\sqrt{A^2 + B^2 + 1}} \quad . \quad (9)$$

The angle between the tilted top surface of the element Δz relative to the bottom surface is $\theta = \cos^{-1} n$ (see Fig. 7). The curvature is

$$1/\rho = \frac{\sin \theta}{(\zeta)_{\text{avg}} + \Delta z} \quad .$$

But, $(\zeta)_{\text{avg}} \ll \Delta z$; that is, for the element at the mid-plane $(\zeta)_{\text{avg}}$ is approximately 0.02 in./in. Therefore,

Table 1. Linear Exposure Coefficients

Column Number	$\bar{A}$	$\bar{B}$	$\bar{C}$	$\bar{A}_o$	$\bar{B}_o$	$\bar{C}_o$
67	-0.95947514	-0.95947514	85.106876	-0.047973757	-0.047973757	4.2553438
79	-0.29047236	+0.55373745	74.397592	-0.014523618	+0.0276868725	3.7198796
80	-0.18271475	-0.18271475	76.553466	-0.0091357375	-0.0091357375	3.8276733
91	-0.26935670	-0.82150570	80.970297	-0.013467835	-0.041075285	4.04851485
92	-0.84513033	-1.0020565	77.273375	-0.042256516	-0.050102825	3.86366875
93	-2.0917830	-2.0917830	71.232338	-0.10458915	-0.10458915	3.5616169
102	-0.25377307	-2.0070107	69.226613	-0.0126886535	-0.100350535	3.46133065
103	-0.79631971	-1.7562773	62.245988	-0.0398159855	-0.087813865	3.1122994
104	-1.9997444	-0.90451756	41.802890	-0.09998722	-0.045225878	2.0901445
105	-0.39036803	-0.39036803	9.5511899	-0.0195184015	-0.0195184015	0.47755949
111	-0.059171354	-1.2588669	19.806193	-0.002958568	-0.062943345	0.99030965
112	-0.15276021	-1.0422152	17.083123	-0.0076380105	-0.05211076	0.085415615
113	-0.34068529	-0.44684100	9.5769913	-0.0170342645	-0.02234205	0.478849565
114	-0.051503072	-0.065322058	1.1905386	-0.0025751536	-0.0032661029	0.05952693
118	-0.0019252243	-0.043139638	0.58454179	-0.00096261215	-0.0021569819	0.0292270895
119	-0.010338253	-0.036766736	0.52343631	-0.0051691265	-0.0018383368	0.0261718155
120	-0.012372867	-0.030950980	0.31163987	-0.00061864335	-0.001547549	0.0155819935

$$1/\rho \cong \frac{\sin\theta}{\Delta z} = \frac{\sqrt{1 - \cos^2\theta}}{\Delta z} = \frac{1}{\Delta z} \sqrt{1 - n^2} \quad .$$

The equation of the plane in terms of the computed coefficients $\bar{A}$, $\bar{B}$, and $\bar{C}$ is

$$\zeta = \bar{A}(\gamma \Delta z \cos \frac{\pi}{2\ell} z) \xi + \bar{B}(\gamma \Delta z \cos \frac{\pi}{2\ell} z) \eta + \bar{C}(\gamma \Delta z \cos \frac{\pi}{2\ell} z) \quad .$$

From which

$$n = \frac{1}{\left[\bar{A}^2(\gamma \Delta z \cos \frac{\pi}{2\ell} z)^2 + \bar{B}^2(\gamma \Delta z \cos \frac{\pi}{2\ell} z)^2 + 1 \right]^{1/2}}$$

and

$$1 - n^2 = \frac{\bar{A}^2(\gamma \Delta z \cos \frac{\pi}{2\ell} z)^2 + \bar{B}^2(\gamma \Delta z \cos \frac{\pi}{2\ell} z)^2}{\bar{A}^2(\gamma \Delta z \cos \frac{\pi}{2\ell} z)^2 + \bar{B}^2(\gamma \Delta z \cos \frac{\pi}{2\ell} z)^2 + 1} \quad .$$

The first two terms of the denominator can be neglected relative to one. The curvature then becomes

$$1/\rho = \gamma \sqrt{\bar{A}^2 + \bar{B}^2} \cos \frac{\pi}{2\ell} z \quad . \quad (10)$$

Unrestrained Bowing

The direction of the axis of rotation can be obtained by setting $\zeta = \text{constant}$, Eq. (8). Then

$$\eta = - (A/B) \xi + \text{constant} \quad .$$

The slope of the axis of rotation in the ξ, η plane is then $-A/B$.

The new position of the top plane of the element can be thought of as resulting from a uniform displacement in the ζ direction plus rotations

about axes parallel to the ξ axis and η axis (see Fig. 8). The three motions are described by the equations

$$\zeta_1 = B_1 \eta + C_1$$

$$\zeta_2 = A_2 \xi + C_2$$

$$\zeta_3 = C_3 \quad (= \zeta_{\text{avg}}) \quad .$$

If

$$\zeta = \zeta_1 + \zeta_2 + \zeta_3$$

then

$$A_2 = A,$$

$$B_1 = B,$$

$$C_1 + C_2 + C_3 = C \quad .$$

The axes of rotation are taken parallel to the ξ and η axes passing through a point $\xi = e_1$ and $\eta = e_2$ corresponding to the centroid of the cross section in elementary beam theory (see Fig. 9). At

$$\eta = e_2$$

$$\zeta_1 = 0$$

then

$$C_1 = - B e_2 \quad .$$

Similarly,

$$C_2 = - A e_1 \quad .$$

Also,

$$c_3 = \zeta_{avg} \quad .$$

The radius of curvature of the plane that rotates about $\eta = e_2$, $\zeta = \zeta_{avg}$ can be determined from similar triangles of Fig. 10. That is,

$$\frac{e_2}{\rho_\eta} = \frac{-Be_2}{\Delta z - \zeta_{avg}} \quad .$$

Since

$$\zeta_{avg} \ll \Delta z \quad .$$

Then

$$\frac{1}{\rho_\eta} = - \frac{B}{\Delta z} \quad .$$

Substituting

$$B = \bar{B} \gamma \Delta z \cos \frac{\pi}{2l} z \quad . \quad (11)$$

The curvature becomes

$$\frac{1}{\rho_\eta} = - \bar{B} \gamma \cos \frac{\pi}{2l} z \quad . \quad (12)$$

Similarly, the curvature in the ξ direction is

$$\frac{1}{\rho_\xi} = - \bar{A} \gamma \cos \frac{\pi}{2l} z \quad . \quad (13)$$

Let the bow of the column in the two perpendicular directions be given by the coordinates x and y as shown in Fig. 4. Then, for small curvature,

$$d^2x/dz^2 \begin{cases} = - \bar{A} \gamma \cos \frac{\pi}{2l} z & ; \quad 0 < x < l \\ = 0 & ; \quad l < x < L \end{cases} \quad (14)$$

$$d^2y/dz^2 \begin{cases} = -\bar{B}\gamma \cos \frac{\pi}{2l} z & ; \quad 0 < z < l \\ = 0 & \quad \quad \quad l < z < L \end{cases} .$$

Integrating gives

$$\begin{aligned} x &= \begin{cases} \bar{A}\gamma \left(\frac{2l}{\pi}\right)^2 \cos \frac{\pi}{2l} z + C_1 z + C_2 & ; \quad 0 < z < l \\ C_3 z + C_4 & ; \quad l < z < L \end{cases} \\ y &= \begin{cases} \bar{B}\gamma \left(\frac{2l}{\pi}\right)^2 \cos \frac{\pi}{2l} z + C_5 z + C_6 & ; \quad 0 < z < l \\ C_7 z + C_8 & ; \quad l < z < L \end{cases} \end{aligned} \quad (15)$$

Both ends are assumed pinned. Then applying the boundary conditions requires

$$C_1 = C_5 = 0$$

$$C_2 = \bar{A}\gamma \frac{2l}{\pi} (L - l)$$

$$C_3 = -\bar{A}\gamma \frac{2l}{\pi}$$

$$C_4 = \bar{A}\gamma \frac{2l}{\pi} L$$

$$C_6 = \bar{B}\gamma \frac{2l}{\pi} (L - l)$$

$$C_7 = -\bar{B}\gamma \frac{2l}{\pi}$$

$$C_8 = \bar{B}\gamma \frac{2l}{\pi} L$$

Substitution yields

$$\begin{aligned} x &= \begin{cases} \bar{A}\gamma\left(\frac{2\ell}{\pi}\right)^2 \left[\cos\left(\frac{\pi z}{2\ell}\right) + \frac{\pi(L-\ell)}{2\ell} \right] & ; \quad 0 \leq z \leq \ell \\ \bar{A}\gamma \frac{2\ell}{\pi} (L-z) & ; \quad \ell < z \leq L \end{cases} \\ y &= \begin{cases} \bar{B}\gamma\left(\frac{2\ell}{\pi}\right)^2 \cos\left(\frac{\pi z}{2\ell}\right) + \frac{\pi(L-\ell)}{2\ell} & ; \quad 0 \leq z \leq \ell \\ \bar{B}\gamma \frac{2\ell}{\pi} (L-z) & ; \quad \ell < z \leq L \end{cases} . \end{aligned} \quad (16)$$

Substitution of the values

$$L = 116 \text{ in.}$$

$$\ell = 100 \text{ in.}$$

$$\gamma = -3.4 \times 10^{-4} \text{ in./in./1000 Mw}\cdot\text{d/AT}$$

gives the maximum deflections at the reactor mid-plane ($z = 0$) for 20 years as (see Table 2)

$$x = -1.7243 \bar{A}$$

$$y = -1.7243 \bar{B} .$$

Restrained Bowing

The macroscopic geometry of the graphite core is assumed to remain unchanged due to irradiation. The core is bound by peripheral bands supporting the outer graphite columns where the flux is low and the tendency to bow is small. Each individual column will initially stand alone, but upon bowing, contact will be made with adjoining columns. The contact forces will restrict motion and consequently cause end reaction forces and stresses in the graphite. These end reaction forces are carried at the bottom of the columns by shear lugs fixed into the core support plate and at the top by the core restraint lattice structure. The behavior of the lattice due to the end reaction forces is discussed in a later section.

Table 2. Bowing Deflection

Column Number	x inches (20 yr)	y inches (20 yr)	x_0 inches (1 yr)	y_0 inches (1 yr)
67	1.65	1.65	0.08272	0.08272
79	0.50	-0.95	0.02504	-0.04774
80	0.31	0.31	0.01575	0.01575
91	0.46	1.42	0.02322	0.07083
92	1.45	1.73	0.07286	0.08639
93	3.61	3.61	0.18034	0.18034
102	0.44	3.46	0.02188	0.17303
103	1.37	3.03	0.06865	0.15142
104	3.45	1.56	0.17241	0.07798
105	0.67	0.67	0.03365	0.03365
111	0.10	2.17	0.00511	0.10853
112	0.26	1.80	0.01317	0.08985
113	0.58	0.77	0.02937	0.03852
114	0.089	0.112	0.00444	0.00563
118	0.003	0.074	0.00016	0.00372
119	0.018	0.063	0.00089	0.00317
120	0.021	0.053	0.00106	0.00267

The time to make contact, t_0 , will differ for each column, but all times are directly proportional to the clearances between the columns. The maximum amplitude of unrestrained bowing over the life of the columns may be large relative to the initial clearance in which case the column may be assumed to be completely restrained.

Upon initial contact the restraint force is assumed to be concentrated at the center of the column. This type of restraining load will not persist for an extended length of time since the column would continue to grow in the shape of a cupids bow which violates the geometry restrictions

(see Fig. 11). The problem may be attacked by replacing the concentrated load after a short time interval with a distributed load and iterating. Due to previous assumptions, the problem does not warrant the additional accuracy obtained by this technique. Instead, the time t_1 was obtained for $a = l/5$ (Fig. 11). At this time the rate of application of the end restraint force is larger than that due to a concentrated force at the center of the column but smaller than that due to the distributed force that completely restrains the column. The increase was taken as 1/5 of the difference between the two limiting conditions. A straight line connecting the two limiting conditions on a rate-time plot was taken as the loading rate (Fig. 12). A second iteration assuming a uniformly distributed load over $l/5$ at the center indicated the assumed line to be slightly conservative.

For the completely restrained column, take the initial shape straight and assume the deflected position to be the same as the unrestrained column. The x-component of the lateral deflection as given by Eq. (16) is

$$x = \begin{cases} \bar{A}\gamma \left(\frac{2l}{\pi}\right)^2 \left[\cos \left(\frac{\pi}{2l} z\right) + \frac{\pi}{2} \frac{(L-l)}{l} \right] & ; 0 < z < l \\ \bar{A}\gamma \frac{2l}{\pi} (z-L) & ; l < z < 2l \end{cases}$$

and

$$\frac{dx}{dz} = -\bar{A}\gamma \frac{2l}{\pi} \sin \frac{\pi}{2l} z \quad ; 0 < z < l$$

$$\frac{d^2x}{dz^2} = -\bar{A}\gamma \cos \frac{\pi}{2l} z \quad ; 0 < z < l$$

$$\frac{d^3x}{dz^3} = \bar{A}\gamma \left(\frac{\pi}{2l}\right) \sin \frac{\pi}{2l} z \quad ; 0 < z < l$$

$$\frac{d^4x}{dz^4} = \bar{A}\gamma \left(\frac{\pi}{2l}\right)^2 \cos \frac{\pi}{2l} z = -q(z) \frac{1}{EI} \quad ; 0 < z < l.$$

Therefore, the distributed load required to keep the column completely restrained is

$$q_x(z) = - \bar{A} \gamma \left(\frac{\pi}{2\ell} \right)^2 EI \cos \frac{\pi}{2\ell} z .$$

The discontinuities in the shear require forces at $z = \pm \ell$ (Fig. 13) of

$$Q_x = \bar{A} \gamma \frac{\pi}{2\ell} EI_y$$

and

$$Q_y = \bar{B} \gamma \frac{\pi}{2\ell} EI_y .$$

These concentrated forces are taken as the reaction forces at the ends of the columns on the top restraint lattice and bottom shear plugs.

The maximum rate of application, $R_{L \max}$, of these lattice forces is

$$R_{L \max} = \frac{dQ_x}{dt} = \bar{A}_0 \gamma \frac{\pi}{2\ell} EI \quad . \quad (17)$$

As before, $\bar{A} = \bar{A}_0 t$.

The equation of the elastic curve of the column initially bowed and then loaded by a concentrated force P_x at the center is

$$x = \bar{A}_0 \gamma \left(\frac{2\ell}{\pi} \right)^2 \left(\cos \frac{\pi}{2\ell} z + \frac{\pi}{2} \frac{L-\ell}{\ell} \right) + \frac{P_x}{EI} \left(-\frac{z^3}{12} + \frac{Lz^2}{4} - \frac{L^3}{6} \right) ; \quad 0 < z < \ell \quad . \quad (18)$$

The magnitude of the force required to keep $x = \Delta$ at $z = 0$ is then

$$P_x = \frac{6EI}{L^3} \left[\Delta - t \bar{A}_0 \gamma \left(\frac{2\ell}{\pi} \right)^2 \left(1 + \frac{\pi}{2} \frac{L-\ell}{\ell} \right) \right] = 2P_L \quad ; \quad 0 < z < \ell \quad (19)$$

where P_L is the lattice force and Δ is the distance the column may bow before contact with the adjacent column. The rate of application R_L of the lattice force is

$$R_L = dP_L/dt = - \frac{3EI}{L^3} \bar{A}_o r \left(\frac{2\ell}{\pi}\right)^2 \left(1 + \frac{\pi}{2} \frac{L-\ell}{\ell}\right) \quad (20)$$

The rate relative to the completely restrained column is found by dividing Eq. (20) by Eq. (17).

$$\frac{R_L}{(R_L)_{\max}} = 3(2/\pi)^3 (\ell/L)^3 \left(1 + \frac{\pi}{2} \frac{L-\ell}{\ell}\right) \quad (21)$$

Substitution of the values

$$\ell = 100$$

$$L = 116$$

gives

$$\frac{R_L}{(R_L)_{\max}} = 0.620 \quad .$$

The time required for $a = \ell/5$ (Fig. 11) can be obtained by substituting $x = \Delta$, $z = \ell/5$, and Eq. (19).

$$P_x = \frac{6EI}{L^3} \left[\Delta - t \bar{A}_o r \left(\frac{2\ell}{\pi}\right)^2 \left(1 + \frac{\pi}{2} \frac{L-\ell}{\ell}\right) \right]$$

into the equation of the elastic curve (Eq. 18). The value of P requires $x = \Delta$ at $z = 0$. This gives, for $t = t_1$,

$$\frac{t_1}{\Delta} = \frac{2\bar{A}_o r \left(\frac{2\ell}{\pi}\right)^2}{14 + e^3 - 3e^2} \left[\left(\cos \frac{\pi}{10} + \frac{\pi}{2} \frac{1-e}{e} \right) + 1/2 \left(1 + \frac{\pi}{2e} - \frac{\pi}{2} \right) (2 + e^3 - 3e^2) \right] \quad (22)$$

where $e = \ell/L$.

Evaluation for the given values of ℓ and L gives

$$t_1/\Delta = - \frac{3.106}{\bar{A}_o} \quad .$$

The initial contact time, t_o , is the distance Δ divided by the bowing rate

$$t_{ox} = \Delta_x / \bar{A}_o \gamma w \quad , \quad t_{oy} = \Delta_y / \bar{B}_o \gamma w^{(3)} \quad (23)$$

where

$$w = \frac{2\ell}{\pi} [2\ell + \pi(L-\ell)] = 5.07144 \times 10^3 \quad .$$

For $\gamma = -3.4 \times 10^{-4}$ in./in./1000 Mwd

$$t_{ox} = -0.580 / \bar{A}_o \quad .$$

The time t_1 relative to the time to make contact, t_o , is

$$\frac{t_1/\Delta}{t_o/\Delta} = \frac{3.106/\bar{A}_o}{0.580/\bar{A}_o} = 5.36 \quad .$$

The values of R_o and T_n in Fig. 12 can now be evaluated since $T_n = 5t_1$. Round-off of the numbers for computation is justifiable, and they were taken as

$$R_{oL} = 0.6 \quad .$$

$$T_n = 25 t_o \quad .$$

The lattice force at any time t is then the area under the curve (Fig. 12).

$$P_L = Q \int_{t_o}^t [R_{oL} + k_L s] ds \quad ; \quad t < 25 t_o \quad (24)$$

³This is not strictly true for columns 67 and 79 which bow toward each other in the y directions. In order to calculate t_{oy} , replace $\bar{B}_o$ by $|\bar{B}_o(67)| + |\bar{B}_o(79)|$.

$$P_L = Q \left\{ \int_{t_0}^{25t_0} [R_{oL} + k_L s] ds + [t - 25t_0] \right\}; \quad t > 25 t_0$$

where k_L is the rate of relative load increase with time.

Calculations of Δ were based on an average installation clearance of 0.045 in. between columns and a difference in thermal expansion of 0.140 in. between the bottom support plate and the upper restraint lattice or an average temperature gap of 0.070 in. The maximum lattice forces and the maximum strain will exist when the reactor is shut down because of the smaller clearance between columns. However, the critical condition for the lattice structure will be at operating temperature when the strength of the steel is lower and creep, if any, will be higher. The values of Δx and Δy used are given in Table 3.

COLUMN LIFE

Even though the properties of graphite change during irradiation, it has been found that the ratio of failure stress to Young's modulus σ_f/E remains nearly constant. It is convenient then to discuss the life expectancy of any given column in terms of the rate of strain application. The total axial strain $\epsilon_z(x,y)$ can be found by superposing the strain caused by limiting the x deflection, and the strain caused by limiting the y deflection, $\epsilon_z(x,y) = \epsilon_z(x) + \epsilon_z(y)$. The components of axial strain caused by completely restraining the beam are

$$\epsilon_z(x)_{\max} = c_x \frac{d^2 x}{dz^2} = \pm c_x \bar{A}_0 t \gamma \cos \left(\frac{\pi}{2l} z \right) \quad (25)$$

and

$$\epsilon_z(y)_{\max} = c_y \frac{d^2 y}{dz^2} = \pm c_y \bar{B}_0 t \gamma \cos \left(\frac{\pi}{2l} z \right)$$

Table 3. Deflection Before Initial Contact

Column Number	Reactor Cold		Reactor Hot	
	Δx (in.)	Δy (in.)	Δx (in.)	Δy (in.)
67	0.045	0.045	0.115	0.115
79	0.225	0.045	0.575	0.115
80	0.180	0.180	0.460	0.460
91	0.225	0.135	0.575	0.345
92	0.180	0.135	0.460	0.345
93	0.135	0.135	0.345	0.345
102	0.180	0.090	0.460	0.230
103	0.135	0.090	0.345	0.230
104	0.090	0.090	0.230	0.230
105	0.045	0.045	0.115	0.115
111	0.135	0.045	0.345	0.115
112	0.090	0.045	0.230	0.115
113	0.045	0.045	0.115	0.115
114	0	0	0	0
118	0	0	0	0
119	0	0	0	0
120	0	0	0	0

where c_x and c_y are the distances from the centroid of the beam.

The rate of strain application at the reactor mid-plane is then

$$R_{e_{\max}} = \frac{d\epsilon_z(x)_{\max}}{dt} = \pm c_x \bar{A}_o \gamma \quad (26)$$

The strain at the mid-plane produced by the concentrated load P (Eq. 19) at time t_o is

$$\epsilon_x = \frac{c_x PL}{4EI_y}$$

where $\epsilon_z(x)$ has been replaced by ϵ_x for notational convenience. The rate of strain application R_ϵ is therefore

$$R_\epsilon = \frac{d\epsilon_x}{dt} = -6C_x \bar{A}_o \gamma \left(\frac{l}{\pi L}\right)^2 \left(1 + \frac{\pi}{2} \frac{L-l}{l}\right) \quad (27)$$

The rate relative to the completely restrained column at time t_o is obtained by dividing Eq. (27) by Eq. (26)

$$R_{o\epsilon} = \frac{R_\epsilon}{R_{\epsilon_{\max}}} = \frac{6}{\pi^2} \left(\frac{l}{L}\right)^2 \left(1 + \frac{\pi}{2} \frac{L-l}{l}\right) \quad (28)$$

which reduces to

$$R_{o\epsilon} = 0.5653 \quad .$$

The strain history is assumed to follow a linear curve (Fig. 12) as was the lattice force. Here again round-off is justified for computation.

$$R_{o\epsilon} = 0.5$$

The strain at any time t is the area under the curve (Fig. 12).

$$\epsilon_x = R_{\epsilon_{\max}} \int_{t_o}^t (R_{o\epsilon} + k_e s) ds \quad ; \quad t \leq 25t_o$$

$$\epsilon_x = R_{\epsilon_{\max}} \left\{ \int_{t_o}^{25t_o} (R_{o\epsilon} + k_e s) ds + (t - 25t_o) \right\} \quad ; \quad t > 25t_o$$

The life T of the column is defined as the time in years of full-power operation required for the sum $\epsilon_x + \epsilon_y$ to reach the critical value ϵ_f .

For EGCR the integrals reduce to

$$\epsilon_f = T^2 \gamma^2 \frac{w}{12} \left(\frac{\bar{A}_o^2}{\Delta x} + \frac{\bar{B}_o^2}{\Delta y} \right) + T \gamma^4 (\bar{A}_o + \bar{B}_o) - \frac{49}{12w} (\Delta x + \Delta y) \quad . \quad (29)$$

Three different values for the critical strain of EGCR graphite were considered; $\epsilon_f = 0.12\%$, $\epsilon_f = 0.16\%$, and $\epsilon_f = 0.20\%$. Life times based on these values are given in Tables 4, 5, and 6. The shorter life times predicted are based on guaranteed minimum flexural strength while the longer life times predicted are necessary to evaluate the effect of the higher forces on the restraint lattice.

Table 4. Column Life T

$$\epsilon_f = 0.12\%$$

Column Number	Life (yr)	Column Number	Life (yr)
67	7.56	103	6.72
79	19.10	104	5.72
80	54.53	105	18.58
91	17.42	111	10.10
92	10.38	112	11.36
93	4.43	113	18.36
102	7.31		

Columns numbered 114, 118, 119, and 120 have an indefinite life expectancy.

Table 5. Column Life T

$$\epsilon_f = 0.16\%$$

Column Number	Life (yr)	Column Number	Life (yr)
67	9.42	103	8.35
79	23.33	104	7.15
80	67.69	105	23.15
91	21.44	111	12.25
92	12.91	112	13.92
93	5.53	113	22.86
102	8.95		

Columns numbered 114, 118, 119, and 120 have an indefinite life expectancy.

Table 6. Column Life

$$\epsilon_f = 0.2\%$$

Column Number	Life (yr)	Column Number	Life (yr)
67	11.13	103	9.88
79	27.26	104	8.48
80	80.37	105	27.36
91	25.27	111	14.22
92	15.33	112	16.26
93	6.58	113	27.02
102	10.48		

Columns numbered 114, 118, 119, and 120 have an indefinite life expectancy.

The maximum strain will occur when the reactor is cold; therefore, the life of the columns were computed based on no temperature gap. An important consequence of this is that columns can be expected to fail during shutting down operations, or any operation in which the core will be cooled.

FORCES ON SUPPORT LATTICE

Lattice Force History

The lattice structure is a web of beams which surround the upper end of each column. The beams are fitted with short lugs which fit into slots in the graphite acting as supports for the column end reaction forces. The directions of these forces are shown in Fig. 14. The magnitudes of these forces are continually changing depending on the amount of restrained bowing and life of each column. Table 7 gives the results obtained from Eq. (23) using the value of the life time (t) based on a failure strain of 0.16%. The force on any section at any given time is then the sum of all the forces which act on that section at that time.

$$P = \sum_{i=1}^m P_i(t)$$

When the lifetime, T, for any column is reached it is presumed to fail in a brittle manner and thus no longer contribute to the total load. Force history curves are shown in Figs. 15 and 16 for sections A and B of Fig. 14 which are the most severely loaded portions of the lattice structure. These curves were used to evaluate the creep in the structure and the load-carrying capacity of the control rod collars.

Table 7. Lattice Forces

Column Number	Q_x (lb/yr)	k_{Lx} (lb/yr ²)	Q_y (lb/yr)	k_{Ly} (lb/yr ²)	$Q_x(t)$ End of Life (lb)	$Q_y(t)$ End of Life (lb)
67	1504.60	28.448	1504.60	28.448	8,958.73	8,958.73
79	455.51	0.331	-868.35	-16.418	104.37	-16,180.58
80	286.52	0.164	286.52	0.164	6,923.09	6,923.09
91	422.40	0.284	1288.25	4.407	861.57	13,773.73
92	1325.30	3.498	1571.39	6.558	5,466.58	8,900.02
93	3280.26	28.578	3280.26	28.578	7,515.37	7,515.37
102	397.96	0.315	3147.32	39.463	2,940.15	15,937.65
103	1248.76	4.142	2754.13	30.219	2,583.06	12,306.29
104	3135.93	39.178	1418.43	8.015	8,869.29	2,458.84
105	852.18	4.157	852.18	4.157	11,179.91	11,179.91
111	113.76	0.028	2420.36	38.071	3,841.73	19,096.59
112	330.42	0.315	2254.30	29.356	719.85	19,918.91
113	736.89	3.136	966.51	5.396	9,174.24	12,914.88

Columns numbered 114, 118, 119, and 120 produce negligible lattice forces.

Maximum Deformation of Members

Installed gaps between the lattice structure and the upper ends of the graphite columns increase when the reactor is put into operation because of the differences in the thermal coefficients of expansion for graphite and stainless steel. If the lattice members shorten during operation due to creep in compression, the graphite could be crushed when the reactor temperature is lowered. The expected creep in the lattice was calculated in the following way from the force-history curves.

Using the stress-strain relationship

$$\dot{\epsilon} = (\sigma/C)^n$$

where C and n are materials properties. The stress for a simple compressive load is

$$\sigma = P/A \quad .$$

Then

$$\dot{\epsilon} = \left(\frac{P}{AC}\right)^n$$

and strain is

$$\epsilon = \left(\frac{1}{AC}\right)^n \int_{t_0}^t (P)^n dt \quad .$$

The force-time histories shown in Figs. 15 and 16 can be approximated by five straight line portions which are described by equations of the form

$$P = \sum_{i=1}^5 P_i = \sum_{i=1}^5 (a_i t + b_i) \quad .$$

The constants a_i and b_i can be determined by solving the pair of equations

$$a_i t_1 + b_i = p_1$$

$$a_i t_2 + b_i = p_2$$

from which

$$a_i = \frac{p_1 - p_2}{t_1 - t_2}$$

$$b_i = \frac{t_1 p_2 - t_2 p_1}{t_1 - t_2} .$$

After substitution and integration

$$\epsilon_i = \frac{1}{(AC)^n} \frac{t_2 - t_1}{(p_2 - p_1)(n+1)} \left\{ p_2^{n+1} - p_1^{n+1} \right\}_i .$$

Using the appropriate values for the 304 SS lattice structure at 1200°F

$$n = 6$$

$$C = 7.32 \times 10^4$$

$$A = 7/8 \text{ in. thickness} \times 7 \text{ in. depth.}$$

The total creep in 20 years of full-power operation for Sections A and B,

$\epsilon = \sum \epsilon_i$, are

$$\epsilon^A = 0.35 \times 10^{-6} \text{ in./in.}$$

$$\epsilon^B = 0.42 \times 10^{-6} \text{ in./in.}$$

Since these are the most severely loaded beam sections in the lattice, it is apparent that the effect of creep is small and may be neglected.

LEAST SQUARES FIT OF FAST-NEUTRON EXPOSURE DATA

The fast-neutron exposure ψ above the threshold energy for graphite shrinkage was computed at the reactor mid-plane by numerical techniques and given in tabular form at points (x_j, y_k) in a fine unequal cartesian gridwork. The exposure in each column at the reactor mid-plane, exclusive of the fuel channels, was fit in the sense of least squares to the equation of a plane $f(z) = A_1 x + A_2 y + A_3$.

The condition of least squares requires that

$$\sum_{jk} R_{jk} \frac{\partial R}{\partial A_i} = 0 \quad (30)$$

where R_{jk} is the residual between the observation $\psi = z_{jk}$ and the computed value $f(z) = A_1 x_j + A_2 y_k + A_3$; and w_{jk} is a weighting factor based on the relative importance of a particular observation with respect to other observations.

$$R_{jk} = z_{jk} - (A_1 x_j + A_2 y_k + A_3) \quad (31)$$

$$\frac{\partial R}{\partial A_1} = -x_j \quad \frac{\partial R}{\partial A_2} = -y_k \quad \frac{\partial R}{\partial A_3} = -1$$

Substituting Eq. (31) into Eq. (30), collecting terms and taking $w_{jk} = 1$, the following equations result, and they may be solved for the coefficients A_1 , A_2 , and A_3 .

$$\Sigma(x_j)^2 A_1 + \Sigma(x_j y_k) A_2 + \Sigma x_j A_3 = \Sigma x_j z_{jk}$$

$$\Sigma(x_j y_k) A_1 + \Sigma(y_k)^2 A_2 + \Sigma y_k A_3 = \Sigma y_k z_{jk}$$

$$\Sigma(x_j) A_1 + \Sigma y_k A_2 + \Sigma 1_{jk} A_3 = \Sigma z_{jk}$$

The coefficients A_1 , A_2 , and A_3 for each of the columns were calculated on an IBM-704 because of the large number of data points z_{jk} . However, a hand calculation using only 15 points from column 112 gave results which differed by not more than 5% with the computer results. The coefficients for the plane of each column are given in Table 1.

HOUR GLASS SHRINKAGE

In addition to the axial shrinkage which causes column bowing, graphite also experiences perpendicular shrinkage which in effect reduces the column bowing rate, and therefore if large would increase the column life and decrease the lattice forces. In order to estimate this "hour glass" effect

the average exposure $\bar{D}$ across the column can be used.

$$\bar{D} = \frac{\iint z \, dx dy}{\iint dx dy}$$

For a square area with sides s and exposure $D = (\bar{A}x + \bar{B}y + \bar{C}) \cos \frac{\pi z}{2l}$ the average exposure is

$$\bar{D} = \left[s/2 (\bar{A} + \bar{B}) + \bar{C} \right] \cos \frac{\pi z}{2l} .$$

The length s will change an amount

$$\delta = \bar{D} \gamma_p s$$

where γ_p is the irradiation growth coefficient in the perpendicular direction. Substitution gives

$$\delta = \frac{\gamma_p s^2}{2} \left[\bar{A} + \bar{B} + \frac{2\bar{C}}{s} \right] \cos \left(\frac{\pi z}{2l} \right) .$$

Since adjacent columns have nearly the same average exposure, only small error will be introduced if δ for a given column is subtracted from the deflection rate previously calculated rather than the average of two adjacent columns $\frac{\delta_i}{2} + \frac{\delta_j}{2}$. Equation (16) for the deflection is then modified to become

$$x_m(x-\delta) = \bar{A} \gamma \left(\frac{2l}{\pi} \right)^2 \left[\cos \left(\frac{\pi z}{2l} \right) + \frac{\pi(L-l)}{2l} \right] - \delta ; \quad 0 < z < l . \quad (31)$$

Values for δ at $z = 0$ are given in Table 8. The variations

$$V_x = \frac{\delta}{x-\delta}$$

$$V_y = \frac{\delta}{y-\delta}$$

are small for the columns with life times less than 20 years. For columns with longer life times the variations are not important.

Table 8. Hour Glass Effect

Column Number	δ inches (20 yr)	V_x (%)	V_y (%)
67	0.14509	9.6	9.6
79	0.15913	45.5	20.0
80	0.15315	94.6	94.6
91	0.15026	47.8	11.8
92	0.12968	9.7	8.1
93	0.07855	2.2	2.2
102	0.10637	32.1	3.2
103	0.08699	6.7	2.9
104	0.03862	1.1	2.5
105	0.00687	1.0	1.0
111	0.01926	23.3	8.9
112	0.01565	6.3	0.8
113	0.00682	1.2	0.9

UNCLASSIFIED
ORNL-LR-DWG 46415AR

Fig. 1. Plan View EGCR Core.

UNCLASSIFIED
ORNL-LR-DWG 49B64A

Fig. 2. Lines of Equal Fast-Neutron Exposure in Graphite Column No. 103.

UNCLASSIFIED
ORNL - LR - DWG 55921

WARPED SURFACE

FIG. 3

Fig. 4. Axial Profile of Fast-Neutron Exposure in EGCR Graphite Column.

UNCLASSIFIED
ORNL - LR - DWG 55924

FIG. 6

UNCLASSIFIED
ORNL - LR - DWG 55925

GENERIC SLICE WITH TOP SURFACE DISPLACED
AXIALLY AND TILTED

FIG. 7

UNCLASSIFIED
ORNL - LR - DWG 55926

equals

COMPONENTS ON UPPER SURFACE DISPLACEMENT

FIG. 8

UNCLASSIFIED
ORNL - LR - DWG 55927

FIG. 9

UNCLASSIFIED
ORNL - LR - DWG 55928

RADIUS OF CURVATURE CORRESPONDING TO ROTATIONAL
COMPONENT OF DISPLACEMENT

FIG. 10

UNCLASSIFIED
ORNL - LR - DWG 55929

DEFLECTION PROFILES FOR A GRAPHITE COLUMN

FIG. 11

UNCLASSIFIED
ORNL - LR - DWG 55930

- R = RATE OF LOADING
 $(R)_{max}$ = RATE OF LOADING IF COLUMN IS COMPLETELY RESTRAINED
 R_0 = RATIO OF LOADING RATE FROM CONCENTRATED FORCE AT INITIAL CONTACT TO COMPLETELY RESTRAINED LOADING RATE
 H = DIFFERENCE BETWEEN RATIOS FOR COMPLETELY RESTRAINED LOADING RATE AND CONCENTRATED LOADING RATE $(1 - R_0)$
 t_0 = TIME FOR COLUMN TO CONTACT ADJACENT COLUMN
 Δ = ACCUMULATED CLEARANCE BETWEEN COLUMNS

RATE OF COLUMN LOADING AS A FUNCTION OF TIME

FIG. 12

UNCLASSIFIED
ORNL - LR - DWG 5593I

BOWING CHARACTERISTICS OF GRAPHITE COLUMNS

FIG. 13

UNCLASSIFIED
ORNL - LR - DWG 55932

FIG. 14. UPPER RESTRAINT LATTICE

UNCLASSIFIED
ORNL - LR - DWG 55933

FIG. 15. LATTICE FORCE HISTORY SECTION - A

UNCLASSIFIED
ORNL - LR - DWG 55934

FIG. 16. LATTICE FORCE HISTORY SECTION - B

DISTRIBUTION

Internal

1-20.	L. A. Curry	52.	J. T. Meador
21.	E. G. Beasley	53-77.	S. E. Moore
22.	M. Bender	78.	A. M. Perry
23.	A. L. Boch	79.	C. A. Preskitt
24.	E. J. Breeding	80.	G. C. Robinson
25.	R. B. Briggs	81.	G. Samuels
26.	F. L. Carlsen	82.	H. W. Savage
27.	R. H. Chapman	83-84.	A. W. Savolainen
28.	R. A. Charpie	85.	W. L. Scott
29.	R. D. Cheverton	86.	L. R. Shobe
30.	J. H. Coobs	87.	M. J. Skinner
31.	J. M. Corum	88.	J. E. Smith
32.	D. A. Douglas	89.	F. J. Stanek
33.	J. Foster	90.	D. H. Stewart, AEC-ORO
34.	A. P. Fraas	91.	E. Storto
35.	D. R. Gilfillan	92.	J. A. Swartout
36-39.	B. L. Greenstreet	93.	J. R. Tallackson
40.	L. H. Jackson, AEC-ORO	94.	D. B. Trauger
41.	P. R. Kasten	95.	J. R. Weir
42.	B. W. Kinyon	96.	G. D. Whitman
43.	R. F. Kirkpatrick, AEC-ORO	97.	C. E. Winters
44.	R. B. Korsmeyer	98.	F. J. Witt
45.	M. E. LaVerne	99.	Laboratory Records - RC
46.	R. N. Lyon	100-109.	Laboratory Records
47.	H. G. MacPherson	110-111.	Central Research Library
48.	W. D. Manly	112.	Y-12 Document Reference Section
49-51.	R. L. Maxwell	113-127.	TISE

External

- 128-139. W. A. Shaw, Auburn University, Auburn, Alabama
- 140-142. R. I. Strough, Pratt and Whitney, Middletown, Connecticut
143. B. F. Langer, Bettis Plant, Westinghouse, Pittsburgh, Pennsylvania
144. H. L. Snider, Lockheed Aircraft Corporation, Marietta, Georgia
145. R. B. McCalley, General Electric Company, Schenectady, New York
146. R. V. Meghreblian, Jet Propulsion Laboratory, Pasadena, California
147. D. R. deHalas, General Electric Company, Richland, Washington
148. S. Mrowzowski, University of Buffalo, Buffalo, New York
149. L. G. Epel, Combustion Engineering, Windsor, Connecticut
150. E. O. Bergman, National Engineering Science Company, Pasadena, Calif.
151. W. F. Banks, Allis-Chalmers, Washington, D. C.
152. A. I. Chalfant, General Atomic, San Diego, California
153. W. E. Crowe, Los Alamos Scientific Laboratory, Los Alamos, N. M.
- 154-155. H. L. Brammer, ACF Industries, Albuquerque, New Mexico
- 156-157. J. C. Ebersole, TVA
158. R. A. Domer, TVA
159. E. Creutz, General Atomic, San Diego, California
160. R. B. Duffield, General Atomic, San Diego, California