MAF 28 1963

1 ID-18251

OAK RIDGE OPERATIONS OFFICE

ATOMIC ENERGY COMMISSION

MASTER

STUDY NO. II-227

ANALYSIS
GRAPHITE CORE STRUCTURE

EXPERIMENTAL GAS COOLED REACTOR

Contract No. AT(10-1)-925

Facsimile Price \$ 17.50

Microfilm Price \$ 8.48

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

Prepared By
ALLIS-CHALMERS MANUFACTURING COMPANY
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N O T I C E

This report summarizes as of the date of the study the status of this phase of the design of the Experimental Gas Cooled Reactor under construction in the Oak Ridge Area. Since the data was developed prior to completion of all design, fabrication and construction, the information is subject to modification during the evolution of the complete design of the entire facility and no attempt has been made to revise, rewrite, edit or otherwise modify the study to maintain the data current with related research and development programs or subsequent design revisions. Users are cautioned to avoid interpretations and conclusions based on the incomplete data contained herein.

ANALYSIS
GRAPHITE CORE STRUCTURE

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PREFACE

This study examines the probable effects of radiation-induced shrinkage of graphite upon the life of the EGCR core. The study establishes that the core will not have unlimited life. The structural considerations which were factored into the core design are set forth.

In the attempt to make the study quantitative as well as qualitative, computations were made using simplified analytical models and extrapolating well beyond existing data on irradiation shrinkage, creep, and stress-strain relationships in graphite at EGCR conditions.

Although the best data which were available were used in these calculations, the necessity to extrapolate beyond that data renders the conclusions of the study speculative and subject to experimental confirmation. A continuing investigation is being carried on by the AEC at Oak Ridge and Hanford to evaluate the properties and behavior of graphite under conditions of service in the EGCR and in future gas-cooled reactors of the EGCR type.

ANALYSIS OF GRAPHITE CORE STRUCTURE

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ANALYSIS OF GRAPHITE CORE STRUCTURE

I. OBJECTIVE

The purpose of this study is to determine the structural and functional adequacy of the EGCR graphite core design. Maximum stress and maximum distortion of the core and the probable operating time before graphite cracking are determined.

II. SUMMARY AND CONCLUSIONS

A. The major cause of stress in EGCR graphite is non-uniform fast-neutron flux, which causes non-uniform shrinkage of graphite components. Differential shrinkage in a component develops both tensile and compressive stresses. Stresses due to other causes are minor compared to those due to the long-term effects of neutron irradiation.

B. Because graphite is much stronger in compression than in tension, the critical stress in EGCR graphite is tensile.

C. Non-uniform irradiation and shrinkage throughout the core life would result in large tensile stresses over most of each column's mid-plane cross section (the location of maximum stress) if graphite always acted elastically over the short term and the long term. Such high stresses would soon exceed the allowable stress limit and cause cracking of several of the graphite columns. However, the tendency of graphite to creep under long-term stress should keep tensile stress in the EGCR well under the maximum allowable level.

D. Continued creep results in considerable strain that may, in the most highly irradiated columns, exceed the strain capability of graphite, resulting in column cracking. The criterion for determining the time of cracking of graphite columns appears to be the point at which the creep-strain results in rupture.

E. Column life before cracking may also be related to the maximum allowable stress at rupture. This stress is used in this report as a basis for comparison wherever the effects of creep are neglected. Stress patterns caused by non-uniform shrinkage are similar to those caused by flexure of a simple beam, and therefore when the criterion of life is the build-up of elastic stress, the allowable stress is taken as the allowable flexural stress rather than the simple tensile stress.

F. Non-uniform shrinkage is the major cause of distortion of graphite components of the core. Greater shrinkage on one side (usually the inward side) of a column causes the column to bow (generally outward) into the surrounding free space.

The maximum amount of this bow for any column in 20 years of core life is about six-tenths of an inch at the core mid-plane; this is the maximum distortion of the core components that could affect functional adequacy. It appears that all other core components can accommodate this bow and remain functional.

G. In general, the amount by which a column tends to bow during 20-year core life exceeds the available free space. The restraint thus imposed causes the flexural stresses on the column cross section. The bowing stress and the stresses which are internally generated in the graphite (due to fast-neutron flux gradients around each fuel channel) are the major, irradiation-induced factors determining time until cracking of core columns may be expected.

H. All irradiation-produced stresses are time-dependent and, unless the limiting effects of creep are considered, a truly maximum graphite tensile stress cannot be stated (except that it cannot exceed the allowable 1800 psi). The maximum critical stress, taking creep into account, should not exceed 1000 psi.

I. Critical stresses calculated in graphite, considering its anisotropic properties, do not differ greatly from those calculated assuming the graphite to be isotropic.

J. Based upon the maximum-stress criterion, the combined internally generated and bowing stresses result in an average period before cracking of all core columns of 14 years, with a minimum period of 6 years.

K. Based upon the maximum creep-strain criterion, the average time until cracking is about 14 years, with a minimum column life of about 11 years. This estimate is felt to be more applicable to the EGCR than results based on the maximum stress criterion.

L. All predicted lifetimes are conservative, since they are based on the assumption that once the criterion of failure, whether maximum stress or maximum strain, has been reached at any one point in a graphite core component, the entire column has reached the point at which it will crack. Obviously, this is an ultraconservative assumption.

M. Overall temperature gradients between opposite sides of a graphite column should be limited to 50F at the bottom of the core and 100 F at the top. At the core mid-plane the radial gradient from the surface of a fuel channel to the nearest side of the column should be limited to 45 F. If these

temperature conditions are not exceeded, the thermal stress in the core graphite will not exceed 400 psi and will not significantly alter the column lifetime predictions given in Appendix 7.

III. RECOMMENDATIONS

A. Because graphite creep data are fragmentary, the approaches in this analysis, as well as the conclusions drawn, are very conservative. Therefore, since the creep rate and maximum creep strain at failure prominently influence the actual stresses and probable life without cracking of any column, more complete creep tests are recommended. Results of definitive tests probably would demonstrate a fully acceptable core life, whether maximum stress or maximum strain is the criterion.

B. The cylindrical, thick-walled geometrical model used for calculation of internally-generated stresses in graphite is considered adequate. Since the effect of creep should limit stresses to allowable levels, the model is not of vital importance to the actual core stress and core life. However, to obtain a more accurate picture of stresses on a column cross section, a mathematical treatment of differential shrinkage, including overlapping effects of adjacent fuel channels, should be attempted.

IV. GIVEN DATA

A. EGCR Drawings

5927-EGCR-MS-271, Core Assembly Bottom Plan
5927-EGCR-MS-272, Core Assembly Top Plan
5927-EGCR-MS-275, Core Assembly Section "A"
5927-EGCR-MS-276, Core Assembly Section "B"
5927-EGCR-MS-277, Core Assembly Section "C"
5927-EGCR-MS-278, Core Bottom Plate
5927-EGCR-MS-281, Core Restraint Lattice Assembly
5927-EGCR-MS-286 to 300, Core Graphite Block Details

B. EGCR Specification RC-2, "Material Specification for Core Graphite", Feb. 26, 1960.

C. Allis-Chalmers Report on Task 227-A, "Shear Test of AGOT Graphite", Feb. 17, 1960.

D. EGCR Study No. II-225. "Design Requirements for Core Structure", Approved Dec. 22, 1959.

E. Shrinkage rate of EGCR graphite (for prediction of column life.)

Needle Coke: 0.02% per 1000 Mwd/AT parallel to extrusion
 0.01% per 1000 Mwd/AT perpendicular to extrusion

F. Maximum allowable flexural stress for EGCR graphite is 1800 psi.

G. EGCR Title I Study No. II-450, "Monolithic Graphite Column Core Concept, EGCR", Sept. 28, 1959.

H. Other given data are included in the various appendices.

V. ASSUMPTIONS

The assumptions used in the various analyses are given in their respective appendices.

VI. DISCUSSION

This analysis was performed in several stages, the results of which are presented in the following appendices:

- Appendix 1- Evaluation of Stress-Strain Curves for EGCR Graphite
- Appendix 2- Stresses Caused by Irradiation- Induced Differential Shrinkage of EGCR Graphite (Using a Simplified, Isotropic Model of the Monolithic Column)
- Appendix 3- Stresses in EGCR Graphite due to Irradiation- Induced Shrinkage for an Anisotropic Simplified Geometrical Model
- Appendix 4- Creep in EGCR Graphite (Literature Survey)
- Appendix 5- Modified Core Arrangement, Control Rods in Centers of Columns
- Appendix 6- Fast Neutron Irradiation Distribution in Core and Reflector Graphite
- Appendix 7- Bowing and Stresses Due to Restraint of Bowing in the EGCR Graphite Columns
- Appendix 8- Analysis of Creep Tests Performed by Allis-Chalmers on AGOT- type Graphite
- Appendix 9- Supplementary Calculations of Graphite Bowing
- Appendix 10- Estimate of Thermal Stress in Core Graphite

The intent of this study has been to examine the major sources of stress and strain in the EGCR graphite core structure

and to determine the lifetime of each column from the standpoint of continuous structural integrity. Examination of the EGCR environment reveals that the major structural problems result from the effects of non-uniform fast-neutron irradiation. Owing to continued bombardment by neutrons, undesirable and, generally, unavoidable changes occur in the crystalline structure of graphite. These changes result eventually in a significant decrease of the gross physical dimensions of graphite, termed "shrinkage" in this report. Dimensional increases or growth also occur, but not simultaneously with decreases. This growth is much smaller than shrinkage and generally occurs at temperatures lower than those predicted for EGCR. Therefore, shrinkage effects only are considered in detail. The rate of shrinkage is a function of the irradiation temperature, the type of graphite coke, the graphitization temperature, and the size and degree of orientation of the particles in the bulk-graphite piece. While the quantitative effect of all these factors cannot be predicted, enough data have been accumulated (by Hanford Operations) to permit predictions on the behavior of certain special types of graphite. For a graphite formulated from a needle-type petroleum coke (specified for the EGCR) the latest Hanford data indicate the following shrinkage rates:

Perpendicular to extrusion axis: 0.0001 in./in. per 1000 Mwd/AT.

Parallel to extrusion axis: 0.0002 in./in. per 1000 Mwd/AT.

Non-uniformity of the neutron flux and consequent non-uniform graphite shrinkage requires adjustment among the various graphite "fibers" to accommodate themselves to their altered relative sizes. This adjustment continues throughout core operation and results in EGCR structural problems of:

- a. Stresses and strains produced in graphite
- b. Long-term creep in graphite with a subsequent large strain.
- c. Reaction of graphite columns on their supports due to the tendency of the fibers to accommodate the dimensional changes. (This is treated in EGCR Study II-229)

The general treatment has been to proceed from a simple and conservative calculation of stress through a series of refinements of approach. Each refinement brings the approach closer to the real behavior of graphite. Thus, the nature of the complicated problem can be most clearly seen. Many stress-producing factors which are examined in Title I studies and found minor were not considered in this report. In this category are: localized contact between graphite and bottom plate; binding of graphite

and its supports; seismic shock; impact of fuel assemblies on the fuel-channel surfaces; and Wigner growth. Tensile rather than compressive stresses were given maximum emphasis because of the much greater strength of graphite in compression.

Descriptions of the work performed are given in detail in the various appendices. The following general summary of these appendices will aid in understanding the method employed.

The shrinkage-induced stresses are of two distinct types:

- a. Internal stresses caused by the variation of the fast neutron flux along the radius of each unit cell consisting of a fuel channel and surrounding graphite moderator.
- b. Stress caused by restraint of bowing which is related to the over-all fast-neutron flux gradient between opposite faces of a graphite column.

These stresses are discussed in detail in the appendices but are summarized below:

1. The first major stress problem arises from the variation of the fast neutron flux along the radius of each cylindrical fuel cell. This flux variation causes differential shrinkage between the fuel channel surface and any other point within the graphite body. The differential strain causes stresses analogous to the thermal stresses encountered in a thick-walled hollow circular cylinder which has an exponential radial temperature gradient. Both tensile and compressive stresses occur. The resultant stress pattern along any radius of a fuel channel is similar to the pattern of a beam in flexure. The presence of from two to four fuel channels in one column in the EGCR greatly complicates the problem of choosing a geometrical model to be used in calculating stresses. However, the simple cylindrical model is considered adequate to describe stresses around any one channel. In those parts of the column cross section where geometrical fit is not exact, or where the models assumed for adjacent channels overlap, the shape of the neutron-flux gradient gives rise to compressive stress. Since graphite is known to be much stronger in compression than in tension and since the flux gradients of adjacent channels do not greatly differ, it is concluded that the stresses computed for the model of one channel, when considered separately from the rest of the column, will not differ greatly from the stresses which result from the more complicated mathematical treatment of the entire column cross section. Neither will the overall stress distribution be greatly affected by recombining the various models which have been separately considered.

The cylindrical model is used to calculate graphite stresses in a conservative manner by considering the fuel channel having the most adverse flux gradient and assuming the existence of this gradient over the entire length of the column. In the first approach, standard formulas for thermal-gradient stresses are used. The anisotropic properties of graphite are neglected and longitudinal, tangential, and radial stresses are calculated for the mid-plane of the model.

Because graphite is an inelastic material, no portion of its tensile-stress-strain curve being a straight line, the stress which would develop as a result of differential shrinkages (i.e., strain) depends greatly on the instantaneous relation between stress and strain (i. e., upon the tangent modulus) and the amount of strain which has accumulated. To calculate the stress at any time in core life, a step-wise year-by-year method is employed. Having calculated the stress accumulation during the initial year of operation, using the initial (i.e., zero-stress) tangent modulus of elasticity, the incremental stresses in the next yearly interval are found by using the tangent modulus approximating the total stress at the end of the first interval and the strain accumulated during the second interval. This approximate process is continued for all intervals up to 20 years. The results are in Appendix 2. Since no available stress-strain curves for graphite are directly applicable to EGCR conditions, Appendix 1 is devoted to developing curves from which to obtain tangent moduli for use in the step-wise process just described. The critical stress is found to be tension at the fuel-channel surface in the direction of the cylinder's axis.

To simulate more closely the actual action of graphite under the influence of irradiation-induced strains, a second series of step-wise calculations are made, taking into account the anisotropic properties of graphite. The resulting critical stresses for any corresponding time interval are only slightly lower than in the previous calculations. The results are in Appendix 3. Considering the maximum allowable tensile stress as the criterion of column failure (because of the similarity of stress patterns to those of flexure), useful life of the most critical column is about eight and nine years for the isotropic and anisotropic cases, respectively neglecting stress due to restraint of bowing).

It is important to recognize that this stress problem is common to any graphite reactor using an eight-inch lattice pitch and having its fuel channels fashioned by holes in graphite blocks. It does not depend strongly upon the cross section of the block if it is 8 in. x 8 in. or greater, nor is it influenced by block length if it exceeds sixteen inches. Thus, unless it is desired to use 4 in. x 4 in. sections, this problem is inherent in a graphite moderated reactor.

As a consequence of the relatively high stresses resulting from the previous conservative calculations, a final step toward depicting the real reaction of graphite to the imposed strains is attempted. Strains are imposed over a period of many years. Consequently, the known tendency of manufactured graphite to creep significantly under stress is considered. It is assumed that creep rates in a fiber, once the stress has reached some acceptable level, will equal or at least counteract a significant portion of the rate at which irradiation-induced strain accumulates. This will result in less net differential change in fiber length for any time in core life and therefore in less stress accumulation. This possibility is considered in Appendix 4. Unfortunately, little data exists which is directly applicable to creep and creep rates under EGCR conditions. Only broad and tentative conclusions can be drawn relative to the effect of creep. Through the utilization of a series of relevant formulas, it can be predicted that the critical tensile stress will level off in the low end of the range between 900 psi and 1300 psi. Cracking will not occur in 20 years if the creep rate (at 800 F and 1000 psi tensile stress) is 10^{-11} in./in./sec or greater. At least this rate can be expected from extrapolation of the available creep data. However, the exact amount of creep-strain which graphite can withstand while accommodating irradiation-induced shrinkage for 20 years can not be definitely ascertained from the literature. To obtain more definite data on the creep rates and the maximum allowable creep-strain at rupture, a simple test program was carried out by Allis-Chalmers. The results of this program are in Appendix 8.

Allis-Chalmers creep-test data indicate that under EGCR conditions stress will level off at 750 to 1000 psi. At this stress, the creep rate will exceed radiation-induced strain rate, thus reinforcing the opinion stated in Appendix 4. A conservative maximum strain-at-failure value (obtained from the test) indicates a minimum column life without cracking greater than that predicted in Appendices 2 and 3, predictions based on the maximum-stress criterion of failure and applying to long-term stresses generated in the graphite from whatever cause.

2. The second major stress problem caused by differential shrinkage of graphite is that of bowing of individual graphite columns. Bowing results from the over-all flux gradient from face to face of any column. Since the inward faces (those nearest the center of the reactor core) are subject to higher flux, their fibers shrink more than those of the outward faces. The effort of the column to accommodate these relative shrinkages results in bowing. The bow is generally outward, because of the shape of the flux gradient. Appendix 6 contains the average exposures that can be expected on the faces of all columns and, from these exposures, Appendix 7 determines the magnitude and direction of the bowing.

If every column were free to bow fully to the amount of potential bow shown in Appendix 7, complete accommodation of all shrinkages would occur. Only minor stresses would be generated internally in a column because of non-linearity of the over-all gradient. However, closely fitting restraint bands encircle the core and restrict the amount of the bow to no more than the free space between the restraint and that particular column. Once a column has used all of its free space, bowing ceases, but the accumulation of differential fiber shrinkage continues. The "restrained bow" is equivalent (if creep is neglected) to an inward deflection of the column from its fully-bowed state. Considering the stiffness of the columns, the imposed deflection causes considerable elastic stress. This can be calculated through the use of standard stress and deflection formulas. Allowance should be made for the variation in the elastic properties of graphite at different stress levels.

Analysis shows that, in 68 of the 120 columns, bowing stresses are not significant. (Appendix 7) The remaining 52 columns are those in a roughly annular zone centered on the moderator-reflector interface. In these, bowing stresses will be relieved through creep and thereby prevent excessive stress levels throughout the life of the core.

However, to provide a conservative value of maximum stress in each column, unrelieved stresses due to bowing are superimposed on the stresses due to internal effects which were calculated in Appendix 3. By the use of proration and accounting for changes in tangent modulus, a year-by-year picture of the accumulation of superimposed stress is obtained. The direct addition is, in itself, conservative. Consequently, the minimum time until cracking of columns noted in Appendix 7 (which is based on a maximum-allowable-stress criterion) is conservative. Furthermore, the effects of creep will greatly increase column life.

Appendix 9 is a series of calculations intended as a refinement of the stress and column-gap calculations in Appendix 7. Both hot and cold core conditions are considered. Non-linear variation (as well as linear) of column shrinkage, tangent modulus, gaps between columns, and restrained bows are also considered. As no significant differences between the results of Appendices 9 and 7 are apparent, the conclusions of the latter appear to be confirmed.

Appendix 10 includes calculation of thermal stress in the graphite columns, based upon the thermal gradients derived in Study No. II-226. The local stress for the gradients given in Study No. II-226 does not exceed 680 psi. To limit the thermal stress to a more conservative value, reduced temperature gradients are recommended.

VII. REFERENCES

- A. ACF Job Report No. 3-230-6.2, " Preliminary Structural Analysis of Graphite Brick for Core of PEGCPR," October 28, 1958.
- B. A-C EGCR Study II-229, "Design and Analysis of Top Grid Structure and Associated Components," May 27, 1960.
- C. A-C EGCR Study II-226, "Temperature Distribution Moderator and Reflector Reactor Core," (For Approval) April 28, 1960.
- D. EGCR Specification RC-2 and RC-2, Rev. 1 (NR), "Material Specification for Core Graphite, EGCR," February 26, 1960 and March 19, 1960 respectively.
- E. A-C EGCR Study II-227 (Rev. 1), "Analysis of Graphite Core Structure, EGCR," January 13, 1960. (Preliminary Issue)
- F. Drawings as listed under " Given Data: A."

APPENDIX 1

EVALUATION OF STRESS-STRAIN CURVES
FOR EGCR GRAPHITE

APPENDIX 1

PRELIMINARY EXAMINATION OF STRESS-STRAIN
CURVES FOR EGCR GRAPHITE

1. The accompanying document, "Preliminary Examination of Stress-Strain Curves for EGCR Graphite," describes the logic employed to arrive at stress-strain curves for core graphite in the irradiation and temperature environments expected in the EGCR. These curves were subsequently to be used in calculating stresses caused by differential irradiation-induced shrinkage within a monolithic-core column. Use of the "tangent-modulus" (i.e. instantaneous rate of change of stress with strain) taken from appropriate stress-strain curves seemed desirable in order to simulate the changing action of graphite with time as the core aged and the general stress level rose as a result of slowly-accumulating strain. The supposed decreasing slope of the stress-strain curve, therefore, held promise of lower and more realistic stresses for any given amount of accumulated shrinkage (strain).

2. This appendix is only a transcription of rough notes describing the evaluation of the logic employed, not a finished report. In some instances (for example, the discussion of alternative curves that might be drawn to represent the effects of different amounts of irradiation, Section 5 of subject document) the actual curves to be used in calculating stresses are not specifically noted (See Appendix 2).

The final curves for use in calculation are:

- a. An upper curve for a particular temperature representing the limit approached at 20-year core life (to yield highest tangent moduli and stress) and
- b. A lower curve representing the room-temperature, un-irradiated condition (to yield the lowest tangent moduli and stress).

It was expected that use of both curves would bracket the actual stresses in the core graphite.

3. In no one place does the available literature give information on graphite under conditions duplicating those of the EGCR. Therefore it was necessary to take information from several sources, each not completely applicable to the EGCR, and combine it in a conservative manner. The general approach was to:

- a. Take room-temperature stress-strain curves for a graphite stiffer than EGCR graphite,

b. Determine that tensile and compressive stress-strain curves were the same,

c. Find the increase in initial elastic modulus (very low stress level) with temperature,

d. Find (for each temperature) the amount of increase in the initial modulus with simultaneous irradiation and temperature-annealing, and,

e. Construct, on the assumption that each change in initial modulus also occurs proportionately in the various tangent moduli, final stress-strain curves accounting for the range of accumulated irradiation over the 20-year core life at temperatures representative of several horizontal cross sections of the core.

4. The calculations for stress, performed in a stepwise (year-by-year) manner so as to use the derived stress-strain curves, are covered in Appendix 2.

TITLE: Preliminary Examination of Stress-Strain
Curves for EGCR Graphite

For E_{11} (Modulus of elasticity parallel to the axis of extrusion)

1. At first we thought we could conservatively ignore the effect of temperature upon the safety factor ($\frac{\sigma_{\text{allow}}}{\sigma_{\text{actual}}}$) since the allowable stress is mentioned as increasing faster than E with temp. (σ_{actual} being $\epsilon(E)$ on an instantaneous basis)

Ref. 1 and 4

2. But, because the initial modulus also experiences changes with irradiation (the amount of change being a function of temperature of irradiation which causes, so to speak, a simultaneous partial annealing of change), we have to consider temperature effect on stress-strain curve. Otherwise, the additional increase in initial modulus could, assuming similar changes in instantaneous tangent modulus, more than erase the otherwise higher increases in allowable stress with temperature (and perhaps with irradiation). Note that allowable tensile stress does not show same increase with temp. as does comp. stress (Ref. 4). However, Ref. 1 (pl) shows the σ_c/σ_e to remain constant up to 1000C.
3. Since for a conservative approach we are now not considering any relaxation of stress, the temperature-dependent strains (exact dependence of damage on temperature not yet known) are taken to have maximum accumulation when reactor operates at full power for twenty years. This gives greatest relative shrinkages so far as we can tell now without an excessive amount of calculation of fine structures for many special cases of loading and so forth. Under these conditions we can isolate core cross-sections of approximately equal temperatures and consider the accumulation of stress in each plane by taking increments of time (say one year) and by taking linear variation of relative shrinkage (and consequently strain).
4. We have then two conditions:

- (a) Operating stresses: Here we attempt to take advantage of increased allowables at operating temperatures and with irradiation (assumed full power) and use the derived σ - ϵ curve at appropriate temp. for finding the T.M. and increments of stress. We do not have much information on variation of allowable stress

Ref (1) moulded + 20% to +75% @ 1000C depending on grade

Extruded + 15% @ 1000C^o

Ref (4) tensile @ 400C = 1.075 x room temp. allowable.

- (b) Shutdown stresses: The possibility of shutdown at any point of reactor life exists so we have to figure out how to use the strains which have accumulated at temperatures where higher T.M. and allowable stress (both temp. and dose dependent) existed. At any time, then, we should take the total accumulated strain, find the associated stress at room temp. ("How"? is the question) and compare it with the room temp. allowable stress as modified by irradiation only.

By assuming that the stress at room temperature due to a total accumulated strain present during the decrease to room temp. (no relaxation) is the same as it would have been through accumulation of strain at room-temp. (i.e. we find the stress at room temp. due to temperature-dependent strain by finding the strain at appropriate temperature (in increments) and then using the room temperature σ - ϵ curve.)

Either "a" or "b" might be critical and we should do both to find out, since these first calculations will be relatively simple and allow us to cut down on calcs required to find the worst case in the more difficult cases of later calcs.

5. (a) In arriving at stress-strain curves the E_{comp} was assumed equal to $E_{tensile}$

Ref 1 moulded graph at room temp.

Ref. 1 and 7 (R.T. - tension (unirradiated))

extruded (R.T. - compression (irradiated)) but w/long anneal to presumably remove most of irradiation effects.

This probably is good to about $\pm 10\%$

- (b) In all data we have (except Ref. 8, which extends to 3×10^{20} thermal neutrons, with ϕ_r/ϕ_t probably equivalent to Hanford) the range of irradiation damage probably does not exceed 20% of the 20-year exposure in any critical part of EGCR and in general the % will be much lower.

For the low exposures (Ref. 5 (p7)) we see that at about 300 MWD/T (note that this MWD/T may not be the same as for EGCR) the rate of increase of ΔE with exposure is very low. It might, therefore, be assumed that, except below exposures which in EGCR are less than a month's operation even at core exterior (if there is any 1/1 correspondence at all between MWD/T in the two reactors), the $\% \Delta E$, for irradiation at any temperature, is independent of exposure. However, at 300°C (Ref. 5) and 300 MWD/T $\Delta E \approx .16$ and Ref. 8 shows $\Delta E \approx .40$ at 300°C and perhaps what would be 25000 MWD/AT in EGCR. Since Ref. 7 says no significant dependence on rate of exposure or flux intensity could be noted in residual ΔE , it might be reasonable, not having any real correlation factors for exposure, to simply prorate the residual ΔE of Ref. 5 (which covers the range of annealing temperatures in EGCR) on the basis $\Delta E(\text{Ref } 8 @ 300)$ for all temperatures.

$$\Delta E(\text{Ref } 5 @ 300)$$

This would require a series of curves ($\sigma - \epsilon$)

- (c) Otherwise, considering the number of approximations involved and the unknown conversion from Ref. 8 to EGCR MWD/T, we might just adopt some compromise number for $\Delta E @ 300C$ for any irradiation (say $\frac{.16 + .40}{2} = .28$) and use just this one curve to reduce the complexity of calculations.

Actually for the first approximation calculations which will deal with only one point, the many curves of (b) will not make much trouble, but for the proposed more exact calculations, it might be very troublesome on examining the whole columns by means of computer programming

Since we have only one reference (8) for the higher ΔE and the graphitization temperature might be low (although the graphite is extruded) and we know that the shrinkage effects are less the higher the graphitization temp, it seems we should use an average since this would give higher $\Delta \sigma$ for the early ΔE and lower for the later ΔE . or conservatively one might use the highest of the range.

6. There is some doubt about which μ (poissons ratio) to use so perhaps a range of values should be used to determine sensitivity of σ to μ . (Geneva papers $\mu = .26$; Ref. 3 $\mu = .14$)
7. For the case where an isotropy must be considered we may have to go through this for $E_{\perp}$ as well and we need $E_{\perp}$ for even the first approximation calc's since the stresses are $\perp$ to extrusion. Perhaps an average should be used $E_{AV} = \frac{E_{\perp} + E_{\parallel}}{2}$ for the isotropic approximation.

(a) From Ref. 4 (and also probably from Geneva Papers)

for AUT graphite

Indicating that we would do the same for $E_{\perp}$ as for $E_{\parallel}$ with respect to temp.

- (b) Ref. 5 (p 6) shows [for all except AGOT-K(II)] a good correspondence in change of $E_{\perp}$ & $E_{\parallel}$ with irradiation and annealing. Therefore we would do the same for $E_{\perp}$ as for $E_{\parallel}$ with respect to irradiation.

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APPENDIX 2

STRESSES CAUSED BY IRRADIATION-INDUCED DIFFERENTIAL SHRINKAGE
OF EGCR GRAPHITE (USING A SIMPLIFIED, ISOTROPIC
MODEL OF THE MONOLITHIC COLUMN)

(I) The following approach to the Core Stress Analysis is based on the Thermal Stresses in a Long, Hollow Cylinder as outlined in Timoshenko's "Strength of Materials" Part II P.228-234. This is a simplified approach to the problem and is based on the following assumptions to give a first approximation for directing the approach of a more detailed analysis later:

1. Irradiation shrinkage ($-\frac{\Delta L}{L}$) is equivalent to thermal expansion (αt).
2. The irradiation is symmetrical about the axis of the cylinder and constant along this axis; therefore, the shrinkage of the cylinder is symmetrical about the axis.
3. During irradiation-induced shrinkage, cross sections of a ring cut from the cylinder by two planes perpendicular to the axis and unit distance apart will remain plane.
4. The shrinkage varies in the radial direction only.
5. The amount of shrinkage for given irradiation is ^{nearly} the same in the parallel and perpendicular directions.
6. The material is isotropic.
7. Since only 1 fuel channel is being considered it is assumed that the interaction of the others will not increase the stress, at least for purposes of this simplified analysis.
8. The cross section mentioned in (3.) is taken sufficiently distant from the ends of the cylinder, because at the ends the stresses in the direction of the axis of the cylinder are zero and the stress distribution is more complicated. It seems reasonable to take the center of the column as the point of maximum stress, since it is the point of maximum damage.
9. The Modulus of Elasticity does ~~not~~ change with irradiation, ~~and~~ with stress level, ~~and~~ with variation of the density across the cross section, but is considered constant for small time intervals (for purposes of this calculation) and the same both in tension and compression.

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10. The temperature does not affect irradiation ^{shrinkage} damage. (See Appendix 1 for Prelim. Examination of Stress-Strain Curves for EGCR Graphite. However, changes in mechanical properties are accounted for)
11. The available information on graphite is incomplete; therefore, to arrive at a conservative answer it is assumed that the stresses in the graphite do not relax.
12. Damage variation with radius is based upon the flux gradient about a "typical" fuel channel, with no neighboring flux depressants (such as experimental tubes), in the absence of a complete "fine structure" of the core fluxes. The absolute values of shrinkages at any point in the core are fitted to the general curve by appropriate constants. From examination of presently available "fine-structure" curves, this is believed to give the most conservative picture of flux gradient across the individual column.
13. Since the effect on breaking strength caused by irradiation is not known the stresses are calculated only up to limits of available σ - ϵ curves. It is recognized that failure may occur below the limits of curves.

(I) Because of the several approximations employed in describing the simplified model (i.e. isotropy, equal shrinkage rates parallel and perpendicular to extrusion, shrinkage independent of temperature, geometric changes in cross-section, symmetrical irradiation, etc) the approach followed in the preliminary stress calculations was a conservative one and intended to give a range within which stresses would fall if there were no relaxation with time and irradiation. Accordingly, the shrinkage rate is taken to be isotropic and at its maximum recommended value (~ 0.004 in/in per 1000 MW/AT).

The concept of no relaxation is itself conservative; in addition, the assumption that parallel planes remain plane and parallel is conservative since it implies no ability of the material to adjust to shrinkages in the "z" direction. Limiting calculation to the midplane of core gives highest gradients. It is believed that stresses calculated will never be exceeded in EGCR.

The stress-strain curves employed are the highest that can be reasonably arrived at with current published information on graphite so as to give a conservative answer. In addition, the lowest (i.e. normal, unirradiated) stress-strain curve is used to provide the lower limit to stress range.

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The preliminary analysis (isotropic case) is based on the following model:

$$r=b=4.49''$$

$$r=a=2.625''$$

Core Midplane

232"

Note r_b chosen to give annular area equivalent to the quarter-column surrounding a typical fuel channel

In order to assume that parallel planes remain plane and parallel, consideration is limited to the center section of the cylinder as shown dotted. This should result in the highest stresses to be obtained anywhere in the cylinder. Poisson's ratio is assumed the same ^(0.25) in all directions.

In this unit annular segment, the flux gradients are taken as those around a typical fuel channel with no nearby depressants. The flux curve is expressed as

$$\phi_r = (6.284 + e^{-.66r}) \phi_c$$

so as to fit already known values at $r=a$ and $r=b$.

For converting to damage (at the rate of $.0004$ in/in per 1000 MWD/AT) ϕ_c at the axial core $\bar{r}$ is equivalent to 2.73×10^{-4} MWD/AT/SEC giving rise to accumulated exposure of 8600 MWD/AT/year at $r=0$. Shrinkages are computed, for the simple case, as if the shrinkage rate was isotropic.

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III) A general expression for σ_r substituting Shrinkage $(-\frac{\Delta L}{L})$ for the expansion (αt) . Ref. Timoshenko's Strength of Materials Part II Page 231

$$\sigma_r = \frac{E}{1+\mu} \left[-\left(\frac{1+\mu}{\mu-1}\right) \frac{1}{r^2} \int_a^r r \left(\frac{\Delta L}{L}\right) dr + \frac{C_1}{1-2\mu} - \frac{C_2}{r^2} + \frac{\mu}{1-2\mu} \epsilon_z \right]$$

Where: $C_1 = \frac{(1+\mu)(1-2\mu)}{\mu-1} \frac{1}{b^2-a^2} \int_a^b r \left(\frac{\Delta L}{L}\right) dr - \mu \epsilon_z$

$$C_2 = \left(\frac{1+\mu}{\mu-1}\right) \frac{a^2}{b^2-a^2} \int_a^b r \left(\frac{\Delta L}{L}\right) dr$$

$$\sigma_r = \frac{E}{1+\mu} \left[-\left(\frac{1+\mu}{\mu-1}\right) \frac{1}{r^2} \int_a^r r \left(\frac{\Delta L}{L}\right) dr + \left(\frac{1+\mu}{\mu-1}\right) \left(\frac{1}{b^2-a^2}\right) \int_a^b r \left(\frac{\Delta L}{L}\right) dr - \frac{\mu}{1-2\mu} \epsilon_z - \left(\frac{1+\mu}{\mu-1}\right) \left(\frac{a^2}{b^2-a^2}\right) \frac{1}{r^2} \int_a^b r \left(\frac{\Delta L}{L}\right) dr + \frac{\mu}{1-2\mu} \epsilon_z \right]$$

$$\sigma_r = \frac{E}{1+\mu} \left[-\left(\frac{1+\mu}{\mu-1}\right) \frac{1}{r^2} \int_a^r r \left(\frac{\Delta L}{L}\right) dr + \left(\frac{1+\mu}{\mu-1}\right) \frac{1}{b^2-a^2} \int_a^b r \left(\frac{\Delta L}{L}\right) dr \left[1 - \frac{a^2}{r^2}\right] \right]$$

$$\sigma_r = \frac{E}{\mu-1} \left[-\frac{1}{r^2} \int_a^r r \left(\frac{\Delta L}{L}\right) dr + \frac{r^2-a^2}{r^2(b^2-a^2)} \int_a^b r \left(\frac{\Delta L}{L}\right) dr \right]$$

$$\sigma_t = \sigma_r + r \frac{d\sigma_r}{dr}$$

$$r \frac{d\sigma_r}{dr} = \frac{E}{\mu-1} \left[\frac{2}{r^2} \int_a^r r \left(\frac{\Delta L}{L}\right) dr - \frac{1}{r^2} (r^2) \left(\frac{\Delta L}{L}\right) + \left(\frac{a^2}{b^2-a^2}\right) \frac{2}{r^2} \int_a^b r \left(\frac{\Delta L}{L}\right) dr \right]$$

$$\sigma_t = \frac{E}{\mu-1} \left[\frac{1}{r^2} \int_a^r r \left(\frac{\Delta L}{L}\right) dr + \frac{(r^2+a^2)}{r^2(b^2-a^2)} \int_a^b r \left(\frac{\Delta L}{L}\right) dr - \left(\frac{\Delta L}{L}\right) \right]$$

$$\sigma_z = \frac{E}{1+\mu} \left[\epsilon_z \left\{ \frac{1-\mu}{1-2\mu} \right\} + \frac{\mu}{1-2\mu} \left\{ \frac{1+\mu}{\mu-1} \left[\frac{\Delta L}{L} \right] + 2C_1 \right\} \right] + \frac{\Delta L}{1-2\mu} \frac{E}{L}$$

where ϵ_z must be evaluated from the condition that the summation of forces in the $r\theta$ plane be zero since the cylinder is free to move longitudinally. i.e.:

$$\int_0^{2\pi} \int_a^b r_3 r dr d\theta = 0 \quad \text{which gives}$$

$$\epsilon_z = -\frac{1+\mu}{1-\mu} \left(\frac{\mu}{\mu-1} + 1 \right) \frac{\int_a^b \frac{\Delta L}{L} r dr}{\int_a^b r dr} - \frac{2\mu C_1}{1-\mu}$$

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As a first trial, taking a total relative shrinkage equivalent to about two years of life:
When: $r = a$; $y = y_a = P + Q \cos \pi \left(\frac{a}{b} \right)$

$r = b$; $y = y_b = P - Q$
and using a trial cosine distribution of shrinkage instead of the exponential distribution:
 $y_a - y_b = Q (\cos \pi \frac{a}{b} + 1)$

$$Q = \frac{y_a - y_b}{\cos \pi \frac{a}{b} + 1}$$

$$P = Q + y_b$$

$$y = \frac{(y_a - y_b)}{\cos \pi \frac{a}{b} + 1} (\cos \pi \frac{r}{b} + 1) + y_b$$

$$\frac{\Delta L}{L} = y - y_b = m (\cos (\pi \frac{r}{b}) + 1)$$

Where: $m = \frac{(y_a - y_b)}{\cos \pi \frac{a}{b} + 1}$

then: $\int_a^r \frac{\Delta L}{L} dr = \int_a^r m [\cos (\pi \frac{r}{b}) + 1] dr$
 $= m \int_a^r \cos (\pi \frac{r}{b}) dr + m \int_a^r 1 dr$

let: $\frac{\pi}{b} r = x$
 $\frac{\pi}{b} dr = dx$

then: $m \int_a^r \cos \frac{\pi}{b} r dr = m \int \frac{b^2}{\pi^2} x \cos x dx = \frac{m b^2}{\pi^2} \int x \cos x dx =$
 $\frac{m b^2}{\pi^2} [\cos x + x \sin x]_{\frac{\pi a}{b}}^{\frac{\pi r}{b}} =$

$$\frac{m b^2}{\pi^2} \left[\cos \left(\frac{\pi}{b} r \right) + \frac{\pi}{b} r \sin \left(\frac{\pi}{b} r \right) - \cos \frac{\pi a}{b} - \frac{\pi}{b} a \sin \left(\frac{\pi a}{b} \right) \right]$$

and: $m \int_a^r 1 dr = \frac{m}{2} [r^2 - a^2]$

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$$\text{Then: } \sigma_t = \frac{E}{\mu-1} \left[\frac{1}{r^2} \left\{ \frac{mb^2}{\pi^2} \left(\cos \frac{\pi r}{b} - \cos \frac{\pi a}{b} + \frac{\pi r}{b} \sin \frac{\pi r}{b} - \frac{\pi a}{b} \sin \frac{\pi a}{b} \right) + \frac{m}{2} (r^2 - a^2) \right\} \right. \\ \left. + \frac{r^2 + a^2}{r^2(b^2 - a^2)} \left\{ \frac{mb^2}{\pi^2} \left(\cos \pi - \cos \frac{\pi a}{b} + \pi \sin \pi - \frac{\pi a}{b} \sin \frac{\pi a}{b} \right) + \frac{m}{2} (b^2 - a^2) \right\} \right. \\ \left. - m \cos \frac{\pi r}{b} - m \right]$$

The maximum value of σ_t should occur when $r=a$

$$\sigma_t(r=a) = \frac{E}{\mu-1} \left[\frac{1}{a^2} \left\{ \frac{mb^2}{\pi^2} \left(\cos \frac{\pi a}{b} - \cos \frac{\pi a}{b} + \frac{\pi a}{b} \sin \frac{\pi a}{b} - \frac{\pi a}{b} \sin \frac{\pi a}{b} \right) + \frac{m}{2} (a^2 - a^2) \right\} \right. \\ \left. + \frac{2a^2}{a^2(b^2 - a^2)} \left\{ \frac{mb^2}{\pi^2} \left(-1 - \cos \frac{\pi a}{b} - \frac{\pi a}{b} \sin \frac{\pi a}{b} \right) + \frac{m}{2} (b^2 - a^2) \right\} \right. \\ \left. - m \cos \frac{\pi a}{b} - m \right]$$

$$\sigma_t(r=a) = \frac{mE}{\mu-1} \left[\frac{2}{(b^2 - a^2)} \left\{ \frac{b^2}{\pi^2} \left(-1 - \cos \frac{\pi a}{b} - \frac{\pi a}{b} \sin \frac{\pi a}{b} \right) + \frac{1}{2} (b^2 - a^2) \right\} - \cos \frac{\pi a}{b} - 1 \right]$$

Consider the cylindrical model of one lattice cell (taking $r_b \approx$ lattice pitch dimension)

$$a = \frac{5.26}{2} = 2.625''$$

$$b = \frac{8.15}{2} = 4.075''$$

(not 4.49" as for equivalent area shown on sheet 1B)

Assume: $y_a = .01$ } shrinkages roughly equivalent to 2 years of core
 $y_b/y_a = .9$ } life at full power.

$$\text{Then: } m = \frac{y_a - y_b}{\cos(\pi \frac{a}{b}) + 1} = \frac{.01 - .009}{\cos \pi \frac{2.625}{4.075} + 1} = \frac{.001}{1 - .438} = \frac{.001}{.562} = .00178$$

$$\text{and } \sigma_t = \frac{.00178 E}{\mu-1} \left[\frac{2}{(4.08)^2 - (2.63)^2} \left\{ \frac{(4.08)^2}{(3.14)^2} \left[-1 + .438 - (.899) 1.93 \right] + \frac{1}{2} [(4.08)^2 - (2.63)^2] \right\} \right. \\ \left. + .438 - 1 \right]$$

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$$\begin{aligned}
 \sigma_t(r=a) &= \frac{.00178E}{\mu-1} \left[\frac{2}{16.7-6.92} \left\{ \frac{16.7}{9.85} [-2.27] + \left(\frac{16.7-6.92}{2} \right) \right\} - .562 \right] \\
 &= \frac{.00178E}{\mu-1} \left[.204(-3.85+4.9) - .562 \right] \\
 &= \frac{.00178E}{\mu-1} \times (-.348) = -.00062 E / \mu - 1
 \end{aligned}$$

If $E = 1.5 \times 10^6$

and $\mu = .25$

$$\text{then } \sigma_t(r=a) = -.00062 \times \frac{1.5 \times 10^6}{(.75)} = \underline{\underline{+1240 \text{ psi}}}$$

This first trial, which does not consider effects of varying tangent modulus and which is for a ^{differential shrinkage} ~~linear~~ equivalent to only about two years of core life, indicates that Wigner Stresses are appreciable. The following calculations will refine this result to include effects of time, and stress levels, at the critical location for maximum relative damage in the assumed model. This location is taken as in the fuel channel nearest the core ϕ and at the core midplane.

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(IV) for σ_r at $r=a$ $n=1/2$. At the core center (see Fig 4)

$$(1) \sigma_r = \frac{E(1.0004)(.86 \times 10^{-4})}{\mu-1} \left[\frac{1}{r^2} \int_a^r r(1.628 + e^{-.66r} - .68) dr + \frac{r^2+a^2}{r^2(b^2-a^2)} \int_a^b r(1.628 + e^{-.66r} - .68) dr - (1.628 + e^{-.66r} - .68) \right]$$

$$(a) \frac{E(1.0004)(.86 \times 10^{-4})}{\mu-1} = \frac{1.82 \times 10^6 \times 3.44 \times 10^{-3}}{(1.25-1)} = -8.35 \times 10^3$$

$$(b) \frac{1}{r^2} \int_a^r r(-.052 + e^{-.66r}) dr = 0$$

$$(c) \frac{r^2+a^2}{r^2(b^2-a^2)} = \frac{2(2.625)^2}{(2.625^2)(4.49^2-2.625^2)} = \frac{2}{(20.2-6.9)} = .1505$$

$$(d) \int_a^b r(-.052 + e^{-.66r}) dr = \left[-\frac{.052r^2}{2} - \frac{r e^{-.66r}}{.66} - \frac{e^{-.66r}}{.66^2} \right]_{2.625}^{4.49}$$

$$= \left[-.026(20.2) - \frac{4.49 e^{-2.96}}{.66} - \frac{e^{-2.96}}{.435} + .026(6.9) + \frac{2.625 e^{-1.73}}{.66} + \frac{e^{-1.73}}{.425} \right]$$

$$\text{where } e^{-2.96} = \frac{1}{19.4} \quad e^{-1.73} = \frac{1}{5.64}$$

$$= [-.525 - .351 - .118 + .179 + .707 + .407]$$

$$= +.299$$

$$(e) -.052 + e^{-1.73} = -.052 + .178 = .126$$

$$(f) -8.35 \times 10^3 [0 + .1505(.299) - .126] = -8.35 [+0.045 - .126] 10^3$$

$$= +.677 \times 10^3 = 677 \text{ psi}$$

(2) for σ_t at $r=b$ using (1) above

$$(a) \frac{1}{r^2} \int_a^b r(1.628 + e^{-.66r} - .68) dr = \frac{1}{4.49^2} (.299) = .0149$$

$$(b) \frac{r^2+a^2}{r^2(b^2-a^2)} = \frac{4.49^2 + 2.625^2}{4.49^2(20.2-6.9)} = \frac{20.2+6.9}{4.49^2(13.3)} = .101$$

$$(c) -.052 + e^{-2.96} = -.052 + .0516 = 0$$

$$(d) -8.35 \times 10^3 [.0149 + .101(.299) - 0] = -8.35 \times 10^3 (.0149 + .0302)$$

$$= -379 \text{ psi}$$

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SCALE = 12

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ALLIS-CHALMERS MFG. CO. DEPT. NPD-W

Nov. 30, 1959

To Solve for ϵ_3 to be used in σ_3 expression:

$$\frac{2\pi E}{1+\mu} \left\{ \epsilon_3 \left(\frac{1-\mu}{1-2\mu} \right) + \frac{2\mu C_1}{1-2\mu} \right\} \left[\frac{r^2}{2} \right]_a^b + \frac{2\pi E}{1-2\mu} \left\{ \frac{\mu}{\mu-1} + 1 \right\} \int_a^b r \frac{\Delta L}{L} dr = 0$$

$$\epsilon_3 \left(\frac{1-\mu}{1-2\mu} + \frac{2\mu C_1}{1-2\mu} \right) = - \frac{1+\mu}{1-2\mu} \left(\frac{\mu}{\mu-1} + 1 \right) \frac{\int_a^b r \frac{\Delta L}{L} dr}{\int_a^b r dr}$$

$$\epsilon_3 = - \frac{1+\mu}{1-\mu} \left(\frac{\mu}{\mu-1} + 1 \right) \frac{\int_a^b r \frac{\Delta L}{L} dr}{\int_a^b r dr} - \frac{2\mu C_1}{1-\mu}$$

$$= - \frac{(1.25)(-.5)}{(.75)(-.75)} \frac{(10.3 \times 10^{-4})}{2 \times 2.69} - \frac{2(.25) C_1}{.75}$$

$$= - 1.725 \times 10^{-4} - .66 C_1$$

$$C_1 = \frac{(1+\mu)(1-2\mu)}{\mu-1} \frac{1}{b^2-a^2} \int_a^b r \frac{\Delta L}{L} dr - \mu \epsilon_3$$

$$C_1 = \frac{(1.25)(.50)}{-.75} \left(\frac{1}{13.3} \right) (10.3 \times 10^{-4}) - .25 \epsilon_3$$

$$C_1 = -.644 \times 10^{-4} - .25 \epsilon_3$$

$$4.835 \epsilon_3 = -1.725 \times 10^{-4} - .66 (-.644 \times 10^{-4})$$

$$= -1.725 \times 10^{-4} + .425 \times 10^{-4} = -1.3 \times 10^{-4}$$

$$\epsilon_3 = -1.3 \times 10^{-4}$$

$$C_1 = -.644 \times 10^{-4} - (.25)(-1.3 \times 10^{-4})$$

$$C_1 = -.644 \times 10^{-4} + .325 \times 10^{-4} = -.319 \times 10^{-4}$$

For σ_3 at $r=a$ $n=1$ yr

$$\sigma_3 = \frac{E}{1+\mu} \left(\epsilon_3 \left\{ \frac{1-\mu}{1-2\mu} \right\} + \frac{\mu}{1-2\mu} \left\{ \frac{1+\mu}{\mu-1} \left[\frac{\Delta L}{L} \right] + 2C_1 \right\} \right) + \frac{\Delta L}{L} \frac{E}{1-2\mu}$$

$$\frac{1.52 \times 10^6}{1.25} \left[-1.3 \times 10^{-4} \left\{ \frac{.75}{.50} \right\} + \frac{.25}{.50} \left\{ \frac{1.25}{-.75} \left[\frac{.8054 - .6800}{1.000} \right] \frac{.56 \times 10^{-4}}{4 \times 10^{-4}} \right\} + 2(-.319 \times 10^{-4}) \right] + \left[\frac{.8054 - .6800}{1.000} \right] \frac{.86 \times 10^{-4}}{4 \times 10^{-4}} (1.52 \times 10^6)$$

$$\frac{1.52 \times 10^6}{1.25} \left[-2.34 \times 10^{-4} + \frac{1}{2} \left\{ 1.666 \left[\frac{.1254 \times 3.44}{1.000} \right] + .508 \times 10^{-4} \right\} + 2 \left[\frac{.1254 \times 3.44}{1.00} \right] (1.52 \times 10^6) \right]$$

$$\frac{1.52 \times 10^6}{1.25} \left[-2.34 \times 10^{-4} + \frac{1}{2} \left\{ -1.666 \left[.432 \times 10^{-3} \right] - .508 \times 10^{-4} \right\} + 2 \left[.432 \times 10^{-3} \right] (1.52 \times 10^6) \right]$$

$$\frac{1.52 \times 10^6}{1.25} \left[-2.34 \times 10^{-4} + \frac{1}{2} \left\{ -7.2 \times 10^{-4} - .508 \times 10^{-4} \right\} \right] + 1.57 \times 10^3$$

$$\frac{1.52 \times 10^6}{1.25} \left[-.619 \times 10^{-3} \right] + 1.57 \times 10^3 = 680 \text{ psi (tension)}$$

STRESSES CAUSED BY IRRADIATION - INDUCED DIFFERENTIAL SHRINKAGE OF EGCR GRAPHITE (USING A SIMPLIFIED, ISOTROPIC MODEL OF THE MONOLITHIC COLUMN) TASK NO. 227

II-227
APPENDIX 2

SIMILAR TO

DR'N R.R.N.
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SCALE = 12

SHEET 7 OF 18

ISSUE

ALLIS-CHALMERS MFG. CO.

DEPT.

NPD-W

Nov. 30, 1959

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A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

For σ_z at $r = b$

$$b\sigma_z = \frac{1.82 \times 10^6}{1.25} \left(-2.314 \times 10^{-4} + \frac{.55}{.50} \{ 2(-.254 \times 10^{-4}) \} \right) + 0$$

$$= \frac{1.82 \times 10^6}{1.25} (-2.314 \times 10^{-4} - .254 \times 10^{-4}) = -377$$

The computed σ_z serves as a check on the values of σ_r and the variation of σ_z with time over the 20 year core life as for σ_r . The tabulated values of σ_r may be used to describe σ_z at the same locations in the cylinder.

STRESSES CAUSED BY IRRADIATION - INDUCED
DIFFERENTIAL SHRINKAGE OF EGCR GRAPHITE
(USING A SIMPLIFIED, ISOTROPIC MODEL OF
THE MONOLITHIC COLUMN) TASK NO. 227

II-227
APPENDIX 2

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(1) for σ_r at $r=a$ $n=1$ yr

$$n\sigma_r = \frac{E(1.0004)(.86 \times 10^4)}{\mu-1} \left[-\frac{1}{r^2} \int_a^r r(1.02 + e^{-.66r}) dr + \frac{r^2 - a^2}{r^2(b^2 - a^2)} \int_a^b r(-.02 + e^{-.66r}) dr \right]$$

for $r=a$ & $r=b$ $n\sigma_r = 0$ for all "n"

(2) for σ_r at $r = \frac{a+b}{2} = \frac{2.625 + 4.49}{2} = 3.558$

(a) $\frac{E(1.0004)(.86 \times 10^4)}{\mu-1} = -8.35 \times 10^3$

(b) $-\frac{1}{r^2} = -\frac{1}{(3.558)^2} = -0.0789$

(c) $\int_a^r r(-.02 + e^{-.66r}) dr = \left[-\frac{.02r^2}{2} - \frac{r}{.66} e^{-.66r} - \frac{1}{.66^2} e^{-.66r} \right]_{2.625}^{3.558}$
 $= \left[-.01(12.68) - \frac{3.56}{.66} e^{-2.35} - \frac{4}{.435} e^{-2.35} + .01(6.9) + \frac{2.625}{.66} e^{-1.73} + \frac{4}{.435} e^{-1.73} \right]$
 $= \left[-.127 - \frac{3.56}{.66(10.5)} - \frac{1}{.435}(10.5) + .069 + .707 + .407 \right]$
 $= \left[-.127 - .514 - .219 + .069 + .707 + .407 \right]$
 $= \left[+.328 \right]$

(d) $\frac{r^2 - a^2}{r^2(b^2 - a^2)} = \frac{3.56^2 - 2.625^2}{3.56^2(4.49^2 - 2.625^2)} = \frac{12.68 - 6.9}{12.68(10.2 - 6.9)} = \frac{5.78}{12.68(3.3)} = .0343$

(e) $\int_a^b r(1.02 + e^{-.66r}) dr = .299$

(f) $\sigma_r\left(\frac{a+b}{2}\right) = -8.35 \times 10^3 \left[-(0.0789)(.328) + (.0343)(.299) \right]$
 $= -8.35 \times 10^3 \left[.0256 + .01025 \right] = +128.5 \text{ psi}$

Because of the generally high level of stresses (even after one year) no attempt will be made, in these first approximations, to superimpose the stresses necessary to maintain complete continuity among all the four model cells within any one column. Such superposition should prove advisable in later calculations for an anisotropic model.

STRESSES CAUSED BY IRRADIATION - INDUCED DIFFERENTIAL SHRINKAGE OF EGCR GRAPHITE (USING A SIMPLIFIED, ISOTROPIC MODEL OF THE MONOLITHIC COLUMN) TASK NO. 227

II-227
APPENDIX 2

SIMILAR TO

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ALLIS-CHALMERS MFG. CO.

DEPT. NPD-W

Nov. 30, 1959

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A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

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EGCR
TANGENTIAL STRESS IN HYPOTHETICAL SIMPLE
CYLINDER (DUE TO IRRADIATION @ 900°F NEAR
CORE & FOR 20 YEAR LIFE) AT OPERATING
TEMPERATURE ASSUMING NO RELAXATION OF STRESS

n YEAR END	EXPOSURE (10 ⁴ MW/AT) $\dot{E}$				$\frac{\Delta T_L}{1000 \text{ MW/AT}}$	TENSION $r=a$						COMPRESSION $r=b$					
	ϕ CHAN SECT	$r=a$	$r=b$	S_E		E TANG. MOD 10 ⁴ PSI	$n\sigma_{Ea}$	$\sum \sigma_{Ea}$ (U=1.0)	$\sum \sigma_{Ea}$ (U=2)		TAN. MOD	$n\sigma_{Eb}$	$\sum n\sigma_{Eb}$ (U=1.0)		$\sum \sigma_{Eb}$ (U=2)		
									T.M.	$\sum \sigma_E$			T.M.	$\sum \sigma_E$			
0	0	0	0	0	.0004	1.82	0	0	1.82	0	1.82	0	0	1.82	0		
-1	.86	.692	.557	.14		1.82	677	677	1.82	542	1.82	379	379	1.82	303		
-2	1.72	1.38	1.11	.27		1.82	677	1354	1.82	1084	1.82	379	758	1.82	606		
-3	2.58	2.08	1.67	.41		1.63	606	1960	1.79	1616	1.82	379	1137	1.82	909		
-4	3.44	2.77	2.23	.54		1.30	476	2436	1.50	2060	1.78	370	1407	1.81	1210		
-5	4.30	3.46	2.78	.68		1.08	402	2838	1.25	2432	1.59	331	1738	1.72	1496		
-6	5.16	4.16	3.34	.82		0.81	300	3138	1.08	2754	1.44	298	2036	1.55	1754		
-7	6.02	4.85	3.90	.95		0.68	253	3388	0.89	30120	1.25	261	2297	1.37	1982		
-8	6.88	5.53	4.45	1.08		0.53	197	3585	0.73	3236	1.13	236	2533	1.28	2195		
-9	7.74	6.23	5.02	1.21		0.30	111	3696	0.61	3417	1.01	209	2742	1.18	2391		
10	8.60	6.92	5.57	1.35		LIMIT OF S-E CURVE				0.49	3562	0.89	185	2927	1.10	2574	
11	9.46	7.61	6.13	1.48					0.31	3654	0.75	156	3083	1.00	2740		
12	10.32	8.30	6.68	1.62							0.69	144	3227	0.89	2888		
13	11.18	8.98	7.24	1.74							0.61	127	3454	0.79	3019		
14	12.04	9.70	7.80	1.90							0.45	94	3548	0.73	3140		
15	12.90	10.4	8.35	2.05							0.31	65	3613	0.68	3253		
16	13.76	11.1	8.93	2.17							LIMIT OF S-E CURVE						
17	14.62	11.75	9.47	2.28										0.55	3445		
18	15.48	12.45	10.03	2.42										0.47	3523		
19	16.34	13.15	10.58	2.57										0.44	3596		
20	17.20	13.85	11.12	2.73										0.39	3661		

TANGENTIAL STRESSES AT OPERATING TEMPERATURES

$$\text{where rel. } \dot{E}_x(r) = .6284 + e^{-.66r}$$

$$\dot{E}_a = .6284 + e^{-.66(2.625)} = .6284 + e^{-1.73} = .6284 + .177 = .8054$$

$$\dot{E}_b = .6284 + e^{-.66(4.49)} = .6284 + e^{-2.96} = .6284 + .0516 = .6800 = k \text{ (i.e. Ref. level)}$$

$$n\sigma_{En} = \frac{E}{1-\nu} \left[\frac{1}{r^2} \int_a^r (.0004)(.628 + e^{-.66r}) \left(\frac{S_E}{1000} \right) dr + \frac{r^2 + a^2}{2(r^2 - a^2)} \int_a^b (.0004)(.628 + e^{-.66r}) \left(\frac{S_E}{1000} \right) dr + \right.$$

$$\text{where } S_E = 0.86 \times 10^4 \text{ MW/AT}$$

Solutions will be obtained for only $r=a=2.625$ and $r=b=4.49$

TASIC NO. 227
APPENDIX 2

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ISSUE

ALLIS-CHALMERS MFG. CO. DEPT. 11

NPD-M

SCALE = 12

N YEAR END	EXPOSURE (10 ⁴ MWD/AT)				M/L 1000 MWD/AT	TENSION				COMPRESSION					
	CHAN. 2FE	r=a	r=b	S _{SE}		E TANG. MOD 10 ⁶ psi	nσ _{ta}	Σ _i nσ _{ta} U=1.0	Σ _i nσ _{ta} (U=.8)	TAN MOD	nσ _{tb}	Σ _i nσ _{tb} U=1.0	Σ _i nσ _{tb} U=.8		
														T.M.	σ _e
0	0	0	0	0	.0004	1.78	0	0	1.78	0	1.78	0	0	1.78	0
1	.86	.692	.558	.14		1.78	661	661	1.78	529	1.78	371	371	1.78	296
2	1.72	1.38	1.11	.27		1.26	470	1131	1.39	941	1.44	300	671	1.78	592
3	2.58	2.04	1.67	.41		1.13	420	1551	1.19	1295	1.26	262	933	1.32	812
4	3.44	2.77	2.23	.54		0.93	346	1897	1.07	1613	1.17	244	1177	1.26	1016
5	4.30	3.46	2.78	.68		0.74	276	2173	0.88	1875	1.10	229	1406	1.15	1209
6	5.16	4.16	3.34	.82		0.59	219	2392	0.75	2098	1.01	209	1615	1.09	1388
7	6.02	4.85	3.90	.95		0.52	193	2585	0.63	2286	0.88	183	1793	1.02	1558
8	6.88	5.53	4.45	1.08		0.45	167	2752	0.55	2450	0.82	171	1964	0.93	1712
9	7.74	6.23	5.02	1.21					0.50	2599	0.70	146	2110	0.85	1853
10	8.60	6.92	5.57	1.35							0.63	131	2241	0.76	1979
11	9.46	7.61	6.13	1.48							0.57	121	2362	0.69	2094
12	10.32	8.30	6.68	1.62							0.52	109	2471	0.64	2200
13	11.18	8.98	7.24	1.74							0.49	102	2575	0.59	2298
14	12.04	9.70	7.80	1.90										0.54	2388
15	12.90	10.4	8.35	2.05										0.52	2474
16	13.76	11.1	8.93	2.17										0.49	2566
17	14.62	11.75	9.47	2.28											
18	15.48	12.45	10.03	2.42											
19	16.34	13.15	10.58	2.57											
20	17.20	13.85	11.12	2.73											

TANGENTIAL STRESSES AT ROOM TEMPERATURE (SHRINK. ACCUM. @ OPER. TEMP)

$$n\sigma_{ta} = \frac{E}{\mu-1} \left[\frac{1}{r^2} \int_a^r (1.0004)(6.28 + e^{-.68r} - .68) \frac{S_{SE}}{1000} dr + \frac{r^2 - a^2}{r^2(r^2 - a^2)} \int_a^r (1.0004)(6.28 + e^{-.68r} - .68) \frac{S_{SE}}{1000} dr - (1.0004)(6.28 + e^{-.68r} - .68) \frac{S_{SE}}{1000} \right]$$

TANGENTIAL STRESSES IN HYPOTHETICAL SIMPLE CYLINDER
(DUE TO SHrink ACCUM. @ 900° F NEAR CODE Q FOR 20 YEAR
LIFE) AT SHUTDOWN TEMPERATURES ASSUMING GRAPHITE
STRAINS TO BE ADJUSTED ACCORDING TO ROOM TEMP.

EGCR
TASK NO. 227
APPENDIX 2
SIMILAR TO
SHEET 11 OF 18
NOV. 30, 1959

ALUS-CHALMERS MFG. CO. DEPT. NPD-W SCALE = 12
A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

RADIAL STRESSES IN HYPOTHETICAL SINGLE CYLINDER
AT OPERATING AND SHUTDOWN TEMPERATURES
ASSUMING NO RELAXATION OF STRESSES (IRRADIATED
NEAR CORE & @ 900°F; $\mu = .26$)

year end n	EXPOSURE (10^4 MWDT/AT) Σ				$\frac{\Delta L}{L}$ PER 1000 MWDT/AT	Operating Temperature						Room Temp.					
	ϕ CMW	r=a	r=b	$\delta \epsilon$		E TAN. MOD. 10 ⁶ psi	$n \sigma_r$ $\left(\frac{a+b}{2}\right)$	$\Sigma n \sigma_r$ $\left(\frac{a+b}{2}\right)$	$\Sigma \epsilon_r$ (U.S.)		E TAN. MOD. 10 ⁶ psi	$n \sigma_r$ $\left(\frac{a+b}{2}\right)$	$\Sigma n \sigma_r$ $\left(\frac{a+b}{2}\right)$	$\Sigma \epsilon_r$ (U.S.)			
									T.M.	$\Sigma \epsilon_r$				T.M.	$\Sigma \epsilon_r$		
TENSION																	
0	0	0	0		.0004	1.82	0	0	1.82	0	1.78	0	0	1.78	0		
1	.86	.692	.557	.14		1.82	129	129	1.82	103	1.78	126	126	1.78	101		
2	1.72	1.38	1.11	.27		1.82	129	258	1.82	206	1.78	126	252	1.78	202		
3	2.58	2.08	1.67	.41		1.82	129	387	1.82	309	1.69	120	372	1.78	303		
4	3.44	2.77	2.23	.54		1.82	129	516	1.82	432	1.44	102	474	1.57	389		
5	4.30	3.46	2.78	.68		1.82	129	645	1.82	515	1.34	95	569	1.43	470		
6	5.16	4.16	3.34	.82		1.82	129	774	1.82	618	1.27	90	659	1.34	546		
7	6.02	4.85	3.90	.95		1.82	129	903	1.82	721	1.26	89	748	1.28	619		
8	6.88	5.53	4.45	1.08		1.82	129	1033	1.82	824	1.23	87	835	1.26	690		
9	7.74	6.23	5.02	1.21		1.82	128	1161	1.82	927	1.21	86	921	1.25	761		
10	8.60	6.92	5.57	1.35		1.71	121	1282	1.81	1029	1.18	84	1005	1.23	830		
11	9.46	7.61	6.13	1.48		1.67	118	1400	1.80	1131	1.16	82	1087	1.21	898		
12	10.32	8.30	6.68	1.62		1.59	113	1518	1.72	1228	1.12	79	1166	1.19	965		
13	11.18	8.98	7.24	1.74		1.55	110	1623	1.69	1324	1.10	78	1244	1.17	1031		
14	12.04	9.70	7.80	1.90		1.50	107	1730	1.64	1417	1.08	76	1320	1.14	1096		
15	12.90	10.4	8.35	2.05		1.44	102	1832	1.60	1507	1.04	74	1394	1.12	1159		
16	13.76	11.1	9.93	2.17		1.35	96	1928	1.55	1595	1.02	72	1466	1.10	1221		
17	14.62	11.75	9.97	2.38		1.29	92	2030	1.51	1681	0.98	69	1535	1.08	1282		
18	15.48	12.45	10.03	2.42		1.25	89	2119	1.47	1764	0.94	67	1602	1.06	1342		
19	16.34	13.15	10.58	2.57		1.22	87	2206	1.41	1844	0.89	63	1665	1.03	1400		
20	17.20	13.85	11.12	2.73		1.18	84	2290	1.35	1921	0.85	60	1725	1.02	1458		

RADIAL STRESSES AT OPERATING AND SHUTDOWN TEMP (SHRINKAGE ACCUMULATED @ OPER. TEMP)

$$n \sigma_r = \frac{E}{\mu - 1} (1.0004) \left(\frac{86 \times 10^4}{1000} \right) \left[-\frac{1}{r^2} \int_a^r (-0.02 + e^{-0.66n}) dr + \frac{r^2 - a^2}{r^2(b^2 - a^2)} \int_a^b (-0.02 + e^{-0.66n}) dr \right]$$

since σ_r at $r=a$ and $r=b$ is zero for all "n" find ϵ_r at $r = \frac{a+b}{2}$ as approx. max.

EGCR

TASK NO. 227
APPENDIX 2

SIMILAR TO

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ISSUE

ALLIS-CHALMERS MFG. CO. DEPT. NPD-W

Nov. 30, 1959

A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

FIG No 1
BASIC REFERENCE CURVE
ASSUMED STRESS-STRAIN CURVE IN TENSION AND COMPRESSION
(II) FOR A60T AT VARIOUS TEMPERATURES

STRESSES CAUSED BY IRRADIATION - INDUCED
DIFFERENTIAL SHRINKAGE OF EGCR GRAPHITE
(USING A SIMPLIFIED, ISOTROPIC MODEL OF
THE MONOLITHIC COLUMN) TASK NO. 227

II-227
TASK No. 227
APPENDIX 2

SIMILAR TO

DR'N R.R.N. LDH	CH'D LDH	APP'D <i>[Signature]</i>	SCALE = 12	SHEET 13 OF 18	ISSUE
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ASSUMED STRESS-STRAIN CURVE FOR EGCR GRAPHITE (II)
ON HORIZONTAL PLANE (AV. TEMP. 600F) FOR ANY VALUE OF
TOTAL IRRADIATION DOSE NEAR BOTTOM OF CORE

STRESSES CAUSED BY IRRADIATION - INDUCED DIFFERENTIAL SHRINKAGE OF EGCR GRAPHITE (USING A SIMPLIFIED, ISOTROPIC MODEL OF THE MONOLITHIC COLUMN) TASK NO. 227

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 Appendix 2

DR'N R.R.N. LDH	CH'D LDH	APP'D	SCALE = 12	SHEET 14 OF 18	ISSUE
ALLIS-CHALMERS MFG. CO. DEPT. NFD-W				Nov. 30, 1959

FIGURE 3

ASSUMED STRESS-STRAIN CURVE FOR EGCR GRAPHITE (11)
ON HORIZONTAL PLANE (AV. TEMP = 700°F TO 800°F) FOR ANY VALUE OF
TOTAL IRRADIATION DOSE BETWEEN BOTTOM & MIDPLANE OF CORE

**STRESSES CAUSED BY IRRADIATION - INDUCED
DIFFERENTIAL SHRINKAGE OF EGCR GRAPHITE
(USING A SIMPLIFIED, ISOTROPIC MODEL OF
THE MONOLITHIC COLUMN) TASK NO. 227**

II-52271
APPENDIX 2

SIMILAR TO

DR'N R.R.N.
L.D.H.

CH'D L.D.H.

APP'D *[Signature]*

SCALE = 12

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ALLIS-CHALMERS MFG. CO.

DEPT. NPD-W

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FIG NO 4
 ASSUMED STRESS-STRAIN CURVE FOR EGCR GRAPHITE (11)
 ON HORIZONTAL PLANE (AV. TEMP = 900°F) FOR ANY VALUE OF
 TOTAL IRRADIATION DOSE NEAR HORIZONTAL CORE MIDPLANE

STRESSES CAUSED BY IRRADIATION - INDUCED
 DIFFERENTIAL SHRINKAGE OF BOCH GRAPHITE
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FIG NO 5
ASSUMED STRESS-STRAIN CURVE FOR EGCC GRAPHITE (II)
ON HORIZONTAL PLANE (AV. TEMP = 1000 F TO 1100 F) FOR ANY VALUE
OF TOTAL IRRADIATION DOSE BETWEEN LID & MIDPLANE
OF CORE

STRESSES CAUSED BY IRRADIATION - INDUCED DIFFERENTIAL SHRINKAGE OF EGCC GRAPHITE (USING A SIMPLIFIED, ISOTROPIC MODEL OF THE MONOLITHIC COLUMN) TASK NO. 227

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ASSUMED STRESS-STRAIN CURVE FOR EGCR GRAPHITE (II)
ON HORIZONTAL PLANE (AV. TEMP 1200°F) FOR ANY VALUE OF
TOTAL IRRADIATION DOSE NEAR THE TOP OF CORE

STRESSES CAUSED BY IRRADIATION - INDUCED
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APPENDIX 3

STRESSES IN EGCR GRAPHITE DUE TO IRRADIATION-
INDUCED SHRINKAGE FOR AN ANISOTROPIC
SIMPLIFIED GEOMETRICAL MODEL

I. The following analysis of shrinkage-induced stresses in graphite of EGCR core is intended to give values for an anisotropic model to be compared with similar values for the previous investigation of an isotropic model. This comparison is intended to show the effect of anisotropy and whether it would be worthwhile to consider such anisotropy in a more detailed analysis.

This analysis follows that of "Wigner Stress" by C.E. ILIFFE except data used are appropriate to EGCR and that cognizance is taken of the generally inelastic nature of graphite by calculating stresses in a stepwise (year-by-year) manner, using the appropriate tangent modulus for any stress level in computing the next yearly increment of stress. The effect of irradiation on the breaking strength is not well known, so all stresses are computed up to the limit of available stress-strain curves to show the possible maximum stresses, although it is recognized that failure may occur at lower stresses.

An exponential distribution of damage was used, symmetrical about the ^{fuel} channel ϕ , as for the isotropic case, and based on the following equation for flux:

$$\phi_r = (.6284 + e^{-.66r}) \phi_c$$

giving

where $\phi_c = 2.73 \times 10^{-4}$ MWD/AT-SEC giving rise to 8600 MWD/AT per year at $r_c = 0$. The shrinkage rates were taken as
 .0004 IN/IN PER 1000 MWD/AT parallel to extrusion
 .00025 IN/IN PER 1000 MWD/AT perpendicular " "

The model employed is a long hollow cylinder as for the isotropic case and, since the implicit assumption of ILIFFE's analysis is that originally plane and parallel surfaces remain

STRESSES IN EGCR GRAPHITE DUE TO IRRADIATION-INDUCED SHRINKAGE FOR AN ANISOTROPIC SIMPLIFIED GEOMETRICAL MODEL

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so after irradiation, the calculation of stresses in this report is limited to sections of the cylindrical model near the horizontal midplane of core.

Since this is the area of maximum relative shrinkage at $a=a$ and $r=r_b$, it is expected that this will give rise to max. stresses in any model. Taking the subject model as near as possible to the core ϕ should give max. stresses in EGCR core.

Note:
 r_b chosen to give annular area equivalent to the quarter-column surrounding a typical fuel channel.

II. The following assumptions were made

1. Because of anisotropy the generalized form of Hooke's law will be used to express stress and strain, the number of ^{unique} coefficients being reduced to five by hexagonal symmetry.
2. Shearing stresses on the coordinate planes (cylindrical coordinates) are zero due to symmetry of irradiation about ϕ of channel.
3. Modulus of elasticity (tangent modulus) changes with irradiation and temperature but will be considered constant over the time interval (one year). Values for tangent modulus are based on "A Preliminary Examination of Stress-Strain Curves for EGCR Graphite," (Appendix 1).
4. Shrinkage varies with r only
5. Tangent Modulus is the same both in tension and in compression.
6. Only one channel will be considered and no interaction occurs between the four channels in a column to increase stresses.
7. Because final data on temperature-dependence of flux damage is not available the damage is taken to be independent of temperature
8. Graphite stresses do not relax through creep, in order to calculate a definitely conservative stress.

Anisotropic Analysis of EGCR Graphite Task 227 Appendix 3

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The initial (i.e. room temperature, unirradiated) properties of EGCR graphite are assumed to be:

$$\left. \begin{aligned} E_{II} &= 1.78 \times 10^6 \\ E_L &= (1.78) \left(\frac{1.5}{1.5} \right) = 1.31 \times 10^6 = .735 E_{II} \end{aligned} \right\} \frac{E_{II}}{E_L} = k_1 = 1.36$$

$$k_2 = \frac{D_{II}}{D_L} = 1.16 \left\{ \begin{aligned} \text{shrinkage rate}_{II} &= .00040 \text{ IN/IN PER 1000 MWD/AT} \\ \text{shrinkage rate}_L &= .00025 \text{ IN/IN " " "} \end{aligned} \right\} @ 900^\circ\text{F}$$

$$\left. \begin{aligned} \text{Poisson's ratio}_{II} &= .29 = \mu_{II} \\ \text{Poisson's ratio}_L &= .123 = \mu_L \end{aligned} \right\} \text{where each ratio gives the strain effect (in a perpendicular direction) of a stress in the direction of the subscript (i.e. II or L)}$$

The values of E are slightly higher than those listed for EBCR graphite because they are obtained from stress-strain curves for non-ABOT graphite. However, since strains are the independent variable in our examination, the E 's employed are conservative from the standpoint of computed stress. The μ 's are calculated to give an average value of .25 and $\mu_{\perp} = .735 \mu_{\parallel}$ (which are thought to be conservative.)

$$\left. \begin{aligned} \epsilon_x &= S_{11}\sigma_x + S_{12}\sigma_y + S_{13}\sigma_z + S_{14}\tau_{yz} + S_{15}\tau_{xz} + S_{16}\tau_{xy} \\ \epsilon_y &= S_{21}\sigma_x + S_{22}\sigma_y + S_{23}\sigma_z + S_{24}\tau_{yz} + S_{25}\tau_{xz} + S_{26}\tau_{xy} \\ \epsilon_z &= S_{31}\sigma_x + S_{32}\sigma_y + S_{33}\sigma_z + S_{34}\tau_{yz} + S_{35}\tau_{xz} + S_{36}\tau_{xy} \\ \gamma_{yz} &= S_{41}\sigma_x + S_{42}\sigma_y + S_{43}\sigma_z + S_{44}\tau_{yz} + S_{45}\tau_{xz} + S_{46}\tau_{xy} \\ \gamma_{xz} &= S_{51}\sigma_x + S_{52}\sigma_y + S_{53}\sigma_z + S_{54}\tau_{yz} + S_{55}\tau_{xz} + S_{56}\tau_{xy} \\ \gamma_{xy} &= S_{61}\sigma_x + S_{62}\sigma_y + S_{63}\sigma_z + S_{64}\tau_{yz} + S_{65}\tau_{xz} + S_{66}\tau_{xy} \end{aligned} \right\} \text{Generalized Hooke's Law}$$

where $S_{ij} = S_{ji}$

and Following "W. gner Stress" C.E. ILIFFE, Report 5212, D.D.C. - P29
for "hexagonal symmetry" $S_{11} = S_{22}$ $S_{13} = S_{23}$ $S_{44} = S_{55}$ $S_{66} = 2(S_{11} - S_{12})$

$$S_{14} = S_{15} = S_{16} = S_{24} = S_{25} = S_{26} = S_{34} = S_{35} = S_{36} = S_{45} = S_{46} = S_{56} = 0$$

ANISOTROPIC ANALYSIS OF EGCR GRAPHITE
TASK 127 APPENDIX 3

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$$\begin{cases} \epsilon_x = S_{11}\sigma_x + S_{12}\sigma_y + S_{13}\sigma_z \\ \epsilon_y = S_{21}\sigma_x + S_{22}\sigma_y + S_{23}\sigma_z \\ \epsilon_z = S_{31}\sigma_x + S_{32}\sigma_y + S_{33}\sigma_z \\ \gamma_{yz} = S_{44}\tau_{yz} \\ \gamma_{xz} = S_{55}\tau_{xz} \\ \gamma_{xy} = S_{66}\tau_{xy} \end{cases}$$

where

$$\begin{aligned} S_{11} &= \frac{1}{E_{\perp}} & S_{31} &= -\frac{\mu_{\perp}}{E_{\perp}} \\ S_{12} &= -\frac{\mu_{\perp}}{E_{\perp}} & S_{32} &= -\frac{\mu_{\perp}}{E_{\perp}} \\ S_{13} &= -\frac{\mu_{\parallel}}{E_{\parallel}} & S_{33} &= \frac{1}{E_{\parallel}} \\ S_{21} &= -\frac{\mu_{\perp}}{E_{\perp}} & S_{44} &= \frac{1}{G_{\parallel}} \\ S_{22} &= \frac{1}{E_{\perp}} & S_{55} &= \frac{1}{G_{\parallel}} \\ S_{23} &= -\frac{\mu_{\parallel}}{E_{\parallel}} & S_{66} &= \frac{1}{G_{\perp}} \end{aligned}$$

After transformation to cylindrical coordinates:

$$\begin{cases} \epsilon_r = \frac{1}{E_{\perp}}(\sigma_r - \mu_{\perp}\sigma_{\theta} - \frac{\mu_{\parallel}\sigma_z}{k_1}) \\ \epsilon_{\theta} = \frac{1}{E_{\perp}}(-\mu_{\perp}\sigma_r + \sigma_{\theta} - \frac{\mu_{\parallel}\sigma_z}{k_1}) \\ \epsilon_z = \frac{1}{E_{\parallel}}(-\mu_{\parallel}\sigma_r - \mu_{\parallel}\sigma_{\theta} + \sigma_z) = \frac{1}{E_{\parallel}}(-\mu_{\parallel}\sigma_r - \mu_{\parallel}\sigma_{\theta} + \sigma_z) \\ \gamma_{\theta z} = \frac{1}{G_{\parallel}}\tau_{\theta z} \\ \gamma_{rz} = \frac{1}{G_{\parallel}}\tau_{rz} \\ \gamma_{r\theta} = \frac{1}{G_{\perp}}\tau_{r\theta} \end{cases}$$

Now where u, v , and w are displacements in r, θ , and z , respectively, and $(\frac{\partial u}{\partial r})_{\perp}$, $(\frac{\partial v}{\partial r})_{\perp}$, and $k_1(\frac{\partial w}{\partial r})_{\parallel}$ are the Wagner dimensional changes perpendicular and parallel to extrusion respectively:

$$\begin{cases} \epsilon_r = \frac{1}{E_{\perp}}(\sigma_r - \mu_{\perp}\sigma_{\theta} - \frac{\mu_{\parallel}\sigma_z}{k_1}) = \frac{\partial u}{\partial r} \\ \epsilon_{\theta} = \frac{1}{E_{\perp}}(-\mu_{\perp}\sigma_r + \sigma_{\theta} - \frac{\mu_{\parallel}\sigma_z}{k_1}) = \frac{u}{r} + \frac{1}{r}\frac{\partial v}{\partial \theta} \\ \epsilon_z = \frac{1}{E_{\parallel}}(-\mu_{\parallel}\sigma_r - \mu_{\parallel}\sigma_{\theta} + \sigma_z) = \frac{\partial w}{\partial z} \\ \gamma_{\theta z} = \frac{1}{G_{\parallel}}\tau_{\theta z} = \frac{\partial v}{\partial z} + \frac{1}{r}\frac{\partial w}{\partial \theta} \\ \gamma_{rz} = \frac{1}{G_{\parallel}}\tau_{rz} = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial r} \\ \gamma_{r\theta} = \frac{1}{G_{\perp}}\tau_{r\theta} = \frac{\partial u}{r\partial \theta} + \frac{\partial v}{\partial r} - \frac{v}{r} \end{cases}$$

Total strains in the first three equations can be obtained by adding the shrinkage effect (ϵ_s, ϵ_s , and $k_1\epsilon_s$ respectively) to the terms between equality signs.

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where $k_2 = 1.6$ (not yet specifying the Wigner strain as negative).

Now considering symmetry of displacements about the ϕ , v is independent of θ , and taking an annular segment far from the ends of the cylinder, as in the isotropic case, $\frac{\partial w}{\partial r} = \frac{\partial w}{\partial \theta} = 0$. Also all the shear strains are zero.

Following ILLIFE "Wigner Stress" the compatibility equations become:

$$(a) \quad r^2 \frac{d^2}{dr^2} (\epsilon_t) + 2r \frac{d}{dr} (\epsilon_t) - r \frac{d}{dr} (\epsilon_r) = 0$$

$$(b) \quad \epsilon_z = \text{constant} = k_3$$

And where all stresses are functions of r only and all shear stresses are zero on the coordinate planes, the equilibrium equations reduce to

$$(c) \quad r \frac{d}{dr} \sigma_r + \sigma_r - \sigma_t = 0$$

Solution of the equations yields (setting Wigner strains as negative)

$$\begin{aligned} (a) \quad \sigma_r &= E_{\perp} \frac{(1+k_2\mu_{11})}{1-\frac{\mu_{11}^2}{k_1}} \left(\frac{1}{r^2}\right) \int_a^r r \left(\frac{\Delta L}{L}\right) dr + \frac{C_1}{2} (\ln r - \frac{1}{2}) + \frac{C_2}{2} + \frac{C_3}{2r^2} \\ (b) \quad \sigma_t &= E_{\perp} \frac{(1+k_2\mu_{11})}{1-\frac{\mu_{11}^2}{k_1}} \left(\frac{1}{r^2}\right) \int_a^r r \left(\frac{\Delta L}{L}\right) dr + \frac{C_1}{2} (\ln r + \frac{1}{2}) + \frac{C_2}{2} - \frac{C_3}{2r^2} \\ (c) \quad \sigma_z &= E_{\perp} \frac{(k_2 k_1 + \mu_{11})}{1-\frac{\mu_{11}^2}{k_1}} \frac{\Delta L}{L} + \mu_{11} C_1 \ln r + \mu_{11} C_2 + k_1 k_3 E_{\perp} \end{aligned}$$

[Note that C_2 as found from (d) or (e) must include effects of k_3 from (f)]

From the boundary conditions $\sigma_r(r=a) = 0$ and $\sigma_r(r=b) = 0$ and the fact that ϕ displacement (i.e. v) = 0

$$C_1 = 0$$

and one may consequently solve for C_2 and C_3 from (d)

$$C_3 = -2 \left(\frac{b^2 a^2}{b^2 - a^2} \right) E_{\perp} \frac{(1+k_2\mu_{11})}{1-\frac{\mu_{11}^2}{k_1}} \left(\frac{1}{b^2}\right) \int_a^b r \left(\frac{\Delta L}{L}\right) dr$$

$$C_2 = -2 \left(\frac{b^2 - a^2}{b^2 - a^2} \right) E_{\perp} \frac{(1+k_2\mu_{11})}{1-\frac{\mu_{11}^2}{k_1}} \left(\frac{1}{b^2}\right) \int_a^b r \left(\frac{\Delta L}{L}\right) dr$$

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IV

As a preliminary to the investigation of stresses in stepwise (year-by-year) fashion we calculate stresses due to a distribution of shrinkage such that (instead of the exponential distribution):

$$\left(\frac{\Delta L}{L}\right)_n = \left(\frac{\Delta L}{L}\right)_b + \left(\frac{r_b - r}{r_b - r_a}\right)^2 \left[\left(\frac{\Delta L}{L}\right)_a - \left(\frac{\Delta L}{L}\right)_b \right]$$

For a model where $\begin{cases} r_b = 4 & (\text{instead of } 4.49 \text{ as for the detailed isotropic investigation}) \\ r_a = 2.62 \end{cases}$

$$\left(\frac{\Delta L}{L}\right)_{11} = \frac{1}{2} \left(\frac{\Delta L}{L}\right)_1$$

$$E_{11} = E_1, E_{\perp}$$

$$\begin{cases} k_1 = 1.2 & (\text{instead of } 1.36) \\ k_2 = 1.5 & (\text{instead of } 1.6) \end{cases}$$

the stress equations can be written

$$\sigma_n = E_{\perp} \left[\frac{1 + \mu_{11} k_2}{1 - \frac{\mu_{11}^2}{k_1}} \right] \left[\left(\frac{\Delta L}{L}\right)_a - \left(\frac{\Delta L}{L}\right)_b \right] [f_1(r, r_a, r_b)]$$

$$\sigma_t = E_{\perp} \left[\frac{1 + \mu_{11} k_2}{1 - \frac{\mu_{11}^2}{k_1}} \right] \left[\left(\frac{\Delta L}{L}\right)_a - \left(\frac{\Delta L}{L}\right)_b \right] [f_2(r, r_a, r_b)]$$

$$\sigma_z = E_{\perp} \left[\frac{k_1 k_2 + \mu_{11}}{1 - \frac{\mu_{11}^2}{k_1}} \right] \left[\left(\frac{\Delta L}{L}\right)_a - \left(\frac{\Delta L}{L}\right)_b \right] [f_3(r, r_a, r_b)]$$

or

$$\sigma_n = E_{\perp} (E_a - E_b) M R_n$$

$$\text{where } M = \frac{1 + .25(1.5)}{1 - \frac{.0625}{1.2}} = 1.45$$

$$\sigma_t = E_{\perp} (E_a - E_b) M R_t$$

$$\sigma_z = E_{\perp} (E_a - E_b) M_3 R_z$$

$$M_3 = \frac{(1.5)(1.2) + .25}{1 - \frac{.0625}{1.2}} = 2.16$$

and for EGCR (Following ILLIFE "Wigner Stress")

r =	2.62	3.31	4.00
R _n =	0	-0.05	00
R _t =	-0.75	+0.10	0.35
R _z =	-0.75	+0.05	0.30

and for a differential shrinkage equivalent to about 2 years of core life:

$$\sigma_n = 0 \quad (\text{at channel wall})$$

$$a\sigma_t = 1.5 \times 10^6 (-0.001) (1.45) (-.75) = 1640 \text{ psi (tension)}$$

$$b\sigma_t = 1.5 \times 10^6 (-0.001) (1.45) (.35) = 765 \text{ psi (comp)}$$

$$a\sigma_z = 1.5 \times 10^6 (-0.001) (2.16) (-.75) = 2440 \text{ psi (tension)}$$

$$b\sigma_z = 1.5 \times 10^6 (-0.001) (2.16) (.30) = 975 \text{ psi (comp)}$$

Indicating that consideration of anisotropy results in higher stresses than for the isotropic case and making desirable a stepwise examination.

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V Returning to the step-wise year-by-year calculation, as for the isotropic case:
 In order to make the various stresses at any temperature linearly dependant on the value of $E_{\perp}$ write:

$$\sigma_r = E_{\perp} \left[\left(\frac{1 + k_2 \mu_{11}}{1 - \frac{\mu_{11}^2}{k_1}} \right) \frac{1}{r^2} \int_a^r r \left(\frac{\Delta L}{L} \right) dr + \frac{C'_1}{2} (\ln r - \frac{1}{2}) + \frac{C'_2}{2} + \frac{C'_3}{2r^2} \right]$$

$$\sigma_{\theta} = E_{\perp} \left[\left(\frac{1 + k_2 \mu_{11}}{1 - \frac{\mu_{11}^2}{k_1}} \right) \left(\left\{ \frac{\Delta L}{L} \right\} - \frac{1}{r^2} \int_a^r r \left(\frac{\Delta L}{L} \right) dr \right) + \frac{C'_1}{2} (\ln r + \frac{1}{2}) + \frac{C'_2}{2} - \frac{C'_3}{2r^2} \right]$$

$$\sigma_z = E_{\perp} \left[\left(\frac{k_2 k_1 + \mu_{11}}{1 - \frac{\mu_{11}^2}{k_1}} \right) \left(\frac{\Delta L}{L} \right) + \mu_{11} C'_1 \ln r + \mu_{11} C'_2 + k_1 k_3 \right]$$

where $C'_1 = 0$ (for an unsplit block)

$$C'_2 = -\frac{2}{b^2 - a^2} \left(\frac{1 + k_2 \mu_{11}}{1 - \frac{\mu_{11}^2}{k_1}} \right) \int_a^b r \left(\frac{\Delta L}{L} \right) dr$$

$$C'_3 = -\frac{2a^2}{a^2 - b^2} \left(\frac{1 + k_2 \mu_{11}}{1 - \frac{\mu_{11}^2}{k_1}} \right) \int_a^b r \left(\frac{\Delta L}{L} \right) dr$$

For C'_3 : $-\frac{2a^2}{a^2 - b^2} = -\frac{2(6.9)}{6.9 - 20.2} = 1.037$

$$\frac{1 + k_2 \mu_{11}}{1 - \frac{\mu_{11}^2}{k_1}} = \frac{1 + 1.6 \times 2.9}{1 - \frac{(2.9)^2}{1.36}} = \frac{1 + 4.64}{1 - 0.618} = 1.562$$

$$\int_a^b r \left(\frac{\Delta L}{L} \right) dr = (0.00025) \left(\frac{.86 \times 10^4}{1000} \right) (2.99) = .643 \times 10^{-3}$$

$$C'_3 = (1.037)(1.562)(.643 \times 10^{-3}) = 1.04 \times 10^{-3}$$

For C'_2 : $-\frac{2}{b^2 - a^2} = -\frac{2}{20.2 - 6.9} = -.1502$

$$C'_2 = (-.1502)(1.562)(.643 \times 10^{-3}) = -.1507 \times 10^{-3}$$

for σ_r at $r=a$ at one year ($n=1$)

$$\sigma_r = E_{\perp} \left[\left(\frac{1 + k_2 \mu_{11}}{1 - \frac{\mu_{11}^2}{k_1}} \right) \frac{1}{r^2} \int_a^r r \left(\frac{\Delta L}{L} \right) dr + \frac{C'_2}{2} + \frac{C'_3}{2r^2} \right]$$

$$= E_{\perp} \left[0 - \frac{.1507 \times 10^{-3}}{2} + \frac{1.04 \times 10^{-3}}{2 \times 6.9} \right] = 0 \quad (\text{check})$$

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for σ_r at $r = \frac{a+b}{2}$ $n = 1$ yr.

$$r = \frac{a+b}{2} = \frac{2.625 + 4.49}{2} = 3.558$$

$$\begin{aligned}\sigma_r &= 1.31 \times 10^6 \left[\frac{(1.562)}{12.68} \int_{2.625}^{3.558} \frac{1}{r} \frac{\partial L}{\partial r} dr - \frac{.1507 \times 10^{-3}}{2} + \frac{1.04 \times 10^{-3}}{2 \times 12.68} \right] \\ &= 1.31 \times 10^6 \left[\frac{1.562}{12.68} \left(.00025 \left(\frac{.86 \times 10^4}{1000} \right) (.323) \right) - .0753 \times 10^{-3} + \frac{.410 \times 10^{-4}}{2} \right] \\ &= 1.31 \times 10^6 \left[.856 \times 10^{-4} - .753 \times 10^{-4} + .410 \times 10^{-4} \right] \\ &= 1.31 \times 10^6 \left[.513 \times 10^{-4} \right] \\ &= 67.2 \text{ psi tension}\end{aligned}$$

for σ_t at $r = a$ $n = 1$ yr.

$$\begin{aligned}\sigma_t &= E \left[\frac{1 + \frac{k_2 k_4}{k_1}}{1 - \frac{\mu_1}{2}} \left(\left\{ \frac{\partial L}{\partial r} \right\}_r - \frac{1}{r^2} \int_a^r r \left(\frac{\partial L}{\partial r} \right)_r dr \right) + \frac{C'_2}{2} - \frac{C'_3}{2r^2} \right] \\ &= 1.31 \times 10^6 \left[1.562 \left(.125 \times .00025 \times \frac{.86 \times 10^4}{1000} - 0 \right) - .0753 \times 10^{-3} + \frac{1.04 \times 10^{-3}}{2 \times 6.9} \right] \\ &= 1.31 \times 10^6 \left[1.562 \left(.27 \times 10^{-3} \right) - .0753 \times 10^{-3} - .0754 \times 10^{-3} \right] \\ &= 1.31 \times 10^6 \left[.421 \times 10^{-4} - .1507 \times 10^{-4} \right] \\ &= 1.31 \times 10^6 \left[2.703 \times 10^{-4} \right] = 354 \text{ psi tension}\end{aligned}$$

for σ_t at $r = b$ $n = 1$ yr.

$$\begin{aligned}\sigma_t &= 1.31 \times 10^6 \left[1.562 \left(0 - \frac{1}{20.2} \int_a^b r \left(\frac{\partial L}{\partial r} \right)_r dr \right) - .0753 \times 10^{-3} - \frac{1.04 \times 10^{-3}}{2 \times 20.2} \right] \\ &= 1.31 \times 10^6 \left[1.562 \left(-\frac{1}{20.2} \right) \left(.00025 \right) \left(\frac{.86 \times 10^4}{1000} \right) (.299) - .0753 \times 10^{-3} - .0257 \times 10^{-3} \right] \\ &= 1.31 \times 10^6 \left[-.0497 \times 10^{-3} - .0753 \times 10^{-3} - .0257 \times 10^{-3} \right] \\ &= 1.31 \times 10^6 \left[-.1507 \times 10^{-3} \right] \\ &= 198 \text{ psi compression}\end{aligned}$$

for σ_z : Due to the presence of constant k_3 in σ_3 expression the following condition is imposed since the model is assumed free for longitudinal (i.e. z) movement:

$$\int \sigma_z r dr = 0 \quad \text{i.e. } \Sigma F_z = 0$$

ANISOTROPIC ANALYSIS OF EGCR GRAPHITE
TASK 227 APPENDIX 3

SIMILAR TO

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$$\sigma_z = E_1 \frac{k_1 k_2 + \mu_{11}}{1 - \frac{\mu_{11}^2}{k_1}} \left(\frac{\Delta L}{L} \right)_1 + \mu_{11} C_1 \ln r + \mu_{11} C_2 + k_1 k_3 E_1$$

The arbitrary constant "K" must be adjusted so that the summation of forces in the Z direction equal zero

$$\int_{r_i}^{r_o} \sigma_z r dr = 0$$

or:

$$\int_a^b [2.635 E_1 \left(\frac{\Delta L}{L} \right)_1 + \mu_{11} C_1 \ln r + \mu_{11} C_2 + k_1 k_3 E_1] r dr = 0$$

where:

$$k_1 = 1.36$$

$$k_2 = 1.6$$

$$\mu_{11} = .29$$

and

$$\frac{k_1 k_2 + \mu_{11}}{1 - \frac{\mu_{11}^2}{k_1}} = \frac{1.36 \times 1.6 + .29}{1 - \frac{.29 \times .29}{1.36}} = \frac{2.178 + .29}{1 - .0618} = \frac{2.468}{.9382} = 2.635$$

but;

$$C_1 = 0 \text{ for unsplit rings}$$

and

$$C_2 = E_1 C_2' = E_1 (-.1507 \times 10^{-3})$$

$$2.635 E_1 \int_a^b r \left(\frac{\Delta L}{L} \right)_1 dr + 0 + \mu_{11} E_1 C_2' \int_a^b r dr + k_3 k_1 E_1 \int_a^b r dr = 0$$

$$k_3 k_1 E_1 \int_a^b r dr = -2.635 E_1 \int_a^b r \left(\frac{\Delta L}{L} \right)_1 dr - \mu_{11} E_1 (-.1507 \times 10^{-3}) \int_a^b r dr$$

$$k_3 = - \left[\frac{2.635 \int_a^b r \left(\frac{\Delta L}{L} \right)_1 dr + .29 (-.1507 \times 10^{-3}) \int_a^b r dr}{1.36 \int_a^b r dr} \right]$$

$$\text{Where } \int_a^b r \left(\frac{\Delta L}{L} \right)_1 dr = .00025 \times \frac{86 \times 10^4}{1000} \times .299 = 0.643 \times 10^{-3}$$

$$\text{and } \int_a^b r dr = \left[\frac{r^2}{2} \right]_a^b = \frac{b^2}{2} - \frac{a^2}{2} = \frac{b^2 - a^2}{2} = \frac{20.2 - 6.9}{2} = \frac{13.3}{2} = 6.65$$

ANISOTROPIC ANALYSIS OF EGGR GRAPHITES
TASK 227 Appendix 3

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$$k_3 = - \left[\frac{2.635 \times 6.43 \times 10^{-3} - .29 \times .1507 \times 10^{-3} \times 6.65}{1.36 \times 6.65} \right] = - \left[\frac{1.693 \times 10^{-3} - .2905 \times 10^{-3}}{9.045} \right]$$

$$k_3 = - \frac{14.025 \times 10^{-4}}{9.045} = -1.552 \times 10^{-4}$$

then:

$$\sigma_z = E_L \frac{k_1 k_2 - \mu_{11}}{1 - \frac{\mu_{11}^2}{k_1}} \left(\frac{\Delta L}{L} \right)_L + \mu_{11} C_1 \ln r + \mu_{11} C_2 + k_1 k_3 E_L$$

where: $C_1 = 0$ for unsplit rings
and $C_2 = E_L C'_2$

$$\sigma_z = E_L \left[2.635 \left(\frac{\Delta L}{L} \right)_L + 0 + .29 (-1.507 \times 10^{-3}) + 1.36 (-1.552 \times 10^{-4}) \right]$$

$$\text{and } \left(\frac{\Delta L}{L} \right)_L (r=a) = 100025 \times \frac{.86 \times 10^{-4}}{1000} \times .1254 = 2.7 \times 10^{-4}$$

$$\left(\frac{\Delta L}{L} \right)_L (r=b) = 0$$

then:

$$\sigma_z (r=a) = 1.31 \times 10^6 \left[7.11 \times 10^{-4} - 0.4365 \times 10^{-4} - 2.11 \times 10^{-4} \right]$$

$$= 1.31 \times 10^6 \times 4.5635 \times 10^{-4}$$

$$\sigma_z (r=a) = \underline{598 \text{ psi tension}}$$

and:

$$\sigma_z (r=b) = 1.31 \times 10^6 \left[0 - .4365 \times 10^{-4} - 2.11 \times 10^{-4} \right]$$

$$= 1.31 \times 10^6 (-2.5465 \times 10^{-4})$$

$$\sigma_z (r=b) = \underline{334 \text{ psi compression}}$$

ANISOTROPIC ANALYSIS OF EGCR GRAPHITE
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Since several of the stresses rapidly become excessive, no attempt will be made to find detailed effect of superimposed loads necessary to maintain the continuity of the four simple cylindrical models in any one column. The axial distribution of flux along any one cylindrical model is not yet definitely known, nor is the radial flux distribution, and both would be necessary to accurately predict the additional stresses.

As an approximation, assume that the longitudinal distribution of radial shrinkage conforms to the deflection of a simply-supported beam under uniform load:

Radial Shrinkage per year at ^{the ϕ of} core mid plane (taking the average exposure on any radial line):

$$\frac{\phi_{AV}}{\phi_E} = \frac{.8054 + .68}{2} = .7427$$

$$\phi_{AV} = .7427 \times .86 \times 10^4 \text{ MWD/AT-YR} \\ = .639 \times 10^3 \text{ MWD/AT-YR}$$

Radial shrinkage rate = 1.6×10^{-3} in/in per 1000 MWD/AT

$$\therefore \text{Av. Rad. Shrinkage} = 6.39 \times 2.5 \times 10^{-4} = 1.6 \times 10^{-3} \text{ in/in/YR}$$

And on radius of 2.625", shrinkage = $1.6 \times 10^{-3} \times 2.625 = 4.19 \times 10^{-3}$ in.

Neglecting the radial distribution of flux for the core as a whole, and assuming that two adjacent cylindrical cells see the same shrinkage, the ^{supposedly independent} unit cell would have to be deflected 4.19×10^{-3} in (after one year) toward its neighbor, by exterior forces, to restore the necessary condition of continuity within a column.

For one year (Assuming for the flexural core that the longitudinal E predominates and the graphites can be treated as isotropic):

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$$\Delta = \frac{5}{384} \frac{w l^4}{E_{II} I}$$

$$\begin{aligned} I &= .049087 (d_o^4 - d_i^4) \\ &= .049087 (8.98^4 - 5.25^4) \\ &= .049087 (6520 - 761) \\ &= .049087 (5759) = 282 \text{ in}^4 \end{aligned}$$

$$w = \frac{384 E_{II} I \Delta}{5 l^4}$$

$$= \frac{384 \times 1.82 \times 10^6 \times 282 \times 4.19 \times 10^{-3}}{5 \times 232^4}$$

$$= .0569 \text{ lb/in (for the first year, needed to force the two adjacent cylinders back together.)}$$

$$E_{II} \text{ at operating temp} = 1.82 \times 10^6$$

Consequent stress:

$$\sigma = \frac{M c}{I} = \frac{.0569 (232)^2 (4.49)}{8 \times 282} \quad (\text{at } r=b \text{ in the unit cell})$$

$$= 6.1 \text{ psi } (\pm)$$

$$\sigma = \frac{M c}{I} = \frac{.0569 (232)^2 (2.625)}{8 \times 282} \quad (\text{at } r=a)$$

$$= 3.57 \text{ psi } (\pm)$$

Because of the low stresses shown, it appears that a more detailed analysis of such superimposed stresses would not be worthwhile along these approximate lines. While it is recognized that a detailed analysis using the theory of elasticity would probably show higher stresses, it is thought that these would be small relative to the other stresses previously computed at any time n . The unit increase in the superimposed stresses (i.e. yearly increase) would always be decreasing because of the changing tangent modulus of stress levels due to the other, larger stresses.

Furthermore, in the unit cell, the channel surface is always in tension longitudinally & in compression at the outer surface. Since the assumed flexure must add to tension on one side of the cell if it subtracts on the other (similarly for compression), the approximate picture of the superimposed stresses does not seem

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critical from standpoint of stress.

VII The bowing of columns will be reduced from previous estimates (based on a linear variation of flux transversely across a column) due to the compensating ^{flux} gradients about adjacent unit cells as considered in this report. It is felt that (even if no creep is considered in the graphite) bowing will be very small with the new flux picture.

Zone A, if it were separate from others, would tend to bow (convex) to the left. So also would zone C. Zones B and D would tend to bow oppositely. Hence the compensating of bows, which would be effected by requirement for continuity of unit cells would reduce overall column bow. The internal restraint would generate stresses which are thought to be small based on section VI.

The amount of bow has not been calculated but it is thought to be certainly less than 0.10 inches (deviation of the channel ϕ from vertical) in 20 years. A full scaled analysis would probably be necessary to prove this figure, but the estimate is based on the amount that the midplane of a single unit cell would have to be deviated in order to return a point on the shrunk mid-plane to the spot it occupied (in space) on the unshrunk mid-plane (i.e. $20 \times 4.19 \times 10^{-3} = .084" \angle .10$)

ANISOTROPIC ANALYSIS OF EGCR GRAPHITE
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CH'D L.D.H.

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ANISOTROPIC ANALYSIS OF EGCR GRAPHITE
TASK 227 Appendix 3

Year and M	EXPOSURE (10 ⁴ MWDT/AT) $\frac{E}{1000 \text{ MWDT/AT}}$					$\frac{\Delta L}{L}$ 1000 MWDT/AT	TENSION $r=2$					COMPRESSION $r=6$				
	E CHAN	$r=2$	$r=6$	δE			E TAN. MOD 10 ⁶ PSI	σ_{2a} $U=1.0$	$\sum \sigma_3$	$\sum \sigma_3$ $U=0.8$		E TAN. MOD 10 ⁶ PSI	σ_{2b} $U=1.0$	$\sum \sigma_3$	$\sum \sigma_3$ $U=0.8$	
										T.M.	$\sum \sigma_3$				T.M.	$\sum \sigma_3$
0	0	0	0	0	.00025	1.35	0	0	1.35	0	1.35	0	0	1.35	0	
1	.86	.692	.56	.14		1.35	598	598	1.35	478	1.35	334	334	1.35	267	
2	1.72	1.31	1.11	.27		1.29	570	1168	1.32	946	1.35	334	668	1.35	534	
3	2.58	2.08	1.67	.41		1.13	500	1668	1.19	1368	1.27	314	982	1.31	793	
4	3.44	2.77	2.23	.54		0.88	394	2064	1.06	1943	1.18	292	1274	1.23	1036	
5	4.30	3.46	2.78	.69		0.55	244	2308	0.66	2177	1.09	270	1544	1.17	1268	
6	5.16	4.16	3.34	.82		0.47	208	2516	0.53	2365	0.98	242	1786	1.09	1384	
7	6.02	4.85	3.90	.95		0.39	173	2689	0.45	2525	0.81	200	1986	1.04	1590	
8	6.88	5.53	4.45	1.09					0.38	2660	0.63	156	2142	0.93	1774	
9	7.74	6.23	5.02	1.21							0.53	131	2273	0.82	1936	
10	8.60	6.92	5.57	1.35							0.48	119	2392	0.65	2064	
11	9.46	7.61	6.13	1.48							0.44	109	2501	0.55	2173	
12	10.32	8.30	6.68	1.62							0.34	84	2585	0.53	2278	
13	11.18	8.98	7.24	1.74							0.32	79	2664	0.48	2473	
14	12.04	9.70	7.80	1.90										0.37	2546	
15	12.90	10.4	8.35	2.05										0.33	2611	
16	13.76	11.1	8.93	2.17												
17	14.62	11.75	9.47	2.28												
18	15.48	12.45	10.03	2.42												
19	16.34	13.15	10.58	2.57												
20	17.20	13.85	11.12	2.73												

LONGITUDINAL STRESSES AT OPERATING TEMPERATURES (ANISOTROPIC MATL)

U is plant utilization factor and $K_3 = 1.552 \times 10^{-4}$

$$\sigma_3 = E_L \left[\left(\frac{K_2 L_2 + u_{21}}{1 - \frac{u_{21}^2}{K_2}} \right) \left(\frac{\Delta L}{L} \right) + u_{21} \epsilon'_2 + K_3 \right]$$

Stresses at room (or other lower temperature) are lower than at operating temperature and will not be tabulated until more definite information is available on the variation of breaking strength with irradiation and temperature.

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	L.D.H.						14	17		
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ANISOTROPIC ANALYSIS OF EGGE GRAPHITE
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n YEAR END	EXPOSURE (10 ⁴ MW/AT)					$\frac{\Delta L}{L}$ 1000 MW/AT	TENSION					r=a		COMPRESSION					r=b	
	CHAN SEC	r=a	r=b	$\Sigma \sigma$	E Tang. Mod 10 ⁶ psi		n σ_{ta} U=1.0	$\Sigma \sigma_{ta}$ U=0.8	$\Sigma \sigma_{ta}$ U=0.8		E TAN. MOD. 10 ⁶ psi	n σ_{tb} U=1.0	$\Sigma \sigma_{tb}$ U=1.0	$\Sigma \sigma_{tb}$ U=0.8						
									T.M.	$\Sigma \sigma$				T.M.	$\Sigma \sigma$					
0	0	0	0	0	1.00025	1.35	0	0	1.35	0	1.35	0	0	1.35	0					
1	.86	.69	.56	.14		1.35	354	354	1.35	283	1.35	198	198	1.35	158					
2	1.72	1.31	1.11	.27		1.35	354	708	1.35	566	1.35	198	396	1.35	316					
3	2.58	2.08	1.67	.41		1.25	328	1036	1.30	838	1.34	197	594	1.35	474					
4	3.44	2.77	2.23	.54		1.16	304	1340	1.22	1094	1.29	189	783	1.32	629					
5	4.30	3.46	2.78	.68		1.07	281	1621	1.15	1315	1.23	180	963	1.28	779					
6	5.16	4.16	3.34	.82		0.91	239	1860	1.08	1541	1.18	173	1136	1.23	923					
7	6.02	4.85	3.90	.95		.76	199	2059	.97	1744	1.13	166	1302	1.19	1062					
8	6.88	5.53	4.45	1.08		.55	145	2204	.83	1918	1.08	159	1461	1.16	1198					
9	7.74	6.23	5.02	1.21		.52	137	2441	.66	2057	1.01	148	1609	1.11	1328					
10	8.60	6.92	5.57	1.35		.40	105	2546	.55	2172	0.92	137	1746	1.07	1553					
11	9.46	7.61	6.13	1.48		.33	88	2634	.53	2298	0.83	122	1868	0.97	1667					
12	10.32	8.30	6.68	1.62					.48	2383	0.76	112	1980	0.89	1770					
13	11.18	8.98	7.24	1.74					.44	2475	0.69	93	2073	0.82	1866					
14	12.04	9.70	7.80	1.90					.37	2553	0.55	81	2184	0.76	1955					
15	12.90	10.4	8.35	2.05					.33	2622	0.53	78	2232	0.66	2032					
16	13.76	11.1	8.93	2.17						0.51	75	2307	0.56	2098						
17	14.62	11.78	9.47	2.28						0.47	69	2376	0.54	2161						
18	15.48	12.45	10.03	2.42						0.44	65	2441	0.53	2223						
19	16.34	13.15	10.58	2.57						0.40	59	2500	0.51	2283						
20	17.20	13.85	11.12	2.73						0.34	50	2550	0.48	2439						

TANGENTIAL STRESSES AT OPERATING TEMPERATURES (ANISOTROPIC MAT'L)

U is plant utilization factor

$$\sigma_t = E_t \left[\frac{(1 + \nu_{t11})}{(1 - \nu_{t11})} \left(\left\{ \frac{\Delta L}{L} \right\}_t - \frac{1}{n} \int_a^n \frac{\sigma}{E} d\sigma \right) + \frac{\sigma'_t}{2} - \frac{C'_t}{2n} \right]$$

Stresses at room temp. are lower than at operating temperatures and will not be tabulated until more definite information is available on the variation of breaking strength with irradiation and temperature.

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ANISOTROPIC ANALYSIS OF EGCR GRAPHITE
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year end n	EXPOSURE (10 ⁴ MWD/AT) ρ				$\frac{DL}{L}$ 1000 MWD/AT	OPERATING TEMPERATURE				ROOM TEMPERATURE			
	ρ GMAW	$\rho = a$	$\rho = b$	$\rho = c$		TAN. MOD. 10 ⁶ PSI	$n\sigma_r$	$\frac{n}{2}\sigma_r$	$\Sigma\sigma_r$ U=0.8	TAN. MOD. 10 ⁶ PSI	$n\sigma_r$	$\frac{n}{2}\sigma_r$	$\Sigma\sigma_r$ U=0.8
0	0	0	0	0	.00025	1.35	0	0	1.35	0			
1	.86	.69	.56	.14		1.35	67	67	1.35	54			
2	1.72	1.31	1.11	.27		1.35	67	134	1.35	108			
3	2.58	2.08	1.67	.41		1.35	67	201	1.35	162			
4	3.44	2.77	2.23	.54		1.35	67	268	1.35	216			
5	4.30	3.46	2.78	.68		1.35	67	335	1.35	270			
6	5.16	4.16	3.34	.82		1.35	67	402	1.35	324			
7	6.02	4.85	3.90	.95		1.33	66	468	1.35	378			
8	6.88	5.53	4.45	1.08		1.32	65	533	1.34	431			
9	7.74	6.23	5.02	1.21		1.31	65	598	1.33	484			
10	8.60	6.92	5.57	1.35		1.29	64	662	1.32	536			
11	9.46	7.61	6.13	1.48		1.26	63	725	1.31	588			
12	10.32	8.30	6.68	1.62		1.24	62	787	1.29	639			
13	11.18	8.98	7.14	1.74		1.23	61	848	1.27	689			
14	12.04	9.70	7.80	1.90		1.21	60	908	1.25	739			
15	12.90	10.4	8.35	2.05		1.19	59	967	1.24	788			
16	13.76	11.1	8.93	2.17		1.18	59	1026	1.23	837			
17	14.62	11.75	9.47	2.28		1.17	58	1084	1.21	887			
18	15.48	12.45	10.03	2.42		1.15	57	1141	1.20	935			
19	16.34	13.15	10.58	2.57		1.13	56	1197	1.18	982			
20	17.20	13.85	11.12	2.73		1.11	55	1252	1.18	1049			

Room Temp. Stresses are always less than operating temp stresses and will not be tabulated until more definite information is available on variation of breaking strength with irradiation temp.

Room Temp. stresses are always less than operating temp. stresses and will not be tabulated until more definite information is available on variation of breaking strength with irradiation temp.

RADIAL STRESSES AT $R = \frac{a+b}{2}$ AT OPERATING AND ROOM TEMP. (ANISOTROPIC MAT'L)

U is plant utilization factor

$$\sigma_r = E_L \left[\left(\frac{1 + \frac{a_2 a_{11}}{a_1}}{1 - \frac{a_{11}}{a_1}} \right) \frac{1}{2} \int_0^R \frac{\Delta L}{L} dL + \frac{C'_2}{2} + \frac{C'_3}{2a^2} \right]$$

FIG NO 12
ASSUMED STRESS-STRAIN CURVE GRAPHITE (I) ON HORIZONTAL PLANE (AV. TEMP. 900 F) FOR ANY VALUE OF TOTAL IRRADIATION DOSE NEAR HORIZONTAL CORE MIDPLANE

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ADDENDUM TO CALCULATIONS FOR ANISOTROPIC MODEL

THE FOREGOING CALCULATIONS AND YEAR-BY-YEAR STRESS SUMMARIES WERE BASED ON AGOT-TYPE GRAPHITE WITH SHRINKAGE RATES

.04 %/1000 MW/D/AT (11)

.025 %/1000 MW/D/AT (1)

AT THE TEMPERATURE OF THE CORE MIDPLANE. THE USE OF A KC - NEEDLE-CORE TYPE GRAPHITE HAS BEEN PROPOSED BECAUSE OF LOWER SHRINKAGE RATES (REF: TRIP REPORT AC-EGCR-1130-REVISED) FOR PREDICTING STRESS LEVELS VS. OPERATING TIME

.02 %/1000 MW/D/AT (11)

.01 %/1000 MW/D/AT (1)

IF WE TAKE THE RATES AS

.02 %/1000 MW/D/AT (11) } CONSERVATIVE
.0125 %/1000 MW/D/AT (1) }

SO AS TO PRESERVE THE RATIO OF $\frac{.04}{.025}$ USED IN ANISOTROPIC CALCULATIONS, THEN WE MAY PRORATE DIRECTLY (ON THE BASIS OF RATE (1)) FROM THE PREVIOUS TABLES BY CHANGING THE INTERVAL OF TIME TO TWO YEARS. THE AMOUNTS OF DIFFERENTIAL RADIATION INDUCED SHRINKAGE^{AND STRESS} CAN THEN BE TAKEN FROM PREVIOUS TABLES, AS FOLLOWS:

LONGITUDINAL STRESSES AT OPERATING TEMP. (REF. P. 14)

YR. END	$\frac{\Delta L}{L}$ (1) 1000 MM/AT	TENSION @ $r=a$				COMPRESSION @ $r=b$				EXP $\frac{10^4}{\text{MM/AT}}$
		U=1.0		U=0.8		U=1.0		U=0.8		
		TAN. MOD	$\Sigma \sigma$	TAN MOD	$\Sigma \sigma$	TAN MOD	$\Sigma \sigma$	TAN MOD	$\Sigma \sigma$	
2	.000125	1.35×10^6	598	1.35×10^6	478	1.35×10^6	334	1.35×10^6	267	.86
4		1.29	1168	1.32	946	1.35	668	1.35	534	1.72
6		1.13	1668	1.19	1368	1.27	982	1.31	793	2.58
8		0.88	2064	1.06	1943	1.18	1274	1.23	1036	3.44
10		0.55	2308	0.66	2177	1.09	1544	1.17	1268	4.30
12		0.47	2516	0.53	2365	0.98	1786	1.09	1384	5.16
14		0.39	2689	0.45	2525	0.81	1986	1.04	1590	6.02
16				0.38	2660	0.63	2142	0.93	1774	6.98
18						0.53	2273	0.82	1936	7.94
20						0.48	2392	0.65	2064	8.60

ANISOTROPIC ANALYSIS OF EGCR GRAPHITE
TASK 227 APPENDIX 3

SIMILAR TO

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TANGENTIAL STRESS AT OPERATING TEMPER.

REF P 15

YR END	$\frac{\Delta L}{L}$ (%) 1000 MWD/AT	TENSION @ $r=a$				COMPRESSION @ $r=b$				EXP 10 ⁴ x MWD/AT
		U=1.0		U=0.8		U=1.0		U=0.8		
		TAN MOD	Σ σ	TAN MOD	Σ σ	TAN MOD	Σ σ	TAN MOD	Σ σ	
2	.000125	1.35x10 ⁶	354	1.35x10 ⁶	283	1.35x10 ⁶	198	1.35x10 ⁶	158	86
4		1.35	708	1.35	566	1.35	396	1.35	316	1.72
6		1.25	1036	1.30	838	1.34	594	1.35	474	2.58
8		1.16	1340	1.22	1094	1.29	783	1.32	629	3.44
10		1.07	1621	1.15	1315	1.23	963	1.28	779	4.30
12		0.91	1860	1.08	1541	1.18	1136	1.23	923	5.16
14		0.76	2059	.97	1744	1.13	1302	1.19	1062	6.02
16		0.55	2204	.83	1918	1.08	1461	1.16	1198	6.88
18		0.52	2441	.66	2057	1.01	1609	1.11	1328	7.44
20		0.40	2546	.55	2172	0.92	1746	1.07	1553	8.60

RADIAL STRESS AT OPERATING TEMP.

REF P. 16

YR END	$\frac{\Delta L}{L} (\%)$ 1000 MWD/AT	TENSION @ $r = \frac{a+b}{2}$				EXP 10 ⁴ x MWD/AT
		U=1.0		U=0.8		
		TAN MOD	Σ σ	TAN MOD	Σ σ	
2	.000125	1.35 x 10 ⁶	67	1.35 x 10 ⁶	54	.96
4		1.35	134	1.35	108	1.72
6		1.35	201	1.35	162	2.58
8		1.35	268	1.35	216	3.44
10		1.35	335	1.35	270	4.30
12		1.35	402	1.35	324	5.16
14		1.33	468	1.35	378	6.02
16		1.32	533	1.34	431	6.88
18		1.31	598	1.33	484	7.44
20		1.29	662	1.32	536	8.60

ANISOTROPIC ANALYSIS OF EGCK GRAPHITE
TASK 227 APPENDIX 3

SIMILAR TO

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IT APPEARS THEN THAT, BASED ON A FLEXURAL ALLOWABLE STRESS OF 1500 PSI (RESERVING 300 PSI FOR CONTINGENCIES), USE OF KC TYPE WILL APPROXIMATELY DOUBLE THE USEFUL LIFE OF THE CORE TO:

$U=1.0$ - 5 years

$U=0.8$ - 7 years

NO CALCULATIONS WERE MADE FOR STRESSES AT THE UPPER AND LOWER EXTREMES OF CORE. DUE TO AXIAL FLUX FALL-OFF, THE STRESSES IN THESE AREAS SHOULD BE DOWN BY A FACTOR OF 4 OR 5 AND A 20 YEAR LIFE COULD BE SHOWN (REF: ORNL LETTER C. PRESKITT TO J. DAVIDSON, JAN 5, 1960).

ANISOTROPIC ANALYSIS OF EGCR GRAPHITE
TASK 227 APPENDIX 3

SIMILAR TO

DR'N <i>RAN</i>	CH'D <i>PVG</i>	APP'D <i>[Signature]</i>	SCALE = 12	SHEET <i>17</i> C OF <i>17</i>	ISSUE
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APPENDIX 4

CREEP IN EGCR GRAPHITE

(Literature Survey)

APPENDIX 4

CREEP IN EGCR GRAPHITE
(LITERATURE SURVEY)

1. Herewith are calculations of the stress-relaxing effects of creep in EGCR graphite. This literature survey and accompanying calculations are intended to answer these questions:

a. Have there been any experiments on graphite creep that can be applied to EGCR?

b. Is there a stress level (below the allowable tensile stress for EGCR graphite) at which the creep rate (with time) equals or exceeds the strain rate due to differential irradiation-induced shrinkage?

c. Is there a limiting stress in EGCR graphite which will be approached and never exceeded as the core ages? How many years will it take to reach the limit?

d. Can a 20-year core life be demonstrated by adding the effects of creep to elastically accumulated stresses calculated for the cylindrical anisotropic model?

2. No experimental work has been done on graphite creep that can be directly applied to EGCR conditions. Results of a literature search (on pp.36-48 of the calculations) show creep (ϵ) to be a sensitive function of time (t), of activation energy (Q), of absolute temperature (T), and of stress (σ). Two formulas relating to a different environment and type of graphite from the EGCR have been abstracted from the literature as the most applicable to the EGCR:

a. $\epsilon = A - K\sigma \exp(-Q/RT) \log_{10} t + Bt$

b. $\epsilon = A_1 \sigma^n \exp(-Q/RT).$

Constants A, A_1 , K and B are assumed to hold for all conditions, and extrapolation to EGCR environmental conditions is assumed valid.

3. Formulas a. and b., plus a third source of information at room temperature, yielded (see pp.4-11 and p.25 of calculations) the following values:

Q k cal/mole	n	T °K	σ psi	t minutes	Formula	ϵ in./in./sec
100	3.1	755	1290	---	b	2.8×10^{-31}
43.6	3.1	755	1290	---	b	$.52 \times 10^{-11}$
	2.6	755	1290	0.5	a	$.75 \times 10^{-11}$
20	1	755	1290	0.5	a	0.9×10^{-11}
----	1	R.T.	929	---		4.6×10^{-10}

The required creep rate to equal the shrinkage-induced strain rate (at the channel surface at the core center, which is the worst) is approximately 10^{-11} in./in./sec. It appears that, if extrapolations are valid, for $Q = 43.6$ K cal/mole, the tensile (critical) stress in the EGCR should level off near 1000 psi. From the literature, the lower activation energies are deemed the more probable.

4. Step-wise calculations of stress accumulation (pp. 25-33) show the following limiting stresses:

Utilization		Formula	n	T	Q	Limit	Years to
factor		--	--	°K	k/cal/mole	psi	Limit
(1)	1.0	b	3	755	43.6	1360	4
(2)	0.8	b	3	755	43.6	1200	7
(3)	1.0	a	3	755	43.6	1350	4.5
(4)	1.0	a	1	755	20	400	2*
(5)	1.0	a	1	755	20	920	4**

NOTE: Items (4) and (5) are for time-dependent creep rate.

* 30-minute interval.

** 100-minute interval.

All the formulas are essentially unchanged from their forms in the literature, with the exception of those extrapolated for EGCR conditions. It would appear that the maximum stress which will be accumulated in EGCR graphite lies in the range 1000 to 1300 psi. The years to reach limit were based on use of AGOT-type graphite with a coke particle similar to Texas coke. If needle-coke-type graphite is used (with shrinkage rates approximately half of Texas coke) the time to reach limit should be roughly doubled, providing creep is similar in the two graphites.

5. The limiting tensile stress in the EGCR cannot be definitely stated without new creep experiments in the appropriate environment on the actual EGCR graphite. The calculated limits, in view of the necessary extrapolations, represent only a range of possible values. If compared with the 1800-psi tensile strength (flexural) specified for EGCR graphite (since the shrinkage-induced stresses assume a pattern similar to flexure), calculated limit stresses show a margin of about 500 psi for accepting any additional short-term stresses. Depending on the magnitude of additional stress, it would appear that a 20-year core life could be demonstrated, if better creep data were available.

C 2

6. No credit was taken in calculations for the supposedly accelerating effect of irradiation on creep rate as the core ages.

7. No calculation of stress accumulation was made for the top and bottom regions of the core. Because of flux decline in these regions, the elastic stresses calculated from the cylindrical, anisotropic model would be low enough to demonstrate approximately 20-year life without recourse to stress relaxation by creep.

Discussion:

(A) Previous calculation of shrinkage-induced stresses in the EGCR graphite did not include the potential strain-relieving effects of creep. Although the stress-producing shrinkage occurs in EGCR graphites on a protracted, long-term basis, each yearly increment of stress was computed on the basis of a stress-strain curve derived from short-term loading. As a consequence, the critical stresses (longitudinal tensile stresses computed from the cylindrical, anisotropic model) rapidly accrued and reached the allowable stress limits in only a few years.

In order to account for the effects of creep and to gain a more realistic picture of the useful lifetime of the core, the following modification of the year-by-year stress calculation is proposed:

- (a) For any unit of time, the differential elongations which occur in "fibers" of EGCR monolithic columns, will be accommodated by a combination of stress-producing, "elastic" strain (the term elastic being broadly used to include all portions of the generally inelastic stress-strain curve of graphite) and non-stress-producing "creep" elongation. That is:

$$\Delta L_i = \frac{L \Delta \sigma_i}{E_{i-1}} + C_i$$

where C_i is a function of stress level (to be determined) at the end of the $(i-1)$ interval just preceding and σ_i depends upon the tangent modulus (E_{i-1}) which is ^{also} a function of the stress level at the end of the $(i-1)$ interval just preceding.

- (b) For any interval of time, the so-called secondary stage of creep will be used in calculating the amount of creep in the above formula. This will be conservative since, at any given stress level, the secondary creep rate is lower than the preceding

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TASK 227 App. 4

SIMILAR TO (REF. TASK 246)

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primary creep rate, and will be more applicable to the time interval which ~~it~~ is practicable to examine in this analysis (secondary creep continues longer than primary creep). By using the secondary creep rate based on the lowest stress in any interval of time (i.e. the stress level at the end of the preceding interval) the contribution of creep is kept conservative, since the secondary creep rate is always increasing during the interval as the stress level rises in the real column, and the final computed ^{shrinkage-induced} stress is conservative at any time. This stress total can then be added to other, short-term stresses that might be produced in the graphite (due to, say, seismic or thermal ~~gradient~~ ^{shock} effects) to predict the structural adequacy of the core under all conditions.

Further, the predicted life (i.e. time to reach maximum allowable, long-term stress) will be conservative since the conservative use of creep allows stress to accumulate at the maximum possible rate.

- (B) In order to choose a suitable formula to represent the creep and creep rate for EGCR graphite and environment, a literature search was made of all available tests and reports for any types of graphite. Unfortunately, no information was found that could be directly applied to EGCR graphite or environments, in their entirety. Consequently, to arrive at a suitable formula for creep, it was necessary to take bits of information from various sources and deal with ranges of values of the various parameters in attempting to fit the separate pieces of information together. Direct extrapolation to EGCR conditions ^(for any one formula) was thought to be inadvisable since creep rate is extremely sensitive to such parameters as

CREEP IN EGCR GRAPHITE (TASK No. 227)

APPENDIX 4

SIMILAR TO

DR'N RRN

CH'D PVG 6/14/60

APP'D

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stress level, absolute temperature, activation energy, and the power to which the stress term is raised. Also, significant variations in creep rate occur from graphite to graphite under similar test conditions.

Three activation energies for the creep process were found that seemed most likely to bracket the true value for EGCR conditions (but the range of values in the literature ran from 20000 cal/mole to 226,000 cal/mole)

20000 cal/mole @ 1300 C to 2000 C (for various graphites)

43,600 " " @ below 2500 C per manufacturers recommendation

111,000 " " @ 2100 C to 2650 C (for AGHT)

All activation energies found followed a downward trend with temperature. Since EGCR operating temperatures will range from 300 C to 550 C approximately, it would seem reasonable to favor the lower values quoted. Consequently, for whatever formulas could be derived from the literature, it was decided to use separate calculations for both 20000 cal/mole and 43600 cal/mole. The actual formulas employed necessarily ~~based~~ extrapolation in reaching EGCR conditions from test conditions, and by using a range of parameters it is thought that the uncertainties in any one formula could be covered by comparison with results of other formulas.

The other area of main uncertainty is the value of the exponent of stress. Values in the literature range from one to 3.88. Those that seem most applicable to EGCR are

1 @ 1300 C to 2000 C (for various graphites)

3.1 @ 2100 C to 2650 C (for AGHT)

To aid in choosing the exponent most suited to EGCR conditions each of the most applicable activation energies was used in calculations of creep rate in appropriate formulas of the literature with several combinations of parameters. These calculations are on pp 12-19

Results of the literature search on pp 36-48

- (c) The final formulas used were arrived at mainly from the three following sources (for each formula it is desired to demonstrate an acceptable creep rate ~~and~~ a useful stress level and the number of years required to reach the maximum attainable stress in EGCR graphite):

CREEP IN EGCR GRAPHITE (TASK No. 227)

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(1) "Investigation of Elastic and Thermal Properties of Carbon-Base Bodies"
WADC Tech-Rpt. 58-360

Creep was investigated at room temperature with National Carbon baked rods, graphitized at 2600°C, and density of 1.54 g/cm³ (approx). It ~~was~~^{is} felt that creep rate of such material at such temperature should roughly define the lower bounds of creep rate that could be expected in EGCR. This creep rate ~~was~~^{is} determined as follows:

In 500 minutes the creep, Δ_c , at 4.672" from B and caused by $P = 980 \text{ gr} = 2.16 \text{ lb}$ was found to be $\approx .4 \times 10^{-3} \text{ in.}$

Assuming the maximum creep to be at B, find the max creep by assuming a load P' to produce a short-time deflection equal to Δ_c at 4.672" from B and find the consequent elastic strain at B. The max. creep strains, assuming a linear distribution in accordance with linear variation of creep with stress, should be the same as elastic strain.

$$\Delta_c = \frac{P' L^3}{3EI} = .4 \times 10^{-3} = \frac{P' (4.672)^3}{3EI}$$

where $E = 1.41 \times 10^6$
from test and
 $I = \frac{\pi (.5)^4}{64} = 3.07 \times 10^{-3}$

$$P' = \frac{3 (1.41 \times 10^6) (3.07 \times 10^{-3}) (.4 \times 10^{-3})}{(4.672)^3}$$

$$= .0509 \text{ lb}$$

Consequent elastic strain at B is:

CREEP IN EGCR GRAPHITE (TASK No. 227)
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$$\epsilon = \frac{Mc}{IE} = \frac{PLc}{IE}$$

$$\epsilon = \frac{.0509 \times 4.672 \times 0.25}{3.07 \times 10^{-3} \times 1.41 \times 10^6}$$

$$= 1.375 \times 10^{-5} \text{ IN/IN}$$

and the actual creep-producing stress was:

$$\sigma = \frac{Mc}{I} = \frac{PLc}{I}$$

$$\sigma = \frac{2.16 \times 5.281 \times .25}{3.07 \times 10^{-3}}$$

$$= 929 \text{ psi}$$

Based on this test then, a creep rate (in a graphite similar to EGCR graphite) of

$$\dot{\epsilon}_{\text{creep}} = \frac{1.375 \times 10^{-5}}{500 \times 60} = 4.58 \times 10^{-10} \text{ IN/IN/SEC}$$

is possible as an average steady state rate, since the available literature shows primary creep to be short-lived relative to 500 minutes. Some tests indicate a decreasing rate with time, whereas others do not; in either event, ~~at any rate~~, the calculated creep rate appears conservative for this particular test.

From calculations done on the anisotropic cylindrical model, we know that differential elongation (strain) due to irradiation-induced shrinkage accumulates in longitudinal fibers of EGCR graphite at a rate to produce 100 psi in two months near the core center. This (@ 900F and with original E) is approximately:

$$\frac{0.64}{1.05} \times 10^{-9} \text{ IN/IN/MIN} \quad \text{OR} \quad \left(\text{see p. 28} \right)$$

$$6.1 \times 10^{-11} \text{ IN/IN/SEC}$$

which is less than the computed creep rate, 4.58×10^{-10} by a factor of twenty. This indicates that the stress in EGCR graphite should never go higher than 900 psi, since all of the strain rate would be absorbed by the non-stress-producing, relaxing creep rate at this level.

Since creep rate is shown by all investigators to increase with temperature it would appear that excessive stress would, from this piece of evidence, never occur in EGCR due to shrinkage (although any

CREEP IN EGCR GRAPHITE (TASK No. 227)

APPENDIX 4

SIMILAR TO

DR'N RRN

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short-term stresses, such as due to thermal shock, would have to be added to the long term stress level in demonstrating final structural adequacy). However, other investigators have found ^{equal} (for ECA graphite) that creep rate at 1000 psi does not ^{the} previously calculated rate until $T = 2400^\circ\text{C}$; consequently, other sources have been investigated to determine whether this lower bound for creep rate (4.58×10^{-10} in/in/sec) can be taken as true.

- (2) The source of information for tests nearest EGCR temperature was ^{an} article by Davidson & Lofky from "Nature", April 12, 1958. Tests were made on graphites with bases such as cellulose carbon, ^{petroleum coke,} and lampblack and on natural graphites at temperatures 1300°C to 2000°C. Creep was found to follow the formula (t in minutes):

$$\epsilon_t = A + k \log t + Bt$$

where: $A, B,$ and k are constants

or
$$\epsilon_t = A + \left[\frac{C}{E_0} \exp\left(-\frac{Q}{RT}\right) \right] \log t + Bt$$

where: C was found to be a "universal" constant for all graphites tested

E_0 was room temp. Young's modulus

where: σ = stress; R = universal gas constant; T = °K; Q was activation energy

Assuming C to really be a "universal" constant we calculate C from the experimental data tabulated for $\frac{kE_0}{\sigma}$ at the experimental $T = 1833\text{K}$

$$C \exp\left(-\frac{Q}{RT}\right) = \frac{kE_0}{\sigma} = 12.2 \times 10^{-2} \quad (\text{for cantilevered cellulose carbon specimens})$$

$$12.2 \times 10^{-2} = C \exp\left(-\frac{20000 \text{ cal/gr mole}}{1.99 \text{ cal/gr mole degree} \times 1833 \text{ degree}}\right)$$

$$12.2 \times 10^{-2} = C e^{-5.48}$$

$$\therefore C = 12.2 \times 10^{-2} \times 240 = 29.3$$

$$\text{and } k = 7.76 \times 10^{-5}$$

$$\left(\text{for } E_0 = 14 \times 10^{10} \text{ dyne/cm}^2 \right. \\ \left. \sigma = 8.9 \times 10^7 \text{ dyne/cm}^2 \right)$$

which agrees with data from "Mechanical Properties of Non-Metallic Brittle Materials" chapter 12.

C in subject article (13) is for spring specimens not cantilevers.

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where σ (1290 psi) and E_0 (2.0×10^6 psi) indicate a general correspondence with the material of EGCR core, although the test temperature is somewhat higher than EGCR.

Let us assume it is possible to extrapolate to EGCR temperatures at the mid plane ($900^\circ\text{F} = 755^\circ\text{K}$) and E_0 ^(1.78×10^6) corresponding to that used in anisotropic calculations. For $\sigma = 1290$ psi then:

$$\begin{aligned} k &= \frac{29.3(1290)}{1.78 \times 10^6} \exp\left(-\frac{20000}{1.99 \times 755}\right) \\ &= 2.12 \times 10^{-2} e^{-13.20} = \frac{2.2 \times 10^{-2}}{5.46 \times 10^5} \\ &= .382 \times 10^{-7} \end{aligned}$$

Taking the time-derivative of the original equation:

$$\dot{\epsilon} = \frac{.434}{t} k + B$$

where B is shown to be a constant $10^{-3} \times k$ in the referenced article and for present purpose can be neglected

$$\begin{aligned} \text{or } \dot{\epsilon} &= \frac{.434}{t} k \quad \text{for the secondary stage of creep} \\ &= \frac{.434(.382 \times 10^{-7})}{t} = \frac{1.66 \times 10^{-8}}{t} \end{aligned}$$

From other investigations, at much higher temperatures, (Ref (1); Ref (7); ^{Ref (8)} Ref (5); Ref (6); see bibliography at end of this report) the ^{secondary} creep rate appears to continue from about one-half minute up to perhaps 15 or 30 minutes, although results of tests vary so widely that no definite limits can be set for this calculation. Taking 30 minutes, to give the lowest creep rate:

$$\dot{\epsilon} = \frac{1.66 \times 10^{-8}}{30} = 5.5 \times 10^{-10} \text{ IN/IN/MIN}$$

$$\text{or } .92 \times 10^{-11} \text{ IN/IN/SEC}$$

which is not inconsistent with the results of room temperature tests already examined. It would appear, then, with an activation energy of 20 kcal/mole, that an acceptable creep rate can be:

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demonstrated by this formula for stresses which are still in the usable range for EGCR. The lower times (such as one-half minute) measured from the beginning of any interval seem more significant for what is actually to happen in EGCR than do the later times (such as 15 minutes). The formula is based on steady-state stress whereas the EGCR stress does not level off until the calculated creep rate equals the strain rate. Consequently, because of the increasing stress level, as time in any interval increases creep rate should tend to go from the early stages of one secondary creep rate to the early stages of the next secondary rate without spending much of the interval in the latter (and significantly lower ^{rate}) stages of the first secondary area. It is true that the ^{linear} decrease of creep rate (in any secondary stage) ^{with time} is greater than the roughly linear increase of stress with time in the same interval; however, the high-primary creep rate associated with any stress in the interval would appear to "mask" this difference in rates. The ^{early} ~~primary~~ ^{probable} portion of secondary creep rate is therefore taken as the most ^{probable} representation of actual occurrence in EGCR.

If $Q = 20 \text{ kcal per mol}$, then the above expression could probably be incorporated into formula of part (A):

$$\Delta \epsilon_i = \frac{L \Delta \sigma_i}{E_{i-1}} + L \int_{t_i}^{t_{i+1}} \dot{\epsilon}_i dt$$

$$= \frac{L \Delta \sigma_i}{E_{i-1}} + L \left[\int_{t_i}^{t_{i+1}} \frac{.434 C \sigma_{i-1}}{E_0 \exp(Q/RT)} \frac{dt}{t} + \int_{t_i}^{t_{i+1}} B dt \right]$$

where $\Delta \sigma_i$ is the increase in stress in any time interval, ($t_{i+1} - t_i$ the interval) due to elastic strain, & E_{i-1} the tangent modulus appropriate to the stress level at the beginning of interval. Strictly speaking, the stress level varies over any interval, but by taking the interval small we will consider stress as constant. The higher the general stress level the less percentage effect this approximation should cause in deviation from actual creep rate. Taking L as one and performing the integration:

CREEP IN EGCR GRAPHITE (TASK No. 227)

APPENDIX 4

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$$\Delta L_i = \frac{\Delta \sigma_i}{E_{i-1}} + \frac{434 C \sigma_{i-1}}{E_0 \exp(Q/RT)} \left[\ln t \right]_{t_i}^{t_{i+1}} + B \left[t \right]_{t_i}^{t_{i+1}}$$

where t_i is to be taken a slightly after the beginning of interval (i.e. near start of secondary creep) to eliminate difficulties with $\ln 0$. Time is always to be measured from the beginning of the interval and not from beginning of core life.

Since the potential strain is proportional to elapsed time, to take the interval as one year (5.11×10^5 minutes) would obviously not give proper weight to the second term (which has a coefficient about 1000 times B) since, relative to a "base" period of say 10 min., ΔL_i would go up by a factor of 5×10^4 whereas creep due to the second term would go up logarithmically by a factor of only 5. It is impractical to take intervals of anywhere near 10 minutes and perform a step wise calculation. To handle practical intervals as large as, say six months, we will:

- Take a typical 30 minute period (roughly corresponding to duration of second stage creep) and calculate the amount of creep in the interval. The small period will be the first of many in a larger interval.
- Subtract creep (a) from ΔL_i and calculate $\Delta \sigma_i$
- Apply the $\Delta \sigma_i$ of the small interval to the much larger interval, say six months, as a constant rate to find $\Delta \sigma_i$ for the big interval.
- Find the stress level at the end of large interval and use it to calculate creep in the next small interval.
- Build the stress level up to its limiting value

This approach, intended to speed the calculation, is thought to be conservative. The potential strain ΔL_i increases equally in each small unit of time over the large interval. With time measured in each small unit individually, the ^{actual} amount of creep increases slightly in each small time as the general stress level increases. Consequently, the actual $\Delta \sigma_i$ in each unit time gets slightly smaller and the stress levels rise at a decreasing rate. Total stress, therefore,

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reaches any specified level more quickly. The effect of this procedure should give a conservative view of the core life and not have too great an effect (given the assumptions made) on the final limiting stress.

The formula breaks down, however, when $Q = 43.6$ kcal/mole. Under the same conditions as before:

$$\begin{aligned} k &= \frac{29.3 \times 1290}{1.78 \times 10^6} \exp\left(-\frac{43600}{1.99 \times 155}\right) \\ &= 2.12 \times 10^{-12} e^{-29.0} = \frac{2.12 \times 10^{-12}}{3.63 \times 10^{12}} \\ &= .585 \times 10^{-14} \end{aligned}$$

and creep rate, even near the beginning of an interval when it is largest (0.5 min. approx) is only $\dot{\epsilon} = \frac{.434 k}{t} = \frac{.434}{.5} \times .585 \times 10^{-14}$

$$= .507 \times 10^{-14} \text{ IN/IN/MIN}$$

$$= .845 \times 10^{-16} \text{ IN/IN/SEC} \ll 10^{-11} \text{ IN/IN/SEC}$$

There is no definite way to decide which Q is more applicable without some special tests at EGCR conditions. It appears that if Q is in the range of 43.6 kcal/mole, a higher exponent of σ would be necessary to show the required creep effects with this formula. References were, then, sought for graphite resembling AGOT and creep formulas with higher Q 's and higher exponents of stress.

- (3) In "Report on Tensile and Creep Properties of Graphite" NEPA 1516 tests were described for AGHT (similar to EGCR graphite) at 2100 C. to 2650 C. AGHT is taken from exterior areas of the furnace whereas AGOT comes from the interior. Q was 110 kcal/mole and the creep rate was expressed as

$$\dot{\epsilon} = A \exp(-Q/RT)$$

where A is an exponential function of stress.

For any stress, within the conditions of test (from which we assume extrapolation to EGCR conditions to be valid), the formula is:

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$$\dot{\epsilon} = 3 \times 10^{-3} \sigma^{3.1} \exp\left(-\frac{Q}{RT}\right) \quad \%/\text{hour}$$

At the subject test activation energy, but at EGCR temperatures: with stress level as for test in (2) assuming the formula unchanged at this new stress:

$$\begin{aligned} \dot{\epsilon} &= 3 \times 10^{-3} (1290)^{3.1} \exp\left(-\frac{110,000}{1.99 \times 755}\right) \\ &= 3 \times 10^{-3} (2.29 \times 10^9) e^{-73.4} \\ &= \frac{3 \times 10^{-3} \times 2.29 \times 10^9}{755 \times 10^{31}} = 903 \times 10^{-25} \%/\text{hr} \ll \text{required rate} \end{aligned}$$

However, at $Q = 43.6 \text{ kcal/mole}$

$$\begin{aligned} \dot{\epsilon} &= 3 \times 10^{-3} (1290)^{3.1} \exp\left(-\frac{43,600}{1.99 \times 755}\right) \\ &= \frac{3 \times 10^{-3} \times 2.29 \times 10^9}{3.63 \times 10^{12}} = 1.88 \times 10^{-6} \%/\text{hr} \\ &= .52 \times 10^{-11} \text{ in/in/sec} \approx \text{required rate} \end{aligned}$$

Taking into account the generally downward trend of activation energy with temperature, the value of 43,600 kcal/mole would seem more appropriate at the EGCR temperatures than the value of 110,000 kcal/mole. However, even the stress-dependent constant could be different at the lower temperatures through change in the exponent of σ ; creep rate could then be very much lower than that calculated. If the exponent were only two, the creep rate would not be higher than required (i.e. approx. $1.39 \times 10^{-9} \%/\text{hr} \ll 10^{-11} \text{ in/in/sec}$).

It should be noted that secondary creep rate is time-independent in these investigations. Therefore, it seems that the formula, whether the exponent is 3.1 or 2, could be reasonably used in computing the accrual of stress year-by-year (or any other time interval), subject to further investigation. However, the possibility of higher exponents for us with $Q = 43.6 \text{ kcal/mole}$ in formula of type (2) does not seem unreasonable.

- (D) Having shown that acceptable creep rates ~~that~~ can be calculated ~~that~~ with certain values for the parameters, a series of calculations will be made to show the effect of varying parameters such as Q , T , t , and n , and to aid in choosing reasonable formulas for computing year-by-year stress increase.

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- (1) Because none of the past investigations of creep in graphite come close to the conditions expected in EGCR environment and because of the great differences among the results of various experimenters, this will be an attempt to examine the effect (upon creep rate) of varying the several parameters of the most applicable of formulas found in the literature. The parameters will be varied so as to represent the extremes of conditions applicable to EGCR.

FORMULA A

From experimental results closest to EGCR operating temperature this formula is taken:

$$\epsilon_{(t)} = A + \frac{C\sigma}{E_0 \exp\left(\frac{Q}{RT}\right)} \log t + Bt$$

where ϵ_t = creep at time t
 σ = steady state stress
 E_0 = Room temp. Young's Mod
 Q = Activation energy
 from the creep process
 R = Universal gas constant
 T = Absolute temp. °K
 C = "Universal" constant
 taken from tests of
 various types of
 cantilevered graphite

$A \neq B$ = constants

Realizing that the formula is strictly valid only for the particular graphite specimens and conditions of experiment, let us suppose that we may extrapolate to EGCR conditions by inserting appropriate values of E_0 , Q , T , t , and generalize, for purposes of the comparative study described above, by adding the exponent "n" to σ . The creep rate is then:

$$\dot{\epsilon}_{(t)} = \frac{C\sigma^n}{E_0 \exp\left(\frac{Q}{RT}\right)} \cdot \frac{.434}{t} + B$$

We will plot, for several activation energies quoted in the literature,

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families of curves for creep rate versus "steady-state" stress level. Each family of curves will be based on the assumption that the process of creep has continued over the full range of stress without fracture. There will be one family of curves for: (a) temperature at bottom of core (b) temperature at core midplane (c) temperature at top of core. Each family will contain curves for ^{several} integral values of "n". For each value of "n", the effect of "t" will be included by drawing two curves: (a) for ~~the~~ a time "t" representative of the beginning of secondary, "steady-state", creep taken from an average of several literature sources (b) for time representing the upper limit of steady state creep, averaged from several sources. The assumption will be made that activation energy is stress-independent (since we have no data to express the dependence, although ~~diminishingly~~ ~~oppose~~ statements for and against this assumption can be found in the literature. Graphite will be assumed not to work harden, although, again, statements both pro and con can be found. Each of these resulting curves will be compared with the rate at which differential elongation (i.e. strain) occurs in EGCR graphite due to irradiation-induced shrinkage, to get a feel for the critical variables and see whether or not the creep rate is ever sufficient to completely accommodate Wigner strains at stresses low enough to prevent fracture in any fibre of an EGCR column. The resultant curves will have this arrangement (for any ^{one} ϕ):

This process will be repeated for other promising formulas for creep in other graphites.

If the required creep rates are ever reached as shown by the

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n	t (sec)	E ₀ 10 ³ psi	Q KCal mole	R Cal mole	T °K	log N 434 (Q/RT)	N	E ₀ N	G psi	CG	① C ₀ E ₀ N	B 1.64 × 10 ⁻⁵ ① 1/SEC	σ ⁿ⁻¹	② C σ ⁿ E ₀ N	③ ② × 434 t	④ + B = ③ 10/10/SEC	
1	30	1.78	20	1.99	755	13.31125	5.77708	5.985 × 10 ⁵	10.65 × 10 ¹¹	200	5.86 × 10 ³	.55 × 10 ⁻⁸	.91 × 10 ⁻¹³	1	.55 × 10 ⁻⁸	.00795 × 10 ⁻⁸	8 × 10 ⁻¹¹
										400	10.72 × 10 ³	1.1 × 10 ⁻⁸	1.82 × 10 ⁻¹³	1	1.1 × 10 ⁻⁸	.0158 × 10 ⁻⁸	16 × 10 ⁻¹¹
1	900	1.78	20	1.99	755	13.31125	5.77708	5.985 × 10 ⁵	10.65 × 10 ¹¹	200	5.86 × 10 ³	.55 × 10 ⁻⁸	.91 × 10 ⁻¹³	1	.55 × 10 ⁻⁸	.00265 × 10 ⁻⁸	.27 × 10 ⁻¹¹
										400	11.72 × 10 ³	1.1 × 10 ⁻⁸	1.52 × 10 ⁻¹³	1	1.1 × 10 ⁻⁸	.00530 × 10 ⁻⁸	.53 × 10 ⁻¹¹
										600	17.58 × 10 ³	1.65 × 10 ⁻⁸	2.73 × 10 ⁻¹³	1	1.65 × 10 ⁻⁸	.00795 × 10 ⁻⁸	.8 × 10 ⁻¹¹
										800	23.44 × 10 ³	2.2 × 10 ⁻⁸	3.64 × 10 ⁻¹³	1	2.2 × 10 ⁻⁸	.0106 × 10 ⁻⁸	1.1 × 10 ⁻¹¹
										1000	29.3 × 10 ³	2.75 × 10 ⁻⁸	4.55 × 10 ⁻¹³	1	2.75 × 10 ⁻⁸	.0132 × 10 ⁻⁸	1.3 × 10 ⁻¹¹
1	30	1.78	20	1.99	533	18.35553	8.19330	1.525 × 10 ⁸	2.715 × 10 ¹⁴	200	5.86 × 10 ³	2.16 × 10 ⁻¹¹	3.6 × 10 ⁻¹⁶	1	2.16 × 10 ⁻¹¹	.031 × 10 ⁻¹¹	.03 × 10 ⁻¹¹
										400	11.72 × 10 ³	4.32 × 10 ⁻¹¹	7.2 × 10 ⁻¹⁶	1	4.32 × 10 ⁻¹¹	.062 × 10 ⁻¹¹	.06 × 10 ⁻¹¹
										600	17.58 × 10 ³	6.48 × 10 ⁻¹¹	10.8 × 10 ⁻¹⁶	1	6.48 × 10 ⁻¹¹	.093 × 10 ⁻¹¹	.09 × 10 ⁻¹¹
										800	23.44 × 10 ³	8.64 × 10 ⁻¹¹	14.4 × 10 ⁻¹⁶	1	8.64 × 10 ⁻¹¹	.124 × 10 ⁻¹¹	.12 × 10 ⁻¹¹
										1400	41.02 × 10 ³	15.11 × 10 ⁻¹¹	25.2 × 10 ⁻¹⁶	1	15.11 × 10 ⁻¹¹	.22 × 10 ⁻¹¹	.22 × 10 ⁻¹¹
										1600	46.58 × 10 ³	17.28 × 10 ⁻¹¹	28.8 × 10 ⁻¹⁶	1	17.28 × 10 ⁻¹¹	.248 × 10 ⁻¹¹	.25 × 10 ⁻¹¹
1	900	1.78	20	1.99	533	18.35553	8.19330	1.525 × 10 ⁸	2.715 × 10 ¹⁴	200	5.86 × 10 ³	2.16 × 10 ⁻¹¹	3.6 × 10 ⁻¹⁶	1	2.16 × 10 ⁻¹¹	.001 × 10 ⁻¹¹	.001 × 10 ⁻¹¹
										8000	234.4 × 10 ³	86.4 × 10 ⁻¹¹	144 × 10 ⁻¹⁴	1	86.4 × 10 ⁻¹¹	.042 × 10 ⁻¹¹	.04 × 10 ⁻¹¹
										20000	586 × 10 ³	216 × 10 ⁻¹¹	3.6 × 10 ⁻¹⁴	1	216 × 10 ⁻¹¹	.10 × 10 ⁻¹¹	.10 × 10 ⁻¹¹
										40000	1172 × 10 ³	432 × 10 ⁻¹¹	7.2 × 10 ⁻¹⁴	1	432 × 10 ⁻¹¹	.21 × 10 ⁻¹¹	.21 × 10 ⁻¹¹
										60000	1758 × 10 ³	648 × 10 ⁻¹¹	10.8 × 10 ⁻¹⁴	1	648 × 10 ⁻¹¹	.31 × 10 ⁻¹¹	.31 × 10 ⁻¹¹

n	t (sec)	E _a 10 ⁶ psi	Q Kcal/mole	R 10 ³ Kcal/mole	T °K	Q/RT	log N (Q/RT)	N	E _a N	σ psi	C σ	① C σ / E _a N	B 1.66 x 10 ⁻⁵ ① 1/sec	σ ⁿ⁻¹	② C σ ⁿ / E _a N	③ ②.434 ±	③+B = ② min/sec
1	30	1.78	20	1.99	839	11.97891	5.19885	1.581 x 10 ⁵	2.81 x 10 ¹¹	200	5.86 x 10 ³	2.09 x 10 ⁻⁸	3.47 x 10 ⁻¹³	1	2.09 x 10 ⁻⁸	.03 x 10 ⁻⁸	30 x 10 ⁻¹¹
										100	2.93 x 10 ³	1.045 x 10 ⁻⁸	1.74 x 10 ⁻¹³	1	1.04 x 10 ⁻⁸	.015 x 10 ⁻⁸	15 x 10 ⁻¹¹
1	900	1.78	20	1.99	839	11.97891	5.19885	1.581 x 10 ⁵	2.81 x 10 ¹¹	200	5.86 x 10 ³	2.09 x 10 ⁻⁸	3.47 x 10 ⁻¹³	1	2.09 x 10 ⁻⁸	.001 x 10 ⁻⁸	1 x 10 ⁻¹¹
										400	11.72 x 10 ³	4.18 x 10 ⁻⁸	6.94 x 10 ⁻¹³	1	4.18 x 10 ⁻⁸	.002 x 10 ⁻⁸	2 x 10 ⁻¹¹
2	30	1.79	20	1.99	765	13.31135	5.77708	5.985 x 10 ⁵	10.65 x 10 ¹¹	200	5.86 x 10 ³	.55 x 10 ⁻⁸	.91 x 10 ⁻¹³	200	110 x 10 ⁻⁸	1.59 x 10 ⁻⁸	1590 x 10 ⁻¹¹
										100	2.93 x 10 ³	.275 x 10 ⁻⁸	.455 x 10 ⁻¹³	100	27.5 x 10 ⁻⁸	.398 x 10 ⁻⁸	398 x 10 ⁻¹¹
2	900	1.78	20	1.99	765	13.31125	5.77708	5.985 x 10 ⁵	10.65 x 10 ¹¹	200	5.86 x 10 ³	.55 x 10 ⁻⁸	.91 x 10 ⁻¹³	200	110 x 10 ⁻⁸	.05 x 10 ⁻⁸	50 x 10 ⁻¹¹
										100	2.93 x 10 ³	.275 x 10 ⁻⁸	.455 x 10 ⁻¹³	100	27.5 x 10 ⁻⁸	.01 x 10 ⁻⁸	10 x 10 ⁻¹¹
2	30	1.78	20	1.99	538	18.85553	8.18330	1.525 x 10 ⁸	2.715 x 10 ¹⁴	200	5.86 x 10 ³	2.86 x 10 ⁻¹¹	3.6 x 10 ⁻¹⁶	200	4.32 x 10 ⁻⁹	.06 x 10 ⁻⁹	6 x 10 ⁻¹¹
										100	2.93 x 10 ³	1.08 x 10 ⁻¹¹	1.8 x 10 ⁻¹⁶	100	1.08 x 10 ⁻⁹	.016 x 10 ⁻⁹	1.6 x 10 ⁻¹¹
2	900	1.78	20	1.99	538	18.85553	8.18330	1.525 x 10 ⁸	2.715 x 10 ¹⁴	200	5.86 x 10 ³	2.16 x 10 ⁻¹¹	3.6 x 10 ⁻¹⁶	200	4.32 x 10 ⁻⁹	.0021 x 10 ⁻⁹	0.2 x 10 ⁻¹¹
										400	11.72 x 10 ³	4.32 x 10 ⁻¹¹	7.2 x 10 ⁻¹⁶	400	17.28 x 10 ⁻⁹	.0083 x 10 ⁻⁹	0.8 x 10 ⁻¹¹
										600	17.58 x 10 ³	6.48 x 10 ⁻¹¹	10.8 x 10 ⁻¹⁶	600	39.98 x 10 ⁻⁹	.0189 x 10 ⁻⁹	1.9 x 10 ⁻¹¹
2	30	1.78	20	1.99	839	11.97891	5.19885	1.581 x 10 ⁵	2.81 x 10 ¹¹	200	5.86 x 10 ³	2.09 x 10 ⁻⁸	3.47 x 10 ⁻¹³	200	4.18 x 10 ⁻⁶	.06 x 10 ⁻⁶	6000 x 10 ⁻¹¹
										100	2.93 x 10 ³	1.045 x 10 ⁻⁸	1.74 x 10 ⁻¹³	100	1.05 x 10 ⁻⁶	.015 x 10 ⁻⁶	1500 x 10 ⁻¹¹
2	900	1.78	20	1.99	839	11.97891	5.19885	1.581 x 10 ⁵	2.81 x 10 ¹¹	200	5.86 x 10 ³	2.09 x 10 ⁻⁸	3.47 x 10 ⁻¹³	200	4.18 x 10 ⁻⁶	.002 x 10 ⁻⁶	200 x 10 ⁻¹¹
										100	2.93 x 10 ³	1.045 x 10 ⁻⁸	1.74 x 10 ⁻¹³	100	1.05 x 10 ⁻⁶	.0005 x 10 ⁻⁶	50 x 10 ⁻¹¹
										20	.586 x 10 ³	2.09 x 10 ⁻⁸	3.47 x 10 ⁻¹³	20	4.18 x 10 ⁻⁷	.020 x 10 ⁻⁷	2 x 10 ⁻¹¹

Note: no calculation made for n=3 at this activation energy since, for n=2, all creep rates above the required level.

(Task No. 227)

Appendix 4

Creep Rates At Q = 20 Kcal/mole for
n = 1, 2, 3 and T = 500, 900, 1050 F.

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E	t (sec)	E ₀ 10 ⁶ psi	Q kcal/mole	R cal/mole	T °K	Q RT	log N ($\frac{Q}{RT}$)	N	E ₀ N	σ psi	Cσ	① $\frac{Cσ}{E_0 N}$	B $1.66 \times 10^{-5} \frac{1}{\text{sec}}$	σ ⁿ⁻¹	② $\frac{Cσ^n}{E_0 N}$	③ $\frac{2 \cdot 434}{t}$	③ + B = $\dot{\epsilon}$ in/in/sec
1	30	1.78	43.6	1.99	755	29.01925	12.59435	3.93×10^{12}	6.99×10^{13}	200	5.86×10^3	$.938 \times 10^{-15}$	1.39×10^{-20}	1	$.938 \times 10^{-15}$	$.012 \times 10^{-15}$	$.012 \times 10^{-15}$
1	900	1.78	43.6	1.99	755	29.01925	12.59435	3.93×10^{12}	6.99×10^{13}	200	5.86×10^3	$.938 \times 10^{-15}$	1.39×10^{-20}	1	$.938 \times 10^{-15}$	$.0061 \times 10^{-15}$	$.6 \times 10^{-18}$
1	30	1.78	43.6	1.99	533	41.10607	17.34003	6.92×10^{13}	12.32×10^{23}	200	5.86×10^3	$.476 \times 10^{-20}$	$.790 \times 10^{-25}$	1	$.476 \times 10^{-20}$	$.0069 \times 10^{-20}$	$.007 \times 10^{-20}$
1	900	1.78	43.6	1.99	533	41.10607	17.34003	6.92×10^{13}	12.32×10^{23}	200	5.86×10^3	$.476 \times 10^{-20}$	$.790 \times 10^{-25}$	1	$.476 \times 10^{-20}$	$.00023 \times 10^{-20}$	$.002 \times 10^{-21}$
1	30	1.78	43.6	1.99	839	26.11397	11.33342	2.1548×10^{14}	3.84×10^{17}	200	5.86×10^3	1.52×10^{-14}	2.52×10^{-19}	1	1.52×10^{-14}	$.022 \times 10^{-14}$	$.02 \times 10^{-14}$
1	900	1.78	43.6	1.99	839	26.11397	11.33342	2.1548×10^{14}	3.84×10^{17}	200	5.86×10^3	1.52×10^{-14}	2.52×10^{-19}	1	1.52×10^{-14}	$.0007 \times 10^{-14}$	$.0007 \times 10^{-14}$
2	30	1.78	43.6	1.99	755	29.01925	12.59435	3.93×10^{12}	6.99×10^{13}	200	5.86×10^3	$.938 \times 10^{-15}$	1.39×10^{-20}	200	1.68×10^{-13}	$.02 \times 10^{-13}$	$.02 \times 10^{-13}$
										400	11.72×10^3	1.68×10^{-15}	2.79×10^{-20}	400	6.72×10^{-13}	$.097 \times 10^{-13}$	$.10 \times 10^{-13}$
										600	29.3×10^3	4.19×10^{-15}	6.96×10^{-20}	1000	4.19×10^{-12}	$.06 \times 10^{-12}$	$.06 \times 10^{-12}$
										800	23.4×10^4	3.35×10^{-14}	5.56×10^{-19}	8000	26.8×10^{-11}	$.4 \times 10^{-8}$	
2	900	1.78	43.6	1.99	755	29.01925	12.59435	3.93×10^{12}	6.99×10^{13}	8000	23.4×10^4	3.35×10^{-13}	5.55×10^{-18}	8000	26.8×10^{-8}	$.01 \times 10^{-11}$	$.01 \times 10^{-11}$
										80000	23.4×10^5	3.35×10^{-13}	5.55×10^{-18}	80000	26.8×10^{-9}	$.013 \times 10^{-9}$	1.3×10^{-11}
2	30	1.78	43.6	1.99	533	41.10609	17.34004	6.92×10^{17}	12.32×10^{23}	10 ⁵	2.93×10^6	$.238 \times 10^{-17}$	$.395 \times 10^{-22}$	10 ⁵	$.238 \times 10^{-17}$	$.003 \times 10^{-12}$	$.003 \times 10^{-12}$
										2x10 ⁶	5.86×10^7	$.476 \times 10^{-14}$	$.79 \times 10^{-21}$	2x10 ⁶	$.852 \times 10^{-11}$	$.138 \times 10^{-11}$	$.138 \times 10^{-11}$
										10 ⁷	2.93×10^8	$.238 \times 10^{-15}$	$.395 \times 10^{-20}$	10 ⁷	$.238 \times 10^{-15}$	$.003 \times 10^{-8}$	$.3 \times 10^{-11}$

ECR

CREEP RATE AT Q=43.6 kcal/mole FOR
h=1,2,3 AND T=500, 900, 1050 F

(TASK NO. 227)

APPENDIX 4

SIMILAR TO

DRN RRN

CHD P16 6/14/60

APD QMD

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C	t (sec)	E _o 10 ⁶ psi	Q cal/mole	R cal/mole	T °K	Q RT	log N .434 Q RT	N	E _o N	σ psi	Cσ	① Cσ E _o N	B 1.66 x 10 ⁻⁵ ① 1/sec	σ ⁿ⁻¹	② Cσ ⁿ E _o N	③ ② .434 E	③+B = ② m ^{1/4} /sec
2	900	1.78	43.6	1.99	533	41.10609	12.84004	6.92 x 10 ¹⁷	12.32 x 10 ²³	10 ⁷	2.93 x 10 ⁸	2.38 x 10 ⁻¹⁵	3.95 x 10 ⁻²⁰	10 ⁷	2.38 x 10 ⁻⁸	.00011 x 10 ⁻⁹	.1 x 10 ⁻¹¹
										10 ⁸	2.93 x 10 ⁹	2.38 x 10 ⁻¹⁶	3.95 x 10 ⁻¹⁹	10 ⁸	2.38 x 10 ⁻⁶	.00011 x 10 ⁻⁶	11 x 10 ⁻¹¹
2	30	1.78	43.6	1.99	839	26.11388	11.33342	2.15 x 10 ¹¹	3.83 x 10 ¹⁷	10 ⁴	2.93 x 10 ⁵	7.65 x 10 ⁻¹²	1.27 x 10 ⁻¹⁷	10 ⁴	7.65 x 10 ⁻⁸	.011 x 10 ⁻³	11 x 10 ⁻¹¹
										10 ³	2.93 x 10 ⁴	7.65 x 10 ⁻¹³	1.27 x 10 ⁻¹⁸	10 ³	7.65 x 10 ⁻¹⁰	.011 x 10 ⁻¹⁰	.11 x 10 ⁻¹¹
2	900	1.78	43.6	1.99	839	26.11388	11.33342	2.15 x 10 ¹¹	3.83 x 10 ¹⁷	10 ⁴	2.93 x 10 ⁵	7.65 x 10 ⁻¹²	1.27 x 10 ⁻¹⁷	10 ⁴	7.65 x 10 ⁻⁸	.00036 x 10 ⁻⁸	.36 x 10 ⁻¹¹
										10 ⁵	2.93 x 10 ⁶	7.65 x 10 ⁻¹¹	1.27 x 10 ⁻¹⁶	10 ⁵	7.65 x 10 ⁻⁶	.00036 x 10 ⁻⁶	36 x 10 ⁻¹¹
3	30	1.78	43.6	1.99	755	29.01925	12.59435	3.93 x 10 ¹²	6.99 x 10 ¹⁸	200	5.86 x 10 ³	9.38 x 10 ⁻¹⁵	1.39 x 10 ⁻²⁰	4 x 10 ⁴	3.35 x 10 ⁻¹¹	.048 x 10 ⁻¹¹	.05 x 10 ⁻¹¹
										400	11.72 x 10 ³	1.68 x 10 ⁻¹⁵	2.77 x 10 ⁻²⁰	16 x 10 ⁴	2.69 x 10 ⁻¹⁰	.039 x 10 ⁻¹⁰	.39 x 10 ⁻¹¹
										600	17.58 x 10 ³	2.52 x 10 ⁻¹⁵	4.17 x 10 ⁻²⁰	36 x 10 ⁴	90.7 x 10 ⁻¹¹	1.31 x 10 ⁻¹¹	1.3 x 10 ⁻¹¹
3	900	1.78	43.6	1.99	755	29.01925	12.59435	3.93 x 10 ¹²	6.99 x 10 ¹⁸	600	17.58 x 10 ³	2.52 x 10 ⁻¹⁵	4.17 x 10 ⁻²⁰	36 x 10 ⁴	90.7 x 10 ⁻¹¹	.044 x 10 ⁻¹¹	.04 x 10 ⁻¹¹
										1000	2.93 x 10 ⁴	4.19 x 10 ⁻¹⁴	6.96 x 10 ⁻¹⁹	10 ⁶	4.19 x 10 ⁻⁸	.0002 x 10 ⁻⁸	.2 x 10 ⁻¹¹
										1800	5.27 x 10 ⁴	7.53 x 10 ⁻¹⁴	1.25 x 10 ⁻¹⁹	3.24 x 10 ⁶	2.44 x 10 ⁻⁸	.0012 x 10 ⁻⁸	12 x 10 ⁻¹¹
3	30	1.78	43.6	1.99	533	41.10609	17.84004	6.92 x 10 ¹⁷	12.32 x 10 ²³	6 x 10 ⁴	17.58 x 10 ³	1.43 x 10 ⁻¹⁵	2.37 x 10 ⁻²³	36 x 10 ⁸	81.5 x 10 ⁻¹⁰	.745 x 10 ⁻¹⁰	7.45 x 10 ⁻¹¹
										10 ⁴	2.93 x 10 ⁵	2.38 x 10 ⁻¹⁵	3.95 x 10 ⁻²³	10 ⁸	2.38 x 10 ⁻¹⁰	.0034 x 10 ⁻¹⁰	.03 x 10 ⁻¹¹
3	900	1.78	43.6	1.99	533	41.10609	17.84004	6.92 x 10 ¹⁷	12.32 x 10 ²³	8 x 10 ⁴	23.4 x 10 ⁵	1.9 x 10 ⁻¹⁵	3.15 x 10 ⁻²³	64 x 10 ⁸	121.6 x 10 ⁻¹⁰	.059 x 10 ⁻¹⁰	.6 x 10 ⁻¹¹
										9 x 10 ⁴	26.4 x 10 ⁵	2.15 x 10 ⁻¹⁵	3.56 x 10 ⁻²³	81 x 10 ⁸	174 x 10 ⁻¹⁰	.084 x 10 ⁻¹⁰	.8 x 10 ⁻¹¹
3	30	1.78	43.6	1.99	839	26.11388	11.33342	2.15 x 10 ¹¹	3.83 x 10 ¹⁷	200	5.86 x 10 ³	9.38 x 10 ⁻¹⁵	2.54 x 10 ⁻¹⁹	4 x 10 ⁴	6.12 x 10 ⁻¹⁰	.0885 x 10 ⁻¹⁰	.89 x 10 ⁻¹¹
										400	11.72 x 10 ³	3.06 x 10 ⁻¹⁴	5.08 x 10 ⁻¹⁹	16 x 10 ⁴	48.96 x 10 ⁻¹⁰	.708 x 10 ⁻¹⁰	7.1 x 10 ⁻¹¹
3	900	1.78	43.6	1.99	839	26.11388	11.33342	2.15 x 10 ¹¹	3.83 x 10 ¹⁷	400	11.72 x 10 ³	3.06 x 10 ⁻¹⁴	5.08 x 10 ⁻¹⁹	16 x 10 ⁴	48.96 x 10 ⁻¹⁰	.0236 x 10 ⁻¹⁰	.2 x 10 ⁻¹¹
										600	17.58 x 10 ³	4.59 x 10 ⁻¹⁴	7.62 x 10 ⁻¹⁹	36 x 10 ⁴	165 x 10 ⁻¹⁰	.0795 x 10 ⁻¹⁰	.8 x 10 ⁻¹¹
										800	23.44 x 10 ³	6.12 x 10 ⁻¹⁴	10.16 x 10 ⁻¹⁹	64 x 10 ⁴	391 x 10 ⁻¹⁰	.189 x 10 ⁻¹⁰	1.9 x 10 ⁻¹¹

ECCL

Creep Rate At Q = 43.6 kcal/mole. For
n = 1, 2, 3 and T = 500, 900, 1050 F

(Task No. 227)

Appendix 4

DRN RRN

CHD Pdg 6/14/60

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B

n	t (sec)	E ₀ 10 ⁶ psi	Q $\frac{\text{kcal}}{\text{mole}}$	R $\frac{\text{cal}}{\text{mole}}$	T °K	$\frac{Q}{RT}$	$\log N$.434 $\frac{Q}{RT}$	N	E ₀ N	σ psi	$\dot{\epsilon}$	$\frac{\sigma}{E_0 N}$	B 1.66×10^{-5} 1/SEC	σ^{n-1}	$\frac{C \sigma^n}{E_0 N}$	$\frac{.434}{t}$	$\frac{.434}{t} + B$ = $\dot{\epsilon}$ 1141/SEC
1	30	1.78	99	1.99	755	65.9729	28.59729	3.956×10^{28}	7.04×10^{34}	1000	2.93×10^4	$.416 \times 10^{-30}$	$.69 \times 10^{-35}$	1	$.416 \times 10^{-30}$	$.006 \times 10^{-30}$	$.006 \times 10^{-30}$
Note: No further calc's for n=1 since $\dot{\epsilon}$ is so small for Q=99																	
2	30	1.78	99	1.99	755	65.9729	28.59729	3.956×10^{28}	7.04×10^{34}	1000	2.93×10^4	$.416 \times 10^{-30}$	$.69 \times 10^{-35}$	1000	$.416 \times 10^{-27}$	$.006 \times 10^{-27}$	$.006 \times 10^{-27}$
Note: No further calc's for n=2 since $\dot{\epsilon}$ is so small for Q=99																	
3	30	1.78	99	1.99	755	65.9729	28.59729	3.956×10^{28}	7.04×10^{34}	1000	2.93×10^4	$.416 \times 10^{-30}$	$.69 \times 10^{-35}$	106	$.416 \times 10^{-24}$	$.006 \times 10^{-24}$	$.006 \times 10^{-24}$
Note: No further calc's. for n=3 since $\dot{\epsilon}$ is so small for Q=99																	
At Q=99 kcal/mole there appears to be no reasonable n for which $\dot{\epsilon}$ can be brought to the required level, at any stress having real meaning for graphite.																	

At Q=99 Kcal/mole there appears to be no reasonable n for which $\dot{\epsilon}$ can be brought to the required level, at any stress having real meaning for graphite.

EGCR

CREEP RATES AT Q=99 Kcal/mole FOR

n=1, 2, 3 and T=500, 900, 1050 F

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(2) The foregoing calculations have shown that, assuming the general validity of extrapolation from the referenced article and its formula, if activation energy is less than perhaps 50 kcal/mole, then the required creep rates can be demonstrated for exponents (of applied stress) that are not inconsistent with results obtained by investigators other than those of the referenced article. The exact value for activation energy, ^{for EGCR conditions} is not available from the literature, and several contradictory values are listed for test run under similar temperature and stress conditions but for different types of graphite. ^{Most} Formulas, where available in the literature, take the general form of a rate-process equation

$$\dot{\epsilon} = A e^{-\frac{Q}{RT}} \sigma^n$$

where A is a "constant" dependent on stress and material. It seems that in order to check this more general formula (which has been applied to test of AGHT graphite at high temperatures) for applicability to EGCR conditions we should perform calculations similar to the preceding, which have proved not applicable in the range of $Q = 100$ kcal/mole.

To do this we shall take $Q = 100$ kcal/mole and examine the three significant EGCR temperatures at various possible stress levels. We will use $A = 3 \times 10^{-3}$ as a constant for all stress levels (since we have no data that would allow us to do otherwise) since it is determined for a graphite similar to AGOT, the EGCR current graphite. AGHT comes from outer portions of furnace whereas AGOT comes from interior of furnace. Extrapolation ^{of creep rates} to lower temperatures from those of reference tests (Doc. NEPA 1516) should be affected by the lower strength and modulus of elasticity but the creep rate should not be changed by a factor of more than two or three. This is probably as good as the extrapolation itself. The formula is then:

$$\dot{\epsilon} = 3 \times 10^{-3} \sigma^n e^{-\frac{Q}{RT}} \quad \%/\text{hour} \quad \text{FORMULA B}$$

where Q will be taken as 100,000 and 43.6 kcal/mole and $n = 1, 2, 3$.

CREEP IN EGCR GRAPHITE (TASK No. 227)

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Appendix 4

STEADY-STATE CREEP RATE FOR $Q=100$ kcal/mole
 per mole For $n=1, 2, 3$ and $T=500, 900, 1050$ F

EGCR

SIMILAR TO

S	E_0 10 ⁶ psi	Q Kcal/mole	R cal/mole	T °K	$\frac{Q}{RT}$	log N $\frac{434 Q}{RT}$	N	σ psi	σ^n	$\frac{\sigma^n}{N}$	$\dot{\epsilon}$ $3 \times 10^{-3} \left(\frac{\sigma^n}{N} \right)$ %/hour	in/in / sec
1	1.78	100	1.99	755	66.55745	28.88615	7.694×10^{28}	200	200	25.49×10^{-28}	77.97×10^{-31}	21.6×10^{-36}
Note: For $n=1$ no useable stress will provide the required creep rate												
2	1.78	100	1.99	755	66.55745	28.88615	7.694×10^{28}	200	4×10^4	$.52 \times 10^{-24}$	1.56×10^{-27}	$.42 \times 10^{-32}$
							1000	1000	10 ⁶	$.13 \times 10^{-12}$	$.39 \times 10^{-25}$	$.11 \times 10^{-30}$
	1.78	100	1.99	839	59.89422	25.99409	9.865×10^{25}	1000	10 ⁶	$.1 \times 10^{-9}$	$.3 \times 10^{-22}$	$.083 \times 10^{-27}$
Note: For $n=2, n=3, n=4, n=5, n=6$ no useable stress will provide the required creep rate												
7	1.78	100	1.99	755	66.55745	28.88615	7.694×10^{28}	1000	10^{21}	$.13 \times 10^{-7}$	$.39 \times 10^{-10} = 3.9 \times 10^{-11}$	$.11 \times 10^{-16}$
6	1.78	100	1.99	839	59.89422	25.99409	9.865×10^{25}	1000	10^{18}	$.1 \times 10^{-7}$	$.3 \times 10^{-10} = 3 \times 10^{-11}$	$.83 \times 10^{-16}$
11	1.78	100	1.99	533	44.28003	40.91753	8.27×10^{40}	1000	10^{33}	$.12 \times 10^{-7}$	$.36 \times 10^{-10} = 3.6 \times 10^{-11}$	1.0×10^{-16}
Note: With $Q=100$ kcal/mole it does not appear that the formula $\dot{\epsilon} = 3 \times 10^{-3} \sigma^n e^{-\frac{Q}{RT}}$ can be extrapolated to EGCR temperatures for any useable σ and any n consistent with results of creep tests on graphite.												
1	1.78	43.6	1.99	755	29.01926	12.59436	3.93×10^{12}	200	200	$.51 \times 10^{-10}$	1.5×10^{-13}	$.41 \times 10^{-18}$
								2×10^4	2×10^4	$.51 \times 10^{-8}$	1.5×10^{-11}	$.41 \times 10^{-16}$
				839	26.11358	11.33342	2.15×10^{11}	200	200	$.93 \times 10^{-9}$	2.79×10^{-12}	$.78 \times 10^{-17}$
							1000	1000	1000	$.47 \times 10^{-8}$	1.4×10^{-11}	$.39 \times 10^{-16}$
				533	41.10609	17.84004	6.919×10^{17}	10 ⁹	10 ⁹	$.14 \times 10^{-8}$	$.42 \times 10^{-11}$	$.12 \times 10^{-16}$
2	1.78	43.6	1.99	755	29.01926	12.59436	3.93×10^{12}	100	10 ⁴	$.25 \times 10^{-9}$	$.75 \times 10^{-11}$	$.21 \times 10^{-16}$
								200	4×10^4	1×10^{-8}	3×10^{-11}	$.93 \times 10^{-16}$
				839	26.11388	11.33342	2.15×10^{11}	100	10 ⁴	$.47 \times 10^{-9}$	1.4×10^{-10}	$.39 \times 10^{-16}$
								50	25×10^2	12×10^{-9}	$.36 \times 10^{-10} = 3.6 \times 10^{-11}$	1.0×10^{-16}
				533	41.10609	17.84004	6.919×10^{17}	1000	10 ⁶	$.14 \times 10^{-11}$	$.42 \times 10^{-14}$	$.16 \times 10^{-19}$
								3×10^4	9×10^8	1.3×10^{-9}	$3.9 \times 10^{-12} = .39 \times 10^{-11}$	1.1×10^{-18}

NOTE: Except for the lowest temperature regions of EGCR, the creep rate becomes equal to required levels at acceptably low stresses and at short periods of time. It is thus possible to find stresses which are acceptable even at the lowest temperatures.

$\dot{\epsilon}$ - CREEP RATE FOR $Q = 20 \text{ kcal/mole} - \text{m/in/SEC.}$

SYMBOLS

$\text{---} T = 755 \text{ K}$
 $\text{---} T = 533 \text{ K}$
 $\text{---} T = 839 \text{ K}$
 t in seconds

σ - STEADY STATE STRESS LEVEL - PSI

$$\dot{\epsilon} = \frac{C \sigma^n}{E_0 \exp\left(\frac{Q}{RT}\right)} \cdot \frac{.434}{t} + B$$

CREEP RATE FOR $Q = 20 \text{ kcal/mole}$

EGCR

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Appendix 4

SIMILAR TO

DR'N RRN

CH'D PVG 6/6/60

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A

B

Required creep rate
at 533 or 539 F
(assuming flux falls
of by factor of six
at core top and bottom)

$\dot{\epsilon}$ - CREEP RATE FOR $Q = 43.6$ kcal/mole - in/in/sec

SYMBOLS
 Formula (2)
 ——— T=755K
 ——— T=533K
 - - - T=839K
 t in seconds

σ Steady State Stress Level - Psi

(1) $\dot{\epsilon} = \frac{C \sigma^n}{E \exp(Q/RT)} \frac{434}{t} + B$ in/in/sec
 (2) $\dot{\epsilon} = 3 \times 10^{-3} \sigma^n \exp(-\frac{Q}{RT})$ %/hour

CREEP RATE FOR $Q = 43.6$ kcal/mole

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$\dot{\epsilon}$ - CREEP RATE FOR $Q = 100 \text{ kcal/mole}$ - IN/IN/SEC

10^{-11} $T=755$
Req'd. creep rate so that
all strain is accommodated
by creep.

σ STEADY STATE STRESS LEVEL - PSI

(1) $\dot{\epsilon} = \frac{C \sigma^n}{E_0 \exp(Q/RT)} \cdot 0.434 + B$ IN/IN/SEC

(2) $\dot{\epsilon} = 3 \times 10^{-3} \sigma^n \exp(-Q/RT)$ %/hour

SYMBOLS

- $T=755 \text{ K}$
- - - $T=533 \text{ K}$
- ... $T=839 \text{ K}$
- ... Formula (2)
- t in seconds

CREEP RATE FOR $Q = 100 \text{ kcal/mole}$

EGCR

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(B) The preceding calculations have shown that acceptable creep rates (i.e. equal to the strain rate) can occur in EGCR graphite and environment at useful stress levels for some combinations of parameters:

$\dot{\epsilon}$	n	T	σ	ϵ	Formula "as is"	Compromise Modified Formula	Reg'd ϵ
rad/mole	K psi	K psi	psi	min	from literature		
160,000	3.1	755	1290	-	$\dot{\epsilon} = 3 \times 10^{-3} \exp(-\frac{Q}{RT})$	$\dot{\epsilon} = 3 \times 10^{-3} \exp(-\frac{Q}{RT})$	1×10^{-11} 1.05×10^{-11} in/in/sec
43,600	3.1	755	1290	-	"	"	0.52×10^{-11} 7×10^{-12} in/in/sec
20,000	2.6	755	1290	0.5	$\dot{\epsilon} = 1434 \frac{T}{T^2}$	$\dot{\epsilon} = .434 \frac{T}{T^2} \exp(-\frac{Q}{RT})$	0.28×10^{-11} 0.75×10^{-11} 0.8×10^{-11} 0.9×10^{-11} 4.6×10^{-10}
	1	755	1290	0.5	"	"	
	1	755	1290	30	"	"	
	1	755	1290	929	"	"	

These of course apply to core midplane. At the top and bottom of the core, strain rates should be down by a factor of at least four to six. (It should be noted that stress accumulation would also be down by a factor of four and acceptable core life for the extremes of core could be shown even without recourse to creep calculations: see addendum to anisotropic stress calculations). Thereafter, then, there should come a time in EGCR life when a limiting stress is reached at the critical area, the midplane. We shall now calculate what this time is. To choose the final formulas for calculating stress accrual, we eliminate, by inspection and knowledge of the general trend of $\dot{\epsilon}$ with temperature, the higher $\dot{\epsilon} = 110$ rad/mole. $\dot{\epsilon} = 20$ rad/mole will be regarded as the most likely value for EGCR conditions, since it was determined with the lowest temperature test currently available, and any errors due to extrapolation should be least! $\dot{\epsilon} = 43.6$ rad/mole will be regarded as a conservative number and some attempt made to modify the formulas employed to accord with this conservatism.

(1) For $\dot{\epsilon} = 20$ rad/mole the formula for creep rate and its integration for creep will be applied directly "as is" to EGCR conditions for comparing stress accumulation:

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EGCR

Appendix 4

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$$\Delta L_i = \frac{L \Delta \sigma_i}{E_{i-1}} + \frac{L \cdot 434 C \sigma_{i-1}}{E_0 \exp\left(\frac{Q}{RT}\right)} \int_{t_i}^{t_{i+1}} \frac{dt}{t} + L \int_{t_i}^{t_{i+1}} B_i dt$$

- where ΔL_i is strain accumulation (potential) in interval t_i to t_{i+1}
 $\Delta \sigma_i$ is stress accumulation in t_i to t_{i+1} due to strain not absorbed in creep
 E_{i-1} is tangent modulus taken from short-term-loading graph at end of t_{i-1} interval
 L = one inch
 E_0 is virgin room temperature Young's modulus
 σ_{i-1} is total stress at end of t_{i-1} interval
 C is "universal" constant = 29.3
 $\frac{C \sigma_{i-1}}{E_0 \exp\left(\frac{Q}{RT}\right)} = k_i$ a stress dependent constant for t_i to t_{i+1}
 $B_i = 10^{-3} \times k_i$ a stress dependent constant for t_i to t_{i+1} where t is in minutes only
 t_i is beginning of any interval (noting that when actual limits are used in integration, the beginning of second stage creep or some similar small Δt will be used so that $t \neq 0$).
 t_{i+1} is end of any interval

Simplifying:
$$\Delta L_i = \frac{\Delta \sigma_i}{E_{i-1}} + 434 k_i \left[\log t \right]_{t_i}^{t_{i+1}} + B_i [t]_{t_i}^{t_{i+1}}$$

* This formula will be strictly applied only to small intervals (30 min) and its results extrapolated to larger intervals (say six months).

(2) For $Q = 43.6$ kcal/mole, two formulas will be employed:

- (a) a form similar to that for $Q = 20$ kcal/mole except that stress-dependence will be of a higher degree, the exponent being a compromise between 1 and 3.1 to 3.9 range of exponents mentioned in the literature: n taken therefore as 2.5. Then:

$$\Delta L_i = \frac{L \Delta \sigma_i}{E_{i-1}} + \frac{L \cdot 434 C \sigma_{i-1} (\sigma_{i-1})^{n-1}}{E_0 \exp\left(\frac{Q}{RT}\right)} \int_{t_i}^{t_{i+1}} \frac{dt}{t} + L B_i \int_{t_i}^{t_{i+1}} dt$$

or simplifying
$$\Delta L_i = \frac{\Delta \sigma_i}{E_{i-1}} + k_i (\sigma_{i-1})^{2.5} \left[\log t \right]_{t_i}^{t_{i+1}} + B_i [t]_{t_i}^{t_{i+1}}$$

* Note above also applies here.

- (b) a formula similar to that for $Q = 110$ kcal/mole, except that the degree of stress dependence is arbitrarily reduced

CREEP IN EGCR GRAPHITE (TASK No. 227)

Appendix 4

SIMILAR TO

DR'N RRN

CH'D P/K 4/16/60

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to an even 3 from 3.1, will be used as is:

$$\Delta L_i = 3 \times 10^{-3} \sigma_{i-1}^3 \exp(-Q/RT) (t_{i+1} - t_i) + \frac{\Delta \sigma_i}{E_{i-1}}$$

It should be noted that, from graphs on pp 22-24, the correspondence of creep rates, calculated from these two general types of formulas, is not too bad for similar sets of parameters in the lower range of activation energy. Therefore it is felt that, in the absence of experimental verification for EGCR conditions, these formulas should give as good a range of values for maximum limiting stress in EGCR as can be obtained from the available data. The results should show acceptable creep at reasonable stresses, if they are to be in general agreement with the opinions of personnel having worked extensively with graphite at nuclear facilities (Ref: A.C. Memo: J.K. Davidson "Summary of Discussion of Creep of Graphite", Dec 14, 59). The formulas, although recognized as not definitive, have been developed in accordance with the philosophy that design of EGCR should proceed on basis of existing technology (Ref: LETTER: L. JACKSON, ORDO: To P.D. Bush, N.E. "GRAPHITE IRRADIATION PROGRAM", Dec 10, 1959).

Creep IN EGCR GRAPHITE (Task 227)

Appendix "4"

SIMILAR TO

DR'N R.R.N

CH'D PVG 6/6/60

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(G) In calculating the year-by-year accumulation of stress, the yearly rate of potential strain is taken from calculations made for anisotropic case:

The worst stress is there found to be tensile, longitudinal, at the surface of a fuel channel. For one year the stresses are

$$\left. \begin{array}{l} \sigma_z = 598 (+) \\ \sigma_t = 354 (+) \\ \sigma_r = 0 \end{array} \right\} \text{ for "use factor" of } 1.0$$

The longitudinal strain is:

$$\begin{aligned} \epsilon_z &= \frac{1}{E_L} (-\mu_L \sigma_r - \mu_L \sigma_t + \frac{\sigma_z}{k_1}) \quad \text{where } k_1 = 1.36 \\ &= \frac{1}{1.32 \times 10^6} (-.213 \times 0 - .213 \times 354 + \frac{598}{1.36}) \\ &= \frac{1}{1.32 \times 10^6} (-75.4 + 440) \\ &= 2.74 \times 10^{-4} \text{ in/in/year longitudinally} \end{aligned}$$

For "use factor" of 0.8 $\epsilon_z = 2.16 \times 10^{-4}$ in/in/yr longitudinally. This rate will be constant (so long as "use factor" is uniform) in any year, and will be used for ΔL_n where n is the number of years elapsed from the beginning of core life.

The process of stress accrual is envisioned as (on a yearly basis):

- (1) Initial interval in which stress rises to some level ($\Delta \sigma_i$) and no creep occurs, since creep in any interval will be based on the stress at beginning of interval which is zero in this case. Total elongation of a one inch fiber is 2.74×10^{-4} inch
- (2) A second interval in which the tendency to elongate is still 2.74×10^{-4} inches. Because an initial stress level exists, a certain amount of creep occurs (as a function of the appropriate exponent of stress) and absorbs some of the tendency to elongate. The remaining elongation is absorbed by stress-producing strain. Unless the formula used shows ^{creep} strain to be time-dependent, the total creep strain will simply be $\epsilon_i t_i$ where t_i is the time interval.

Creep in EGGR Graphite (Task 227)

Appendix 4

SIMILAR TO

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(3) For each succeeding interval, the amount of creep strain increases. The increase in stress is less in each succeeding interval. Finally, an interval is reached in which all potential strain is absorbed by creep and stress never proceeds any higher. This final stress should be used in combination with all short term loads to demonstrate adequate structural strength in the EGCR core column.

(4) Each ^{cross-section of each} column reaches the limiting stress at a different time in core life, but, for all cross sections on the same horizontal plane, the limiting stress should be the same. The plane of worst stress without creep will be examined in detail (i.e. core mid-plane) although, due to temperature differences, higher limiting stress may occur on other horizontal cross-sections. The effect of long-term thermal gradients will be considered separately; but, since their effect is generally to increase the stress level at the beginning of the first (and every) interval, from standpoint of the limiting stress, the limit would be reached more quickly although the value would be the same. By considering, thermal gradient stresses separately and adding to creep-limit stresses, the total should be conservative. Where higher limiting stress may occur (top of core) the stress level is low enough to absorb all strain elastically and still demonstrate a 20 year life without resort to creep.

In all calculations, the assumption is made that graphite is capable of accepting the amount of creep-strain necessary to accommodate the ^{total} potential elongation without fracture. For 20 years, if all the ~~elongation~~ ^{total} went into creep, the creep strain would be

$$20 \times 2.74 \times 10^{-4} = 54 \times 10^{-4} \text{ in/in/20 yr} \\ = .54 \% / 20 \text{ yr}$$

Depending on temperature and stress level (and on type of graphite) various references show elongation of graphite ranging from .2% to 16% at or before time of fracture. Although EGCR conditions are different from those of references, it would appear that EGCR graphite should be capable of the necessary creep. Particularly, since the

CREEP IN EGCR GRAPHITE (TASK 227)

APPENDIX 4

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referenced tests run no longer than 100 hours and, in EGCR, the graphite has 20 years to adjust itself slowly to the strain. Over any period then we will assume that creep continues as dictated by the formulas (taken from results of short-term tests) without fracture.

Activation energy is taken to be stress-independent (although statements "pro" and "con" exist in literature. In any interval, time is measured from the beginning of interval, not from the beginning of core life. Formulas from the preceding calculations of anisotropic graphite will be used in calculating $\Delta\sigma_i$:

$$(2) \Delta\sigma_i = \left(\frac{1}{2}\right) E_{i-1} (2.635 [\text{potential strain} - \text{creep strain}] - 2.546 \times 10^{-4})$$

The creep strain considered will always be taken as a result of the secondary "steady-state" creep rate, since this is less than the short-lived "primary" rate and continues for most of the interval.

For formulas where $\Delta\sigma_i$ (calculated for 30 minute intervals) is to be extrapolated linearly to six months the conversion is:

$$\frac{2.635 \times 10^5}{30} = .878 \times 10^4$$

$$\Delta\sigma_{\text{six mos}} = \Delta\sigma_i (.878 \times 10^4)$$

Since $\Delta\sigma_i$ for 30 minutes is actually very small, the extrapolation to the six month period will be based on the residual strain in the 30 minute interval and projecting to six months for use in a stress formula taken from calculations based on the cylindrical anisotropic model.

Since ϵ is a function of t , another interval (100 minutes) is examined to show the effect of time. The conversion factor for $\Delta\sigma_i$ is here $.292 \times 10^4 \Delta\sigma_i = \Delta\sigma_{\text{six mos.}}$

Tension and compression creep are assumed to be similar (Ref 6) although compressive stresses are not critical.

CREEP IN EGCR GRAPHITE (TASK 227)

APPENDIX 4

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CREEP IN EGCR GRAPHITE (TASK 227)
 NOMINAL STRESSES AT CODE MIDPLANE
 (V=1.0) FOR Q = 43.6 kcal/mile AT THE
 CHANNEL SURFACE

Appendix 4

SIMILAR TO

YEAR END		ΔL_i	σ_{i-1}	E_{i-1} (1)	n	① σ_i^n	② exp(-Q/RT)	③ $t_{i-1} - t_i$ hr	creep 5×10^{-3} ④ ⑤ ⑥ (%/hr)(hr)	creep ⑤ (in/in) ④ (10 ⁻²)	⑥ $\Delta L_i - \Delta L_{i-1}$ in/in	⑦ 2.66-24x10 ⁻⁴	$\Delta \sigma_i$ ⑦ E_{i-1}
YR	U	in/in	psi	10 ⁴ psi									
0	1	0	0	1.35	3.0	0	.254x10 ⁻¹²	0	0	0	0	0	0
1		2.7x10 ⁻⁴	598	1.29		2.13x10 ⁶		8.76x10 ³	1421.8x10 ⁻⁶	1.42x10 ⁻⁵	2.56x10 ⁻⁴	4.06x10 ⁻⁴	523
2		2.7x10 ⁻⁴	1121	1.14		1.41x10 ⁹			9.41x10 ⁻³	9.4x10 ⁻⁵	1.76x10 ⁻⁴	1.98x10 ⁻⁴	226
3		2.7x10 ⁻⁴	1347	1.03		2.44x10 ⁹			16.3x10 ⁻³	16.3x10 ⁻⁵	1.07x10 ⁻⁴	.18x10 ⁻⁴	19
4		2.7x10 ⁻⁴	1366	1.03		2.55x10 ⁹			17.0x10 ⁻³	17x10 ⁻⁵	1.0x10 ⁻⁴	0	0
0	.8	0	0	1.35	3.0	0	.254x10 ⁻¹²	0	0	0	0	0	0
1		2.16x10 ⁻⁴	478	1.32		1.09x10 ⁶		8.76x10 ³	.73x10 ⁻³	.73x10 ⁻⁵	2.09x10 ⁻⁴	2.93x10 ⁻⁴	374
2		2.16x10 ⁻⁴	852	1.23		.62x10 ⁹			4.13x10 ⁻³	4.13x10 ⁻⁵	1.75x10 ⁻⁴	1.95x10 ⁻⁴	240
3		2.16x10 ⁻⁴	1092	1.15		1.30x10 ⁹			8.69x10 ⁻³	8.69x10 ⁻⁵	1.29x10 ⁻⁴	.75x10 ⁻⁴	97
4		2.16x10 ⁻⁴	1159	1.13		1.56x10 ⁹			10.39x10 ⁻³	10.39x10 ⁻⁵	1.12x10 ⁻⁴	.31x10 ⁻⁴	35
5		2.16x10 ⁻⁴	1184	1.12		1.66x10 ⁹			11.1x10 ⁻³	11.1x10 ⁻⁵	1.05x10 ⁻⁴	.13x10 ⁻⁴	15
6		2.16x10 ⁻⁴	1199	1.12		1.72x10 ⁹			11.5x10 ⁻³	11.5x10 ⁻⁵	1.01x10 ⁻⁴	.026x10 ⁻⁴	3
7		2.16x10 ⁻⁴	1202	1.12		1.74x10 ⁹			11.6x10 ⁻³	11.6x10 ⁻⁵	1.00x10 ⁻⁴	0	0
0	1	0	0	1.35	2.5	0	.254x10 ⁻¹²	0	0	0	0	0	0
1		2.7x10 ⁻⁴	598	1.29		8.7x10 ⁶		8.76x10 ³	58.1x10 ⁻⁶	.58x10 ⁻⁵	2.70x10 ⁻⁴	4.42x10 ⁻⁴	570
2		2.7x10 ⁻⁴	1169	1.13		4.79x10 ⁷			31.97x10 ⁻⁵	.51x10 ⁻⁵	2.67x10 ⁻⁴	4.34x10 ⁻⁴	491
3		2.7x10 ⁻⁴	1659	0.88		1.17x10 ⁸			7.81x10 ⁻⁴	.78x10 ⁻⁵	2.62x10 ⁻⁴	4.21x10 ⁻⁴	370
4		2.7x10 ⁻⁴	2029	0.57		1.91x10 ⁸			12.75x10 ⁻⁴	.128x10 ⁻⁴	2.57x10 ⁻⁴	4.08x10 ⁻⁴	233
			2262										

It appears that, unless n $\approx$ 3 or better, the effect of creep will be negligible using this set of parameters. Stresses and max life will not differ materially from those calculated for the anisotropic case w/o creep

It appears that, unless $n \approx 3$ or better, the effect of creep will be negligible using this set of parameters. Stresses and max life will not differ materially from those calculated for the anisotropic case w/o creep

$$\Delta L_i = 3 \times 10^{-3} \sigma_{i-1}^n \exp(-Q/RT) (t_{i+1} - t_i) + \frac{\Delta \sigma_i}{E_{i-1}}$$

$$\exp(-Q/RT) = \exp\left(\frac{43,600}{1.99 \times 10^3 \times 165}\right) = .254 \times 10^{-12}$$

$$\Delta \sigma_i(x) = E_{i-1} (2.635 \text{ (c)} - 2.546 \times 10^{-4}) = \text{(From anisotropic calculations)}$$

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CREEP IN EGGR GRAPHITE (TASK 227)
LONGITUDINAL STRESSES AT CORE MIDPLANE (FOR $\bar{v} = 1.0$)
AT CHANNEL SURFACE ($Q = 20$ kcal/mole)

Appendix 4

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YR END	t_i min.	t_{i+1} min.	① Δu_{i+1} - Δu_i	ΔL_i in/in	② σ_{i-1} psi	E_{i-1} (1) 10^6 psi	③ K $\frac{1}{psi}$	①②③④	B $K \sigma_{i-1}$ 1000	⑤ $B(t_{i+1} - t_i)$ in/in	⑥ Δu_i psi	⑦ ΔL_i in/in	⑧ Residual ΔL_i (Projected for 6 mos.)
0	0	0	0	0	0	1.35	113×10^{-11}	0	0	0	0	0	1.37×10^{-4}
0.5	0	2.63x10 ⁵	-	1.37×10^{-4}	0	1.35		0	0	0	0	0	
	1	30	3.401	1.36×10^{-8}	299	1.35		1.145×10^{-8}	3.37×10^{-17}	$.01 \times 10^{-8}$	1.16×10^{-8}	$.50 \times 10^{-8}$	$.438 \times 10^{-4}$
1.0	30	2.63x10 ⁵	-	4.28×10^{-4}	395	1.35		1.52×10^{-8}	4.46×10^{-17}	$.01 \times 10^{-8}$	1.53×10^{-8}	$.03 \times 10^{-8}$	96
	1	30	3.401	1.56×10^{-8}	395	1.35		1.52×10^{-8}	4.46×10^{-17}	$.01 \times 10^{-8}$	1.53×10^{-8}	$.03 \times 10^{-8}$	$.027 \times 10^{-4}$
1.5	30	2.63x10 ⁵	-	$.027 \times 10^{-4}$	401	1.35		-	-	-	-	-	6
	1	30	3.401	1.56×10^{-8}	401	1.35		1.54×10^{-8}	4.54×10^{-17}	$.01 \times 10^{-8}$	1.55×10^{-8}	$.01 \times 10^{-8}$	$.009 \times 10^{-4}$
2.0	30	2.63x10 ⁵	-	$.009 \times 10^{-4}$	403	1.35		-	-	-	-	-	
	1	100	4.6	5.2×10^{-8}	299	1.35	1.13×10^{-11}	1.57×10^{-8}	3.4×10^{-17}	$.03 \times 10^{-8}$	1.6×10^{-8}	3.6×10^{-8}	1.05×10^{-4}
0.5	100	2.63x10 ⁵	-	1.05×10^{-4}	528	1.31		-	-	-	-	-	229
	1	100	4.6	5.2×10^{-8}	528	1.31		2.76×10^{-8}	6.0×10^{-17}	$.06 \times 10^{-8}$	2.82×10^{-8}	2.38×10^{-8}	$.696 \times 10^{-4}$
1.0	100	2.63x10 ⁵	-	$.696 \times 10^{-4}$	693	1.25		-	-	-	-	-	165
	1	100	4.6	5.2×10^{-8}	693	1.25		3.59×10^{-8}	7.8×10^{-17}	$.09 \times 10^{-8}$	3.67×10^{-8}	1.53×10^{-8}	$.446 \times 10^{-4}$
1.5	100	2.63x10 ⁵	-	$.446 \times 10^{-4}$	782	1.22		-	-	-	-	-	89
	1	100	4.6	5.2×10^{-8}	782	1.22		4.08×10^{-8}	8.8×10^{-17}	$.09 \times 10^{-8}$	4.17×10^{-8}	1.03×10^{-8}	$.301 \times 10^{-4}$
2.0	100	2.63x10 ⁵	-	$.301 \times 10^{-4}$	841	1.22		-	-	-	-	-	59
	1	100	4.6	5.2×10^{-8}	841	1.22		4.37×10^{-8}	9.5×10^{-17}	$.10 \times 10^{-8}$	4.47×10^{-8}	$.73 \times 10^{-8}$	$.213 \times 10^{-4}$
2.5	100	2.63x10 ⁵	-	$.213 \times 10^{-4}$	883	1.21		-	-	-	-	-	42
	1	100	4.6	5.2×10^{-8}	883	1.21		4.60×10^{-8}	1.0×10^{-16}	$.10 \times 10^{-8}$	4.70×10^{-8}	$.50 \times 10^{-8}$	$.146 \times 10^{-4}$
3.0	100	2.63x10 ⁵	-	$.146 \times 10^{-4}$	911	1.21		-	-	-	-	-	28
	1	100	4.6	5.2×10^{-8}	911	1.21		4.75×10^{-8}	1.03×10^{-16}	$.10 \times 10^{-8}$	4.85×10^{-8}	$.35 \times 10^{-8}$	$.602 \times 10^{-4}$
3.5	100	2.63x10 ⁵	-	$.102 \times 10^{-4}$	921	1.21		-	-	-	-	-	20
	1	100	4.6	5.2×10^{-8}	921	1.21		4.77×10^{-8}	1.04×10^{-16}	$.10 \times 10^{-8}$	4.87×10^{-8}	$.33 \times 10^{-8}$	$.096 \times 10^{-4}$
4.0	100	2.63x10 ⁵	-	$.096 \times 10^{-4}$	940	1.21		-	-	-	-	-	19

Note: Since stresses saturate at low stresses, no calculation will be made for $\bar{v} = 0.8$

- $\Delta L_i = \frac{\Delta \sigma_i}{E_{i-1}} + \frac{.434 C \sigma_{i-1}}{E_{i-1} \exp(Q/RT)} [\Delta u_i]_{t_i}^{t_{i+1}} + B [t]_{t_i}^{t_{i+1}}$
- $K = \frac{C(.434)}{E_{i-1} \exp(Q/RT)} = \frac{29.3(.434)}{1.78 \times 10^{16} \cdot 2.75 \times 10^{-5}} = 1.13 \times 10^{-11}$
- $\Delta \sigma_{i-1} = E_{i-1} (\Delta L_i - B(t_{i+1} - t_i)) = \frac{2.635 \times 1.37 \times 10^{-4} - 1.273 \times 10^{-4}}{1.37 \times 10^{-4}}$

* from anisotropic calc. adjusted for 6 month interval instead of year ($t_{i+1} - t_i = 30$)

APPENDIX 4

Creep In EGGR Graphite (Tack 227)
Longitudinal Stresses At Core Midplane (For $U = 1.0$)
At Channel Surface ($Q = 43.1$ kcal/mole)

SIMILAR TO

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VR	t_i	t_{i+1}	① $\ln t_{i+1} - \ln t_i$	ΔL_i	σ_{i-1}	E_{i-1} (L) 10^6 psi	② $(\sigma_{i-1})^3$	③ K	④ $10^3 \sigma_i^4$	B $\frac{K \sigma_{i-1}}{1000}$	⑤ $B(t_{i+1} - t_i)$ in/in	⑥ $④ + ⑤ = ⑥$ in/in	⑦ $\Delta L_i - ⑥$ in/in	D σ_i psi *	⑧ Residual D σ_i (Pro- rated for 6 months)
0	0	0	0	0	0	1.35	0	1.825×10^{-18}	0	0	0	0	0	0	1.37×10^{-4}
0.5	0	2.63×10^5	—	1.37×10^{-4}	299	1.35	—	—	—	—	—	—	—	299	—
	1	30	3.401	1.56×10^{-8}	299	1.35	2.68×10^9	—	16×10^{-10}	5.4×10^{-18}	16×10^{-18}	16×10^{-10}	1.56×10^{-8}	negl.	1.37×10^{-4}
1.0	30	2.63×10^5	—	1.37×10^{-4}	598	—	—	—	13.3×10^{-10}	10.9×10^{-18}	—	13.3×10^{-10}	1.43×10^{-8}	299	—
	1	30	3.401	1.56×10^{-8}	598	1.29	8.44×10^8	—	—	—	—	—	1.43×10^{-8}	negl.	1.25×10^{-4}
1.5	30	2.63×10^5	—	1.25×10^{-4}	897	—	—	—	40.1×10^{-10}	15.7×10^{-18}	—	40.1×10^{-10}	1.46×10^{-8}	299	—
	1	30	3.401	1.56×10^{-8}	897	1.26	6.44×10^8	—	—	—	—	40.1×10^{-10}	1.46×10^{-8}	negl.	1.00×10^{-4}
2.0	30	2.63×10^5	—	1.00×10^{-4}	1061	—	—	—	74×10^{-10}	19.3×10^{-18}	—	74×10^{-10}	$.82 \times 10^{-8}$	299	—
	1	30	3.401	1.56×10^{-8}	1061	1.20	1.19×10^9	—	—	—	—	74×10^{-10}	$.82 \times 10^{-8}$	negl.	$.72 \times 10^{-4}$
2.5	30	2.63×10^5	—	$.72 \times 10^{-4}$	1201	—	—	—	108×10^{-10}	22×10^{-18}	negl.	1.08×10^{-8}	$.48 \times 10^{-8}$	140	—
	1	30	3.401	1.56×10^{-8}	1201	1.19	1.74×10^9	—	—	—	—	1.08×10^{-8}	$.48 \times 10^{-8}$	negl.	$.42 \times 10^{-4}$
3.0	30	2.63×10^5	—	$.42 \times 10^{-4}$	1282	—	—	—	130×10^{-10}	23.4×10^{-18}	—	1.30×10^{-8}	$.26 \times 10^{-8}$	81	—
	1	30	3.401	1.56×10^{-8}	1282	1.19	2.11×10^9	—	—	—	—	1.30×10^{-8}	$.26 \times 10^{-8}$	negl.	$.227 \times 10^{-4}$
3.5	30	2.63×10^5	—	$.227 \times 10^{-4}$	1326	—	—	—	145×10^{-10}	24.2×10^{-18}	—	1.45×10^{-8}	$.11 \times 10^{-8}$	44	—
	1	30	3.401	1.56×10^{-8}	1326	1.18	2.33×10^9	—	—	—	—	1.45×10^{-8}	$.11 \times 10^{-8}$	negl.	$.096 \times 10^{-4}$
4.0	30	2.63×10^5	—	$.096 \times 10^{-4}$	1345	—	—	—	151×10^{-10}	24.5×10^{-18}	—	1.51×10^{-8}	$.05 \times 10^{-8}$	19	—
	1	30	3.401	1.56×10^{-8}	1345	1.18	2.44×10^9	—	—	—	—	1.51×10^{-8}	$.05 \times 10^{-8}$	negl.	$.044 \times 10^{-4}$
4.5	1	30	3.401	—	1353	—	—	—	—	—	—	—	—	8	—
(②-1) ^{2.5}															
0	0	0	0	0	0	1.35	0	1.825×10^{-18}	0	0	0	0	0	0	1.37×10^{-4}
0.5	0	2.63×10^5	—	1.37×10^{-4}	299	1.35	—	—	—	—	—	—	—	299	—
	1	30	3.401	1.56×10^{-8}	299	1.35	1.55×10^9	—	9.64×10^{-12}	5.4×10^{-18}	16×10^{-18}	9.64×10^{-12}	1.56×10^{-8}	negl.	1.37×10^{-4}
1.0	30	2.63×10^5	—	1.37×10^{-4}	598	—	—	—	5.45×10^{-11}	negl.	negl.	5.5×10^{-11}	1.56×10^{-8}	negl.	1.37×10^{-4}
1.5	30	2.63×10^5	—	1.37×10^{-4}	897	—	—	—	—	—	—	—	—	299	—

Since each multiplication of σ_{i-1} by 2 raises the contribution of creep by a factor of approximately 6, with $n = 2.5$ the limiting stress will not occur until $\sigma \approx 13000$ psi. Consequently no further calculations will be made for $n < 3.0$. Core life would be predicted from anisotropic calculations.

No calculations made for $U = 0.8$

- $\Delta L_i = \frac{D \sigma_i}{E_{i-1}} + \frac{.434 C (\sigma_{i-1})^n}{E_{i-1} \exp(Q/RT)} [\ln t]_{t_i}^{t_{i+1}} + B [t]_{t_i}^{t_{i+1}}$
- $K = \frac{C (.434)}{E_{i-1} \exp(Q/RT)} = \frac{29.3 \times .434}{1.78 \times 10^6 \exp(\frac{43600}{1.99 \times 755})} = 1.925 \times 10^{-18}$
- $D \sigma_{i(n)} = E_{i-1}(L) [2.635 \times 1.37 \times 10^{-4} - 1.73 \times 10^{-4}] \frac{8}{1.37 \times 10^{-4}}$

* taken from anisotropic calc and adjusted for 6 month interval instead of year ($t_{i+1} - t_i = 30$)

(H)

The effect of prolonged irradiation on the creep rate in graphite was not found described in the literature in any quantitative way. It is the opinion of those who have worked with irradiated graphite that irradiation should increase the rate (ref: A.C. IOM by J.K. Davidson "Summary of Discussion of Creep of Graphite", Dec 14, 1955). "Creep of Engineering Materials", p 310, says that one can expect non-cubic and strongly anisotropic materials to be seriously affected in their creep behavior by irradiation. Any self-healing of the effects of irradiation is apparently a function of the number of free electrons which can bond without preference to any atom in the lattice. Since AGOT is a relatively poor conductor (down from copper by a factor of 400 to 500), there should be few free electrons. Consequently, graphite ^{creep} could be significantly affected by ~~creep~~ irradiation. It would appear the consensus is for an accelerated creep. Therefore, all calculations in this report, not having taken any credit for greater creep as the core ages, would appear conservative.

CREEP IN EGCR GRAPHITE (TASK 227)

APPENDIX 4

SIMILAR TO

DR'N R.R.N.	CH'D PVLG 6/16/60	APP'D <i>[Signature]</i>	SCALE = 12	SHEET 37 OF 48	ISSUE
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CONCLUSIONS

1. Without tests made specifically for EGCR conditions, a limiting stress accounting for creep cannot be definitely stated. However, creep will occur in significant amounts in EGCR.
2. From the available data, extrapolation of referenced formulas indicates a probable range of limiting tensile stress from 900 to 1300 psi. As far as can be determined, the probability is that limiting stress will lie in the low end of this range.
3. For addition to short-term stress, in demonstrating the overall structural adequacy of the core, a rough number would be 1000 psi, since it is believed that all approaches were conservative. Tension and compression stress limits may be taken the same, although compressive stresses have never been critical and the corresponding creep was not calculated.
4. Only longitudinal fibers were treated (at the core midplane, 755K) to find the limiting stress at the channel surface. Such stresses were found to be critical in previous calculations on the cylindrical anisotropic model. ^{Appendix 3} Other longitudinal fibers will also approach this limit stress as the core ages beyond the time when the channel surface fiber stress levels off. Tangential and radial fibers should saturate at even lower stresses, since, in some investigations, the creep rate (I) has been found higher than creep rate (II). No calculations have, therefore, been made for limits of σ_r and σ_t . No calculations have been made for stresses at top and bottom of core, since, due to decline of flux, it is believed that elastically computed stresses at these points are low enough to demonstrate a 20 year life without recourse to relaxation through creep.
5. Since the shrinkage stresses, which are the largest imposed, are essentially of same distribution as flexural stresses, comparison with currently specified min. flexural stress of 1800 psi, indicates that a 20 year life could be demonstrated for EGCR core, if more definite creep information were available. If the definite information were available, it might be worthwhile to examine other areas near the core midplane to account for creep sensitivity to absolute temp. since this is greater than stress decline axially.

CREEP IN EGCR GRAPHITE (TASK 227)

Appendix 4

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GRAPHITE CREEP INFORMATION

I "High-Temperature Short-Time Creep of Graphite"

by H.E. Martens; L.D. Jaffe; D.D. Button

Jet Propulsion Laboratory (JPL-EP-593)

Starting materials — petroleum coke and coal-tar pitch

Temperature of tests — 3000 to 6300°F

Length of tests — up to 8 hours

Type of stress — tensile

Types of graphite — 3449; 9425; AGR; and H3LM

Graphitizing temp — all above 4100°F

Creep rates — 10^{-7} to 10^{-3} 1/sec at stresses 1600 to 4000 psi.

The creep rate increased continuously with increasing temperature. The creep rate was lower when stress was applied $\parallel$ rather than $\perp$ to the grain.

Poisson ratio — 0.18 $\perp$ and 0.12 $\parallel$

Activation energy — 170 to 240 Kcal/mole

This study showed no third-stage-creep region. Most of these tests were stopped prior to fracture.

Creep rate formula:

$$\dot{\epsilon} = A_{\epsilon} e^{-\frac{\Delta H_{\epsilon}}{RT}}$$

or

$$\frac{1}{t} = A_t e^{-\frac{\Delta H_t}{RT}}$$

$\dot{\epsilon}$ = creep rate

ΔH = activation energy

t = time

R = gas constant

T = absolute temperature (degrees K)

A = constant

The subscripts " ϵ " and " t " are used to identify the two fixed terms in each expression.

EGCR CREEP CALCS

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II "Report on Tensile and Creep Properties of Graphite"

By R. E. Adams ; and H. R. Nelson

Battelle Memorial Inst. (NEPA 1516)

Types of graphite — AGHT (extruded) + C-18 (molded)

Graphitizing temp. — about 3000°C

Length of tests — approximately 15 hours

Temperature of tests — up to 5100°F

Type of stress — tensile

Creep rates — Data indicated that the creep rates of C-18 graphite were about equal in the || and ⊥ direction. Comparisons could not be made on the AGHT because of the great difference in strength. This investigation has not determined the effect of time on failure of graphite subjected to creep. The creep rate increased with increasing temperature, and increasing stress. No third stage creep was observed in these tests.

Activation energy — 110 kcal/mole

Creep rate formula:

$$\text{Creep rate} = A e^{-\frac{Q}{RT}}$$

Q = activation energy

R = gas constant

T = absolute temperature (degrees K)

A = constant — dependent on stress and material

Empirical Equations for Creep rate based on these tests:

For AGHT — Creep rate = $3 \times 10^{-3} \sigma^{3.1} e^{-\left(\frac{180,000}{RT}\right)}$ %/hr.

For C-18 — Creep rate = $8 \times 10^{-6} \sigma^{3.88} e^{-\left(\frac{110,000}{RT}\right)}$ %/hr.

EGCR CREEP CALCS

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III "Investigation of Elastic and Thermal Properties of Carbon-Base Bodies"
By S. Mrozowski; J.F. Andrew; J. Repetski; H.L. Strauss; D.C. Wobschall
University of Buffalo (WADC TR 58-360)

Type of Graphite — National Carbon baked rods.

Graphitizing temp. — 2900°C

Length of tests — 500 minutes

Temperature of tests — room temperature

Type of stress — bending

Creep rates — This experiment shows that the creep rate is decreased if the rod is worked. The amount of creep is small compared with the deformation of the rod. This group feels it is safe to expect that the creep is dependent mostly on the binder bridges and only slightly on the coke material.

IV "Summary Report on Stress Rupture and Creep Testing of Coated and Uncoated Graphite and Beryllium Carbide at Elevated Temps."
By B. Zweig; and M.D. Burdick
Fairchild Engine and Airplane Corp. (NEPA-1511)

Type of Graphite — Grade A (extruded) parallel

Temperature of tests — 1800°F

Length of test — 51 hours

Type of stress — tensile — 1000 psi

Creep rate — 0.2×10^{-4} %/hr.

Type of Graphite — Grade B (extruded) perpendicular

Temperature of tests — 1800°F

Length of test — 93 hours

Type of stress — tensile — 1080 psi

Creep rate — 1.4×10^{-4} %/hour

EGCR CREEP CALCS

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V "High-Temperature Mechanical Properties of Graphite. I. Creep in Compression" by P. Wagner and A.R. Driesner
Los Alamos Scientific Lab (Journal of Applied Physics - Feb., 1959)

Type of Graphite — H4LM and 3 grades made at Los Alamos (all molded)
Temperature of tests — 2000° to 2500°C

Type of Stress — Compression

Activation energy — 50 kcal/mole

Creep rate — $\dot{\epsilon} = -K (\sigma/\sigma_B)^n e^{-\left(\frac{E}{RT}\right)}$

where; $\dot{\epsilon}$ = steady-state (second stage) creep rate

"K" and "n" = empirical constants

σ = stress required to observe the creep

σ_B = stress required to produce failure

E = activation energy

R = gas constant

T = absolute temperature (degrees K)

Working equation for all type B data: (Type B behavior is analogous to the behavior of graphite in tension. In tension there is little or no area reduction in the test section during the steady-state (second stage) creep and failure occurs without a third stage.)

$$\dot{\epsilon} = -1.75(\sigma/\sigma_B)^{3.8} e^{-\left(\frac{50,000}{RT}\right)}$$

In general it may be stated that either an increase in stress or an increase in temperature produced an increase in the creep rate. Dorn* has shown that the activation energy is independent of stress over the temperature range 500°K to the melting point. In the temperature range 2273 to 2758°K, this was also found to be true.

* J. E. Dorn, Minerals Research Laboratory, University of California, 3rd Tech. Report (August 1, 1957)

EGCR CREEP CALCS

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VL "High-Temperature Mechanical Properties of Graphite: II. Creep in Tension" by R. Wagner; A.R. Driesner; and L.A. Hasting
Los Alamos Scientific Lab (Journal of Applied Physics - Feb, 1959)

Type of Graphite — H4LM (molded); ATJ (molded); CS-312 (extruded);
and 4 molded grades containing uranium made
at Los Alamos.

Temperature of tests — 2000 to 3000°C

Type of stress — tensile

Activation energy — 69 kcal/mole

Creep rate — 10^{-7} to 10^{-4} cm/cm-sec

$$\dot{\epsilon} = F(u) [k(\sigma/\sigma_0)]^n e^{-(E/RT)}$$

Where: $\dot{\epsilon}$ = steady-state (second stage) creep rate

$F(u)$ = function of the uranium concentration

"k" and "n" = empirical constants

σ = stress required to observe the creep

σ_0 = stress required to produce failure

E = activation energy

R = gas constant

T = absolute temperature (degrees K)

$F(u) = a + bu + cu^2$ — a, b, + c are constants

Inserting the experimental constants, the correlation for steady-State tensile creep becomes:

$$\dot{\epsilon} = (4 + 80u - 125u^2) (\sigma/\sigma_0)^{3.8} e^{-(69000/RT)}$$

It was noted by the authors with interest that the dependence of the creep rate on the stress is the same in both compression and tension. The constancy of the stress dependence in graphite for the two processes indicates that an interchange of steady-state creep data in tension and in compression may be possible within the limits of the experiments described here.

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VII "Some Mechanical Properties of Graphite at Elevated Temperatures"

by C. Malmstrom; R. Keen; and L. Green Jr.

North American Aviation, Inc. (Journal of Applied Physics - May 1951)

Type of Graphite — ECA (now designated as AUF) — extruded

Graphitizing temp. — 3000°C

Temperature of tests — 2100 to 2900°C

Applied Stress — 500 to 5500 psi

Type of stress — tensile

Activation energy — 226,000 cal/mole

Creep rate — With reference to Figure 14 of this article it is noted that for the temperature range 2100 to 2900°C the creep rate increases with increasing temperature and increasing stress. The authors suggest that their data may be interpreted as an indication that the creep rate may be governed by two different mechanisms, one predominant at high temperatures, the other prevailing at low temperatures. Creep rates ranged from 10^{-8} ^{11/11-sec} with 3000psi stress to 10^{-6} ^{11/11-sec} with 7000psi at 2100°C.

VIII "Plasticity of Graphite"

by H. W. Davidson; and H. H. W. Losty

The General Electric Co., Ltd. (Nature - April 12, 1958)

Materials of test — pitch coke, petroleum coke, lamp black, cellulose and natural graphite. (all extruded)

Temperature of tests — 1,300 to 2000°C

Type of stress — Bending

Creep deformation — $D_t = A + k \log_{10} t + Bt$ (1)

Where;

D_t = Strain at time "t"

t = time in minutes

A, k and B = constants for each experiment

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"Plasticity of Graphite" (Continued)

Creep recovery — $D_e^2 = A^2 + K \log t$ (2)

Where; D_e^2 = creep recovery at time "t"

t = time in minutes

A² and K² = constants

The coefficients K and B in equations (1) and (2) above are linearly dependent on the applied stress at constant temperature and are related to the absolute temperature as follows:

$$K = K(\text{stress}) \exp\left(-\frac{\Delta E}{RT}\right) \quad (3)$$

and $B = K^2(\text{stress}) \exp\left(-\frac{\Delta E^2}{RT}\right) \quad (4)$

Where; K and K² = constants

ΔE and ΔE^2 = Activation energies

R = gas constant

T = Absolute temperature (degrees K)

Evidence shows that $K = \frac{C}{m}$ in equation 3 above

Where m = elastic modulus at room temperature appropriate to the stress system applied.

C = a constant for all the materials studied

(C = 13 for springs and 28 for cantilever specimens)

The constant $\Delta E = 21 \text{ kcal/mole}$ (for petroleum coke + cellulose Carbon)

The information given above is also found in "Mechanical Properties of Non-Metallic Brittle Materials" Edited by W. H. Walton Chapter 12 entitled "Elastic and Plastic Properties of Carbon and Graphite" by H. W. Davidson and H. H. W. Losty — General Electric Company Ltd.

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IX "The Industrial Graphite Engineering Handbook"
Copyright 1959 by Union Carbide Corporation
Section 5A - Mechanical Properties
Article 5A.04.01 - Creep

The steady state creep rate of fabricated carbon bodies depends not only on the stress applied and the temperature of the body, but also on the previous thermal history of the material involved, and the base form of carbon from which it is made. Graphite heat-treated at 3000°C does not flow appreciably below 2300°C . At this latter temperature, the creep rate is about 0.25 per cent per hour when stressed at 85 per cent of its room-temperature tensile strength. The activation energy for the creep process has been calculated from the slopes of the curves in Figure 5A.04.02 of this article. Below 2500°C the activation energy is 43.6 kcal/mole, and above 2500°C , it is 226 kcal/mole.

The time required for graphite to reach second stage, or linear creep, is much shorter at temperatures above 2500°C than below, indicating, along with the change in activation energy at this temperature, that a different process comes into play. Below 2500°C , the time for primary creep is of the order of hours, and above this temperature, it is on the order of minutes.

X "An Improved Method For Determining Activation Energies of Relaxation Processes"

by G.J. Dienes; W.E. Parkins; R. Stello
North American Aviation, Inc. (NAA-SR-60)

The activation energy values calculated in this report were averaged, and the maximum deviation from the average was found to be about 10 per cent. The final results are given below:

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For AGOT-KC Graphite of 22.7 MWD/CT Exposure

Temperature Range

Average Activation Energy

140-180°C (low state)	29.2 Kcal/mole
1100-1200°C (intermediate state)	58.2 Kcal/mole
1400-1500°C (high state)	100.5 Kcal/mole

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DR'N L D H	CH'D 906 6/16/60	APP'D <i>[Signature]</i>	SCALE = 12	SHEET 46 OF 48	ISSUE
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SIMILAR TO REF. TASK 246

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APPENDIX 5

MODIFIED CORE ARRANGEMENT, CONTROL
RODS IN CENTERS OF COLUMNS

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APPENDIX 5 : MODIFIED CORE ARRANGEMENT - CONTROL RODS IN
CENTER OF COLUMNS

SUMMARY:

The present arrangement of core columns as shown on AC dwg no. 5927-EGCR-MS-270 is retained.

The modified core arrangement, with control rods in the centers of columns, is rejected for the following reasons:

1. Since starting this evaluation, ORNL have indicated that cooling of the control rod is not a problem; that natural convection and radiation are sufficient to keep control rod temperature within acceptable limits.
2. The current core reference design provides that columns be restrained from bowing in excess of 1" maximum.
3. There are many design, analysis, and manufacturing changes required to effect the change to the center-of-column control rods and the reasons for making such a change are not strong enough to justify the change.

EVALUATION OF NEW ARRANGEMENT OF
CORE COLUMNS FOR EGCR

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APPENDIX No. 5

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NEW CORE ARRANGEMENT

It has been proposed to rearrange the columns in the EGCR core so as to have control rod channels passing through the centers of columns. The purpose of this arrangement is to have a control rod channel which is not open to the voids between columns.

POINT 1 - In order to assure that the control rod (C/R) channels are not open to the void spaces, a seal must be provided between the bottom plate and the control rod channel in the graphite column.

POINT 2 - In order to place C/R's in the centers of columns, it will be necessary to use some 8x16 columns to fill spaces between 16x16 columns (Fuel channel pitch is 8", Control rod channel pitch is 24", and basic brick dimension ^{must be} 8x8, 8x16, or 16x16)

DISCUSSION

In examining the above stated proposition, there are several approaches to sizing and arranging the graphite columns. Obviously, the first move is to place each control rod channel in the center of a 16" square column. The next step can be either of the following:

A) Place 8x16" columns between ~~the~~ 16" square columns so that the 16" faces abutt. This leaves 8" square spaces to be filled in with 8" square columns.

EVALUATION OF NEW ARRANGEMENT OF
CORE COLUMNS FOR EGCR

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APPENDIX No. 5

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B) Place 8" X 16" columns between the 16" square columns so that all space may be filled in with one size block.

From the standpoint of minimizing number of dies required and minimizing number of pieces to be made and handled, alternative B is preferred.

The third step is to fill in the remaining space in the core, taking care to use shapes which result in minimum number of pieces and minimum machining on any one piece. The result is that most of the remaining columns can be of 16" X 16" cross section and 8 peripheral bricks formerly cut from 16" X 16" stock can be cut from the 8" X 16" stock. ~~plus~~

shown on AC sketch NO. SK-MS-270D

This arrangement results in the following distribution of block sizes and types (Note that flue gasket channels are not considered here, they still fall on the edges and corners of blocks).

BASIC BLOCK SIZE	TYPE	NO. REQ'D
8 X 16	2 HOLES - 5 1/4"	54
	1 HOLE - 5 1/4"	8
	NO HOLES	8
	<u>TOTAL</u>	70 ←
16 X 16	4 HOLES - 5 1/4"; 1 HOLE - 4"	21
	2 HOLES 5 1/4"; 1 HOLE 4"	4
	2 HOLES 5 1/4"; 1 □ 10 1/4" D.	8
	3 HOLES 5 1/4"; 1 □ 10 1/4" D.	4
	NO HOLES; 1 □ 10 1/4" D.	4
	NO HOLES	24
	<u>TOTAL</u>	65 ←

EVALUATION OF NEW ARRANGEMENT OF
CORE COLUMNS FOR EGCR

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APPENDIX NO. 8

SIMILAR TO

DR'N *JM* CH'D APP'D *N* SCALE X = 12 SHEET 2 OF 5 ISSUE

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In addition, there are 16 additional blocks required for special shapes in the periphery of the core.

Total No. OF COLUMNS REQ'D = 151 ←

ADVANTAGES

1. Control rod cooling passage is continuous; hence control rod cooling is more reliable.

DISADVANTAGES

- A. SEALING - Present plan for sealing between bottom plate and graphite calls for sealing each fuel channel separately. If C/R channels must also be sealed, the amount of column end face cut away to accommodate seals becomes excessive.
- B. SEISMIC KEYS - Present plan for restraining the bottoms of the core columns calls for square seismic keys at the center of the face of each column. If C/R channels must be sealed, this will interfere with seismic keys. The alternative would be to devise another keying scheme but those considered to date require that additional material be removed from the column end face to accommodate those seismic keys.

EVALUATION OF NEW ARRANGEMENT OF
CORE COLUMNS FOR EGCR

TASK NO. 238

11/25/59

APPENDIX No. 5

SIMILAR TO

DR'N <i>JM</i>	CH'D	APP'D <i>M</i>	SCALE $\times = 12$	SHEET 3 OF 3	ISSUE
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A

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A B C

C. RESTRAINT LATTICE - The tops of the core columns are presently restrained by a lattice embedded in ~~the~~ each graphite column. The lattice members pass through the centers of the column end faces and maximum restraint is provided with a minimum of metal. If the new concept described on p. 1-2 is adopted, the restraint scheme will have to be reevaluated and ~~be~~ redesigned so that it will accommodate the 16"X16" and the 8"X16" pieces. On initial inspection, this appears to be a difficult problem.

D. INSTRUMENTATION - With the arrangement described on p. 1-2 ~~is not~~, installation of thermocouples in the graphite & moderator is difficult because control rods are in centers of whole (16"X16") blocks and all other moderator blocks (except for 12 at the periphery) are 8"X16 and thus have little area left in which to introduce thermocouple leads.

E. MANUFACTURE -

1. An additional die is required to extrude the 8"X16 shape (this would appear to be more economical than cutting 16"X16" in half)
2. It is not known if an 8"X16" X 20 ft piece can be graphitized. The ratio of width to height of the section may have a bearing on the success of graphitizing operations.
3. Additional set up operations and additional tools and jigs will probably be required to machine the two block types.

EVALUATION OF NEW ARRANGEMENT OF
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4. Handling of the 8"x16" block may be different (and possibly hazardous to the piece itself) because of its low I/C in one direction.
5. Accuracy of machining may be more critical in the 8"x16" block because of the reduced overall section.
6. Total number of blocks required is 151 compared to 120 for the present EGCR core arrangement.

F. GENERAL - A considerable amount of time and effort have been expended on the concept which provides for 16x16 blocks throughout. If a change is made to the concept described on p. 1-2, a considerable amount of re-engineering and redesign will be required on the core structure. This is not only a matter of ^{A.C.}man hours, but of calendar hours as well. New studies would probably have to be made by the carbon companies to determine manufacturing and machining procedures and new cost studies would also be required. This type of effort is not under our direct control and therefore we would not be in a position to expedite them.

EVALUATION OF NEW ARRANGEMENT OF
CORE COLUMNS FOR EGCR

TASK NO. 238

11/25/59
APPENDIX No. 6

SIMILAR TO

DR'N *gm*

CH'D

APP'D *M*

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ATOMIC ENERGY DIVISION
NUCLEAR POWER DEPARTMENT
WASHINGTON, D. C.

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APPENDIX 6

FAST NEUTRON IRRADIATION DISTRIBUTION IN
CORE AND REFLECTOR GRAPHITE

APPENDIX 6

FAST NEUTRON IRRADIATION DISTRIBUTION
IN CORE AND REFLECTOR GRAPHITE

Data are given below on the fast neutron irradiation of reactor graphite. This is presented here for use in determining the bowing of the graphite columns of the reactor core and reflector. Irradiation data are given in Table 1 in terms of Mw days per adjacent ton of fuel per second of reactor operation, under the conditions of reactor full-power operation (84.3 Mw). The two types of numbers presented are:

1. Average irradiation over each face of the graphite columns per cm of height for the particular position where the axial neutron flux is a maximum value.
2. Average irradiation over the cross-sectional area of each graphite column at the position where the axial neutron flux is a maximum.

It is assumed that the ratio of maximum-to-average flux in the axial direction is 1:5.

Method of Calculation

The data tabulation below is the result of calculations using data from various sources. These are:

1. Two dimensional radial flux distribution obtained from a "PDQ" code calculation done by ORNL. This calculation was done using a detailed mock-up of the core, including each fuel channel and empty experimental tubes. This data should give the correct overall core distribution.
2. One dimensional fuel cell radial flux distribution obtained from a "GNU" code calculation done at ORNL. This is a many energy group calculation in cylindrical geometry and should give the correct fuel cell irradiation distribution.
3. Memorandum from Mr. E. Wagner to Mr. J. K. Davidson, dated October 27, 1959 (EGCR File No. 107) in which the radiation damage distribution in a fuel cell was calculated.

Calculations are done as follows:

- (a) The assumption is made that the variation of the total flux above 0.18 Mev through the reactor is the same as the variation of the graphite damage.
- (b) Using data from sources 2 and 3, the absolute value of the

graphite irradiation at the inside surface of the fuel assembly sleeve is obtained for a core average flux distribution. This value is used to convert all relative irradiation values to absolute values. The ratio of graphite irradiation at the fuel cell boundary to the sleeve inside surface, and the ratio of the average column graphite irradiation in the fuel cell to the value at the sleeve inside surface are obtained.

- (c) From source 1, a typical symmetrical fuel cell was picked and the ratio of the fast flux at the fuel cell boundary to the fast flux at the inside surface of the fuel assembly sleeve was obtained. It was found that this ratio was almost the same as that obtained from sources 2 and 3, so it was assumed that source 1 not only gave the correct overall damage distribution through the core, but also within each fuel cell.
- (d) From source 1, the average flux values at the sleeve inside surface were obtained for each fuel channel and from these the ratio of the radial maximum-to-average core fast flux was determined. Using the value of the ratio of the average graphite irradiation in a fuel cell to value at the sleeve inside surface that was obtained in (b) above, the average graphite irradiation in each graphite column in the core was determined.
- (e) Using source 1, the average values of the fast flux across each face of every column were determined. For the graphite columns in the reflector, the average graphite irradiation values over the cross-sectional area for each column were determined by assuming a linear variation of irradiation between the faces, and calculating an arithmetical average of the irradiation values on the faces.

Figure 1
Tabulation of Irradiation in Graphite Columns

Column	Average ^f irradiation over column face given in Mwd/A.T.-sec for core operation at 84.3 Mw				Average irradiation over cross-sectional area of column Mwd/A.T.-sec at core operation of 84.3 Mw
	Face No. 1	Face No. 2	Face No. 3	Face No. 4	
270-67	1.437×10^{-4}	1.319×10^{-4}	1.319×10^{-4}	1.437×10^{-4}	1.412×10^{-4}
270-68	1.489×10^{-4}	1.464×10^{-4}	1.423×10^{-4}	1.319×10^{-4}	1.534×10^{-4}
270-69	1.393×10^{-4}	1.254×10^{-4}	1.308×10^{-4}	1.464×10^{-4}	1.433×10^{-4}
270-70	0.9910×10^{-4}	0.5074×10^{-4}	0.9078×10^{-4}	1.254×10^{-4}	1.053×10^{-4}
270-71	0.1615×10^{-4}	0.02312×10^{-4}	0.1466×10^{-4}	0.5074×10^{-4}	$0.2096 \times 10^{-4} *$
270-72	0.006681×10^{-4}	0.0003493×10^{-4}	0.006001×10^{-4}	0.02312×10^{-4}	$0.009037 \times 10^{-4} *$
270-80	1.423×10^{-4}	1.326×10^{-4}	1.326×10^{-4}	1.423×10^{-4}	1.469×10^{-4}
270-81	1.308×10^{-4}	1.017×10^{-4}	1.035×10^{-4}	1.326×10^{-4}	1.240×10^{-4}
270-82	0.9078×10^{-4}	0.4143×10^{-4}	0.6569×10^{-4}	1.017×10^{-4}	0.8633×10^{-4}
270-83	0.1466×10^{-4}	0.01848×10^{-4}	0.1004×10^{-4}	0.4143×10^{-4}	$0.1700 \times 10^{-4} *$
270-84	0.006001×10^{-4}	0.000851×10^{-4}	0.005061×10^{-4}	0.01848×10^{-4}	$0.007598 \times 10^{-4} *$
270-93	1.035×10^{-4}	0.5721×10^{-4}	0.5721×10^{-4}	1.035×10^{-4}	0.7753×10^{-4}
270-94	0.6569×10^{-4}	0.1780×10^{-4}	0.1035×10^{-4}	0.5721×10^{-4}	$0.3776 \times 10^{-4} *$
270-95	0.1004×10^{-4}	0.007999×10^{-4}	0.01521×10^{-4}	0.1780×10^{-4}	$0.07541 \times 10^{-4} *$
270-96	0.005061×10^{-4}	0^+	0^+	0.007999×10^{-4}	$0.006530 \times 10^{-4} *$
270-105	0.1035×10^{-4}	0.01749×10^{-4}	0.01749×10^{-4}	0.1035×10^{-4}	$0.06050 \times 10^{-4} *$
270-106	0.01521×10^{-4}	0^+	0^+	0.01749×10^{-4}	$0.01635 \times 10^{-4} *$

- * These averages were calculated by assuming a linear variation of irradiation between faces and taking the value $(\sum_1 x_i) 1/4$ where X_i is the average irradiation on Face No. 1.
- + These values were assumed to be zero since they are on the outside edge of the reflector. If these data lead to excessive bowing, a more accurate determination of these values should be made.

RELATIVE IRRADIATION DAMAGE VALUES OF GRAPHITE
VS. DISTANCE FROM CENTER OF FUEL CELL

$$\text{Damage} = \int_0^{\infty} \Sigma_s(E) \phi(E) F(E) J(E) dE$$

$$J(E) = 1.0$$

$F(E)$ = energy lost by neutron

Figure 2

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Distance From Center
of Fuel Cell (inches)

Graphite
sleeve

Edge of
Fuel Cell

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FIGURE 3

TABULATION OF RELATIVE FAST FLUX VALUES IN A RADIAL PLANE

Radial Max. Flux / Ave. Flux = 1.318 over Core

NOTE: All data is normalized so that the average flux over the inside surface of all fuel assembly sleeves is equal to 1.0.

Column	Average Fast Flux Values on Inside Surface of Fuel Assembly Sleeve For Fuel Channel No.:				Average Fast Flux Values on Graphite Column Face* No.:				Average Fast Flux over Column Cross Section
	#126	#127	#193	E-4-5	1	2	3	4	
270-67	1.268	1.235	1.235	.7069	.8708	.7994	.7994	.8708	.8556
270-68	#128	#129	#144	#145					
	1.290	1.317	1.245	1.295	.9026	.8870	.8623	.7999	.9298
270-69	#130	#131	#146	#147					
	1.273	1.164	1.243	1.128	.8443	.7603	.7926	.8870	.8683
270-70	#132	#133	#148	#149					
	1.007	.7950	.9691	.7622	.6006	.3075	.5502	.7603	.6383
270-71									
					.09786	.01401	.08882	.3075	.1270
270-72					.004049	.0002117	.003637	.01401	.005477
270-80	#161	#162	#177	#178					
	1.264	1.247	1.247	1.170	.8623	.8037	.8037	.8623	.8903
270-81	#163	#164	#179	#180					
	1.167	1.039	1.051	.9027	.7926	.6163	.6270	.8037	.7515
270-82	#165	#166	#181	#182					
	.8813	.6867	.7493	.5789	.5502	.2511	.3981	.6163	.5232
270-83					.08882	.01120	.06082	.2511	.1030
270-84					.003637	.000516	.003067	.0112	.009605
270-93	#195	#196	#208	E-4-9					
	.8861	.6901	.6901	.1670	.6270	.3467	.3467	.6270	.4699
270-94	#197	#198	E-4-9						
	.5543	.4351	.1458		.3981	.1079	.06270	.3467	.2289
270-95					.06082	.009848	.009221	.1079	.04570
270-96					.003067	~0	~0	.009848	.001979
270-105					.06270	.01060	.01060	.0627	.03665
270-106					.009221			.01060	.004955

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FAST NEUTRON IRRADIATION DISTRIBUTION IN CORE AND REFLECTOR GRAPHITE

TASK NO. 227
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SIMILAR TO

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* Faces are numbered as shown in sketch :

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IN CORE AND REFLECTOR GRAPHITE

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CALCULATIONS

b.] 1] From Source (3) above the graphite irradiation at the fuel assembly sleeve inside surface for the conditions:

- a. 84.3 megawatts fore power operation
- b. average core flux

is 1.33×10^{-4} MWD/AT-second

This is based upon a conversion factor of

$$10^{20} \text{ nvt} = 2300 \text{ MWD/AT}$$

for the total neutron flux above 1.0 MEV in energy. This conversion factor is taken from a letter to W.F. Banks from D.R. DeHales, dated October 30, 59.

A recent correction by ORNL changes this factor to

$$10^{20} \text{ nvt} = 1900 \text{ MWD/AT}$$

The above irradiation figure should then be:

$$1.10 \times 10^{-4} \text{ MWD/AT-second}$$

Assuming an axial max. to average fast flux distribution of 1.5, then the average radial graphite irradiation at the fuel assembly sleeve inside surface is 1.65×10^{-4} MWD/AT-sec. at the ~~peak~~ position of peak axial flux.

2] The ratio of graphite irradiation at the fuel cell boundary to the sleeve inside surface = $\frac{.70}{1.0} = .70$
(from Source (3))

3] To obtain an average the ratio of the average graphite irradiation in a fuel cell to the value at the sleeve inside surface the source (3) above is used. This source gives an analytical fit to a plot of the irradiated graphite damage function through a fuel cell. The expression is

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.6609 + exp.[-.7875r] where r is measured in inches from the center of a fuel lattice cell, and the curve is normalized to 1.0 at the inside surface of the fuel assembly sleeve.

To find the average irradiation in the graphite (not including the sleeve) one integrates

$$\frac{\int_{r_1}^{r_2} 2\pi r \phi(r) dr}{\int_{r_1}^{r_2} 2\pi r dr}$$

using the appropriate boundaries.

$$\begin{aligned} \int_{r_1}^{r_2} 2\pi r \phi(r) dr &= \int_{r_1}^{r_2} 2\pi r [a + \text{Exp.}[-br]] dr \\ &= 2\pi \int_{r_1}^{r_2} ar + r \text{Exp.}[-br] dr = 2\pi \left[\frac{ar^2}{2} \right]_{r_1}^{r_2} + \frac{e^{-br}}{b^2} (-br-1) \Big|_{r_1}^{r_2} \\ &= 2\pi \left[\frac{a(r_2^2 - r_1^2)}{2} + \frac{e^{-br_2}(-br_2-1)}{b^2} - \frac{e^{-br_1}(-br_1-1)}{b^2} \right] \\ &= 2 \times 3.1416 \left[\frac{.6609}{2} (4.514^2 - 2.625^2) + \frac{e^{-.7875 \times 4.514}}{.7875^2} (-.7875 \times 4.514 - 1) \right. \\ &\quad \left. - \frac{e^{-.7875 \times 2.625}}{.7875^2} (-.7875 \times 2.625 - 1) \right] \\ &= 30.613 \end{aligned}$$

$$\begin{aligned} \int_{r_1}^{r_2} 2\pi r dr &= \pi(r_2^2 - r_1^2) = 3.1416(4.514^2 - 2.625^2) \\ &= 42.366 \end{aligned}$$

$$\text{Average irradiation} = \frac{30.613}{42.366} = .72258$$

= ratio of average graphite irradiation in a fuel cell to the value at the sleeve inside surface.

The actual plot of graphite Damage thru a fuel cell is shown

on Figure 2.

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c.) Fuel channel #129 was chosen to be used in calculating (using source ①) the ratio of fast flux at the fuel cell boundary to that at the fuel assembly sleeve inside surface. Source ① showed that the fast flux ~~around~~ ⁱⁿ this fuel cell was very symmetrical. The two (average) values were obtained by a simple numerical integration. The result showed that the ratio is ~~0.686~~ 0.686 this is very close to the value obtained from ~~the~~ source ③

d.) From ~~source ①~~, simple
Simple numerical integration (trapezoidal rule) was used to obtain the relative - average fast flux values at the sleeve inside surface for each fuel channel. These are tabulated in Figure 3. Assuming that these values are typical of the flux ~~in~~ throughout the core, a radial maximum to average ~~fast~~ ratio was obtained of the core fast flux. Thus if $\bar{\Phi}_i$ = average fast flux at inside surface of fuel ~~at~~ assembly sleeve for fuel channel (i) then the core average = $\frac{\sum_i \bar{\Phi}_i}{\sum_i (i)}$

Using the maximum $\bar{\Phi}_i$ value to represent the core maximum, the max/ave ratio = 1.318
This is almost the same as the radial max/ave. core power ratio. (of 1.285).

Using the value of ^{0.7226} ~~0.7~~ for the ratio of the average graphite irradiation to the sleeve inside surface value irradiation, the average irradiation for ~~the~~ the cross sectional area of each column was found by a simple numerical average:

$$\bar{\Phi}_c = \frac{\sum_i (\bar{\Phi}_s)_i}{4} \times 0.7226$$

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where $\bar{\Phi}_c$ = average irradiation of column
 $(\bar{\Phi}_s)_i$ = average irradiation of inside surface of
 fuel assembly sleeve for column (i)

These values are tabulated in Figure 3.

e.]

Using, again, the simple numerical integration (trapezoidal rule) the average fast flux values across each face of a column were determined. These are tabulated in Figure 3.

Note: To obtain ~~graphite~~^{an} average graphite irradiation values over the cross sectional area of ~~the~~ each column in the reflector (where no fuel channels are located), a ~~the~~ linear variation of irradiation between the faces of each column is assumed, and an arithmetical average of the average irradiation ~~on~~ on each face was found for each block. These values are tabulated on Figure 3.

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FAST NEUTRON IRRADIATION DISTRIBUTION
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APPENDIX 7

BOWING AND THE STRESSES DUE TO RESTRAINT OF
BOWING IN THE EGCR GRAPHITE COLUMNS

PREFACE

The purpose of this appendix is to examine the bowing problem in the EGCR columns caused by the overall fast neutron flux exposure gradient across each column.

Flux exposure values are those presented in Appendix 6. Shrinkage rates are those derived by extrapolation of actual data from Hanford for needle core graphite. The amount of possible bowing is calculated using the maximum differential strains to be expected from the given flux exposure and shrinkage rate.

Restrained bowing stresses are computed using the stress-strain relationships for graphite as postulated in appendices 1 and 2. Total stresses are computed by adding the bowing stress to the internal stress calculated in Appendix 3.

Individual column lifetimes are predicted based on an 1800 psi rupture stress (flexural) for the EGCR graphite. Although plant utilization factors of 0.8 and 1.0 are evaluated, the final lifetime predictions are based upon the 0.8 load factor.

APPENDIX 7

BOWING AND THE STRESSES DUE TO RESTRAINT
OF BOWING IN THE EGCR GRAPHITE COLUMNS

1. Herewith are calculations for the amount of bowing to be expected in any EGCR column in 20 years, plus the amount of stress induced in any column as part of its bowing is restrained by bands encircling the core midplane. Bowing is calculated in the directions of the two core quadrant lines for each column.

2. The calculations are based on (a) KC graphite with shrinkage rates of 0.02% per 1000 Mwd/AT and 0.01% per 1000 Mwd/AT parallel and perpendicular to the extrusion, respectively, (b) an approximately sinusoidal axial variation of flux, (c) latest exposure values over each column cross section as listed in Appendix 6.

The assumption is made that the linear component of the exposure gradient (from face to face) in any direction is the major factor in determining the bowing in that direction.

3. A detailed summary of potential bowing (unrestrained) is on pp. 14 and 15 of the calculations. The largest bows at core midplane are for 20 years:

X - direction		
	<u>U = 1.0</u>	<u>U = 0.8</u>
(a) Flux sine curve over full core length	Col 70 = 3.18 in.	2.54 in.
(b) Flux sine curve over core length minus 4 ft	Col 70 = 2.82 in.	2.25 in.
(c) (b) with linear component of exposure gradient modified to account for internal effects	Col 70 = --	1.80 in.
Y - direction		
	<u>U = 1.0</u>	<u>U = 0.8</u>
(a) Flux sine curve over full core length	Col 102 = 2.18 in.	2.54 in.
(b) Flux sine curve over core length minus 4 ft	Col 102 = 2.82 in.	2.25 in.
(c) (b) with linear component of exposure gradient modified to account for internal effects.	Col 70 = --	1.80 in.

4. The maximum amount by which potential bows are restrained (i.e., potential bow minus available gaps) are for 20 years (p. 22 of calculations) and $U = 0.8$:

	<u>X Direction</u>	<u>Y Direction</u>
(a) Case (b) above	Col 70 = 2.11"	Col 102 = 1.67"
(b) Case (c) above	Col 70 = 1.66"	Col 102 = 2.12"

5. The maximum tensile point-stress at a corner (exclusive of internally generated stresses) occurring in any column, assuming no creep and that graphite is capable of maintaining continuity over the range of required strain, is for 20 years:

(a) Case (b) first above	6140 psi	Col 94
(b) Case (c) first above	4515 psi	Col 94

20-year tensile points-stresses for all columns are on p. 22.

6. The total maximum tensile point-stress (including internal stresses) occurs in Column 93 at the fuel-channel surface. (A summary of total maximum tensile stress, obtained approximately, is on pp. 25-26 of calculations.) This maximum is 5217 psi after 20 years' operation (plant load factor of 0.8). This is lower than the stress shown above since a compressive stress component is present at the corner fibers due to the internal stress pattern.

A comparison of the maximum total tensile stress in the column subject to greatest accumulated internal stress (Col. 68) and in the column subject to greatest accumulated bowing stress (Col. 94) shows that both columns reach the specified maximum allowable flexural stress (1800 psi) in about ten years. This indicates that, from the standpoint of stress, core life is as much a function of the inherent stress-producing qualities of non-uniformly irradiated graphite as it is of the particular core construction now employed in the EGCR.

BOWING CALCULATIONS

DISCUSSION

- (I) DUE TO NON-UNIFORM EXPOSURE OVER THE COLUMN CROSS-SECTION (AT ANY HEIGHT) LONGITUDINAL FIBERS SHRINK VARYING AMOUNTS. THE DIFFERENTIAL SHRINKAGE, IF IT IS FREE TO OCCUR WITH NO RESTRAINT OTHER THAN INTERNAL, CAUSES EACH COLUMN IN THE CORE TO BOW AS ADJACENT CROSS-SECTIONS ASSUME RELATIONS TO ACCOMMODATE THE VARYING LENGTHS OF FIBERS. THIS BOWING IS COMPUTED HERE, FOR ALL CORE COLUMNS, ON THE ASSUMPTION THAT, ONCE THE RELATIVE STRAINS IN THE FIBERS OF FACES ON OPPOSITE SIDES OF COLUMNS HAVE BEEN DETERMINED, THE BOW CAN BE CLOSELY APPROXIMATED BY CONSIDERING ONLY THE LINEAR COMPONENT (FROM SIDE-TO-SIDE OF COLUMN) OF THE OVERALL SHRINKAGE GRADIENT. THE ACTUAL GRADIENT CONTAINS A NON-LINEAR COMPONENT, BUT, SINCE THE FINAL RADIUS OF CURVATURE (AND BOW) MUST CONFORM TO THE ACTUAL CHANGES IN LENGTH ON THE TWO FACES REGARDLESS OF WHAT LENGTH CHANGES MAY HAVE OCCURRED INTERNALLY, THE BOW IS HANDLED ON THE BASIS OF A LINEAR ^{OVERALL} GRADIENT. IN VIEW OF THE APPROXIMATE NATURE OF EXPOSURE DATA AND SHRINKAGE RATES WITH EXPOSURE, THIS METHOD GIVES AS ^{AN} A GOOD APPROXIMATION AS PRACTICABLE IN THE TIME AVAILABLE. TO ACCORD WITH THE PROPOSED CHANGE TO KC GRAPHITE, SHRINKAGE RATE (II) HAS BEEN TAKEN AS .02%/1000 MW/AT. BY TAKING A LINEAR GRADIENT THE STRAIN CAN BE EQUALIZED ON OPPOSITE FACES AND THE NEUTRAL AXIS OF THE BOWED COLUMN WILL BE THE CENTROIDAL AXIS, MAKING POSSIBLE USE OF STANDARD APPROACHES FROM STRENGTH OF MATERIALS. SINCE THE BOWING IS PREDOMINANTLY A FUNCTION OF LONGITUDINAL SHRINKAGES, THE MATERIAL HAS BEEN TREATED AS ROUGHLY ISOTROPIC AND VALUES FOR ELASTIC CONSTANTS IN PARALLEL DIRECTION HAVE BEEN USED. THE EFFECT OF AXIAL FLUX GRADIENT IN THE CORE HAS ALSO BEEN INCLUDED.

- (II) IT IS RECOGNIZED THAT THE NON-LINEAR COMPONENT OF THE OVERALL GRADIENT WILL HAVE A REDUCING EFFECT ON THE TOTAL BOW (SEE P11-13+20) AND SEVERAL CALCULATIONS HAVE BEEN PERFORMED

EGCR BOWING CALCULATIONS
TASK 227 APPENDIX 7

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SIMILAR TO

DR'N RRN

CH'D PUG 6/21/60

APP'D *gm*

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TO GIVE BOWING VALUES WITH AND WITHOUT THIS REDUCTION:

- (1) FOR EACH COLUMN, BOWS HAVE BEEN COMPUTED IN THE DIRECTIONS OF THE TWO CORE QUADRANT LINES (X & Y) FOR ^{TOTAL} 20 YR. LIFE:

- (a) WITH UTILIZATION FACTOR OF $U=1.0$ AND $U=0.8$
- (b) WITH TWO SHAPES OF AXIAL FLUX DISTRIBUTION
- (c) WITH NO REDUCTION FOR EFFECT OF NON-LINEAR COMPONENT OF OVERALL GRADIENT

- (2) AS IN (1) BUT:

- (a) WITH UTILIZATION FACTOR OF 0.8 ONLY
- (b) WITH ONLY ONE AXIAL FLUX DISTRIBUTION
- (c) WITH A REDUCTION FACTOR (APPROXIMATE) FOR EACH COLUMN APPLIED TO THE LINEAR COMPONENT OF OVERALL GRADIENT

IT IS FELT THAT THE BOW COMPUTED IN (2) WILL REPRESENT THE CLOSEST APPROXIMATION TO THE MAXIMUM ^{UNRESTRAINED} BOWS THAT WOULD OCCUR AT THE END OF 20 YEARS IN EGCR. VALUES IN (1) ARE INTENDED TO SHOW THE EFFECT OF SOME PARAMETERS AND INDICATE RANGE.

- (III) IF THE BOWING IN EACH COLUMN COULD PROCEED UNRESTRAINED, NO STRESSES WOULD DEVELOP. HOWEVER, AT THE CORE MIDPLANE, CIRCUMFERENTIAL RESTRAINTS PREVENT ANY RADIAL GROWTH OF THE CORE OTHER THAN A SMALL AMOUNT DUE TO THERMAL EXPANSION. CONSEQUENTLY, THE ONLY SPACE WHICH IS AVAILABLE FOR ACCOMMODATING BOW IS THAT WHICH EXISTS BECAUSE OF PRE-SET INSTALLATION GAPS BETWEEN COLUMNS, DIFFERENTIAL THERMAL EXPANSION OF COLUMNS AND BOTTOM RATE, AND IRRADIATION-INDUCED TRANSVERSE SHRINKAGE OF COLUMNS. (IN THIS REPORT, ^{SPACE} GAPS DUE TO THERMAL EFFECTS (BETWEEN COLUMNS AND BETWEEN REFLECTOR AND CIRCUMFERENTIAL BANDS) IS COMPUTED BUT NOT USED IN CALCULATING STRESSES DUE TO RESTRAINT OF BOWING; THE REACTOR CAN BE SHUT DOWN WITH COLUMNS IN BOWED CONDITION AND THE "COLD" CASE IS CRITICAL.) THE SMALLEST SUCH SPACES ARE BETWEEN REFLECTOR COLUMNS AND CIRCUMFERENTIAL BANDS. AS ONE MOVES IN TO THE CORE, EACH COLUMN HAS A POTENTIAL SPACE

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INTO WHICH TO BOW THAT GROWS SUCCESSIVELY LARGER, COLUMN BY COLUMN, AS THE NUMBER OF INSTALLATION GAPS OUT TO THE BANDS PLUS SHRINKAGE OF OUTER COLUMNS ^{INCREASES} ~~GROWS~~. THE DIFFERENCE BETWEEN THE POTENTIAL BOWING AND THE AVAILABLE SPACE RESULTS IN RESTRAINED BOWING WHICH PRODUCES STRESS, RESEMBLING FLEXURAL STRESS. FOR EACH COLUMN, THIS REPORT COMPUTES THE SHRINKAGE GAPS FOR 20 YEARS AND ADDS THESE TO THE INSTALLATION GAPS TO GET TOTAL 20 YR GAPS, USING EXPOSURE NUMBERS FOR $U=1.0$ (pp.14-15). SINCE, FOR THOSE COLUMNS WHERE STRESS BECOMES VERY LARGE, THE ^{SHRINKAGE} ~~INSTALLATION~~ GAPS REPRESENT ON A SMALL PART OF THE REQUIRED SPACE, TO SAVE TIME, THE SHRINKAGE GAPS FOR $U=1.0$ ARE USED EVEN WHERE COLUMN BOWING IS COMPUTED ON BASIS OF $U=0.8$.

THE STRESS INDUCED BY RESTRAINED DEFLECTION IS APPROXIMATED BY USING STANDARD DEFLECTION FORMULAS AND TREATING THE MATERIAL AS ISOTROPIC. BECAUSE OF TIME LIMITATIONS, THE 20 YEAR STRESS IS COMPUTED FOR ALL COLUMNS ON THE BASIS OF A UNIFORM $E_{II} = 1.5 \times 10^6$ PSI (p.18) RATHER THAN TO COMPUTE STRESS ACCUMULATION YEAR-BY-YEAR, STARTING WITH THE APPROPRIATE INITIAL TANGENT MODULUS. SINCE ANY TEMPERATURE-INDUCED GAPS BETWEEN COLUMNS ARE RELATIVELY SMALL, THE TANGENT MODULUS APPROACH, IF USED, WOULD HAVE TO START WITH AN INITIAL U_{MOD} FOR $T=900^\circ F$ TO BE CONSERVATIVE, RATHER THAN ROOM TEMPERATURE VALUES. AS A CHECK ON THE ^{20 YEAR} RESULTS OBTAINED FROM USE OF A UNIFORM $E_{II} = 1.5 \times 10^6$, A YEAR BY YEAR COMPUTATION ^(PP 21-24) WAS MADE FOR BOWING STRESS IN THE COLUMN SHOWING WORST POINT-STRESS (TENSILE); THE RESULTS OF THE TWO COMPUTATIONS AGREE VERY CLOSELY, INDICATING THAT A UNIFORM E COULD BE USED IN QUICKLY EXAMINING OTHER COLUMNS.

TO THE BOWING STRESS, IN THE COLUMN SHOWING GREATEST POINT-STRESS, IS ADDED THE STRESSES DUE TO SHRINKAGE IN THE ASSUMED ^{ANISOTROPIC} CYLINDRICAL MODEL OF THE FUEL CHANNEL NEAREST THE MAXIMUM POINT STRESS. SUCH ADDITIONAL STRESSES ARE PRORATED (FOR THE

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FIRST YEAR) FROM RESULTS OF THE ORIGINAL ANISOTROPIC CALCULATIONS ON THE BASIS OF NEW, REDUCED VALUES OF MAXIMUM FLUX IN THE WORST CHANNEL (ORIGINAL CALCS.) AND ON THE RELATION BETWEEN THE APPROPRIATE FUEL CHANNEL ~~AND~~ IN THE WORST COLUMN AND THE WORST FUEL CHANNEL OF THE CORE. THE TOTAL STRESS IN THIS WORST BOWED COLUMN IS FOUND TO APPROACH THE LIMIT STRESS (TENSILE) IN THE SAME TIME AS DOES THE MAXIMUM STRESS COMPUTED FOR THE CYLINDRICAL ANISOTROPIC MODEL HAVING THE WORST FLUX CONDITION. THIS INDICATES THAT BOWING AND INTERNAL STRESSES ARE PROBLEMS OF EQUAL MAGNITUDE, AND THAT THE FACT THAT LONG COLUMNS EXPERIENCE LARGE BOWING DOES NOT LIMIT THE CORE LIFE (FROM THE STANDPOINT OF STRESS) ANYMORE THAN DOES THE GENERATION OF INTERNAL STRESSES DUE TO SHRINKAGE, WHICH IS INHERENT IN GRAPHITE WHEN IRRADIATED AND NOT A FUNCTION OF A PARTICULAR TYPE OF CORE STRUCTURE.

THE BOWING STRESS IS CALCULATED AS THOUGH THERE WERE NO CREEP AND THE GRAPHITE CAN CONTINUE TO STRAIN BEYOND WHAT WOULD ORDINARILY BE THE MAXIMUM TENSILE STRESS. THE SHAPE OF VARIOUS COLUMN CROSS-SECTIONS IS ACCOUNTED FOR IN THE FORMULAS FOR COMPUTING STRESS. (p 19-20)

(pp 25-26)
AN APPROXIMATION^A OF THE TOTAL POINT-STRESSES FOR THE COLUMNS IN AN OCTANT OF THE CORE IS OBTAINED BY ^{LITERALLY} PROPORTIONATING THE 20 YEAR POINT STRESS (DUE TO RESTRAINED BOWING) AND ADDING THE INTERNAL STRESS FOR THE FUEL CHANNEL NEAREST THE MAXIMUM POINT-STRESS IN THE APPROPRIATE COLUMN. THE INTERNAL STRESSES ARE PROPORTIONATED FROM ORIGINAL ANISOTROPIC CALCULATIONS IN THE MANNER ALREADY DESCRIBED. THIS CALCULATION GIVES AN OVERALL PICTURE OF CORE LIFE THAT CAN BE EXPECTED FROM THE PRESENT DESIGN WITHOUT RECOURSE TO CREEP. THIS ESTIMATE OF LIFE IS THEREFORE CONSERVATIVE.

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A		B		C	
DR.N R.R.N		CH.D.P.V. 6/21/60 APP.D. <i>mm</i>		DEF. <i>NPD-W</i>	
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BECAUSE THE COLUMN WITH WORST BOWING-PLUS-INTERNAL STRESS IS ONE WITH A RELATIVELY SMALL GAP TO ACCOMMODATE BOWING, PROPORTION OF BOWING STRESS ON A LINEAR BASIS UP TO THE MAXIMUM (USING $E_{AV} = 0.15 \times 10^6$) WOULD NOT INTRODUCE SERIOUS ERRORS IN THE NUMBER OF YEARS BEFORE DICER LIFE. FOR OTHER COLUMNS, WHERE GAPS ARE LARGER, LINEAR PROPORTIONING FROM 20 YEAR MAXIMUM POINT-STRESSES (SEE P. 18) WILL GIVE CONSERVATIVE ESTIMATE OF GORE LIFE, SINCE, THE GREATER THE GAP AVAILABLE, THE GREATER THE NUMBER OF YEARS IN WHICH NO POINT-STRESS BUILDS UP. IN THIS PERIOD OF TIME TOTAL STRESS IS DUE ONLY TO INTERNAL STRESSES. THEREFORE, LINEAR PROPORTION OF STRESSES SHOULD GIVE A CONSERVATIVE ESTIMATE OF ALL COLUMN LIFE, FOR COLUMNS WITH GAPS GREATER THAN THAT FOR COLUMN WITH WORST BOWING STRESSES. THESE INCLUDE MOST COLUMNS WHERE TOTAL STRESS REACHES HIGH LEVELS IN TWENTY YEARS.

FORMULAS FOR COMPUTING BOWING
BASED ON THE LINEAR COMPONENT OF
SHRINKAGE GRADIENT ACROSS A BRICK

FOR A BEAM OF OVERALL RECTANGULAR CROSS-SECTION AND DIMENSION w IN THE DIRECTION OF BOWING, TWO ORIGINALLY PARALLEL PLANES

NOTE: LINEAR GRADIENT
EQUALIZES STRAINS ON
OPPOSING FACES AND
PUTS N.A. AT CENTROID.

NORMAL TO THE AXIS OF THE BEAM ACQUIRING ANGLE $d\theta$ BETWEEN THEM DUE TO BOWING. FOR SMALL $d\theta$ (I.E. SMALL DEFLECTIONS)

$$\frac{\epsilon dz}{w} = d\theta \quad \text{or} \quad \frac{d\theta}{dz} = \frac{\epsilon}{w}$$

WHERE ϵ IS THE DIFFERENTIAL STRAIN (IN/IN) BETWEEN THE TWO OPPOSITE FACES. FOR SMALL DEFLECTIONS THE ANGLE, θ , AT ANY POINT IS

$$\theta = \frac{dy}{dz}$$

FOR THE DIRECTION OF BOW SHOWN, THE CHANGE OF $\theta(+)$ WITH INCREASING z IS NEGATIVE. THEREFORE

$$\frac{d(\frac{dy}{dz})}{dz} = -\frac{\epsilon}{w}$$

$$\frac{d^2y}{dz^2} = -\frac{\epsilon}{w}$$

ϵ_z CAN BE EXPRESSED AS

$$\frac{(E_D - E_A) N \alpha}{1000 w}$$

WHERE E_D AND E_A ARE THE EXPOSURES (IN $\frac{\text{MWD/AT}}{1000}$) PER UNIT TIME, N THE TOTAL TIME, AND α THE SHRINKAGE RATE (II) FOR THE GRAPHITE USED (IN $\frac{\text{IN/IN}}{1000 \text{ MWD/AT}}$), I.E. $0.0002 \frac{\text{IN/IN}}{1000 \text{ MWD/AT}}$ FOR K.C. GRAPHITE.

ASSUMING THAT THE AXIAL VARIATION OF EXPOSURE TAKES A

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SINE SHAPE, TWO CASES ARE EXAMINED.

CASE I

AS A CONSERVATIVE ESTIMATE, ASSUME THAT THE SIGNIFICANT FLUX HAS A SINE SHAPE FROM END TO END OF COLUMN:

$$(E_B - E_A)_z = \sin\left(\frac{\pi z}{L}\right)(E_B - E_A)_{\max}$$

WHERE $(E_B - E_A)_{\max}$ IS TAKEN AT $z = \frac{L}{2}$, THEN

$$\frac{d^2 y}{dz^2} = -\frac{S}{W} = -\frac{N_d}{W} \frac{(E_B - E_A)_{\max}}{1000} \sin\left(\frac{\pi z}{L}\right) = -\frac{K_1}{W} \sin\left(\frac{\pi z}{L}\right)$$

$$\frac{dy}{dz} = \frac{K_1 L}{W \pi} \cos\left(\frac{\pi z}{L}\right) + C_1$$

$$y = \frac{K_1 L^2}{W \pi^2} \sin\left(\frac{\pi z}{L}\right) + C_1 z + C_2 \quad (\text{positive } y \text{ is outward bow})$$

FROM SYMMETRY WHEN $\begin{cases} z=0 & y=0 \\ z=\frac{L}{2} & \frac{dy}{dz}=0 \end{cases} \therefore C_2 = 0$
 $\therefore C_1 = 0$

AND $y_{\max} = \frac{K_1 L^2}{1000 W \pi^2} \quad @ \quad z = \frac{L}{2}$

WHERE W IS RETAINED SEPARATE FROM K BECAUSE DIMENSIONS OF COLUMNS VARY THROUGHOUT THE CORE

K_1 FOR 20 YEARS (FOR ANY ONE COLUMN)

$$K_1 = (20)(365)(24)(60)(60)(.0002) \frac{(E_B - E_A)_{\max}}{1000} \text{ max/sec}$$

$$= 12.6 \times 10^4 \frac{(E_B - E_A)_{\max}}{1000} \text{ max/sec}$$

$(E_B - E_A)_{\max} \text{ max/sec}$ CAN BE TAKEN FROM p 10 IN UNITS OF 10^{-4} MW/D/AT-SGL

$$y_{\max(20)} = 12.6 \times 10^4 \frac{(E_B - E_A)_{\max} \times 10^{-4}}{1000} \frac{(232)^2}{W \pi^2}$$

$$= 6.88 \times 10^5 \frac{(E_B - E_A)_{\max} \text{ max/sec} \times 10^{-4}}{W} = \frac{68.8}{W} (E_B - E_A)$$

CASE 2

INFORMATION ON THE AXIAL DISTRIBUTION OF FLUX (SUPPLIED BY ORNL) SHOWS A DECLINE TO ZERO AT ABOUT TWO FEET FROM EACH END OF THE CORE. FOR THIS CASE, WHICH IS PROBABLY A CLOSER

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APPROXIMATION OF WHAT OCCURS IN THE CORE BOWING, ASSUMING A SINE DISTRIBUTION WE HAVE STILL:

$$\frac{d^2 y}{dz^2} = -\frac{E_z}{W}$$

BUT WHEN

$$\begin{aligned} 0 < z < 24 & \quad E_z = 0 \\ 208 < z < 232 & \quad E_z = 0 \\ 24 < z < 208 & \quad E_z = \frac{(E_B - E_A)_z N_d}{1000W} \end{aligned}$$

WHERE $(E_B - E_A)_z = (E_B - E_A)_{\max} \sin(\beta z + \lambda)$
FROM C TO D

AND $\frac{d^2 y}{dz^2} = -\frac{N_d (E_B - E_A)_{\max} \sin(\beta z + \lambda)}{1000W} = -\frac{K_2}{W} \sin(\beta z + \lambda)$

$$\frac{dy}{dz} = \frac{K_2}{W} \frac{1}{\beta} \cos(\beta z + \lambda) + C_1$$

$$y = \frac{K_2}{W} \frac{1}{\beta^2} \sin(\beta z + \lambda) + C_1 z + C_2$$

NOW WHEN

$$0 < z < 24$$

$$\frac{d^2 y}{dz^2} = 0$$

$$\frac{dy}{dz} = C_3$$

$$y = C_3 z + C_4$$

BUT WHEN $z = 0 \quad y = 0$ AND $C_4 = 0$

WHEN $z = 24$

$$\frac{dy}{dz} = C_3$$

and $C_3 = \frac{K_2}{W} \frac{1}{\beta} \cos(\beta z + \lambda) + C_1 = \frac{K_2}{W} \frac{1}{\beta} + C_1$

WHEN $z = 1/2$

$$\frac{dy}{dz} = 0$$

$$\therefore C_1 = 0$$

$$\therefore C_3 = \frac{K_2}{W\beta}$$

BUT AT $z = 24$

$$\therefore 24 C_3 = \frac{K_2}{W\beta^2} \sin(0) + C_2$$

$$24 C_3 = C_2$$

AND $y = \frac{K_2}{W\beta^2} \sin(\beta z + \lambda) + 24 \frac{K_2}{W\beta}$

and $y_{\max} = \frac{K_2}{W} \left(\frac{1}{\beta^2} + \frac{24}{\beta} \right)$

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$$\text{when } \beta = 24 \quad \beta_3 + \lambda = 0$$

$$(\beta = 116) \quad \beta_3 + \lambda = \pi/2$$

$$\begin{cases} 24\beta + \lambda = 0 \\ 116\beta + \lambda = \pi/2 \end{cases}$$

$$92\beta = \pi/2$$

$$\beta = 1.705 \times 10^{-2}$$

$$y_{\max} = \frac{K_2}{W} \left(\frac{1}{(1.705 \times 10^{-2})^2} + \frac{24}{1.705 \times 10^{-2}} \right) = \frac{K_2}{W} (3.44 \times 10^3 + 1.41 \times 10^3)$$

$$= \frac{K_2}{W} (4.85 \times 10^3)$$

And For 20 YEARS:

$$y_{\max} = 12.6 \times 10^4 \frac{(E_B - E_A) \times 10^{-4}}{1000 W} \frac{1}{\lambda} (4.85 \times 10^3) \quad [E_B - E_A \text{ IN } 10^{-4} \frac{\text{MM}}{\text{AT-SEC}}]$$

WHERE IN THE CASE I THE FACTOR 4.85×10^3 WAS 5.64×10^3

$$y_{\max} = \frac{61.2}{W} (E_B - E_A)$$

$E_B - E_A$ CAN BE TAKEN FROM P 10

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when $(\beta = 24) \beta_3 + \lambda = 0$
 $(\beta = 116) \beta_3 + \lambda = \pi/2$

$\begin{cases} 24\beta + \lambda = 0 \\ 116\beta + \lambda = \pi/2 \end{cases}$
 $92\beta = \pi/2$
 $\beta = 1.705 \times 10^{-2}$

$$y_{\max} = \frac{K_2}{W} \left(\frac{1}{(1.705 \times 10^{-2})^2} + \frac{24}{1.705 \times 10^{-2}} \right) = \frac{K_2}{W} (3.44 \times 10^3 + 1.4 \times 10^3)$$

$$= \frac{K_2}{W} (4.85 \times 10^3)$$

And For 20 YEARS:

$$y_{\max} = 12.6 \times 10^4 \frac{(E_B - E_A) \times 10^{-4}}{1000 W} \text{ max/sec } (4.85 \times 10^3)$$

$[E_B - E_A \text{ IN } 10^{-4} \frac{\text{MWD}}{\text{AT-SEC}}]$

WHERE IN THE CASE I THE FACTOR 4.85×10^3 WAS 5.64×10^3

$$y_{\max} = \frac{61.1}{W} (E_B - E_A)$$

$E_B - E_A$ CAN BE TAKEN FROM P 10 .

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SIMILAR TO

Note: (1) central exposures in 10-4 mwd/at-sec
 (2) full power. So also average edge exposures.
 (3) Taken from Appendix 6 - COLUMN IDENTIFICATION CIRCLED.

AVERAGE EXPOSURES OVER THE ENTIRE
CROSS-SECTION AND ALONG EACH SIDE IN EGCR
UTILIZATION FACTOR = 1.0

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A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

20 YEAR DIFFERENTIAL EXPOSURES AT CORE MIDPLANE

ORIGINAL AVERAGE VALUES OF EXPOSURE ON EACH OF THE SIDES OF A COLUMN CAN BE TAKEN FROM ORNL ^{FOUR GROUP} CALCULATION OF THE EGCR CORE (216 FUEL CHANNEL, 8 EMPTY) BY PDQ CODE; SUCH VALUES, IN MWD/AT ARE SHOWN ON P.10. THE ^{OVERALL} GRADIENT OF SHRINKAGE ACROSS ANY COLUMN (AT THE CORE MIDPLANE CAN THEREFROM BE CALCULATED AND, ^{WHEN} FITTED TO THE AXIAL DISTRIBUTION CURVE, USED IN DETERMINING THE MAXIMUM COLUMN BOWING (EXCLUSIVE OF ANY CREEP EFFECTS).

SUCH AN APPROACH DOES NOT TAKE INTO ACCOUNT ANY OPPOSITION TO BOWING DEVELOPED BY THE NON-LINEAR COMPONENT OF THE SHRINKAGE GRADIENT ACROSS A COLUMN. THE EFFECT OF THE TOTAL GRADIENT IS TO CAUSE PARTS OF EACH COLUMN TO TEND TO BOW IN OPPOSITE DIRECTIONS, SOME PARTS MORE THAN OTHERS. STRESSES DEVELOPED (EXCLUSIVE OF CREEP CONSIDERATIONS) REDUCE THE OVERALL TENDENCY TO BOW BY REDUCING THE OVERALL GRADIENT OF STRAIN IN THE EXTERIOR FIBERS.

THE AMOUNT OF THIS REDUCTION HAS BEEN ESTIMATED BY TAKING THE MIDPLANE OF THE COLUMN EXPERIENCING THE WORST LINEAR GRADIENT AND DIVIDING ITS CROSS-SECTION INTO A TEN-BY-TEN GRID WITH EACH GRID INTERSECTION ASSIGNED A NUMBER PROPORTIONAL TO THE FLUX AT THAT LOCATION*; SUCCESSIVE APPROXIMATION AT EACH OF THE JOINTS WAS PERFORMED ASSUMING THAT, WITHIN THE ELASTIC LIMITATION OF GRAPHITE, ALL THE AREAS TRIBUTARY TO AN INTERSECTION TEND TO APPROACH A WEIGHTED AVERAGE OF THEIR INDIVIDUAL INITIAL OR INSTANTANEOUS VALUES (THE FLUX VALUES REPRESENTING THE SHRINKAGE OF INDIVIDUAL FIBERS WHICH ARE OF COURSE COMPLETELY CONNECTED TO ADJACENT FIBERS IN THE CROSS-SECTION).

* See page 27

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COLUMN 70 WITH AN X-GRADIENT OF $(1.25 - 0.51) \times 10^{-4}$ MWD/AT-SEC AND Y-GRADIENT OF $(0.99 - 0.91) \times 10^{-4}$ MWD/AT-SEC WAS EXAMINED. THE SUCCESSIVE APPROXIMATION PROCESS WAS FOUND TO REDUCE THE X-GRADIENT BY 20% WITH NEGLIGIBLE EFFECT ON THE RELATIVELY SMALL Y-GRADIENT^(0.27). ALTHOUGH THE AMOUNT OF CHANGE WILL VARY FROM BRICK TO BRICK DEPENDING ON THE RELATIVE SIZE OF THE TWO ORIGINAL GRADIENTS, THIS DOES SHOW THAT SIGNIFICANT AMOUNTS OF REDUCTION CAN BE EXPECTED, ALTHOUGH SOME INITIAL GRADIENTS ARE SO LARGE THAT NOT EVEN 20% REDUCTIONS WILL REDUCE THE BOWING TO NON-CRITICAL LEVELS.

IN ADDITION TO CALCULATION OF BOWING DUE TO ORIGINAL GRADIENTS, A SERIES OF BOWS WILL BE CALCULATED WITH GRADIENTS REDUCED BY AMTS. AS FOLLOWS (ESTIMATED SINCE TIME IS NOT AVAILABLE FOR SEVERAL SUCCESSIVE APPROX.):

BRICK	- LARGE X-GRAD	-	- 20%	} AND VICE VERSA
	SMALL Y-GRAD	-	NO CHANGE	
BRICK	- APPROXIMATELY	-		
	EQUAL X AND Y			
	GRADIENTS OF			
(a)	MEDIUM SIZE	-	- 10% (BOTH)	
(b)	LARGE GRADIENTS	-	- 20% (BOTH)	
(c)	SMALL GRADIENTS	-	NO CHANGE (BOTH)	

FOR BOTH THESE SETS OF GRADIENTS, THE FLUX GRADIENT WILL BE USED IN FORMULAS DERIVED FOR BOWING AND THE CONSEQUENT SHRINKAGE GRADIENTS COMPUTED ON THE BASIS OF SHRINKAGE RATE OF .02% PER 1000 MWD/AT (PARALLEL) RATHER THAN USING THE SHRINKAGE GRADIENTS (REDUCED OR NON-REDUCED) DIRECTLY.

IT SHOULD BE NOTED THAT FOLLOWING THIS PROCEDURE IMPLIES THAT THE BOWING WILL PROCEED ALWAYS ELASTICALLY AND THAT LENGTH CHANGES WILL CONTINUE TO ACCRUE IN EACH FIBER FOR ALL OF ANY TIME PERIOD (SAY TWENTY YEARS). HOWEVER, WHAT INFORMATION THERE IS AVAILABLE ON CREEP INDICATES THAT AT SOME STRESS (WHICH OF COURSE IS REACHED IN A DEFINITE TIME BY EACH FIBER) CREEP RATE EQUALS OR EXCEEDS SHRINKAGE RATE. AT SUCH TIME, THEN, THE LENGTH OF THE PARTICULAR FIBER WOULD

EGCR BOWING CALCULATIONS

TASK 227 APP 7

SIMILAR TO

DR'N RRN	CH'D PUG 6/21/60	APP'D <i>[Signature]</i>	SCALE = 12	SHEET 12 OF 27	ISSUE
ALLIS-CHALMERS MFG. CO. DEPT. NPD - W			JAN 15, 1960		

CEASE TO CHANGE, AND, ALTHOUGH STRAINS WOULD CONTINUE TO ACCUMULATE IN OTHER FIBERS, THESE ^{SATURATED} FIBERS WOULD CEASE TO CONTRIBUTE TO BOWING. ON THE ASSUMPTION THAT EDGE FIBERS REACH THEIR LIMITING STRESS (1000 PSI, SAY, FROM CREEP CALCULATIONS) IN ABOUT FOUR YEARS AT THE ~~COLUMN~~ ^{CORE} CENTER (SEE ANISOTROPIC CALCULATIONS), ANY BOWING CALCULATED ON THE BASIS OF LINEAR SHRINKAGE GRADIENTS FROM EDGE TO EDGE COULD BE REDUCED BY THE RATIO OF FOUR YEARS TO TWENTY YEARS (OR WHATEVER PERIOD OF OVERALL EXPOSURE IS INVOLVED).

SINCE NOT ALL ^{PORTIONS OF} FIBERS ALONG THE COLUMN LENGTH REACH THEIR LIMITING STRESS SIMULTANEOUSLY (THE TIME REQUIRED BEING GREATER THE GREATER THE DISTANCE FROM CORE MIDPLANE) THE PROCESS OF FINDING ACTUAL FINAL BOWING WOULD PROBABLY HAVE TO BE STEP-WISE AND TIME CONSUMING. IF MORE DEFINITE CREEP INFORMATION WERE AVAILABLE, IT IS FELT THE PROCESS COULD YIELD SIGNIFICANTLY REDUCED OVERALL BOWING FIGURES FOR ALL COLUMNS.

EGCR BOWING CALCULATIONS
TASK 227 APP. 7

SIMILAR TO

DR'N	RRN	CH'D	PUG 4/21/60	APP'D	<i>[Signature]</i>	SCALE	=12	SHEET	13	OF	27	ISSUE
ALLIS-CHALMERS MFG. CO. DEPT.								NPD-W		JAN 15, 1960		

TOTAL GAPS AVAILABLE IN 20 YRS AT THE CORE MIDPLANE TO ACCOMMODATE BOWING

(1)

INSTALLATION GAPS: .03 UNIFORM

THERMAL EXPANSION OF GRAPHITE := $(16)(900-70)(3.9 \times 10^{-6})$
= .0517"

GAP OPENING DUE THERMAL
EXPANSION OF TOP GRID
AND PLATE = $(16)(500-70)(6.4 \times 10^{-6})$ = .044
= $(16)(450-70)(7.2 \times 10^{-6})$ = .112

RESULTANT GAPS (NON-SHRINKAGE) := .078" (AVER)
.08" HOT 12(.078-.052+.03)
.08" COLD

USING AGOT VALUE FOR
HC GRAPHITE

TAKING TOP GRID AS
502 STL @ 1050

CLEARANCE BETWEEN CORE AND
RESTRAINT BAND : .000 COLD
.100 HOT

Top GRID From 502
ST.; BAND OF MATL
WITH $\alpha = 7.5 \times 10^{-6}$ @
900 F

EXPANSION OF TOP CORE $(7.2 \times 10^{-6})(95)(980) = .67$
EXPANSION OF BOTTOM CORE $(6.4)(10^{-6})(95)(430) = .26$
AVERAGE EXPANSION CORE
(MIDPLANE) .46

EXPANSION OF RESTRAINT $(7.5)(10^{-6})(95)(830) = .59$

CLEARANCE HOT .13" USE .10"

(2)

FROM THE STANDPOINT OF RESTRAINED BOWING THE COLD CONDITION WILL
BE THE WORST CASE. THIS WILL ALSO BE CONSERVATIVE SINCE THE STRESSES
CAUSED BY RESTRAINT SHOULD BE COMPARED WITH ROOM TEMPERATURE, SHORT-
TERM STRENGTH OF GRAPHITE.

Col.		.085	.09	.09	.07	.026	.018
COL.		67	68	69	70	71	72
x gap	.085	.650	.475	.295	.135	.04	.0005
y gap		.650	.605	.468	.307	.128	.00054
COL.		79	80	81	82	83	84
x gap	.07	.605	.425	.260	.127	.04	.0004
y gap		.475	.425	.303	.179	.078	.00044
COL.		91	92	93	94	95	96
x gap	.09	.468	.303	.174	.086	.034	.0003
y gap		.295	.260	.174	.087	.035	.00034
COL.		102	103	104	105	106	
x gap	.07	.307	.179	.087	.035	.008	
y gap		.135	.127	.086	.035	.008	
COL.		111	112	113	114		
x gap	.026	.128	.078	.034	.008		
y gap		.04	.04	.034	.008		
COL.		118	119	120			
x gap	.018	.0005	.0004	.0003			
y gap		.0005	.0004	.0003

AT THE CORE RESTRAINT, THE AVAILABLE GAPS ARE SIMPLY
HALF THE SHRINKAGE OF EACH COLUMN.

TOTAL GAP AT ANY COLUMN IS THE SUM OF ALL SHRINKAGE AND IN-
STALLATION GAPS OUT TO THE CIRCUMFERENTIAL RESTRAINTS.

EGCR BOWING CALCULATIONS
TASK 27 APP. 7.

SIMILAR TO

DR'N

CH'D PVG 6/21/60

APP'D *gm*

SCALE = 12

SHEET 14 OF 27

ISSUE

ALLIS-CHALMERS MFG. CO.

DEPT.

NPD-W

JAN 15, 1960

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A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

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TRANSVERSE SHRINKAGE @ RATE .01%/1000 MWD/AT		UTILIZATION FACTOR = 1.0	
Col	$\frac{F_0}{\sec}$ 10^{-4}	$\frac{F_0}{\text{yr}}$ 1000 MWD/AT	$\frac{F_0}{20 \text{ yr}}$ 1000 MWD/AT
67	1.41	4.45	89.0
68	1.53	4.83	96.6
69	1.43	4.51	90.2
70	1.05	3.31	66.1
71	.209	.66	13.2
72	.009	.0294	.569
79	1.53	4.8	96.0
80	1.47	4.64	92.9
81	1.24	3.92	78.0
82	0.86	2.71	54.1
83	0.17	.536	10.92
84	.008	.0252	.504
91	1.43	4.52	90.4
92	1.24	3.92	78.3
93	0.78	2.46	49.1
94	0.38	1.2	24.0
95	.075	.236	47.2
96	.006	.0189	.378
102	1.05	3.31	66.1
103	0.86	2.71	54.2
104	0.38	1.2	24.0
105	.061	.192	3.84
106	.016	.0505	10.1
111	.209	.66	13.2
112	.17	.536	10.72
113	.075	.236	47.2
114	.016	.0505	1.1
118	.009	.0284	.568
119	.008	.0252	.504
120	.006	.0189	.378

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MAXIMUM BOWING AT CORE MIDPLANE FOR 20 YR LIFE
WITH UNMODIFIED DIFFERENTIAL EXPOSURES

COL	$E_4 - E_2$		$E_1 - E_3$		K_1 W	CASE 1				CASE 2				K_2 W		
	U=1.0		U=0.8			Δx		Δy		Δx		Δy				
	U=1.0	U=0.8	U=1.0	U=0.8		U=1.0	U=0.8	U=1.0	U=0.8	U=1.0	U=0.8	U=1.0	U=0.8			
67	.12	.096	.12	.096	(4.59) $E_4 - E_2$	0.52	0.40	0.52	0.40	0.46	0.36	0.40	0.36	(4.05) $E_4 - E_2$		
68	-.14	-.112	.07	.056		-0.60	-0.48	0.30	0.24	-0.53	-0.43	0.27	0.21			
69	.21	.168	.08	.064		0.90	0.72	0.34	0.28	0.80	0.64	0.30	0.25			
70	.74	.59	.08	.064		3.18	2.54	0.34	0.28	2.82	2.25	0.30	0.25			
71	.49	.39	.01	.008		2.10	1.68	0.04	0.03	1.86	1.49	0.03	0.03			
72	.02	.016	.001	.0008		0.09	0.07	0.004	0.003	0.08	0.06	.004	.003			
79	.07	.056	-.14	-.112		0.30	0.24	-0.60	-0.48	0.26	0.21	-0.53	-0.43			
80	+.09	.072	.09	.072		0.39	0.30	0.39	0.31	0.36	0.27	0.36	0.27			
81	.31	.248	.27	.216		1.33	1.07	1.16	1.00	1.18	0.95	1.03	0.89			
82	.61	.488	.25	.20		2.62	2.10	1.08	0.96	2.33	1.86	0.96	0.76			
83	.39	.312	.05	.04	(5.73) $E_4 - E_2$	1.68	1.34	0.22	0.17	1.49	1.19	0.19	0.15	(5.1) $E_4 - E_2$		
84	.017	.0136	.001	.0008		0.00	0.08	0.004	0.003	0.09	0.07	.004	.003			
91	.08	.064	.21	.168		0.34	0.28	0.90	0.72	0.30	0.25	0.80	0.64			
92	+.27	.216	.31	.248		1.16	1.00	1.25	1.00	1.03	0.89	1.11	0.89			
93	.47	.376	.47	.376		2.02	1.62	2.02	1.62	1.79	1.44	1.79	1.44			
94	.39	.296	.56	.448		1.59	1.27	2.41	1.93	1.41	1.03	2.14	1.72			
95	.19	.152	.085	.068		0.82	0.65	0.39	0.29	0.73	0.58	0.33	0.26			
96	.008	.0064	.005	.004		(13.8) $E_4 - E_2$	0.11	0.09	0.021	0.017	0.10	0.08	0.018		0.015	(12.2) $E_4 - E_2$
102	.08	.064	.74	.592			0.34	0.28	3.18	2.54	0.30	0.25	2.82		2.26	
103	.25	.20	.61	.488			1.07	0.86	2.62	2.10	0.95	0.76	2.33		1.87	
104	.56	.448	.37	.296	2.41		1.93	1.59	1.27	2.14	1.72	1.41	1.13			
105	.083	.0664	.083	.0664	0.36		0.29	0.36	0.29	0.32	0.26	0.32	0.26			
106	.017	.0136	.015	.012	0.07		0.06	0.06	0.05	0.06	0.05	0.05	0.04			
111	.01	.008	.49	.392	0.04		0.03	2.10	1.68	0.04	0.03	1.87	1.49			
112	.05	.04	.39	.312	0.28		0.23	1.68	1.34	.19	0.15	1.49	1.19			
113	.085	.068	.19	.152	0.37		0.29	0.82	0.65	.33	.26	.73	.58			
114	.015	.012	.017	.0136	0.06		0.05	0.07	0.06	0.05	0.04	0.06	0.05			
118	.001	.0008	.02	.016	(4.59) $E_1 - E_3$	.004	.003	0.09	0.07	.004	.003	.08	.06	(4.08) $E_1 - E_3$		
119	.001	.0008	.017	.0136		(5.73) $E_1 - E_3$	.004	.003	0.098	0.08	.004	.003	.087		.067	(5.1) $E_1 - E_3$
120	.005	.004	.008	.0064			(13.8) $E_1 - E_3$	.021	.017	.316	0.252	.019	.015		.096	
*	$\frac{K_1}{W} = 7.3$		AND $\frac{K_2}{W} = 3.82$		UNLESS OTHERWISE NOTED											

EGCR BOWING CALCULATIONS
TASK 227 App.7.

SIMILAR TO

DR'N	RRN	CH'D	PHG 6/2/60	APP'D	<i>[Signature]</i>	SCALE	=12	SHEET	16 OF 27	ISSUE	
ALLIS-CHALMERS MFG. CO.						DEPT.		NPD-W			
								JAN 15, 1960			

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A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

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MAXIMUM BOWING AT CORE MIDPLANE FOR 20 YR LIFE
WITH UNMODIFIED DIFFERENTIAL EXPOSURES

COL	$E_4 - E_2$		$E_1 - E_3$		K_1 W	CASE 1				CASE 2				K_2 W
	U=1.0		U=0.8			Δx		Δy		Δx		Δy		
	U=1.0	U=0.8	U=1.0	U=0.8		U=1.0	U=0.8	U=1.0	U=0.8	U=1.0	U=0.8	U=1.0	U=0.8	
67	.12	.096	.12	.096		0.52	0.40	0.52	0.40	0.46	0.36	0.40	0.36	
68	-.14	-.112	.07	.056		-0.60	-0.48	0.30	0.24	-0.53	-0.43	0.27	0.21	
69	.21	.168	.08	.064		0.90	0.72	0.34	0.28	0.80	0.64	0.30	0.25	
70	.74	.59	.08	.064		3.18	2.54	0.34	0.28	2.82	2.25	0.30	0.25	
71	.49	.39	.01	.008		2.10	1.68	0.04	0.03	1.86	1.49	0.03	0.03	
72	.02	.016	.001	.0008	(4.59) $E_4 - E_2$	0.09	0.07	0.004	0.003	0.08	0.06	.004	.003	(4.08) $E_4 - E_2$
79	.07	.056	-.14	-.112		0.30	0.24	-0.60	-0.48	0.26	0.21	-0.53	-0.43	
80	+.09	.072	.09	.072		0.39	0.30	1.39 1.68	0.31	0.36	0.27	0.36	0.27	
81	.31	.248	.27	.216		1.33	1.07	1.16	1.00	1.18	0.95	1.03	0.89	
82	.61	.488	.25	.20		2.62	2.10	1.08	0.86	2.33	1.86	0.96	0.76	
83	.39	.312	.05	.04		1.68	1.34	0.22	0.17	1.49	1.19	0.19	0.15	
84	.017	.0136	.001	.0008	(5.73) $E_4 - E_2$	0.00	0.08	0.004	0.003	0.09	0.07	.004	.003	(5.1) $E_4 - E_2$
91	.08	.064	.21	.168		0.34	0.28	0.90	0.72	0.30	0.25	0.80	0.64	
92	+.27	.216	.31	.248		1.16	1.00	1.25	1.00	1.03	0.89	1.11	0.89	
93	.47	.376	.47	.376		2.02	1.62	2.02	1.62	1.79	1.44	1.79	1.44	
94	.39	.296	.56	.448		1.59	1.27	2.41	1.93	1.41	1.03	2.14	1.72	
95	.19	.152	.085	.068		0.82	0.65	0.39	0.29	0.73	0.58	0.33	0.26	
96	.008	.0064	.005	.004	(13.8) $E_4 - E_2$	0.11	0.09	0.021	0.017	0.10	0.08	0.018	0.015	(12.2) $E_4 - E_2$
102	.08	.064	.74	.592		0.34	0.28	3.18	2.54	0.30	0.25	2.82	2.26	
103	.25	.20	.61	.488		1.07	0.86	2.62	2.10	0.95	0.76	2.33	1.87	
104	.56	.448	.37	.296		2.41	1.93	1.59	1.27	2.14	1.72	1.41	1.13	
105	.083	.0664	.083	.0664		0.36	0.29	0.36	0.29	0.32	0.26	0.32	0.26	
106	.017	.0136	.015	.012		0.07	0.06	0.06	0.05	0.06	0.05	0.05	0.04	
111	.01	.008	.49	.392		0.04	0.03	2.10	1.68	0.04	0.03	1.87	1.49	
112	.05	.04	.39	.312		0.28	0.23 0.17	1.68	1.34	.19	0.15	1.49	1.19	
113	.085	.068	.19	.152		0.37	0.29	0.82	0.65	.33	.26	.73	.58	
114	.015	.012	.017	.0136		0.06	0.05	0.07	0.06	0.05	0.04	0.06	0.05	
118	.001	.0008	.02	.016	(4.59) $E_1 - E_3$	.004	.003	0.09	0.07	.004	.003	.08	.06	(4.08) $E_1 - E_3$
119	.001	.0008	.017	.0136	(5.73) $E_1 - E_3$	.004	.003	0.098	0.08	.004	.003	.087	.067	(5.1) $E_1 - E_3$
120	.005	.004	.008	.0064	(13.8) $E_1 - E_3$	.021	.017	.116	0.087	.019	.015	.096	.078	(12.2) $E_1 - E_3$
*	$\frac{K_1}{W} = 4.3$		AND $\frac{K_2}{W} = 3.82$		UNLESS OTHERWISE NOTED									

EGCR BOWING CALCULATIONS
 TASK 227 App.7.

SIMILAR TO

DR'N	RRN	CH'D	PVG 6/2/60	APP'D	<i>jm</i>	SCALE	=12	SHEET	16 OF 27	ISSUE	
ALLIS-CHALMERS MFG. CO.						DEPT.		NPD-W		JAN 15, 1960	

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A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

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MAXIMUM BOWING AT CORE MIDPLANE FOR 20 YEAR LIFE
WITH MODIFIED DIFFERENTIAL EXPOSURES

COL	E ₄ -E ₂ U=0.8 UNMODIFIED	MODIFYING FACTOR	E ₁ -E ₃ U=0.8 UNMODIFIED	MODIFYING FACTOR	K ₂ * W	CASE 2	
						Δx	Δy
67	.096	.9	.096	.9		0.32	0.32
68	-.112	1.	.056	1.		-0.43	0.21
69	.168	.9	.064	1.0		0.59	0.25
70	.59	.8	.064	1.		1.80	0.25
71	.39	.8	.008	1.		1.19	0.03
72	.016	1.	.0008	1.	4.08 (E ₄ -E ₂)	0.06	.003
79	.056	1.	-.112	1.		0.21	-0.43
80	.072	.9	.072	.9		0.24	0.24
81	.248	.9	.216	.9		0.86	0.74
82	.488	.8	.20	.9		1.49	0.68
83	.312	.8	.204	1.		0.97	0.15
84	.136	1.	.0008	1.	5.1 (E ₄ -E ₂)	0.07	.003
91	.064	1.	.168	.9		0.25	.58
92	.216	.9	.248	.9		0.94	.85
93	.376	.8	.376	.8		1.15	1.15
94	.296	.8	.448	.8		0.91	1.38
95	.152	.9	.068	1.		0.52	0.26
96	.0064	1.	.004	1.	12.2 (E ₄ -E ₂)	0.08	1.05
102	.064	1.	.592	.8		0.25	1.81
103	.20	.8	.488	.8		0.61	1.50
104	.448	.8	.296	.8		1.38	0.91
105	.0664	1.	.0664	1.		0.26	0.26
106	.0136	1.	.012	1.		0.05	0.04
111	.008	1.	.392	.8		0.03	1.19
112	.04	1.	.312	.8		0.15	0.96
113	.068	1.	.152	.9		.26	0.52
114	.012	1.	.0136	1.		0.04	0.05
118	.0008	1.	.016	0.8	4.08 (E ₁ -E ₃)	.003	.05
119	.0008	1.	.0136	0.8	(5.1) E ₁ -E ₃	.003	.06
120	.004	1.	.0064	1.	12.2 (E ₁ -E ₃)	.015	.02

* $K_2/W = 3.52$ UNLESS OTHERWISE NOTE; ** MODIFYING FACTORS ASSIGNED BY APPROXIMATION.

EGCR BOWING CALCULATIONS
 TASK 227 APP. 7.

SIMILAR TO

DR'N RRN	CH'D PUG 6/24/60	APP'D <i>[Signature]</i>	SCALE = 12	SHEET 17 OF 27	ISSUE
ALLIS-CHALMERS MFG. CO.			DEPT. NPD-W	JAN 15, 1960	

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A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

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MAXIMUM RESTRAINED BOWING (20 YR) AND CONSEQUENT STRESS

COL	AVAILABLE SPACE		CASE 2, U=0.8				RESTRAINED Δ				BOWING STRESS					MAX. PT (+)
			MODIFIED		UNMODIF.		MODIFIED		UNMOD		ON SIDE					
	X	Y	Δx	Δy	Δx	Δy	Δx	Δy	Δx	Δy	2	1	4	3		
67	.650	.350	.32	.32	0.36	.36	.05	.05	.07	.07	-107	+107	+107	-107	214	
68	.475	.605	-.43	.21	-.43	.21	-.05	0	-.07	0	+107	0	+107	0	290	
69	.295	.468	.59	.25	.64	.25	.29	0	.34	0	+145	0	-145	0	107	
70	.135	.307	1.80	.25	2.25	.25	1.66	0	2.11	0	-620	0	+620	0	145	
71	.04	.828	1.19	.003	1.49	.03	1.15	0	1.45	0	-727	0	+727	0	620	
72	.0005	.0005	.06	.003	.06	.003	.0595	.0025	.0595	.0025	-3550	0	+3550	0	727	
79	.605	.425	.21	-.43	.21	-.43	0	.05	0	-.07	-4510	0	+4510	0	3550	
80	.425	.425	.24	.24	.27	.27	0	0	0	0	-2460	0	+2460	0	4510	
81	.260	.303	.86	.74	.95	.89	.60	.44	.89	.59	-3100	0	+3100	0	2460	
82	.127	.179	1.49	.68	1.86	.76	1.36	.50	1.73	.50	-119	-5.4	+119	+5.4	3100	
83	.04	.078	0.97	.15	1.19	.15	.93	.07	1.15	.07	-119	-5.4	+119	+5.4	124	
84	.0004	.0004	.07	.003	.07	.003	.0696	.0024	.0696	.0024	0	-107	0	+107	107	
91	.468	.295	.25	.58	.25	.64	.11	.28	.17	.34	0	-145	0	+145	145	
92	.203	.260	.74	.85	.82	.95	.44	.59	.52	.69	0	0	0	0	0	
93	.174	.174	1.15	1.15	1.44	1.44	.98	.98	1.27	1.27	-1280	+950	+1280	-950	2350	
94	.086	.087	.91	1.38	1.13	1.72	.92	1.29	1.04	1.83	-1470	+1210	+1470	-1210	2680	
95	.034	.035	.52	.26	.58	.26	.49	.22	.55	.22	-2910	+1070	+2910	-1070	3980	
96	.0003	.0003	.08	.015	.08	.015	.0797	.0147	.0797	.0147	-3700	+1240	+3700	-1240	4940	
102	.307	.135	.25	1.81	.25	2.26	0	1.67	0	2.12	-1990	+143	+1990	-143	2130	
103	.179	.127	.61	1.50	.76	1.87	.43	1.37	.58	1.74	-2460	+143	+2460	-143	2600	
104	.087	.086	1.38	.91	1.72	1.13	1.29	.82	1.63	1.04	-111	-5.6	+111	+5.6	117	
105	.035	.035	.26	.26	.26	.26	.22	.22	.22	.22	-111	-5.6	+111	+5.6	117	
106	.001	.001	.05	.04	.05	.04	.0499	.0399	.0499	.0399	-236	+600	+236	-600	836	
111	.128	.04	.03	1.19	.03	1.49	0	1.15	0	1.45	-364	+728	+364	-728	1092	
112	.078	.04	.15	.96	.15	1.19	.07	.92	.07	1.15	-940	+1265	+940	-1265	2200	
113	.035	.034	.26	.52	.26	.58	.22	.49	.22	.55	-110	+1430	+110	-1430	2540	
114	.001	.001	.04	.05	.04	.05	.0399	.0499	.0399	.0499	-2800	+2100	+2800	-2100	4200	
118	.0005	.0005	.003	.05	.003	.06	.0025	.05	.0025	.06	-2720	+2720	+2720	-2720	5440	
119	.0004	.0004	.003	.012	.003	.069	.0026	.06	.0026	.07	-1750	+2760	+1750	-2760	4515	
120	.0003	.0003	.015	.02	.015	.02	.0147	.0147	.0147	.0144	-220	+3920	+220	-3920	4140	

NOTE: $E_{11} = 1.5 \times 10^6$ USED AS FIRST TRIAL TO TAKE INTO ACCOUNT THE DECLINE IN TANGENT MODULUS AS STRESS INCREASES

EGCR BOWING CALCULATIONS

TASK 227. App. 7.

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SIMILAR TO

DR'N	RRN	CH'D	PH 6/24/60	APP'D	SCALE	=12	SHEET	18 OF 27	ISSUE
ALLIS-CHALMERS MFG. CO. DEPT.					NPD-W		JAN 15, 1960		

STRESS DUE TO RESTRAINED BOWING

ONCE THE AMOUNT OF RESTRAINED BOWING HAS BEEN CALCULATED FOR ANY CORE LIFE, THE STRESSES PRODUCED ARE CALCULATED BY TREATING THE RESTRAINED BOW AS A DEFLECTION IMPOSED UPON A COLUMN (OF SQUARE CROSS-SECTION) WITH SLIGHT INITIAL CURVATURE, THE CURVATURE BEING SMALL ENOUGH TO ^{ALLOW} TREATING THE BEAM AS ORIGINALLY STRAIGHT. SINCE IT IS UNLIKELY THAT POINT CONTACT BETWEEN ADJACENT COLUMNS WILL OCCUR OVER ANY SIGNIFICANT PERIOD OF TIME (PARTICULARLY AT RESTRAINT LEVELS PRODUCING HIGHER STRESSES), STRESSES ARE COMPUTED ASSUMING A UNIFORM BEARING BETWEEN COLUMNS. IF THE ^{OTHER} EXTREME OF A POINT LOAD WERE USED, THE STRESS FOR ANY DEFLECTION WOULD BE ONLY ABOUT 20% HIGHER. THE ACTUAL BEARING BETWEEN COLUMNS LIES BETWEEN THE TWO EXTREMES, PROBABLY CLOSEST TO UNIFORM BEARING CONDITION; HENCE THE STRESS CALCULATED BY ASSUMING UNIFORM BEARING IS PROBABLY GOOD TO WITHIN TEN PERCENT. NO ACCOUNT OF ANISOTROPY IS TAKEN BECAUSE OF TIME LIMITATIONS AND THE APPROXIMATE NATURE OF THIS CALCULATION. ALL COMPUTED STRESSES ARE FOR EACH COLUMN MIDPLANE ONLY, AS THE WORST CASE

FOR ANY DIRECTION (X OR Y)

$$\delta = \frac{5WL^4}{384EI}$$

$$M = \frac{WL^2}{8}$$

$$\sigma = \frac{Mc}{I}$$

$$\sigma = \frac{WL^2c}{8I}$$

$$W = \frac{\sigma 8I}{L^2c}$$

AND SUBSTITUTING

$$\delta = \frac{5 \cdot \sigma \cdot 8 \cdot I \cdot L^4}{384 L^2 c E I} = \frac{L^2 \sigma}{9.6 c E}$$

$$\sigma = \frac{9.6 c E \delta}{L^2}$$

WHERE E IS E_{II} AND IS TAKEN AS AN AVERAGE 15×10^6 OVER 20 YEAR CORE LIFE, AND c IS ADJUSTED TO THE SHARE OF THE CROSS-SECTION. FOR COLUMNS c IS 8" EXCEPT

COL. 118 = 7.5" (Y)	COL. 72 = 7.5" (X)
119 = 6" (Y)	84 = 6" (X)
120 = 5" (Y)	96 = 5" (X)

EGCR BOWING CALCULATIONS
TASK 227 App. 7.

SIMILAR TO

DR'N RRN	CH'D PUG 6/21/60	APP'D <i>[Signature]</i>	SCALE = 12	SHEET 19 OF 27	ISSUE
ALLIS-CHALMERS MFG. CO. DEPT. NPD-W			JAN 15, 1961		

A

B

A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

1 C 2

THE MULTIPLYING FACTORS FOR STRESS ARE:

$$\sigma = \frac{(9.6)(1.5 \times 10^4)(8)}{(232)^2} \delta = \frac{21.4}{2.67 \times 10^2} \delta \quad \text{FOR NORMAL } 16 \times 16" \text{ COL.}$$

$$\sigma = \frac{(9.6)(1.5 \times 10^4)(7.5)}{(232)^2} \delta = 20.1 \delta \quad \text{COL 119 \& COL 72}$$

$$\sigma = \frac{(9.6)(1.5 \times 10^4)(6)}{(232)^2} \delta = 16 \delta \quad \text{COL 119 \& COL 84}$$

$$\sigma = \frac{(9.6)(1.5 \times 10^4)(5)}{(232)^2} \delta = 6.68 \delta \quad \text{COL 120 \& COL 96}$$

20 YEAR VALUES OF STRESS DUE TO BOWING ARE ON Pg. 18.

SINCE BOWING OCCURS IN TWO DIRECTIONS FOR EACH COLUMN, THE MAXIMUM TENSILE STRESS OCCURS AT A CORNER, WHERE THE TOTAL POINT STRESS IS THE SUM OF MAXIMUM FIBER STRESSES DUE TO BOWING IN THE TWO DIRECTIONS.

ONCE THE CORNER WITH MAXIMUM ^{BOWING} STRESS HAS BEEN DETERMINED, THE STRESS DUE TO NON-LINEAR FLUX GRADIENT IN THE CYLINDRICAL ANISOTROPIC MODEL OF THE NEAREST FUEL CHANNEL IS SUPERIMPOSED, AT THE CORNER AND AT THE CLOSEST POINT OF THE FUEL CHANNEL SURFACE. AT THE CHANNEL SURFACE, 73% CORNER STRESS IS ADDED TO ^{TENSILE} INTERNAL STRESS. AT THE CORNER, THE COMPRESSIVE STRESS FROM THE CYLINDRICAL MODEL IS SUBTRACTED FROM THE CORNER BOWING STRESS; THE VALUE OF THE

GENERATED INTERNALLY, COMPRESSIVE STRESS OCCURS AT 4.49" FROM CHANNEL CENTER OF THE ANISOTROPIC MODEL, BUT IS SUBTRACTED FROM TENSILE BOWING STRESS AT 5.6" AS AN APPROXIMATION SINCE THIS IS NOT THE ^{POINT OF} GREATEST TENSILE STRESS IN THE COLUMN

BOWING STRESSES ARE BASED ON BOW (20 YR) FOR $U=0.8$ AS CLOSEST APPROXIMATION TO EGCR CONDITIONS.

EGCR BOWING CALCULATIONS
TASK 227 App. 7

SIMILAR TO

DR'N RRN	CH'D PVG 6/21/60	APP'D <i>[Signature]</i>	SCALE = 12	SHEET 20 OF 27	ISSUE
ALLIS-CHALMERS MFG. CO.			DEPT. NPD-W	JAN 15, 1960	

PRORATING INTERNALLY GENERATED STRESSES FROM ORIGINAL ANISOTROPIC CALCULATIONS (FOR $U=0.8$) IS BASED ON NEW MAXIMUM FLUX IN THE WORST FUEL CHANNEL (2.17×10^{-4} MW/D/AT-SEC VS 2.73×10^{-4} MW/D/AT-SEC) AND ON THE RELATION BETWEEN THE MAXIMUM AVERAGE FLUX AT THE WORST-CHANNEL FUEL SLEEVE AND AT THE ~~WORST~~ FUEL SLEEVE OF THE CHANNEL NEAREST THE POINT OF MAXIMUM STRESS. FOR INSTANCE, FOR THE COLUMN WITH WORST POINT-STRESS DUE TO BOWING (NO 94), THE RELATIVE SLEEVE FLUXES ARE $\frac{1.37}{1.37}$ AND .55 RESPECTIVELY. FOR THE FIRST YEAR TENSILE STRESS AT COLUMN 94 THEN

$$\sigma_1 = 478 (.5) \left(\frac{2.17}{2.73} \right) \left(\frac{.55}{1.37} \right) = 76 \text{ PSI} \quad (\text{SEE P. 24})$$

WHERE THE FACTOR (.5) IS DUE TO THE REDUCED SHRINKAGE RATE; I.E. (HALF THAT OF THE ORIGINAL CALCULATIONS) = .02 % / 1000 MW/D/AT. (11)

BEYOND THE FIRST YEAR, EACH ^{YEARLY} INCREMENT OF STRESS IS COMPUTED BY PRORATING ON THE BASIS OF INSTANTANEOUS TANGENT MODULUS OVER ORIGINAL MODULUS ($1.35 \times 10^6 = E_0(1)$) AS IN THE ORIGINAL ANISOTROPIC CALCULATIONS.

THE ABOVE PROCEDURE, IF ^{STRICTLY} APPLIED TO THE WORST COLUMN (FOR BOWING STRESS) IN A YEAR BY YEAR MANNER INSTEAD OF FOR 20 YEAR TOTAL LIFE (AS IN PP 17-18) ^{IS} ~~IS~~ TIME CONSUMING. BECAUSE ONE YEAR-BY-YEAR CALCULATION, ^{FOR THIS COLUMN} ACTUALLY CHECKED VERY CLOSELY WITH THE STRESSES COMPUTED BY USE OF AVERAGE $E_{(11)}$, ETC, FOR OTHER COLUMNS IN THE CORE, A SHORTENED PROCEDURE IS USED TO CALCULATE ACCUMULATION OF WORST STRESS WITH TIME: (PP 25-26)

- (a) BOWING STRESS IS PRORATED LINEARLY, IN 2 YEAR INTERVALS, DIRECTLY FROM THE 20 YEAR VALUES LISTED ON P 18.
- (b) INTERNALLY GENERATED STRESSES FOR THE APPROPRIATE FUEL CHANNEL IN EACH COLUMN ARE TAKEN FOR 2 YEAR

EGCR BOWING CALCULATIONS

TASK 227 APP. 7.

SIMILAR TO

DR'N RRN

CH'D PVG 6/21/60

APP'D

SCALE = 12

SHEET 21 OF 27

ISSUE

ALLIS-CHALMERS MFG. CO.

DEPT.

NPD-W

JAN 15, 1960

INTERVALS FROM THE SAME PROCEDURE AS DESCRIBED ABOVE.
 APPROPRIATE FUEL CHANNEL DATA IS TAKEN FROM APPENDIX 6.
 THE DESIGNATION OF CORNERS A & ^{POINT}B MAY CHANGE LOCATION IN
 COLUMN TO SUIT DIRECTION OF BOWING.

$$\sigma_{L=1} = 478 (.5) \left(\frac{2.17}{2.73} \right) \left(\frac{\text{EXP.}}{1.37} \right)$$

$$\sigma_{L=1} = 267 (.5) \left(\frac{2.17}{2.73} \right) \left(\frac{\text{EXP.}}{1.37} \right)$$

THESE APPROXIMATIONS ARE TO BE BASED ON TWO YEAR INTERVALS
 AND ALL BOWING STRESSES ARE TO BE BASED ON BOWS CALCULATED
 WITH THE MODIFIED LINEAR COMPONENT OF SHRINKAGE GRADIENT
 FOR $U = 0.8$.

A SUMMARY OF RESULTS ARE ON PP 25-26.

EGCR BOWING CALCULATIONS
 TASK 227 APP. 7

SIMILAR TO

DR'N	RRN	CH'D	PV6 6/24/60	APP'D	(Signature)	SCALE	=12	SHEET	22	OF	27	ISSUE
ALLIS-CHALMERS MFG. CO.						DEPT.		NPD-W		JAN 15, 1960		

DRN	YEAR END	TRANSVERSE SHRINKAGE	AVAILABLE GAP		MODIFIED EXPOSURE BOWING		RESTRAINED BOWING		STRESS				FOR CORNER (1-4) Max Pt. STRESS (+)	TAN-MOD. 106
			x	y	Δx	Δy	x	y	ON STOE					
									1	2	3	4		
RRN	0	0	.060	.060	0	0	0	0	0	0	0	0	0	1.82
	1	.0019	.061	.061	.046	.069	0	.008	23	0	23	0	23	1.82
	2	.0038	.063	.062	.091	.138	.028	.076	195	72	195	72	267	1.82
	3	.0057	.064	.064	.137	.207	.073	.143	368	188	368	188	556	1.82
	4	.0076	.065	.065	.181	.276	.116	.211	542	298	542	298	840	1.82x
	5	.0085	.067	.066	.227	.345	.160	.279	717	411	717	411	1128	1.82x
	6	.0114	.068	.067	.272	.414	.204	.348	895	525	895	525	1420	1.82x
	7	.0133	.070	.069	.318	.483	.248	.414	1060	638	1060	638	1698	1.82x
	8	.0152	.071	.070	.363	.552	.292	.482	1234	752	1234	752	1986	1.82x
	9	.0171	.072	.071	.409	.621	.337	.550	1409	876	1407	876	2283	1.82x
	10	.0190	.074	.072	.455	.690	.381	.618	1567	990	1567	990	2657	1.82x
	11	.0209	.075	.074	.501	.759	.426	.685	1716	1106	1716	1106	2822	1.80x
	12	.0228	.076	.075	.546	.828	.470	.753	1862	1218	1862	1218	3090	1.78x
	13	.0247	.078	.076	.592	.897	.514	.821	1995	1326	1995	1326	3321	1.72x
	14	.0266	.079	.077	.637	.966	.558	.919	2126	1428	2126	1428	3654	1.63x
	15	.0285	.080	.078	.683	1.035	.603	.957	2245	1529	2245	1529	3794	1.58x
	16	.0304	.082	.080	.728	1.104	.646	1.024	2360	1624	2360	1624	3984	1.54x
	17	.0323	.083	.081	.774	1.173	.691	1.092	2474	1716	2474	1716	4198	1.50x
	18	.0342	.084	.082	.819	1.242	.735	1.160	2583	1790	2583	1790	4373	1.38x
	19	.0361	.086	.083	.865	1.311	.779	1.228	2688	1875	2688	1875	4663	1.35x
	20	.0380	.087	.085	.91	1.380	.823	1.295	2785	1958	2785	1958	4743	1.32x

EGCR BOWING CALCULATIONS

Task 227 APR 7.

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SIMILAR TO

CH.D.P. 6/21/60

AP.D. [initials]

SCALE

SHEET 23 OF 27

ISSUE

ALLIS-CHALMERS MFG. CO. DEPT. NPD-W

JAN 15, 1960

A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

STRESS ACCUMULATION IN COLUMN (#94)

SUBJECT TO GREATEST BOWING (x+y)

DUE TO RESTRAINED BOWING

NOTE: (1) E_h (INITIAL) IS TAKEN AS 1.82x10⁶ NOT 1.5x10⁶ WHICH WAS USED AS AN AVERAGE VALUE WHEN STEP-WISE PROCEDURE WAS NOT FOLLOWED.

(2) U=0.8

CORNER (1-4)

STRESS ACCUMULATION IN COLUMN (#94)
SUBJECT TO GREATEST BOWING (x+y)
DUE TO RESTRAINED BOWING

NOTE: (1) E_N (INITIAL) IS TAKEN AS 1.82x10⁶ NOT 1.5x10⁶ WHICH WAS USED AS AN AVERAGE VALUE WHEN STEP-WISE PROCEDURE WAS NOT FOLLOWED.

(2) $u = 0.8$

DRN L D H REN	CH'D PVG 6/24/60	APP'D	SCALE = 12	SHEET 24 OF 37	ISSUE	YEAR END 71	$\frac{\Delta L}{L}$ 1000 MWD/RT	TENSION $U = 0.8 \quad r = 2.625$			COMPRESSION $U = 0.8 \quad r = 4.49$			.73 X (1-4) STRESS FROM PREC. PG.	σ_A	σ_B
								E TAN. MOD 10 ⁶ PSI	σ_z	$\Sigma \sigma_z$	E TAN. MOD. 10 ⁶ PSI	σ_z	$\Sigma \sigma_z$			
EGCR Bowing Calculations TASK 227 App. 7 1 C 7						0	.000125	1.35	0	0	1.35	0	0	0	0	0
						1		1.35	76	76	1.35	43	43	17	-20	+93
						2		1.35	76	152	1.35	43	86	195	+191	+377
						3		1.35	76	228	1.35	43	129	416	+427	+129
						4		1.35	76	304	1.35	43	172	613	+668	+644
						5		1.35	76	380	1.35	43	215	848	+913	+545
						6		1.34	75	455	1.35	43	258	1035	+1228	+917
						7		1.32	74	529	1.35	43	301	1240	+1490	+785
						8		1.31	73	602	1.35	43	344	1375	+1769	+1228
						9		1.29	72	674	1.34	43	387	1600	+2052	+1490
						10		1.27	71	745	1.33	42	429	1790	+2344	+1769
						11		1.24	69	814	1.32	42	471	1940	+2615	+2052
						12		1.22	68	882	1.31	42	513	2180	+2874	+2344
						13		1.20	67	949	1.30	41	554	2350	+3132	+2615
						14		1.19	67	1016	1.29	41	595	2520	+3369	+2874
						15		1.17	66	1082	1.28	41	636	2660	+3606	+3132
						16		1.16	65	1147	1.27	40	676	2790	+3842	+3369
						17		1.14	64	1211	1.26	40	716	2940	+4057	+3606
						18		1.11	62	1273	1.24	39	755	3070	+4271	+3842
						19		1.09	61	1334	1.23	39	794	3210	+4463	+4057
						20		1.07	60	1394	1.22	39	833	3350	+4674	+4271

STRESS AT CORNER EQUAL TO FROM PRECEDING PG. MINUS σ_z

STRESS AT CHANNEL SURFACE EQUAL TO .73 X (1-4) FROM PRECEDING PAGE PLUS σ_z

STRESS ACCUMULATION IN COLUMN (#94)
SUBJECT TO GREATEST BOWING (x+y)
COMPUTED FROM CYLINDRICAL
ANISOTROPIC STRESS MODEL
OF THE CHANNEL W/ MAX. FAST FLUX
PLUS BOWING STRESSES

A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

STRESS AT CORNER EQUAL TO
FROM PRECEDING PG. MINUS σ_z

STRESS Accumulation IN COLUMN (#94)
SUBJECT TO GREATEST BOWING (x+y)
COMPUTED FROM CYLINDRICAL
ANISOTROPIC STRESS MODEL
OF THE CHANNEL W/ MAX. FAST FLUX
PLUS BOWING STRESSES

STRESS AT CHANNEL
SURFACE EQUAL TO
.73 X (1-4) FROM PRE-
CEDING PAGE PLUS
 σ_z

COLUMN No.			67		68		69		70		71		72		80		81		82		83	
YEAR	MAX. STRESS POINT	STRESS LOCATION	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
2	(1-4) 67 (1-2) 79 (3-4)	BOWING STRESS	21	15	11	8	62	45	355	259	246	180	12	9	0	0	246	180	398	290	199	145
		INTERNAL STRESS	-204	366	-212	380	-206	368	-162	291	-	365	-	-	-204	365	-188	336	-142	254	-	-
		TOTAL STRESS	-183	381	-201	388	-144	413	193	450	246	180	12	9	-204	365	58	516	256	544	199	145
4			42	30	22	16	124	90	710	518	492	360	24	18	0	0	492	360	796	580	398	290
			408	730	-424	757	-412	736	-324	562	-	427	-	-	-408	727	-376	672	-274	508	-	-
			-366	760	-402	773	-284	826	386	1100	492	360	24	18	-408	727	116	1032	512	1084	398	290
6			63	45	33	24	186	135	1065	777	738	540	36	27	0	0	738	540	1194	870	597	435
			-609	1066	-633	1106	-445	1074	-466	860	-	1063	-	-	-609	1063	-563	988	-426	754	-	-
			-546	1111	-600	1130	-429	1209	579	1637	738	540	36	27	-609	1063	195	1828	768	1624	597	435
8			84	60	44	32	248	180	1420	1036	984	720	48	36	0	0	984	720	1592	1160	796	580
			-809	1380	-834	1430	-612	1390	-643	1120	-	1327	-	-	-804	1377	-743	1281	-566	987	-	-
			-725	1440	-790	1462	-564	1570	777	2156	984	720	48	36	-804	1377	241	2001	1026	2147	796	580
10			105	75	55	40	310	225	1795	1295	1230	900	60	45	0	0	1230	900	1990	1450	995	725
			-988	1670	-1026	1718	-498	1674	-797	1363	-	1666	-	-	-988	1666	-916	1552	-702	1209	-	-
			-878	1745	-971	1758	-688	1904	978	2658	1230	900	60	45	-988	1666	314	2452	1258	2659	995	725
12			126	90	66	48	372	270	2130	1554	1476	1080	72	54	0	0	1476	1080	2388	1740	1894	870
			-1166	1908	-1208	1955	-1178	1919	-944	1593	-	1	-	-	-1166	1904	-1083	1793	-833	1415	-	-
			-1040	1998	-1142	2003	-806	2189	1196	3147	1476	1080	72	54	-1166	1904	393	2873	1555	3155	1194	870
14			147	105	77	56	434	315	2485	1818	1722	1260	84	63	0	0	1722	1260	2986	2030	1893	1015
			-1337	2087	-1381	2141	-1350	2099	-1086	1800	-	-	-	-	-1337	2083	-1243	1987	-961	1606	-	-
			-1290	2192	-1304	2197	-916	2414	1399	3613	1722	1260	84	63	-1337	2083	479	3247	1825	3636	1393	1015
16			168	120	88	64	496	360	2840	2072	1968	1440	96	72	0	0	1968	1440	3184	2320	1592	1860
			-1499	2233	-1548	2291	-1513	2246	-1224	1968	-	-	-	-	-1499	2230	-1396	2149	-1085	1779	-	-
			-1331	2353	-1460	2355	-1017	2606	1616	4040	1968	1260	96	72	-1499	2230	568	3589	2099	4099	1592	1160
18			189	135	99	72	558	405	3195	2331	2214	1620	108	81	0	0	2214	1620	3582	2610	1791	1305
			-1649	2351	-1700	2427	-1663	2380	-1356	2108	-	-	-	-	-1649	2368	-1544	2281	-1206	1933	-	-
			-1460	2486	-1601	2499	-1205	2785	1839	4439	2214	2214	108	81	-1649	2368	670	3901	2246	4543	1791	1305
20			210	150	110	80	620	450	3550	2590	2460	1800	120	90	0	0	2350	1800	3980	2900	2180	1450
			-1782	2473	-1836	2537	-1797	2500	-1483	2286	-	-	-	-	-1782	2490	-1679	2401	-1322	2057	-	-
			-1572	2623	-1724	2617	-1177	2950	2067	4816	2460	1800	120	90	-1782	2490	671	4201	2658	4487	2130	1450

EGCR BOWING CALCULATIONS

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SIMILAR TO

DRN RRM LON

CHD PIV. 6/21/60

APPD. 6/21/60

SCALE

=12

SHEET 28 OF 27

ISSUE

ALLIS-CHALMERS MFG. CO.

DEPT.

NRD-W

A-C MFG. CO. MILWAUKEE, WIS. FORM NO. 6833-3

JAN 15, 1960

COLUMN No.			84		93		94		95		96		105		106							
YEAR	MAX. STRESS POINT	STRESS LOCATION	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
2		BOWING STRESS	12	9	420	316	452	330	144	105	8	6	94	69	19	14						
		INTERNAL STRESS	—	—	-142	254	-86	152	—	—	—	—	—	—	—	—						
		TOTAL STRESS	12	9	278	570	366	482	144	105	8	6	94	69	19	14						
4			24	18	840	632	904	660	288	210	16	12	188	138	38	28						
			—	—	-284	508	-172	304	—	—	—	—	—	—	—	—						
			24	18	556	1140	732	964	288	210	16	12	188	138	38	28						
6			36	27	1260	948	1356	990	432	315	24	18	282	207	57	42						
			—	—	-426	754	-258	455	—	—	—	—	—	—	—	—						
			36	27	834	1702	1098	1445	432	315	24	18	282	207	57	42						
8			48	36	1680	1264	1808	1320	576	420	32	24	376	276	76	56						
			—	—	-566	987	-374	602	—	—	—	—	—	—	—	—						
			48	36	1114	2251	1434	1922	576	420	32	24	376	276	76	56						
10			60	45	2100	1560	2260	1650	720	525	40	30	470	345	95	70						
			—	—	-702	1209	-459	745	—	—	—	—	—	—	—	—						
			60	45	1398	2769	1801	2395	720	525	40	30	470	345	95	70						
12			72	54	2520	1996	2712	1980	864	630	48	36	564	414	114	84						
			—	—	-833	1415	-543	882	—	—	—	—	—	—	—	—						
			72	54	1687	3311	2169	2862	864	630	48	36	564	414	114	84						
14			84	63	2940	2112	3164	2310	1008	735	56	42	658	483	133	98						
			—	—	-961	1606	-625	1016	—	—	—	—	—	—	—	—						
			84	63	1979	3818	2539	3326	1008	735	56	42	658	483	133	98						
16			96	72	3360	2528	3616	2640	1152	840	64	48	752	552	152	112						
			—	—	-1085	1779	-706	1147	—	—	—	—	—	—	—	—						
			96	72	2275	4307	2910	3787	1152	840	64	48	752	552	152	112						
18			108	81	3780	2844	4068	2970	1296	945	72	54	846	621	171	126						
			—	—	-1206	1933	-785	1273	—	—	—	—	—	—	—	—						
			108	81	2574	4777	3283	4243	1296	945	72	54	846	621	171	126						
20			120	90	4200	3160	4520	3300	1520	1050	80	60	940	690	190	140						
			—	—	-1322	2057	-863	1394	—	—	—	—	—	—	—	—						
			120	90	2978	5217	3657	4694	1520	1050	80	60	940	690	190	140						

EGCR BOWING CALCULATIONS
TASK 227 APP.7

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SIMILAR TO

DR. N	RRN	LOH	CH. D	PVC	6/21/60	APP. D	AND	SCALE	= 12	SHEET	28 OF 27	ISSUE	
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A

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WEIGHTING FACTORS (W.F.) ARE THE RATIO OF THE AREA ABOUT A NODAL POINT TO THE AREA ENCLOSED BY ONE SQUARE OF THE NET. THERE ARE 5 WEIGHTING FACTORS FOR THIS CONFIGURATION. SEE SHADED AREAS BELOW.
(ALSO SEE p 11-13. THIS APPENDIX)

AREA TYPE
A : 0.25
B : 0.50
C : 0.66
D : 0.22
E : 1.0

AVERAGING FACTORS = $\Sigma W.F.$ ABOUT A NODAL POINT. THERE ARE 14 COMBINATIONS OF WEIGHTING FACTORS LISTED BELOW.

JOINT TYPE
1. - 1.25
2. - 1.91
3. - 1.72
4. - 2.16
5. - 2.50
6. - 2.10
7. - 2.04
8. - 2.60
9. - 3.82
10. - 2.54
11. - 3.44
12. - 3.10
13. - 4.32
14. - 5.00

*Indicates cross-section to which distribution applies

BASE LINE FOR EXPOSURE

RELATIVE SHRINKAGE DISTRIBUTIONS
FOR COLUMN NO. 70

Task 207 App 7
EGCR BOWLING GALS.
P. 27.
JAN 15, 1960

R2W
LON

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APPENDIX 8

ANALYSIS OF CREEP TESTS PERFORMED BY ALLIS-CHALMERS
ON AGOT-TYPE GRAPHITE

PREFACE

The purpose of this appendix is to analyze data from creep tests performed in the Allis-Chalmers Laboratory and to apply the test results to the EGCR graphite to determine the effects of creep on life of selected core columns.

Using the test data, a value of creep rate is determined. Using the highest neutron flux exposure value computed in appendix 6, a radiation induced strain rate is determined. The radiation induced strain rate is shown to be no greater than the creep rate.

Using the test data, a value of rupture strain is determined. Using the maximum radiation-induced strain rate, the time to reach rupture strain is determined.

Individual column lifetimes are predicted based on a rupture strain of 0.06%.

APPENDIX 8

ANALYSIS OF CREEP TESTS PERFORMED BY ALLIS-CHALMERS
ON AGOT-TYPE GRAPHITE

1. This Appendix includes calculations which analyze the results of creep tests performed by Allis-Chalmers on nuclear-quality graphite. The calculations are intended to:

a. Determine the maximum strain-at-failure in tension due to creep.

b. Determine creep rates which occur at various times in the tests.

c. Compare the maximum strain-at-failure with the maximum strains which are expected to develop in EGCR graphite as a result of differential (i.e., non-uniform) irradiation-induced shrinkage over 20 years of core life, to show whether strain failure will occur.

d. Compare the creep rate with the rate at which strain (i.e., differential shrinkage) is expected to develop in the EGCR. If the comparison demonstrates that a limiting stress exists at which the 2 rates are equal, there should be no net change in fiber length once the limiting stress is reached.

The calculations indicate the maximum strain-at-failure of AGOT graphite to be at least 0.06%. This compares favorably with the preliminary value of 0.08% transmitted by ORNL.* Based on a plant utilization factor of 0.8, this calculated value, compared to the maximum strain which can be expected in EGCR (0.09%), indicates a minimum life (for the column subjected to greatest strain) of 14 years. Other columns will have significantly longer lives.

For tensile stresses in the range of 550 to 750 psi, the minimum creep rate at room temperature was calculated as 2.3×10^{-8} in./in./hr and at 800 F as 3.7×10^{-7} in./in./hr. Compared with the maximum rate of strain accumulation in the worst EGCR column (3.8×10^{-8} in./in./hr), the calculated rate appears adequate to limit graphite tensile stresses to below 1000 psi. Therefore, the estimate of maximum expected stress (900 to 1300 psi), as noted in Appendix 4, appears confirmed.

From results of this test, exclusively, the maximum strain rather than the maximum stress cannot necessarily be taken as the criterion of graphite failure in the EGCR. From this

* Informal Communication, January 1960

test an average minimum column life of 14 years should be expected. Because the stress in EGCR builds up from zero and is not at a constant high level, as in this series of tests, this predicted minimum life is certainly conservative (creep rate and strain being sensitive functions of stress).

This predicted life is based primarily on the average exposures at the surfaces of fuel channels in the plane of peak axial flux. Comparing this with the "average" life of all columns shown in Figure V of Appendix 9, based on the maximum allowable stress (i.e., approximately 13.3 years), one sees little difference in the two criteria. However, assuming that the peak flux on fuel channel surfaces is about 1.3 times the average, a minimum life based on the maximum allowable strain would be about 10.8 years. Comparing this value with the minimum life of Appendix 9 for roughly the same column (i.e., about 8 years), it appears that the maximum allowable stress governs. But since the creep rates calculated in this report indicate that stress will level out somewhere below 1000 psi, and since the strain will continue to accumulate, the conclusion is reached that the maximum allowable strain is ultimately the governing criterion. The minimum column life is then about 10.8 years and the average about 14 years. These are felt to be very conservative estimates, because they are based on the most pessimistic estimates (perhaps high by a factor of two) of the strains which will actually develop in the EGCR.

2. A series of tests have been conducted by Allis-Chalmers to determine the creep characteristics of nuclear-grade graphite. To simulate the type of stress pattern which is expected to develop in EGCR graphite (see Appendices 3 and 7), the tests were performed on graphite beams $3/4$ in. x $3/4$ in. x 24 in., using standard ASTM third-point loading. The flexural stresses developed simulated the changes from tension to compression which occur over the cross sections of EGCR columns. Tests were conducted at room temperature and at 800 F. Applied loads were constant and of a magnitude sufficient to produce maximum flexural stress (computed elastically) in the neighborhood of 750 psi, roughly corresponding to lower limits of the expected limiting stress estimated for EGCR graphite (see Appendix 4).

3. Details of the testing procedure are contained in a separate report. The deflections at several points along the beam length were measured several times over a period of weeks. The deflections at any one point were found to increase significantly with time, both at room temperature and at 800 F, indicating the presence of creep. The high-temperature tests were continued to failure with rupture occurring at the points of loading. Room temperature tests are continuing. Deflections of the high-temperature specimens were considerably greater than those of room-temperature specimens; hence the fracture of

the high-temperature specimen would be expected first, as has occurred. However, it is thought that some necessary movements of specimens may have inadvertently contributed to premature failure of the high-temperature specimens; consequently, it is felt that any maximum strains-at-failure computed in this report are conservative.

4. The method of analysis used to treat the experimental data was generally one of fitting a curve to simultaneous deflections of selected points along the beam length. (As a preliminary to fitting the curves, the experimental data for any one beam were all adjusted to a single reference line.) The equation selected for fitting was a third-degree polynomial because the form of the equation defining elastic deflection is cubic. Successive differences for the data points of several test specimens revealed no great advantage in higher-or lower-degree equations. Arbitrary constants required to fit the selected points are determined by writing and expanding the determinant equation. With the constants known, the successive derivatives can be found. The strain at any point on the beam's extreme fiber can be found from the relation: $\epsilon = d^2y/dx^2$. Because of the way in which the cubic relation fits the actual curve of the beam, use of this relation is restricted arbitrarily to portions of the beam where the fit is closest.

In determining the maximum strain, only the point of known failure was considered for the high-temperature specimens. With the proper abscissa value inserted in the second derivative of the fitted equation, the strain at failure can be found. The creep rate, which is a function of stress level, is found by determining the creep strain (as above) at any one point for several times during the test duration. A plot of the strains versus time can be used to find the creep rate by graphically determining the slope. The effect of stress on creep rate is handled in this analysis by determining a range of stress within which the actual stress in the beam will probably lie. Use of a range is necessary because the exponential effect of stress on creep is not explicitly known for EGCR graphite.

ANALYSIS OF CREEP DATA OBTAINED
BY ALLIS-CHALMERS RESEARCH & DEVELOPMENT LAB

TABLES I THROUGH IV PRESENT THE RELATIVE CREEP DEFLECTIONS OF SPECIMENS 1, 2, 4, & 5 AS ABSTRACTED FROM THE DATA ORIGINALLY RECORDED BY THE R&D STAFF. THE ORIGINAL DATA HAS BEEN MODIFIED SO THAT ALL DATA FOR ANY ^{ONE} SPECIMEN IS RELATIVE TO ONE REFERENCE LINE.

IT IS PROPOSED TO FIND (a) THE MAXIMUM CREEP STRAIN THAT GRAPHITE CAN UNDERGO WITHOUT STRUCTURAL FAILURE AND (b) THE VARIATION OF CREEP RATE WITH TIME ^{AT} ANY STRESS.

FOR (b) THE DATA FROM TABLES I AND IV ARE GRAPHED (FIG. I & FIG. II) AND 1 SMOOTH CURVES DRAWN TO ELIMINATE SOME OF THE IRREGULARITIES OF ORIGINAL DATA. THESE GRAPHS ARE FOR ONE HOT SPECIMEN AND ONE COLD SPECIMEN TO BE REPRESENTATIVE OF THE VARIOUS TESTS PERFORMED. THE GENERAL PROCEDURE WILL BE TO:

1. SUBTRACT THE ORDINATES OF HIGHEST CURVE (I.E. ORIGINAL STRAIGHTNESS PLUS UNLOADED SAG) FROM THOSE OF ANOTHER CURVE, USE THESE AS ORDINATES REPRESENTING STRAINED CONDITION.
2. BY METHOD OF SELECTED POINTS AND SUCCESSIVE DIFFERENCES FIT A POLYNOMIAL TO THE SECOND CURVE.
3. FIND, FOR THE ~~FIVE~~ POINTS OF THE MIDDLE THIRD OF BEAM AND FOR MIDPOINTS OF THE END THIRDS, THE SECOND DERIVATIVE OF THE FITTED EQUATION.
4. ON THE ASSUMPTION THAT ^{TRANSVERSE} PLANES REMAIN PLANE AFTER BENDING, ^{TOTAL} FIND THE LONGITUDINAL STRAIN (AT THE FIVE SELECTED POINTS) FOR THE SECOND CURVE: $\epsilon_x = \frac{w}{L} \frac{d^2 y}{dx^2}$ WHERE W IS BEAM DEPTH
- 5.* SINCE THE TEST SET-UP DID NOT ALLOW FOR MEASUREMENT OF THE ORIGINAL LOADED ELASTIC CURVE, ^{ONE MIGHT} COMPUTE THE ORIGINAL STRAIN WITH BENDING MOMENTS AND MOMENT OF INERTIA USED AS IN NORMAL ELASTIC PROBLEMS USING A TYPICAL VALUE OF GRAPH-^{ITE} MODULUS OF ELASTICITY AT THE APPROPRIATE TEMPERATURES.
* COMPUTE THE NOMINAL STRESS (AT SELECTED POINTS) ON THE SAME BASIS.
* (BECAUSE CREEP MEASURES WERE MADE WITH THE BEAM UNLOADED, THIS STEP

ANALYSIS OF A.C. CREEP TESTS ON EGCR
GRAPHITE

TASK 227
APPENDIX 8

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DR'N R.R.N.	CH'D PVG 6/6/60	APP'D <i>[Signature]</i>	SCALE = 12	SHEET 1 OF 45	ISSUE
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SHOULD NOT BE NECESSARY).

6. FIND THE ^{NET} STRAIN DUE TO CREEP. PLOT, FOR STRAINS AT ANY ONE POINT (I.E. AT ANY ONE NOMINAL STRESS), THE NET STRAIN VERSUS TIME. THE VARIOUS SLOPES SHOULD GIVE CREEP RATE VERSUS TIME AS DESIRED

NOTE THAT STEP 5, IMPLIES $n=1$ IN THE RELATION $\epsilon_{\text{CREEP}} = K\sigma^n$ (WHERE K IS A CONSTANT) SO THAT I_c (TAKING INTO ACCOUNT CREEP EFFECTS) IS THE NORMAL CROSS-SECTION MOMENT OF INERTIA. THE VALUE OF n IS NOT KNOWN BUT, IF TIME PERMITS, STEPS 5 & 6 COULD BE DONE FOR A SERIES OF VALUES OF n TO TEST SENSITIVITY TO THIS EFFECT. (REF. "CREEP OF ENGINEERING MATERIALS" FINNIE & HELLER p 136-138)

FOR (a) THE MAXIMUM STRAIN WILL BE FOUND FROM THE FITTED CURVES FOR SPECIMEN #5 SINCE THIS SPECIMEN ^{ONLY} HAS FAILED. AT THE LAST MEASUREMENTS PRIOR TO FAILURE THE BEAM WAS AS SHOWN FOR 4/11/60 (FIG II). SINCE THE BEAM FAILED ON 4/22/60, ANY ^{COMPUTED} MAXIMUM STRAIN SHOULD BE CONSERVATIVE. PROCEEDURE IS TO:

- (1) TAKE TOTAL ORDINATES OF CURVE FOR 4/11/60, AND BY METHOD OF SELECTED POINTS FIT A POLYNOMIAL TO CURVE
- (2) FIND THE $\frac{d^2y}{dx^2}$ MAX
- (3) FIND MAX. TOTAL STRAIN FROM $\epsilon = w \frac{d^2y}{dx^2}$ ASSUMING ^{TRANSVERSE} PLANES REMAIN PLANE AFTER BENDING (WHERE w IS THE DEPTH OF BEAM) (THIS ASSUMES THAT y -COORDINATES OF ORIGINAL STRAIGHTNESS OF BEAM ARE SMALL RELATIVE TO THOSE AT TIME OF FAILURE)

THE DEGREE OF POLYNOMIAL CHOSEN TO FIT THE SMOOTHED DATA POINTS COULD BE TAKEN AS 3. TABLES I, II, & III, SHOW SUCCESSIVE DIFFERENCES TAKEN FROM ORDINATES OF CURVES FOR SPECIMEN #5 SHOW NO STRONG CONVERGENCE OF THIRD DIFFERENCES, BUT CONVERGENCE OF THIRD DIFFERENCE APPEARS AS GOOD AS THAT OF HIGHER OR LOWER DIFFERENCES. SINCE STANDARD ELASTIC DEFLECTION FORMULAS (ROARK "FORMULAS FOR STRESS AND STRAIN" p 102) SHOW

ANALYSIS OF CREEP TESTS FOR EGCR

TASK 22J
APP. 8

SIMILAR TO

DR'N RRM	CH'D PVG 6/16/60	APP'D <i>[Signature]</i>	SCALE = 12	SHEET 2 OF 45	ISSUE
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DEFLECTION TO BE A 3RD POWER FUNCTION OF THE OTHER COORDINATE, THE 3RD POWER ^{COULD} BE CHOSEN FOR CREEP DEFLECTION POLYNOMIAL. IT MAY BE THAT AN EXPONENTIAL OR TRANSCENDENTAL EXPRESSION WOULD BETTER FIT THE DEFLECTED CURVES IN LATER STAGES OF TEST (FOR EXAMPLE PERHAPS A CATENARY) BUT IN THE INTEREST OF ^{OBTAINING} AN ESTIMATE OF STRAINS AS QUICKLY AS POSSIBLE THE POLYNOMIAL IS CHOSEN FOR FIRST TRIAL

ALTHOUGH THIRD DEGREE EQUATION CAN BE BETTER FITTED TO POINTS ON THE REAL CURVE, A SECOND DEGREE EQUATION MIGHT BETTER FIT THE OVERALL REAL DEFLECTED SHAPE. THIS SIMPLER EQUATION WILL ALSO BE TRIED FOR FIT AND, IF AS GOOD AS THE CUBIC, WILL BE USED, SINCE IT PROBABLY WILL APPLY TO ALL PARTS OF THE DEFLECTED SHAPE WHEREAS THE CUBIC MAY HAVE POINTS OF INFLECTION NOT PRESENT IN THE REAL BEAM.

ANALYSIS OF CREEP TESTS FOR EQCR

TASK 227
APP. 8.

SIMILAR TO

DR'N R. R. M.	CH'D P16 6/16/60	APP'D	SCALE = 12	SHEET 3 OF 45	ISSUE
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DETERMINING THE CONSTANTS OF EQUATION
FOR FITTING CURVE OF MAXIMUM SAG IN SPECIMEN #5

WITH THE ASSUMED RELATION

$$-y + a + bx + cx^2 + dx^3 = 0$$

THE FOLLOWING POINTS ARE FOUND FROM THE GRAPH OF DATA FOR 4/11/60
(FROM FIG II): WHEN $x = 4"$, $y = -.0594"$

$$x = 10", y = -.0995"$$

$$x = 14", y = -.0958"$$

$$x = 18", y = -.0607"$$

FOLLOWING WORTHING & GEFFNER "TREATMENT OF EXPERIMENTAL DATA" p. 68
FOR DETERMINING COEFFICIENTS BY THE METHOD OF SELECTED POINTS, THE
DETERMINANT EQUATION IS:

$$\begin{vmatrix} -y & 1 & x & x^2 & x^3 \\ .0594 & 1 & 4 & 16 & 64 \\ .0995 & 1 & 10 & 100 & 1000 \\ .0958 & 1 & 14 & 196 & 2744 \\ .0607 & 1 & 18 & 324 & 5832 \end{vmatrix} = 0$$

AND EXPANSION IS

$$-y \times 1 \times 10 \times 196 \times 5832 = -11,430,720y$$

$$.0594 \times 1 \times 14 \times 324 (x^3) = 269x^3$$

$$.0995 \times 1 \times 18 \times 64 (x^2) = 114x^2$$

$$.0958 \times 1 \times 1000 \times 16 (x) = 1532x$$

$$.0607 \times 2744 \times 100 \times 4 \times 1 = 66624$$

$$-(x^3) 16 \times 10 \times 1 \times .0607 = -9.7x^3$$

$$64 \times 100 \times 14 \times 1 \times y = 89600y$$

$$-1000 \times 196 \times 18 \times .0594 \times 1 = -209,563$$

$$-2744 \times 324 \times .0995 \times 1 (x) = -88461x$$

$$-5832 \times .0958 \times 1 \times 4 (x^2) = -2235x^2$$

FROM WHICH, THE EQUATION IS:

ANALYSIS OF CREEP TESTS FOR EGCK

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APP. 8.

SIMILAR TO

DR'N R.R.H.	CH'D PVG 6/16/60	APP'D <i>[Signature]</i>	SCALE = 12	SHEET 4 OF 45	ISSUE
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$$0 = -11,341,120y - 142,939 - 86,929x - 2121x^2 + 259x^3$$

OR

$$y = -.0126 - .00766x - .000187x^2 + .0000228x^3$$

TESTING FOR FIT AT $x=4$

$$y(4) = -.0126 - .03064 - .00299 + .00146 = -.0447 \quad \text{VS. THE GRAPH VALUE OF } y(4) = -.0594$$

AND AT $x=14$

$$y(14) = -.0126 - .107 - .0366 + .0626 = -.0936 \quad \text{VS. GRAPH VALUE OF } y(14) = -.0958$$

OTHER CALCULATED POINTS ARE

$x=0$	$y = -.0126$	VS. ———
$x=1$	$y = -.0204$	-.0255
$x=10$	$y = -.0851$	-.0895
$x=12$	$y = -.0921$	-.1010
$x=20$	$y = -.058$	-.0860
$x=22$	$y = -.0297$	-.0080

THE EQUATION OF ^{1ST} DERIVATIVE IS USED TO FIND THE LOW POINT OF FITTED CURVE

$$\frac{dy}{dx} = 0 = -.00766 - .000374x - .0000684x^2$$

COMPLETING THE SQUARE

$$684x^2 - 3740x - 76600 = 0$$

$$x^2 - 5.469x + \left(\frac{5.469}{2}\right)^2 = 112 + \left(\frac{5.469}{2}\right)^2$$

$$x - \frac{5.469}{2} = \sqrt{112 + 7.47}$$

$$x = \pm 10.93 + 2.734$$

$$x = +13.66 \text{ OR } -8.20$$

IT SHOULD BE NOTED THAT, BECAUSE OF THE THIRD DEGREE TERM, THE FITTED EQUATION HAS A POINT OF INFLECTION IN THE VICINITY OF $x=3$ AND DOES NOT VERY WELL FIT THE REAL SHAPE OF THE BEAM ALTHOUGH IT WAS FITTED TO POINTS ON THE CURVE. THEREFORE, BECAUSE OF ROUGH SYMMETRY IN THE REAL DEFLECTED SHAPE, THE DETERMINATION OF REAL STRAIN FROM THE SECOND DERIVATIVE EQUATION SHOULD BE LIMITED TO VALUES OF $x \gg 8$, PREFERENCE BEING GIVEN TO DETERMINATIONS FROM RIGHT-HAND SIDE OF BEAM.

ANALYSIS OF CREEP TESTS FOR EGCR

TASK 227
APP. 8

SIMILAR TO

DR'N R.R.V.	CH'D PKG 6/16/60	APP'D <i>gmd</i>	SCALE = 12	SHEET 5 OF 45	ISSUE
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IN THE INTEREST OF SIMPLICITY IN OTHER, MORE EXTENDED, CALCULATIONS, A SECOND DEGREE EQUATION WILL ALSO BE FITTED TO THE 4/11/60 CURVE FOR COMPARISON. IF THE SECOND DEGREE CURVE WORKS AS WELL AS THE CUBIC, THE SIMPLER EQUATION WILL BE USED HENCEFORTH:

$$\begin{array}{ll} \text{WHEN } x = 4 & y = -.0594 \\ x = 12 & y = -.1010 \\ x = 16 & y = -.0805 \end{array}$$

THE DETERMINANT EQUATION IS (FOR $y = a + bx + cx^2$):

$$\begin{vmatrix} -y & 1 & x & x^2 \\ .0594 & 1 & 4 & 16 \\ .1010 & 1 & 12 & 144 \\ .0805 & 1 & 16 & 256 \end{vmatrix} = 0$$

THE EXPANSION IS:

$$\begin{aligned} & -y \times 1 \times 12 \times 256 + .0594 \times 1 \times 16 (x^2) + .1010 \times 1 \times 16 (x) + .0805 \times 144 \times 4 \times 1 \\ & - (x^2) \times 4 \times 1 \times .0805 + 16 \times 12 \times 1 \times y - 144 \times 16 \times .0594 \times 1 - 256 \times .1010 \times 1 (x) = 0 \\ & -285.0y + .628x^2 - 24.24x - 90.49 = 0 \\ & y = -.0314 - .00842x + .000218x^2 \end{aligned}$$

CALCULATED POINTS ARE

x = 0	y = -.0314	vs. -.0105	FROM GRAPH
x = 4	y = -.0616	" -.0594	
x = 10	y = -.0938	" -.0995	
x = 12	y = -.1010	" -.1010	
x = 16	y = -.1103	" -.0805	
x = 20	y = -.1126	" -.0355	

$$\frac{dy}{dx} = -.00842 + .000436x \quad \text{AND THE MIN. } y \text{ IS AT APPROX. } x = 19.4''$$

THIS CURVE IS PLOTTED IN FIG II, BUT, ALTHOUGH FITTING FAIRLY WELL IN LEFT MOST THIRD OF BEAM, IS INFERIOR TO THE CUBIC. HENCE THE CUBIC WILL BE USED FOR DETERMINING STRAINS, WITH ATTENTION BEING GIVEN TO THOSE AREAS WHERE THE SHAPE OF PLOTTED CUBIC DOES NOT CORRESPOND TO THE REAL SHAPE OF BEAM.

ANALYSIS OF CREEP TESTS FOR EGCR

TASK 227
APR 8

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DETERMINING THE STRAIN IN SPECIMEN
#5 AT LAST MEASUREMENT PRIOR TO FRACTURE

KNOWING THE EQUATION OF DEFLECTED CURVE OF SPECIMEN #5 ON 4/11/60 (THE LAST MEASUREMENT PRIOR TO FRACTURE OF THE BEAM) A CONSERVATIVE ESTIMATE OF THE MAXIMUM ALLOWABLE TOTAL STRAIN^(IN/IN) CAN BE OBTAINED FROM

$$\epsilon = \frac{w}{2} \frac{d^2y}{dx^2}$$

SINCE THE $\frac{d^2y}{dx^2}$ IS POSITIVE FOR INCREASING X (WITH COORDINATE DIRECTIONS AS SHOWN). THE ASSUMPTION IS MADE THAT THE GRAPHITE ACTS THE SAME IN CREEP UNDER TENSION AND UNDER COMPRESSION.

$$\begin{aligned} d\theta &= \frac{\epsilon dx}{\frac{w}{2}} \\ \frac{dy}{dx} &= \frac{\epsilon dx}{\frac{w}{2}} \\ \frac{d^2y}{dx^2} &= \frac{\epsilon}{\frac{w}{2}} \end{aligned}$$

SINCE $y = -.0126 - .00766x - .000187x^2 + .0000228x^3$
 $\frac{dy}{dx} = -.00766 - .000374x + .0000684x^2$
 $\frac{d^2y}{dx^2} = -.000374 + .0001368x$

THEREFORE FOR X NEAR THE MIDDLE OF BEAM WHERE MAXIMUM STRAIN UNDER LOAD IS TO BE EXPECTED

@ $x=10$ $\frac{d^2y}{dx^2} = -.000374 + .001368 = .000994$
 $x=12$ $= -.000374 + .001642 = .001268$
 $x=14$ $= -.000374 + .001915 = .001541$

IT WAS FOUND THAT FRACTURE OF SPECIMEN #5 OCCURRED AT POINTS OF LOAD, INDICATING THAT SOME UNKNOWN MECHANISM OR OCCURRENCE NOT MEASURED BY THE R&D TESTS EXISTED IN THE GRAPHITE. SINCE DATA DOES NOT REVEAL WHAT THIS MIGHT BE, WE WILL ALSO FIND THE NOMINAL STRAINS AT LOAD POINTS ($x=7$ & $x=15$); BECAUSE THE PECULIARITIES OF THE CUBIC EQUATION, THE VALUE OF STRAIN FOR $x=7$ WILL BE CALCULATED ONLY FOR REFERENCE.

ANALYSIS OF CREEP TESTS FOR EGCR

TASK 227
APP 8

SIMILAR TO

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$$@ x = 7 \quad \frac{dy}{dx} = - .000374 + .000957 = .000583$$

$$y = 15 \quad = - .000374 + .002053 = .001679$$

SINCE $w = .75"$, $w/2 = .375$ AND THE CORRESPONDING STRAINS ARE

@ $x = 10$	$\epsilon = .375 \times .000944 = .000373$	
$x = 12$	$\epsilon = .375 \times .001268 = .000476$	
$x = 14$	$\epsilon = .375 \times .001541 = .000579$	
$x = 7$	$\epsilon = .375 \times .000583 = .000219$	(REF. ONLY)
$x = 15$	$\epsilon = .375 \times .001679 = .000630$	

BECAUSE OF THE WAY THE POLYNOMIAL FITS THE MEASURED SHAPE OF THE DEFLECTED BEAM, PREFERENCE SHOULD BE GIVEN TO STRAIN VALUES CALCULATED FOR THE RIGHT HAND SIDE OF THE BEAM (I.E. FOR $x \geq 10$) IT IS FOUND THEREFORE THAT STRAIN VARIES FROM ABOUT .04% TO ABOUT .06%, THE HIGHER VALUE BEING FOR A POINT OF ACTUAL FAILURE. SINCE THE LAST AVAILABLE MEASUREMENT WAS ABOUT TWO WEEKS BEFORE ACTUAL FAILURE, THE ULTIMATE STRAIN IS UNKNOWN BUT .06% SEEMS A CONSERVATIVE NUMBER FOR MAXIMUM STRAIN. IT IS BELIEVED BY R. & D PERSONNEL CONDUCTING THE TESTS THAT IMPACT LOADS INVOLVED IN REMOVING AND INSERTING SPECIMENS IN THE FURNACE (AS WELL AS WHILE THE SPECIMEN WAS STATIONARY IN THE FURNACE) COULD HAVE CONTRIBUTED TO PREMATURE FAILURE; THUS, THE .06% FIG. SEEMS EVEN MORE CONSERVATIVE.

THE .06% MAXIMUM-STRAIN-TO-RUPTURE AS CALCULATED AGREES FAIRLY WELL WITH VALUES OBTAINED BY ORNL FOR SIMPLE TENSION AT HIGH TEMPERATURE. ORNL SHOWS .08% AT RUPTURE, IN CURVES RECEIVED FROM DR. MANLY (1/27/60) AT THE CORE DESIGN REVIEW MEETING OF ABOUT THAT DATE.

CONSIDERABLE OXIDATION OF THE ^{HIGH-TEMPERATURE} CREEP SPECIMEN OCCURRED. EXTERNAL DIMENSIONS WERE NOT AFFECTED BUT THERE WAS PITTING THAT APPARENTLY EXTENDED TO THE BEAM INTERIOR. SINCE SUCH PITTING WILL NOT OCCUR IN EGCR, THE TEST RESULTS ARE PROBABLY CONSERVATIVE FOR THIS REASON ALSO.

ANALYSIS OF CREEP TESTS FOR EGCR

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FITTING A CUBIC EQUATION TO SPECIMEN #4
LAST MEASUREMENTS PRIOR TO FRACTURE

AS A CHECK ON MAXIMUM STRAINS CALCULATED FOR SPECIMEN #5, THE LAST MEASUREMENTS PRIOR TO FRACTURE FOR SPECIMEN #4 ARE TAKEN FROM TABLE III AND PLOTTED ON FIG. II. THE PLOTTED POINTS ARE

x=0	y = -.0159
x=2	y = -.0346
x=4	y = -.0694
x=6	y = -.0861
x=8	y = -.1016
x=10	y = -.1094
x=12	y = -.1096
x=14	y = -.1022
x=16	y = -.0851
x=18	y = -.0746
x=20	y = -.0349
x=22	y = -.0162

A CUBIC EQUATION IS FITTED TO THE FOLLOWING POINTS FROM GRAPH

$\left. \begin{array}{l} x=6 \quad y = -.0885 \\ x=10 \quad y = -.1088 \\ x=14 \quad y = -.1015 \\ x=18 \quad y = -.0717 \end{array} \right\}$	$y = a + bx + cx^2 + dx^3$
--	----------------------------

FOLLOWING THE METHOD FOR SPECIMEN #5, THE DETERMINANT EQUATION IS

$$\begin{vmatrix} -y & 1 & x & x^2 & x^3 \\ .0885 & 1 & 6 & 36 & 216 \\ .1088 & 1 & 10 & 100 & 1000 \\ .1015 & 1 & 14 & 196 & 2744 \\ .0717 & 1 & 18 & 324 & 5832 \end{vmatrix} = 0$$

ANALYSIS OF CREEP TESTS FOR EGCR

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[Signature]

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THE EXPANSION IS:

$$\begin{aligned}
 -y \times 1 \times 10 \times 196 \times 5832 &= -11,430,720 y \\
 .0885 \times 1 \times 14 \times 324 (x^3) &= 401.4 x^3 \\
 .1088 \times 1 \times 18 \times 216 (x^2) &= 423 x^2 \\
 .1015 \times 1 \times 1000 \times 36 (x) &= 3654 x \\
 .0717 \times 2744 \times 100 \times 6 \times 1 &= 118,046 \\
 - (x^3) 36 \times 10 \times 1 \times .0717 &= -25.8 x^3 \\
 216 \times 100 \times 14 \times 1 \times y &= 302400 y \\
 - 1000 \times 196 \times 18 \times .0885 \times 1 &= -312,228 \\
 - 2744 \times 324 \times .1088 \times 1 (x) &= -96729 x \\
 - 5832 \times .1015 \times 1 \times 6 (x^2) &= -3551.7 x^2
 \end{aligned}$$

$$\begin{aligned}
 y &= -.0174 - .00836 x - .000281 x^2 + .0000337 x^3 \\
 \frac{dy}{dx} &= -.00836 - .000562 x + .0001011 x^2 \\
 \frac{d^2y}{dx^2} &= -.000562 + .0002022 x
 \end{aligned}$$

$$\therefore \text{THE POINT OF INFLECTION IS } x = \frac{.000562}{.0002022} \approx 2.8''$$

AS FOR SPECIMEN #5, THE FITTED CURVE DOES NOT EXACTLY MATCH THE ORIGINAL SHAPE IN ABSOLUTE ORDINATES BUT DOES PARALLEL THE ORIGINAL WITH A SIMILAR SHAPE. SINCE THE STRAIN IS TAKEN AS A FUNCTION OF $\frac{d^2y}{dx^2}$, THE FITTED CURVE SEEMS ADEQUATE. PREFERENCE IS AGAIN GIVEN TO RIGHT-HAND SIDE. THE FITTED CURVE IS PLOTTED IN FIG. II.

$$\begin{aligned}
 \frac{d^2y}{dx^2} @ x=10 &= -.000562 + .0002022 = .00146 \\
 x=14 &= -.000562 + .002282 = .00227 \\
 x=15 &= -.000562 + .00304 = .00244
 \end{aligned}$$

$$E_{10} = .375 \times .00146 = .000546$$

$$E_{14} = .375 \times .00227 = .00085$$

$$E_{15} = .375 \times .00244 = .000915 \quad (\text{POINT OF FAILURE})$$

IT WOULD APPEAR THAT THE .06% VALUE FROM SPECIMEN #5 IS CONFIRMED AND SHOWN CONSERVATIVE.

ANALYSIS OF CREEP TESTS FOR EGCR

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APP'D *gm*

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SIGNIFICANCE OF THE TOTAL STRAIN AT
RUPTURE RELATIVE TO EXPECTED STRAIN IN EGCR

FROM THE TABULATED RATES OF EXPOSURE ON VARIOUS FACES OF ANY COLUMN (II-227, APP. 6, FIG 1) THE GREATEST DIFFERENTIAL EXPOSURE FROM SIDE-TO-SIDE OF ANY COLUMN IS $.74 \times 10^{-4}$ MWD/AT-SEC FOR COLUMN 70. IN 20 YEARS, THIS DIFFERENCE BECOMES (ASSUMING FULL POWER UTILIZATION FACTOR = 1.0):

$$(.74 \times 10^{-4})(20 \times 365 \times 24 \times 60 \times 60) = .74 \times 10^{-4} (6.31 \times 10^8) \\ = 4.66 \times 10^4 \text{ MWD/AT}$$

SINCE THE COLUMN IS 16" ACROSS, THE DIFFERENTIAL EXPOSURE PER INCH IS $\frac{4.66 \times 10^4}{16} = 2.91 \times 10^3$ MWD/AT-IN (ASSUMING LINEAR VARIATION)

AT THE SHRINKAGE RATE (II) OF .0002 IN/IN/1000 MWD/AT AS PREDICTED FOR THE NEEDLE-COKE GRAPHITE TO BE USED, THE TOTAL DIFFERENTIAL CHANGE IN AXIAL LENGTH OF EXTREME FIBERS OF THE COLUMN IS

$$\Delta L = (2 \times 10^{-4}) \left(\frac{4.66 \times 10^4}{1000} \right) = 93.2 \times 10^{-4} \text{ IN}$$

THE MAXIMUM ΔL ABOUT THE NEUTRAL AXIS WHICH DEVELOPS AS THE COLUMN BOWS TO ACCOMMODATE THIS CHANGE IN FIBERS IS (ASSUMING A SYMMETRICAL COLUMN)

$$\Delta L_{(N.A.)} = \frac{93.2 \times 10^{-4}}{2} = 46.6 \times 10^{-4} \text{ IN } 8"$$

CONSEQUENTLY THE MAXIMUM STRAIN DEVELOPED IN A COLUMN DUE TO THE OVERALL DIFFERENTIAL IRRADIATION-INDUCED SHRINKAGE IS

$$\epsilon = \frac{\Delta L}{L} = \frac{46.6 \times 10^{-4}}{8} = 5.83 \times 10^{-4} \text{ IN/IN}$$

THIS IS LESS THAN THE CALCULATED STRAIN (6×10^{-4} IN/IN) AT TIME OF RUPTURE IN A.C. R&D. TEST SPECIMENS. SINCE A CONSERVATIVE APPROACH HAS BEEN TAKEN, IT APPEARS THAT THE MAXIMUM PERMISSIBLE STRAIN WILL NOT BE EXCEEDED SO AS TO CAUSE FAILURE OF ANY PART OF EGCR GRAPHITE PRIOR TO 20 YRS. OF LIFE.

ANALYSIS OF CREEP TESTS FOR EGCR GRAPHITE

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ANOTHER SOURCE OF STRAIN IN THE EGCR GRAPHITE IS THE ^{RADIAL} EXPOSURE GRADIENT WHICH EXISTS AROUND EACH FUEL CHANNEL. FROM II-227, APP 6, P 3, THE AVERAGE RATE OF EXPOSURE AT THE INSIDE SURFACE OF THE FUEL SLEEVE IS (ON THE PLANE OF PEAK AXIAL FLUX) 1.65×10^{-4} MWD/AT-SEC. FROM II-227, APP 6, FIG 2, THE PROPORTIONS OF THIS RATE THAT EXIST AT THE FUEL CHANNEL SURFACE AND THE SURFACE OF THE HYPOTHETICAL "FUEL CELL" ARE .795 AND .690 RESPECTIVELY. THEREFORE, THERE EXISTS A TOTAL DIFFERENTIAL EXPOSURE (OVER THE 2" BETWEEN THESE TWO SURFACES) OF

$$(.795 - .690)(1.65 \times 10^{-4}) = .1735 \times 10^{-4} \text{ MWD/AT-SEC OVER 2"}$$

FROM FIG. 2, HOWEVER, ~~THE~~ STEEPER GRADIENT PROBABLY EXTENDS OVER 1" (FROM 2.625 TO 3.625 IN FIG. 2) OF AMOUNT

$$(.795 - .615)(1.65 \times 10^{-4}) = .132 \times 10^{-4} \text{ MWD/AT-SEC}$$

BUT DUE TO THE STRESS-REVERSAL PATTERNS PREDICTED IN II-227, APP 2 & 3, THE PROBABLE STRAIN IS FOUND BY:

$$\text{TOTAL DL} = (.1735 \times 10^{-4})(6.31 \times 10^8) \left(\frac{2 \times 10^{-4}}{1000} \right) = 2.19 \times 10^{-3} \text{ IN 2"}$$

RELATIVE TO THE NEUTRAL AXIS WHICH DEVELOPS AS THE LIGAMENTS AROUND FUEL CHANNELS FLEX TO ACCOMMODATE THESE CHANGES, THE STRAIN IS

$$\epsilon = \frac{\text{DL}}{L} = \frac{2.19 \times 10^{-3}}{2} = 1.09 \times 10^{-3} \text{ IN/IN IN 20 YEARS.}$$

COMPARED TO THE CONSERVATIVELY CALCULATED MAXIMUM PERMISSIBLE STRAIN (6×10^{-4}), AND TAKING INTO ACCOUNT A UTILIZATION FACTOR OF 0.8, THE ^{AVERAGE} PROBABLE LIFE OF EGCR COLUMNS (BEFORE FIRST STRAIN CRACKS OCCUR) IS

$$\text{LIFE} = 20 \left(\frac{6 \times 10^{-4}}{0.8 \times 1.09 \times 10^{-3}} \right) = 13.8 \text{ YRS.}$$

IT APPEARS THEN, THAT, IF CREEP OCCURS IN EGCR GRAPHITE AS PREDICTED BY PREVIOUS STRESS CALCULATIONS OR AS DEMONSTRATED BY THESE R&D TESTS, THE MAXIMUM STRESS WILL NOT BE THE CRITERION OF FAILURE BUT THE MAXIMUM STRAIN WILL BE. AN AVERAGE LIFE, ^{CONSERVATIVELY} ASSUMING THAT SUCH A LOCALIZED STRAIN FAILURE MEANS THE END OF USEFULNESS, SHOULD BE IN THE NEIGHBORHOOD OF 14 TO 15 YEARS, ACCORDING TO A.C. TESTS.

ANALYSIS OF CREEP TESTS FOR EGCR GRAPHITE

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SIMILAR TO

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IF THE MAXIMUM STRAIN FROM ORNL TESTS BE USED (.0008 ~~W/IN~~), WITH
THE 0.8 UTILIZATION FACTOR, THE EGCR CORE LIFE SHOULD BE

$$LIFE = 20 \left(\frac{.0008}{0.8 \times 1.09 \times 10^3} \right) = 18.5 \text{ yrs.}$$

ANALYSIS OF CREEP TESTS FOR EGCR GRAPHITE

TASK 227
APP 8

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SIMILAR TO

DR'N RRN

CH'D PV6 6/16/60

APP'D

SCALE = 12

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NPD-W

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RELATIVE DEFLECTIONS OF GRAPHITE BEAM WITH
CREEP READINGS ADJUSTED FOR CHANGES IN REFERENCE HEIGHT
(BASED ON REFERENCE HEIGHT OF STANDARD BLOCK)

SPECIMEN NO 1 WITHOUT LOAD

DATE (TEST)	1/15/60 (BEGIN)	1/19/60	1/30/60 2:40 PM	1/30/60 5:10 PM	1/25/60	1/27/60	2/1/60	2/5/60	2/15/60	2/25/60	3/7/60
REFER. HGT.	.020	.025	.025	.025	.025	.025	.025	.030	.030	.030	.030
POINT											
1	.0090*	.0106	.0108	.0107	.0109	.0113	.0107	.0112	.0119	.0114	.0120
2	.0101	.0140	.0140	.0147	.0149	.0145	.0151	.0154	.0162	.0161	.0165
3	.0108	.0169	.0170	.0178	.0181	.0184	.0185	.0190	.0198	.0197	.0200
4	.0115	.0192	.0200	.0205	.0214	.0210	.0215	.0220	.0229	.0226	.0229
5	.0115	.0207	.0218	.0222	.0222	.0219	.0230	.0236	.0246	.0243	.0247
6	.0118	.0214	.0231	.0231	.0237	.0230	.0241	.0246	.0255	.0252	.0259
7	.0118	.0219	.0238	.0234	.0237	.0231	.0245	.0246	.0259	.0252	.0262
8	.0117	.0215	.0225	.0228	.0237	.0231	.0245	.0246	.0258	.0252	.0262
9	.0110	.0201	.0208	.0216	.0222	.0223	.0238	.0236	.0247	.0237	.0253
10	.0106	.0171	.0199	.0200	.0185	.0185	.0205	.0207	.0214	.0205	.0219
11	.0091	.0137	.0162	.0155	.0151	.0153	.0163	.0165	.0171	.0167	.0176
12	.0071	.0105	.0114	.0104	.0097	.0100	.0102	.0111	.0116	.0106	.0118
13	.0049	.0055	.0059	.0055	.0044	.0040	.0039	.0045	.0048	.0044	.0057

* VALUES FOR ALL POINT (1) MEASUREMENTS ARE UNCERTAIN SINCE RELATION BETWEEN HEIGHT OF REFERENCE SURFACE AND HEIGHT OF ENDS OF BEAM IS UNDETERMINED. THEREFORE, PLOTTED CURVES SHOULD BEGIN WITH POINT 1, ELIMINATING END POINT.

TABLE I

ANALYSIS OF CREEP TESTS FOR EGCE GRAPHITE

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APP 8

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DRN R.R.M.

CHD PIG 6/16/60 APD [Signature] SCALE = 12

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A

B

A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6633-3

RELATIVE DEFLECTIONS OF GRAPHITE BEAM
SPECIMEN # 1 (CONT)

TEST DATE	3/22/60	4/11/60	4/29/60								
REFER. HGT.	.0300	*** .0400	*** .0400								
POINT		***									
1	.0117	-.0001	.0002								
2	.0161	.0132	.0129								
3	.0203	-.0250	.0254								
4	.0228	.0358	.0358								
5	.0246	.0426	.0431								
6	.0260	.0472	.0475								
7	.0260	.0486	.0489								
8	.0260	.0489	.0491								
9	.0250	.0486	.0490								
10	.0217	.0421	.0425								
11	.0174	.0323	.0331								
12	.0116	.0198	.0199								
13	.0049	.0065	.0072								

*** FROM THIS TIME ^{ON} SPECIMEN IS MOVED FOR EACH SET OF MEASUREMENTS, BECAUSE ^{SMALL} SURFACE PLATE CANNOT ACCOMMODATE SPECIMEN'S PERMANENTLY. TABULATED VALUES OBTAINED FROM TEST RESULTS BY: "INDICATOR ON BASE SFC. + ~~ONE~~ MINUS INDICATOR ON POINT."

*** MINUS SIGN INDICATES ORIGINAL REFERENCE PLANE BELOW THE POINT ON BEAM, ACCORDING TO RECORDED TEST DATA.

TABLE I (CONT)

ANALYSIS OF CREEP TESTS FOR ESCR GRAPHITE

TASK 227
APPENDIX

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DRN

RRM.

CHD PUG 6/16/60

APD

DEPT. NPD-2

SCALE

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DEPT.

NPD-2

RELATIVE DEFLECTIONS OF POINTS ON GRAPHITE BEAM
CREEP READINGS ADJUSTED FOR CHANGES IN REFERENCE HEIGHT
OF STANDARD BLOCK (I.E. GAGE ZERO SETTING)
SPECIMEN NO 2 WITHOUT LOAD

TEST DATE	1/15/60 (BEGIN)	1/18/60	1/20/60 355 PM	1/20/60 410 PM	1/25/60	1/27/60	2/1/60	2/5/60	2/15/60	2/25/60	3/7/60
REFER. HGT	.020	.0250	.0250	.0258	.0250	.0250	.0250	.0300	.0300	.0300	.0300
POINT											
1	.0040*	.0067	.0066	.0062	.0065	.0064	.0059	.0064	.0066	.0064	.0070
2	.0058	.0109	.0106	.0108	.0106	.0106	.0104	.0113	.0118	.0115	.0122
3	.0068	.0147	.0145	.0145	.0149	.0147	.0152	.0139	.0163	.0158	.0166
4	.0075	.0179	.0184	.0172	.0182	.0182	.0188	.0199	.0203	.0197	.0208
5	.0087	.0214	.0210	.0200	.0209	.0210	.0216	.0225	.0233	.0224	.0238
6	.0095	.0226	.0226	.0227	.0228	.0221	.0236	.0244	.0248	.0245	.0260
7	.0097	.0231	.0230	.0222	.0234	.0233	.0241	.0246	.0254	.0250	.0261
8	.0096	.0237	.0235	.0227	.0237	.0234	.0244	.0250	.0255	.0251	.0264
9	.0105	.0233	.0231	.0218	.0237	.0233	.0241	.0249	.0254	.0252	.0261
10	.0117	.0228	.0225	.0215	.0229	.0227	.0229	.0239	.0244	.0243	.0251
11	.0125	.0203	.0204	.0198	.0207	.0201	.0204	.0214	.0217	.0212	.0222
12	.0121	.0168	.0172	.0169	.0173	.0171	.0172	.0176	.0180	.0177	.0188
13	.0122	.0139	.0141	.0141	.0143	.0141	.0138	.0143	.0144	.0140	.0153

* See Comment On Specimen 1 Data

TABLE II

Analysis Of Creep Tests For EGGE GRAPHITE

TASK 227
APP8

SIMILAR TO

DRN A.R.N. CHD P/B 6/16/60 APPD *gms* SCALE = 12 SHEET 14 OF 95 ISSUE

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RELATIVE DEFLECTIONS OF GRAPHITE BEAM
SPECIMEN # 2 (CONT.)

TEST DATE	3/22/60	4/11/60 **	4/29/60 **								
REFER. HGT.	.0300	.0400	.0400								
POINT											
1	.0062	-.0019	-.0012								
2	.0115	.0089	.0086								
3	.0165	.0180	.0181								
4	.0205	.0267	.0263								
5	.0235	.0359	.0314								
6	.0255	.0363	.0361								
7	.0255	.0366	.0358								
8	.0263	.0366	.0360								
9	.0258	.0351	.0348								
10	.0248	.0310	.0310								
11	.0216	.0237	.0236								
12	.0195	.0156	.0154								
13	.0144	.0069	.0071								

* * FOR COMMENT SEE SPECIMEN 1 DATA.

TABLE II (CONT)

Analysis of Creep Tests for EGGR Graphite

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SIMILAR TO

DRN R.R.N.

CHD PW 6/16/60

APPD

DEPT. APP-2

SCALE

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ALLIS-CHALMERS MFG. CO.

DEPT.

APP-2

A

B

A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3-14

RELATIVE DEFLECTIONS OF POINTS ON GRAPHITE BEAM
CREEP READINGS ADJUSTED FOR CHANGES IN REFERENCE HEIGHT
OF STANDARD BLOCK (I.E. GAGE ZERO SETTING)
SPECIMEN NO 4 HOT WITHOUT LOAD

TEST DATE	1/21/60	1/22/60	1/22/60	1/27/60	1/28/60	1/29/60	2/2/60	2/3/60	2/4/60	2/5/60	2/5/60
REFER. HGT	0	0	0	.025	.025	.025	.025	.025	** .025	.025	
POINT											
1	.2242*	.2226	.2212	.2201	.2182	.2179	.2157	.2166	.2165	.2164	.2163
2	.2240	.2178	.2150	.2119	.2104	.2098	.2074	.2081	.2094	.2093	.2075
3	.2232	.2134	.2091	.2045	.2024	.2021	.1997	.1996	.2011	.2010	.1991
4	.2229	.2090	.2036	.1981	.1963	.1954	.1925	.1926	.1948	.1946	.1923
5	.2221	.2067	.1994	.1929	.1918	.1910	.1880	.1880	.1901	.1891	.1869
6	.2213	.2052	.1972	.1904	.1898	.1887	.1850	.1854	.1881	.1871	.1852
7	.2213	.2050	.1964	.1895	.1892	.1885	.1845	.1845	.1873	.1866	.1836
8	.2212	.2049	.1963	.1894	.1892	.1885	.1843	.1845	.1873	.1866	.1839
9	.2204	.2051	.1968	.1900	.1910	.1901	.1854	.1861	.1889	.1877	.1859
10	.2202	.2072	.2003	.1944	.1955	.1950	.1906	.1921	.1934	.1929	.1913
11	.2205	.2103	.2062	.2016	.2027	.2021	.1987	.1994	.2009	.2005	.1991
12	.2208	.2150	.2135	.2102	.2114	.2111	.2091	.2095	.2103	.2102	.2089
13	.2225	.2206	.2196	.2182	.2200	.2194	.2186	.2186	.2195	.2194	.2180

* SEE COMMENT ON SPECIMEN NO 1

** NEW FURNACE

TABLE III

Analysis of Creep Tests For EGGE GRAPHITE

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TASK 227
APP 8

DRN	RPM.	CHD	APD	SCALE	ISSUE
		PMG 6/16/60	PMG	=12	
ALLIS-CHALMERS MFG. CO. DEPT. NPD-W					
SHEET 18 OF 45					
6/12/60					

RELATIVE DEFLECTIONS OF GRAPHITE BEAM
SPECIMEN # 4 (CONT.)

TEST DATE.	2/8/60	2/9/60	2/11/60	2/15/60	2/22/60	2/25/60	3/7/60	4/11/60	4/22/60		
REF. HGT.	.025	.025	.025	.025	.025	.025	.025	.040*	**		
POINT											
1	.2136	.2119	.2126	.2103	.2109	.2099	.2089	.2083			
2	.2029	.1998	.1983	.1979	.1966	.1917	.1899	.1896			
3	.1932	.1897	.1869	.1856	.1822	.1754	.1730	.1548			
4	.1850	.1804	.1786	.1773	.1719	.1655	.1639	.1581			
5	.1795	.1739	.1721	.1704	.1640	.1563	.1541	.1226			
6	.1760	.1709	.1684	.1659	.1599	.1509	.1479	.1248			
7	.1755	.1701	.1674	.1651	.1586	.1493	.1454	.1188			
8	.1760	.1702	.1678	.1658	.1592	.1504	.1473	.1146			
9	.1793	.1737	.1715	.1696	.1627	.1551	.1537	.1220			
10	.1844	.1801	.1777	.1758	.1694	.1629	.1602	.1361			
11	.1923	.1883	.1870	.1853	.1779	.1725	.1687	.1496			
12	.2041	.2015	.2013	.1999	.1943	.1905	.1897	.1793			
13	.2154	.2143	.2137	.2136	.2096	.2066	.2075	.2080			

* SPECIMEN LOADED BUT OUT OF FURNACE FOR PREVIOUS TWO WEEKS

** SPECIMEN FAILED AT POINTS OF APPLIED LOAD.

TABLE III (CONT.)

ESCH. CHAMP TEST ANALYSIS

194

TASK 327
APP 81

SIMILAR TO

DRN REL

CHD PUG 6/16/60

APPD

APD

DEPT. NPD-12

SCALE

=12

SHEET 19 OF 45

ISSUE

ALLIS-CHALMERS MFG. CO.

DEPT.

RELATIVE DEFLECTIONS OF POINTS ON GRAPHITE BEAM
CREEP READINGS ADJUSTED FOR CHANGES IN REFERENCE HEIGHT
OF STANDARD BLOCK (I.E. FOR GAGE ZERO SETTING)
SPECIMEN #5 HOT WITHOUT LOAD

TEST DATE	2/3/60	2/4/60	2/5/60	2/8/60	2/9/60	2/11/60	2/15/60	2/22/60	2/25/60	3/7/60	4/11/60
REFER. HGT.	.025	.025	.025	.025	.025	.025	.025	.025	.025	.025	.040 **
POINT											
1	.2199*	.2184	.2173	.2130	.2116	.2105	.2089	.2089	.2071	.2049	.2058
2	.2181	.2136	.2113	.2051	.2024	.2004	.1988	.1976	.1935	.1919	.1826
3	.2172	.2095	.2062	.1982	.1929	.1898	.1886	.1845	.1785	.1777	.1606
4	.2159	.2048	.2005	.1911	.1853	.1815	.1797	.1743	.1667	.1643	.1393
5	.2152	.2022	.1971	.1868	.1791	.1757	.1733	.1667	.1583	.1564	.1263
6	.2144	.2014	.1961	.1845	.1766	.1722	.1695	.1624	.1537	.1497	.1204
7	.2139	.2008	.1945	.1829	.1748	.1703	.1682	.1592	.1504	.1468	.1156
8	.2136	.2006	.1945	.1830	.1751	.1711	.1683	.1607	.1521	.1495	.1185
9	.2130	.2006	.1946	.1837	.1759	.1722	.1699	.1621	.1540	.1512	.1241
10	.2137	.2035	.1993	.1891	.1836	.1797	.1777	.1701	.1633	.1624	.1395
11	.2172	.2092	.2055	.1973	.1923	.1900	.1883	.1820	.1768	.1756	.1618
12	.2203	.2149	.2133	.2080	.2049	.2038	.2031	.1971	.1937	.1941	.1864
13	.2234	.2212	.2199	.2180	.2159	.2161	.2150	.2119	.2097	.2104	.2117

* SEE COMMENT ON SPECIMEN #1

** SPECIMEN BROKE 4/22/60 AT POINTS OF APPLIED LOAD.

TABLE IV

EGGE CREEP TEST ANALYSIS

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TASK 27
APP

SIMILAR TO

DRIN RAN

CHD PUG 6/16/60

APPD

DEPT. NPD-2

SCALE

= 12

SHEET 20 OF 45

ISSUE

ALLIS-CHALMERS MFG. CO.

A B C

TABLE V.
SUCCESSIVE DIFFERENCES OF SPECIMEN #5 CREEP
DATA* FOR DETERMINING DEGREE OF FITTED POLYNOMIAL.

x	y	Δy	$\Delta^2 y$	$\Delta^3 y$	$\Delta^4 y$	$\Delta^5 y$	$\Delta^6 y$	$\Delta^7 y$	$\Delta^8 y$
0	-.0008	-.0059							
2	-.0067		+13						
		-.0046		-2					
4	-.0113		+11		+2				
		-.0035		0		-4			
6	-.0148		+11		-2		+7		
		-.0024		-2		+3		-5	
8	-.0172		+9		+1		+2		-2
		-.0015		-1		+5		-7	
10	-.0187		+8		+6		-5		-14
		-.0007		+5		0		-21	
12	-.0194		+13		+6		-26		+100
		+ .0006		+11		-26		+79	
14	-.0188		+24		-20		+53		-162
		+ .0030		-9		+27		-83	
16	-.0158		+15		+7		-30		
		+ .0045		-2		-3			
18	-.0113		+13		+4				
		+ .0058		+2					
20	-.0055		+15						
		+ .0073							
22	+ .0018								

* SEE TABLE IV. POINT #1 ^{OF 2/3/60} IS TAKEN AS (0,0) FOR CURVE OF PURPOSES OF DETERMINING DIFFERENCES. DATA FROM 2/4/60.

EGCR CREEP TEST ANALYSIS

TASK 227
APR 8

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SIMILAR TO

DR'N <i>RLH</i>	CH'D <i>PVL 6/16/60</i>	APP'D <i>[Signature]</i>	SCALE = 12	SHEET 21 OF 45	ISSUE
PROPERTY OF ALLIS-CHALMERS MFG. CO. DEPT. <i>NPD-W</i>				<i>6/12/60</i>	

TABLE VI
SUCCESSIVE DIFFERENCES OF SPECIMEN #5 CREEP
DATA* FOR DETERMINING DEGREE OF FITTED POLYNOMIAL

X	Y	Δy	$\Delta^2 y$	$\Delta^3 y$	$\Delta^4 y$	$\Delta^5 y$	$\Delta^6 y$	$\Delta^7 y$
0	-.0150	-150						
2	-.0300	-124	+26	-18				
4	-.0424	-116	+8	+13	+31			
6	-.0540	-95	+21	+19	+6	-25	+3	
8	-.0635	-55	+40	+3	-16	-22	+26	+23
10	-.0690	-12	+43	-9	-12	+4	+51	+25
12	-.0702	+22	+34	+34	+43	+55	-153	-204
14	-.0680	+90	+68	-21	-55	-98	+168	+321
16	-.0590	+137	+47	-6	+15	+70	-73	-241
18	-.0453	+178	+41	+6	+12			
20	-.0275	+225	+47					
22	-.0050							

* SEE TABLE IV. POINT #1 OF 2/3/60 TAKEN AS (0,0) FOR DETERMINING DIFFERENCES. DATA FROM ^{CURVE OF} 3/7/60.

EGCR CREEP TEST ANALYSIS

TASK 227
APP 8

197

DR'N R.R.N.	CH'D PUG 6/14/60	APP'D	SCALE =12	SHEET 22 OF 45	ISSUE
Property of ALLIS-CHALMERS MFG. CO. DEPT. MPD-W			SIMILAR TO 6/12/60		

A B C

TABLE VII
SUCCESSIVE DIFFERENCES OF SPECIMEN #5 CREEP
DATA* FOR DETERMINING DEGREE OF FITTED POLYNOMIAL

X	Y	Δy	$\Delta^2 y$	$\Delta^3 y$	$\Delta^4 y$	$\Delta^5 y$	$\Delta^6 y$
0	-.0105	-275					
2	-.0380	-214	+61				
4	-.0594	-186	+28	-33	+39		
6	-.0740	-152	+34	+6	+49	+10	
8	-.0932	-63	+89	+55	-96	-145	-155
10	-.0995	-15	+48	-41	+60	+156	+305
12	-.1010	+52	+67	+19	+15	-45	-205
14	-.0958	+153	+101	+34	-90	-105	-60
16	-.0805	+198	+45	-56	+65	+155	+260
18	-.0607	+252	+54	+9	-30	-95	-250
20	-.0355	+285	+33	-21			
22	-.0070						

* SEE TABLE II. POINT #1 OF 2/3/60
 TAKEN AS (0,0) FOR DETERMINING DIFFERENCES.
 DATA FROM ^{CURVE OF} 4/11/60

EGCR CREEP TEST ANALYSIS

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 APP 8

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SIMILAR TO

DR'N R-R-N	CH'D P/16 6/16/60	APP'D <i>[Signature]</i>	SCALE = 12	SHEET 23 OF 45	ISSUE
ALLIS-CHALMERS MFG. CO. DEPT. NPD-W			6/12/60		

A

B

DETERMINATION OF STRAIN RATE
AT VARIOUS STRESS LEVELS

IF IT BE ASSUMED THAT (FOLLOWING FINNIE & HELLER "CREEP OF ENGINEERING MATERIALS" PP 135-140) THE CREEP RATE VARIES WITH STRESS AS

$$\dot{\epsilon} = B\sigma^n \quad (1)$$

THEN, IF PLANE TRANSVERSE SECTIONS REMAIN PLANE AFTER BENDING, THE CREEP RATE IN ANY LONGITUDINAL FIBER OF THE TEST SPECIMEN IS

$$\dot{\epsilon}_y = \dot{\epsilon}_{\max} \frac{y}{y_{\max}} \quad (2)$$

WHERE y IS THE DISTANCE FROM THE NEUTRAL AXIS AND $y_{\max} = \frac{W}{2} = .375$. CONSEQUENTLY

$$\sigma_y = \sigma_{\max} \left(\frac{y}{y_{\max}} \right)^{\frac{1}{n}} \quad (3)$$

IF THE SECTION IS IN EQUILIBRIUM THEN

$$\int_{-y_{\max}}^{+y_{\max}} \sigma_y dA = 0 \quad (4)$$

AND

$$\int_{-y_{\max}}^{+y_{\max}} \sigma_y y dA = M_{\text{APPLIED}} \quad (5)$$

FOR THE SQUARE TEST SPECIMENS THE NEUTRAL AXIS IS THE AXIS OF SYMMETRY AND (3) AND (5) YIELD

$$\sigma_{\max} = \frac{M W}{2I} \left(\frac{2n+1}{3n} \right) \quad (6)$$

WHERE I IS THE ORDINARY CROSS-SECTIONAL MOMENT OF INERTIA. CONSEQUENTLY, CALLING I_c A TRANSFORMED MOMENT OF INERTIA

$$I_c = \left(\frac{3n}{2n+1} \right) I \quad (7)$$

AND

$$\sigma_{\max} = \frac{M W}{2I_c} \quad (8)$$

THEREFORE, SINCE FOR ANY POINT ALONG THE TEST BEAM, THE EXTERNAL APPLIED MOMENT (M) CAN BE CALCULATED AND FOR ANY " n " THE I_c CAN BE FOUND, THE MAXIMUM STRESS CAN BE FOUND FOR CORRELATION

EGOR CREEP TEST ANALYSIS

TASK 227
APP 8

199

SIMILAR TO

DR'N <i>RAH</i>	CH'D <i>PHS 6/16/60</i>	APP'D <i>[Signature]</i>	SCALE = 12	SHEET <i>24</i> OF <i>45</i>	ISSUE
ALLIS-CHALMERS MFG. CO. DEPT. <i>NPD-W</i>				<i>6/12/60</i>	

WITH STRAINS FOUND BY FITTING CUBIC POLYNOMIALS TO THE SMOOTHED CURVES PLOTTED IN FIG. I & FIG. II.

THE ACTUAL EXTERNAL LOADS ARE

AND THE MOMENT DIAGRAM IS

THE ORDINARY MOMENT OF INERTIA IS

$$I = \frac{bw^3}{12} = \frac{(.75)(.75)^3}{12} = .0263 \text{ in}^4$$

FROM THE CREEP LITERATURE CITED IN A.C. REPORT II-227 APPENDIX 4, "n" SEEMS TO VARY FROM 1 TO 3.

$$\begin{aligned} \text{FOR } n=1 \quad I_c &= I = .0263 \text{ in}^4 \\ n=2 \quad I_c &= \left(\frac{3 \times 2}{2 \times 2 + 1} \right) I = .0316 \text{ in}^4 \\ n=3 \quad I_c &= \left(\frac{3 \times 3}{2 \times 3 + 1} \right) I = .0338 \text{ in}^4 \end{aligned}$$

BECAUSE OF THE WAY A CUBIC POLYNOMIAL IS FOUND TO FIT THE ACTUAL DEFLECTED CURVE (SEE PP), ONLY STRAINS FROM Q TO Q_R WILL BE CORRELATED TO STRESS. BECAUSE OF TIME LIMITATIONS AND THE ACCURACY OF FIT IT SEEMS UNORTHWILE ONLY TO CORRELATE STRESS AND CREEP STRAIN FOR TWO POINTS: POINT "b" (POINT OF FRACTURE) AND HALF-WAY BETWEEN "b" AND Q_R WHICH CORRESPONDS TO x=19 IN FIGS I & II.

$$\begin{aligned} \text{FOR } n=1 \quad @ \quad x=b=15 \quad \sigma &= \frac{52 \times .375}{.0263} = 742 \text{ psi} \\ x=19 \quad \sigma &= \frac{26 \times .375}{.0263} = 371 \text{ psi} \end{aligned}$$

$$\begin{aligned} \text{FOR } n=2 \quad @ \quad x=15 \quad \sigma &= \frac{52 \times .375}{.0316} = 617 \text{ psi} \\ x=19 \quad \sigma &= \frac{26 \times .375}{.0316} = 309 \text{ psi} \end{aligned}$$

$$\begin{aligned} \text{FOR } n=3 \quad @ \quad x=15 \quad \sigma &= \frac{52 \times .375}{.0338} = 577 \text{ psi} \\ x=19 \quad \sigma &= \frac{26 \times .375}{.0338} = 289 \text{ psi} \end{aligned}$$

SINCE NOT ENOUGH TESTS WERE MADE TO ALLOW CORRELATION OF SEVERAL STRAIN VALUES AT ANY ONE STRESS, THE ABOVE VALUES CAN BE USED ONLY TO DETERMINE THE PROBABLE RANGE OF STRESS.

EGCR CREEP TEST ANALYSIS

TASK 227
APPV

200

SIMILAR TO

DR'N RR24

CH'D P16 6/14/60

APP'D *[Signature]*

SCALE = 12

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ISSUE

ALLIS-CHALMERS MFG. CO.

DEPT.

NPD-W

6/12/60

THE PROBLEM IS THEN TO FIT A POLYNOMIAL TO ^{EACH OF} THE SUCCESSIVE STAGES OF DEFLECTION SHOWN IN FIGS I & II (USING METHODS SIMILAR TO THOSE FOR FINDING MAXIMUM STRAIN AT RUPTURE, SEE PP) AND TO FIND THE CREEP STRAIN AT $x=15$ AND $x=19$ BY MEANS OF

$$\epsilon = \frac{w}{2} \frac{d^2y}{dx^2} \quad (\text{DERIVED ON P.})$$

FOR THE STRAIN RATE, THE STRAIN ^{AT A GIVEN POINT} WILL BE PLOTTED AGAINST TIME, THE SLOPE GIVING THE TIME RATE OF CREEP STRAIN.

THE CURVE-FITTING EQUATIONS WILL BE FITTED TO ORDINATES AT $x=6, x=10, x=14, x=18$. THESE ORDINATES WILL BE SCALED FROM FIGS I & II BY SUBTRACTING FROM THE ORDINATE OF ANY CURVE THE ORDINATE OF THE UPPER-MOST CURVE (I.E. FROM THE UNLOADED, ORIGINAL STRAIGHTNESS CURVE). THE FITTED EQUATION WILL BE FOR THE CREEP DEFLECTION ONLY, SINCE ALL TEST MEASUREMENTS WERE MADE WITH BEAMS UNLOADED.

FOR SPECIMEN #1 - FIG I THE NET ORDINATES ARE

DATE	x	y	TIME FROM START OF TEST (1/15/60)
1/18/60	6	-.0077	72 HR
	10	-.0094	
	14	-.0089	
	18	-.0054	
1/27/60	6	-.0090	288 HR
	10	-.0113	
	14	-.0107	
	18	-.0065	
3/7/60	6	-.0113	1224 HR
	10	-.0143	
	14	-.0137	
	18	-.0090	

EGCR CREEP TEST ANALYSIS

TASK 227
APP 8

206

DR'N RRN	CH'D PUG 6/16/60	APP'D <i>[Signature]</i>	SCALE = 12	SIMILAR TO	SHEET 26 OF 45	ISSUE
ALLIS-CHALMERS MFG. CO.			DEPT. NPD-W	6/12/60		

A

B

C

SPECIMEN #1 (CONT.)

DATE	X	Y	TIME
4/11/60	6	-.0252	2065 HR
	10	-.0352	
	14	-.0363	
	18	-.0233	
4/29/60	ALMOST AS FOR	SAME 4/11/60	2495 HR

FOR SPECIMEN #5 - FIG II - THE NET ORDINATES ARE

DATE	X	Y	TIME FROM START OF TEST (2/3/60)
2/4/60	6	-.0108	24 HR.
	10	-.0128	
	14	-.0123	
	18	-.0080	
2/5/60	6	-.0148	48 HR
	10	-.0192	
	14	-.0182	
	18	-.0123	
2/15/60	6	-.0355	288 HR
	10	-.0452	
	14	-.0433	
	18	-.0280	
3/7/60	6	-.0500	768 HR
	10	-.0632	
	14	-.0615	
	18	-.0423	
4/11/60	6	-.0738	1608 HR
	10	-.0937	
	14	-.0900	
	18	-.0575	

EGCR CREEP TEST ANALYSIS

TASK 227
APP 8

202

DR'N RRT.	CH'D PVG 6/16/60	APP'D <i>(Signature)</i>	SCALE = 12	SHEET 27 OF 45	ISSUE
ALLIS-CHALMERS MFG. CO. DEPT. NPD-W			SIMILAR TO 6/12/60		

A

B

FOR SPEC #1 (1/18/60) TO FIT AN EQUATION OF THE FORM $y = a + bx + cx^2 + dx^3$
THE DETERMINANT EQUATION IS:

$$\begin{vmatrix} -y & 1 & x & x^2 & x^3 \\ .0077 & 1 & 6 & 36 & 216 \\ .0094 & 1 & 10 & 100 & 1000 \\ .0089 & 1 & 14 & 196 & 2744 \\ .0054 & 1 & 18 & 324 & 5832 \end{vmatrix} = 0$$

THE EXPANSION IS (CALLING $-y = r$, $.0077 = s$, $.0094 = t$, $.0089 = \mu$, $.0054 = v$)

$$\begin{aligned} -y \times 1 \times 10 \times 196 \times 5832 &= r Q_1 = -y (11,430,720) = -11,430,720y \\ .0077 \times 1 \times 14 \times 324 (x^3) &= s Q_2 = .0077 (4536 x^3) = 34.9 x^3 \\ .0094 \times 1 \times 18 \times 216 (x^2) &= t Q_3 = .0094 (3888 x^2) = 36.5 x^2 \\ .0089 \times 1 \times 1000 \times 36 (x) &= \mu Q_4 = .0089 (36,000 x) = 320.4 x \\ .0054 \times 2744 \times 100 \times 6 \times 1 &= v Q_5 = .0054 (1,646,400) = 8890.6 \\ - (x^3) 36 \times 10 \times 1 \times .0054 &= v Q_6 = .0054 (-360 x^3) = -1.9 x^3 \\ 216 \times 100 \times 14 \times 1 \times y &= -r Q_7 = y (302,400) = 302,400y \\ - 1000 \times 196 \times 18 \times .0077 \times 1 &= s Q_8 = .0077 (-3,528,000) = -27,165.6 \\ - 2744 \times 324 \times .0094 \times 1 (x) &= t Q_9 = .0094 (-889,056 x) = -8357x \\ - 5832 \times .0089 \times 1 \times 6 (x^2) &= \mu Q_{10} = .0089 (-34992 x^2) = -311 x^2 \end{aligned}$$

SINCE, IN ALL DETERMINANTS, THE SELECTED POINTS ARE THE SAME, ONLY THE FIRST COLUMN OF ELEMENTS CHANGES. HENCE, WITH THE ABOVE Q'S, THE EXPANSION OF ALL DETERMINANTS FOR SPECIMENS #1 AND #5 CAN BE DONE BY ASSIGNING THE PROPER VALUES TO r, s, t, μ, v AND MULTIPLYING BY APPROPRIATE Q.

FOR THIS TEST:

$$0 = -y - .00164 - .000722x - .00002466x^2 + .000002965x^3$$

$$\frac{dy}{dx} = -.000722 - .0004932x + .00008895x^2$$

$$\frac{d^2y}{dx^2} = -.0004932 + .0001779x$$

$$\text{point of inflection is at } x \approx \frac{.00004923}{.0001779} = 2.76$$

$$@ x = 15 \quad \frac{d^2y}{dx^2} = -.0004932 + .000267 = .000218$$

$$x = 19 \quad \frac{d^2y}{dx^2} = -.0004932 + .000338 = .000289$$

EGCR CREEP TEST ANALYSIS

TASK 227
APP 8

203

SIMILAR TO

DR'N RRM

CH'D 2/5/60

APP'D [Signature]

SCALE = 12

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ISSUE

ALLIS-CHALMERS MFG. CO.

DEPT. NPD-W

6/12/60

A

B

C

AND THE STRAIN IS

$$\epsilon_{15} = .375 \times .000218 = .000082 \text{ in/in}$$

FROM $\epsilon = \frac{1}{2} \frac{d\epsilon}{dx}$

$$\epsilon_{14} = .375 \times .000289 = .000108 \text{ in/in}$$

CHECKING THE FIT OF CURVE FOR SPEC #1 (1/18/60)

@ X=0

$$y = -.00164$$

vs .0015

X=4

$$\begin{aligned} y &= -.00164 \\ &+.00289 \\ &-.000395 \\ &-.004925 \\ &+.00019 \\ &-.004735 \end{aligned}$$

vs +.0057

X=2

$$\begin{aligned} y &= -.00164 \\ &+.00144 \\ &+.000099 \\ &-.003183 \\ &+.000024 \\ &-.003159 \end{aligned}$$

vs .0037

X=10

$$\begin{aligned} y &= -.00164 \\ &+.00722 \\ &+.002466 \\ &-.01133 \\ &+.00296 \\ &-.00837 \end{aligned}$$

vs .0095

X=14

$$\begin{aligned} y &= -.00164 \\ &+.0101 \\ &-.00483 \\ &-.01657 \\ &+.00814 \\ &-.00843 \end{aligned}$$

vs .0088

X=18

$$\begin{aligned} y &= -.00164 \\ &+.01300 \\ &+.00798 \\ &-.02262 \\ &+.01786 \\ &-.00536 \end{aligned}$$

vs .0053

WHERE CHECK POINTS ARE NET ORDINATES FROM FIG. I. FITTED CURVE IS SHOWN DOTTED IN FIG. I.

EGOR CREEP TEST ANALYSIS

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App 8

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SIMILAR TO

DR'N RRN

CH'D PUG

APP'D

SCALE = 12

SHEET 29 OF 45

ISSUE

ALLIS-CHALMERS MFG. CO.

DEPT. NPD-W

6/12/60

A

B

A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

A

B

C

FOR SPECIMEN # 1 (1/27/60), THE DETERMINANT EQUATION IS:

$$\begin{vmatrix} -y & 1 & x & x^2 & x^3 \\ .0090 & 1 & 6 & 36 & 216 \\ .0113 & 1 & 10 & 100 & 1000 \\ .0107 & 1 & 14 & 196 & 2744 \\ .0065 & 1 & 18 & 324 & 5832 \end{vmatrix} = 0$$

AND THE EXPANSION IS

$$-y Q_1 = -11,430,720 y$$

$$.0090 Q_2 = .0090 (4536 x^3) = 40.8 x^3$$

$$.0113 Q_3 = .0113 (3888 x^2) = 43.9 x^2$$

$$.0107 Q_4 = .0107 (36000 x) = 385 x$$

$$.0065 Q_5 = .0065 (1,646,400) = 10,702$$

$$.0065 Q_6 = .0065 (-360 x^3) = -2.3 x^3$$

$$y Q_7 = 302,400 y$$

$$.0090 Q_8 = .0090 (-3,528,000) = -31,752$$

$$.0113 Q_9 = .0113 (-889,056 x) = -10,046 x$$

$$.0107 Q_{10} = .0107 (-34,992 x^2) = -374 x^2$$

THE EQUATION IS THEN

$$y = -.00189 - .000868x - .0000296x^2 + .00000346x^3$$

$$\frac{dy}{dx} = -.000868 - .0000592x + .00001038x^2$$

$$\frac{d^2y}{dx^2} = -.0000592 + .00002076x$$

$$\text{THE POINT OF INFLECTION IS } x \approx = \frac{.0000592}{.00002076} = 2.8''$$

$$@ x = 15 \quad \frac{d^2y}{dx^2} = -.0000592 + .0003114 = .0002522$$

$$x = 19 \quad \frac{d^2y}{dx^2} = -.0000592 + .0003944 = .0003352$$

$$\text{AND } \epsilon_{15} = .375 \times .00025 = .00009375 \quad \text{IN/IN}$$

$$\text{FROM } \epsilon = \frac{w}{L} \frac{d^2y}{dx^2}$$

$$\epsilon_{19} = .375 \times .0003352 = .0001257 \quad \text{IN/IN}$$

EGCR CRACK TEST ANALYSIS

TASK 227
APP 8

205

SIMILAR TO

DR'N R.R.H.

CH'D PVC

APP'D

SCALE

=12

SHEET 30 OF 45

ISSUE

ALLIS-CHALMERS MFG. CO.

DEPT.

NPP-W

6/12/60

A

B

CHECKING FIT OF CURVE FOR SPEC #1 (1/27/60)

$$\begin{array}{rcl}
 x=0 & y = & -.00189 \\
 x=1 & y = & -.00189 \\
 & & .000868 \\
 & & .0000296 \\
 & & \hline
 & & -.0027876 \\
 & & + .00000346 \\
 & & \hline
 & & -.00278
 \end{array}$$

$$\begin{array}{rcl}
 x=2 & y = & -.00189 \\
 & & .001736 \\
 & & .0001184 \\
 & & \hline
 & & -.0037444 \\
 & & + .0000277 \\
 & & \hline
 & & -.0037167
 \end{array}$$

$$\begin{array}{rcl}
 x=4 & y = & -.00189 \\
 & & .003472 \\
 & & .000474 \\
 & & \hline
 & & -.005836 \\
 & & + .000221 \\
 & & \hline
 & & -.005615
 \end{array}$$

$$\begin{array}{rcl}
 x=10 & y = & -.00189 \\
 & & .00868 \\
 & & .00296 \\
 & & \hline
 & & -.01553 \\
 & & + .00346 \\
 & & \hline
 & & -.01007
 \end{array}$$

$$\begin{array}{rcl}
 x=14 & y = & -.00189 \\
 & & .01252 \\
 & & .00580 \\
 & & \hline
 & & -.02021 \\
 & & + .00949 \\
 & & \hline
 & & -.01072
 \end{array}$$

$$\begin{array}{rcl}
 x=18 & y = & -.00189 \\
 & & .01562 \\
 & & .00959 \\
 & & \hline
 & & -.02710 \\
 & & + .02018 \\
 & & \hline
 & & -.00692
 \end{array}$$

FITTED CURVE IS SHOWN DOTTED ON FIG. I.

EGCR CREEP TEST ANALYSIS

TASK 227
APP 8

206

SIMILAR TO

DR'N RRN.

CH'D PVG

APP'D *[Signature]*

SCALE = 12

SHEET 31 OF 45

ISSUE

ALLIS-CHALMERS MFG. CO.

DEPT. NPD-W

6/12/60

A

B

FOR SPECIMEN #1 (3/7/60) THE DETERMINANT EQUATION IS

$$\begin{vmatrix} -y & 1 & x & x^2 & x^3 \\ .0113 & 1 & 6 & 36 & 216 \\ .0143 & 1 & 10 & 100 & 1000 \\ .0137 & 1 & 14 & 196 & 2744 \\ .0090 & 1 & 18 & 324 & 5832 \end{vmatrix} = 0$$

AND THE EXPANSION IS

$$\begin{aligned} -y Q_1 &= -y (11,430,720) \\ .0113 Q_2 &= .0113 (4536x^3) = 51.3x^3 \\ .0143 Q_3 &= .0143 (3888x^2) = 55.6x^2 \\ .0137 Q_4 &= .0137 (36000x) = 493x \\ .0090 Q_5 &= .0090 (1,644,480) = 14,818 \\ .0090 Q_6 &= .0090 (-360x^3) = -3.2x^3 \\ y Q_7 &= y (302400) \\ .0113 Q_8 &= .0113 (-3,528,000) = -39,866 \\ .0143 Q_9 &= .0143 (-889,056x) = -12,714x \\ .0137 Q_{10} &= .0137 (-34,992x^2) = -479x^2 \end{aligned}$$

THE EQUATION IS:

$$y = -.00225 - .00110x - .0000380x^2 + .00000432x^3$$

$$\frac{dy}{dx} = -.00110 - .0000760x + .00001296x^2$$

$$\frac{d^2y}{dx^2} = -.0000760 + .00002592x$$

$$\text{POINT OF INFLECTION AT } x = \frac{.0000760}{.00002592} \approx 2.93"$$

$$@ x=15 \quad \frac{d^2y}{dx^2} = -.0000760 + .0003888 = +.0003128$$

$$x=19 \quad \frac{d^2y}{dx^2} = -.0000760 + .0004925 = +.0004165$$

AND

$$E_{15} = .375 (.0003128) = .000117 \quad \text{IN/IN}$$

$$E_{19} = .375 (.0004165) = .000156 \quad \text{IN/IN}$$

EGCR CREEP TEST ANALYSIS

TASK 227
APP 8

207

SIMILAR TO

DR'N RR-N.

CH'D PVB

APP'D *[Signature]*

SCALE = 12

SHEET 32 OF 45

ISSUE

ALLIS-CHALMERS MFG. CO.

DEPT.

NEO-W

6/12/60

CHECKING THE FIT OF CURVE FOR SPEC. #1 (3/7/60)

$$x=0 \quad y = -.00225$$

$$x=1 \quad y = \begin{array}{r} -.00225 \\ .00110 \\ .0004 \\ -.00339 \\ +.00000 \\ -.00339 \end{array}$$

$$x=2 \quad y = \begin{array}{r} -.00225 \\ .0022 \\ .00015 \\ -.00460 \\ +.00003 \\ -.00457 \end{array}$$

$$x=4 \quad y = \begin{array}{r} -.00225 \\ .0044 \\ .00061 \\ -.00726 \\ +.00028 \\ -.00698 \end{array}$$

$$x=10 \quad y = \begin{array}{r} -.00225 \\ .0110 \\ .00380 \\ -.01705 \\ +.00432 \\ -.01273 \end{array}$$

$$x=14 \quad y = \begin{array}{r} -.00225 \\ .0154 \\ .00745 \\ -.02510 \\ +.01185 \\ -.01325 \end{array}$$

$$x=18 \quad y = \begin{array}{r} -.00225 \\ .0198 \\ .01231 \\ -.03436 \\ +.02519 \\ -.00617 \end{array}$$

THE FITTED CURVE IS SHOWN DOTTED IN FIG. I

EGCR CREEP TEST ANALYSIS

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TASK 227
APP 8

SIMILAR TO

DR'N	RRN.	CH'D	PVG	APP'D	SCALE	=12	SHEET 33 OF 45	ISSUE
ALLIS-CHALMERS MFG. CO.				DEPT.	NPD-W			6/12/60

FOR SPECIMEN # 1 (4/11/60) THE DETERMINANT EQUATION IS

$$\begin{vmatrix} -y & 1 & x & x^2 & x^3 \\ .0252 & 1 & 6 & 36 & 216 \\ .0352 & 1 & 10 & 100 & 1000 \\ .0363 & 1 & 14 & 196 & 2744 \\ .0233 & 1 & 18 & 324 & 5832 \end{vmatrix} = 0$$

AND THE EXPANSION IS

$$\begin{aligned} -y Q_1 &= -y (-11,430,720) \\ .0252 Q_2 &= .0252 (4536 x^3) = 114 x^3 \\ .0352 Q_3 &= .0352 (3888 x^2) = 137 x^2 \\ .0363 Q_4 &= .0363 (36000 x) = 13068 x \\ .0233 Q_5 &= .0233 (1,644,400) = 38,361 \\ .0233 Q_6 &= .0233 (-360 x^3) = -8.38 x^3 \\ y Q_7 &= y (302,400) \\ .0252 Q_8 &= .0252 (-3,528,000) = -88906 \\ .0352 Q_9 &= .0352 (-889,056 x) = -31295 x \\ .0363 Q_{10} &= .0363 (-34,992 x^2) = -1270 x^2 \end{aligned}$$

THE EQUATION IS

$$y = -.00454 - .00269x - .000102x^2 + .00000953x^3$$

$$\frac{dy}{dx} = -.00269x - .000204x + .00002859x^2$$

$$\frac{d^2y}{dx^2} = -.000204 + .00005718x$$

THE POINT OF INFLECTION IS AT $x \approx \frac{.000204}{.00005718} \approx 3.6''$

$$@ x=15 \quad \frac{d^2y}{dx^2} = -.000204 + .0008577 = +.0006537$$

$$x=19 \quad \frac{d^2y}{dx^2} = -.000204 + .0010864 = .0008824$$

$$\begin{aligned} \text{AND } \epsilon_{15} &= .375 (.0006537) = .000245 \quad \text{IN/IN} \\ \epsilon_{19} &= .375 (.0008824) = .000331 \quad \text{IN/IN} \end{aligned}$$

EGOR CREEP TEST ANALYSIS

TASK 227
APP 8

209

DR'N RRTN	CH'D PVG 4/17/60	APP'D <i>[Signature]</i>	SCALE = 12	SHEET 34 OF 45	ISSUE
ALLIS-CHALMERS MFG. CO.			DEPT. NPD-W	6/12/60	

A

B

A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

CHECKING THE FIT OF CURVE FOR SPEC. #1 (4/11/60)

$$x = 0 \quad y = -.00454$$

$$x = 1 \quad y = \begin{array}{r} -.00454 \\ .00269 \\ .00010 \\ \hline -.00175 \\ +.00001 \\ \hline -.00132 \end{array}$$

$$x = 2 \quad y = \begin{array}{r} -.00454 \\ .00538 \\ .00041 \\ \hline -.01033 \\ +.00008 \\ \hline -.01025 \end{array}$$

$$x = 4 \quad y = \begin{array}{r} -.00454 \\ .01086 \\ .00163 \\ \hline -.01693 \\ +.00001 \\ \hline -.01632 \end{array}$$

$$x = 10 \quad y = \begin{array}{r} -.00454 \\ .0269 \\ .0102 \\ \hline -.04164 \\ +.00953 \\ \hline -.03211 \end{array}$$

$$x = 14 \quad y = \begin{array}{r} -.00454 \\ .03766 \\ .00999 \\ \hline -.04219 \\ +.02615 \\ \hline -.01604 \end{array}$$

$$x = 18 \quad y = \begin{array}{r} -.00454 \\ .04842 \\ .03305 \\ \hline -.08601 \\ +.05558 \\ \hline -.03043 \end{array}$$

THE ^{FITTED} CURVE IS SHOWN DOTTED IN FIG. I.

EGCR CREEP TEST ANALYSIS

TASK 227
APP 8

210

DR'N R.R.N.	CH'D PVG 6/17/60	APP'D <i>[Signature]</i>	SCALE = 12	SHEET 35 OF 45	ISSUE
ALLIS-CHALMERS MFG. CO.			DEPT. NDD-W	6/12/60	

FOR SPECIMEN #5 (2/4/60) THE DETERMINANT EQUATION IS

$$\begin{vmatrix} -y & 1 & x & x^2 & x^3 \\ +.0108 & 1 & 6 & 36 & 216 \\ +.0128 & 1 & 10 & 100 & 1000 \\ +.0123 & 1 & 14 & 196 & 2744 \\ +.0080 & 1 & 18 & 324 & 5832 \end{vmatrix} = 0$$

$$-y Q_1 = -y (11,430,720)$$

$$+.0108 (4536 x^3) = 48.99 x^3$$

$$+.0128 (3888 x^2) = 49.77 x^2$$

$$+.0123 (36,000 x) = 442.8 x$$

$$+.0080 (1,646,400) = 13171$$

$$+.0080 (+36,0 x^3) = -2.88 x^3$$

$$y (302,400) =$$

$$+.0108 (-3,528,000) = -38,102$$

$$+.0128 (-889,056 x) = -11380 x$$

$$+.0123 (-34992 x^2) = -430.4 x^2$$

THE EQUATION IS

$$y = -.00224 - .000983 x - .0000342 x^2 + .00000414 x^3$$

$$\frac{dy}{dx} = -.000983 - .0000684 x + .00001242 x^2$$

$$\frac{d^2y}{dx^2} = -.0000684 + .00002484 x$$

$$\text{POINT OF INFLECTION AT } x \approx \frac{.0000684}{.00002484} \approx 2.75$$

$$@ x=15 \quad \frac{d^2y}{dx^2} = -.0000684 + .000373 = .000305$$

$$@ x=19 \quad \frac{d^2y}{dx^2} = -.0000684 + .000472 = .000404$$

$$\epsilon_{15} = .375 (.000305) = .000114 \quad \text{IN/IN}$$

$$\epsilon_{19} = .375 (.000404) = .000151 \quad \text{IN/IN}$$

EGCR CREEP TEST ANALYSIS

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TASK 227
APP 8

SIMILAR TO

DR'N RRN

CH'D PVG 6/17/60

APP'D

SCALE = 12

SHEET 36 OF 45

ISSUE

ALLIS-CHALMERS MFG. CO.

DEPT. NDD-W

6/12/60

A

B

A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

FOR SPECIMEN # 2 (275/60) THE DETERMINANT EQUATION IS

$$\begin{vmatrix} -y & 1 & x & x^2 & x^3 \\ .0148 & 1 & 6 & 36 & 216 \\ .0192 & 1 & 10 & 100 & 1000 \\ .0182 & 1 & 14 & 196 & 2744 \\ .0123 & 1 & 18 & 324 & 5832 \end{vmatrix} = 0$$

$$-y(11,430,720) =$$

$$.0148(4536x^3) = 67.13x^3$$

$$.0192(3888x^2) = 74.65x^2$$

$$.0182(36,000x) = 655.2x$$

$$.0123(1,646,400) = 20251$$

$$.0123(-360x^3) = -4.42x^3$$

$$y(302,400) =$$

$$.0148(-3,528,000) = -52214$$

$$.0192(-889,056x) = -17070x$$

$$.0182(-34892x^2) = -636.85x^2$$

THE EQUATION IS

$$y = -.00287 - .001475x - .000505x^2 + .0000563x^3$$

$$\frac{dy}{dx} = -.001475 - .00101x + .0001689x^2$$

$$\frac{d^2y}{dx^2} = -.00101 + .0003378x$$

$$\text{POINT OF INFLECTION AT } x \approx \frac{.00101}{.0003378} = 2.99$$

$$\textcircled{a} \quad x=15 \quad \frac{d^2y}{dx^2} = -.00101 + .000506 = .000405$$

$$\textcircled{b} \quad x=19 \quad \frac{d^2y}{dx^2} = -.00101 + .000642 = .000541$$

$$e_{15} = .375(.000405) = .000151$$

$$e_{19} = .375(.000541) = .000202$$

EGCR CREEP TEST ANALYSIS

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TASK 227
APP 8

SIMILAR TO

DR'N R.R.M.	CH'D PUG 6/17/60	APP'D [Signature]	SCALE = 12	SHEET 37 OF 45	ISSUE
ALLIS-CHALMERS MFG. CO.			DEPT. NPD-W	6/12/60	

A

B

FOR SPECIMEN # 2 (2/15/60) THE DETERMINANT EQUATION IS

$$\begin{vmatrix} -y & 1 & x & x^2 & x^3 \\ .0355 & 1 & 6 & 36 & 216 \\ .0452 & 1 & 10 & 100 & 1000 \\ .0433 & 1 & 14 & 196 & 2744 \\ .0280 & 1 & 18 & 324 & 5832 \end{vmatrix} = 0$$

$$\begin{aligned} -y (11,430,720) & \\ .0355 (4536 x^3) &= 161.0 x^3 \\ .0452 (3888 x^2) &= 175.7 x^2 \\ .0433 (36,000 x) &= 1559 x \\ .0280 (1,646,400) &= 46099 \\ .0280 (-360 x^3) &= -10.1 x^3 \\ y (302,400) &= \\ .0355 (-3,528,000) &= -125244 \\ .0452 (-889,056 x) &= -40185. x \\ .0433 (-34992 x^2) &= -1515.2 x^2 \end{aligned}$$

THE EQUATION IS:

$$y = -.00711 - .00347 x - .0002408 x^2 + .0000136 x^3$$

$$\frac{dy}{dx} = -.00347 - .0002408 x + .0000408 x^2$$

$$\frac{d^2y}{dx^2} = -.0002408 + .0000816 x$$

$$\text{POINT OF INFLECTION AT } x = \frac{.0002408}{.0000816} = 2.95"$$

$$@ x = 15 \quad \frac{d^2y}{dx^2} = -.0002408 + .00122 = .00098$$

$$x = 19 \quad \frac{d^2y}{dx^2} = -.0002408 + .00155 = .00131$$

AND

$$\epsilon_{15} = .375 (.00098) = .000368 \text{ IN/IN}$$

$$\epsilon_{19} = .375 (.00131) = .000494 \text{ IN/IN}$$

EGCK CREEP TEST ANALYSIS

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TASK 227
APP 8

SIMILAR TO

DR'N RBN

CH'D PVG 6/12/60

APP'D

[Signature]

SCALE

= 12

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ISSUE

PROPERTY OF ALLIS-CHALMERS MFG. CO.

DEPT.

NPD-W

6/12/60

A

B

FOR SPECIMEN #5 (3/7/60) THE DETERMINANT EQUATION IS

$$\begin{vmatrix} -y & 1 & x & x^2 & x^3 \\ .0500 & 1 & 6 & 36 & 216 \\ .0632 & 1 & 10 & 100 & 1000 \\ .0615 & 1 & 14 & 196 & 2744 \\ .0423 & 1 & 18 & 324 & 5832 \end{vmatrix} = 0$$

$$-y (11,430,720) =$$

$$.0500 (4536 x^3) = 226.8 x^3$$

$$.0632 (3888 x^2) = 245.7 x^2$$

$$.0615 (36,000 x) = 2214 x$$

$$.0423 (1,646,400) = 69,643$$

$$.0423 (-360 x^3) = -15.2 x^3$$

$$y (302,400) =$$

$$.0500 (-3,528,000) = -176,400$$

$$.0632 (-889,056 x) = -56,188 x$$

$$.0615 (-34,992 x^2) = -2,152 x^2$$

THE EQUATION IS

$$y = -.009593 - .00485x - .000171x^2 + .0000190x^3$$

$$\frac{dy}{dx} = -.00485 - .000342x + .0000570x^2$$

$$\frac{d^2y}{dx^2} = -.000342 + .000114x$$

$$\text{POINT OF INFLECTION AT } x = \frac{.000342}{.000114} = 3"$$

$$@ x=15 \quad \frac{d^2y}{dx^2} = -.000342 + .00171 = .00137$$

$$x=19 \quad \frac{d^2y}{dx^2} = -.000342 + .00217 = .00183$$

$$\epsilon_{15} = .375 (.00137) = .000514 \text{ IN/IN}$$

$$\epsilon_{19} = .375 (.00183) = .000686 \text{ IN/IN}$$

EGCR CREEP TEST ANALYSIS

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TASK 227
APP 8

SIMILAR TO

DR'N RRN

CH'D PUG 6/12/60

APP'D [Signature]

SCALE = 12

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ISSUE

Property of ALLIS-CHALMERS MFG. CO.

DEPT. NPD-W

6/12/60

A

B

A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

FOR SPECIMEN #5 (4/11/60) THE DETERMINANT EQUATION IS

$$\begin{vmatrix} -y & 1 & x & x^2 & x^3 \\ .0738 & 1 & 6 & 36 & 216 \\ .0937 & 1 & 10 & 100 & 1000 \\ .0900 & 1 & 14 & 196 & 2744 \\ .0575 & 1 & 18 & 324 & 5832 \end{vmatrix} = 0$$

$$-y (11,430,920)$$

$$.0738 (4536 x^3) = 334.76 x^3$$

$$.0937 (3888 x^2) = 364.31 x^2$$

$$.0900 (36,000 x) = 3240.0 x$$

$$.0575 (1,644,400) = 94668$$

$$.0575 (-360 x^3) = -20.7 x^3$$

$$y (302,400)$$

$$.0738 (-3,528,000) = -260,366$$

$$.0937 (-889,056 x) = -83305 x$$

$$.0900 (-34992 x^2) = -31493 x^2$$

THE EQUATION IS

$$y = -.01489 - .00719 x - .00025 x^2 + .0000282 x^3$$

$$\frac{dy}{dx} = -.00719 - .00050 x + .000846 x^2$$

$$\frac{d^2y}{dx^2} = -.00050 + .001692 x$$

$$\text{POINT OF INFLECTION AT } x = \frac{.0005}{.00169} \approx 3"$$

$$@ x=15 \quad \frac{d^2y}{dx^2} = -.00050 + .00254 = .00204$$

$$x=19 \quad \frac{d^2y}{dx^2} = -.00050 + .00321 = .00271$$

$$\epsilon_{16} = .375 (.00204) = .000764 \text{ IN/IN}$$

$$\epsilon_{19} = .375 (.00271) = .00101 \text{ IN/IN}$$

EGCR CREED TEST ANALYSIS

TASK 227
APP 8

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SIMILAR TO

DR'N R.R.N.	CH'D PUG 6/17/60	APP'D	SCALE = 12	SHEET 40 OF 45	ISSUE
PROPERTY OF ALLIS-CHALMERS MFG. CO. DEPT. NPD-W				6/12/60	

THE STRAIN VS. TIME FOR SPECIMENS 1 & 5 IS PLOTTED IN FIG. III. IN ORDER TO ESTIMATE THE EFFECT OF STRESS THE STRAINS ARE TAKEN AT THE THIRD AND SIXTH POINTS OF BEAMS; FOR EACH OF THESE POINTS, A RANGE OF STRESS HAS BEEN CALCULATED BECAUSE OF THE UNKNOWN EXPONENTIAL VARIATION OF STRESS AND STRAIN.

THE SLOPES OF THE CURVES ARE:

SPEC. # 1 @ 400 HRS $\frac{(.000145 - .00011)}{(1200 - 0)} = \frac{.000035}{1200} = 2.9 \times 10^{-8}$ IN/IN/HR
 1400 HRS $\frac{(.00031 - 0)}{(2000 - 400)} = \frac{.00031}{1600} = 1.94 \times 10^{-7}$
 2400 HRS $\frac{(.000352 - .000324)}{(2800 - 1600)} = \frac{.000028}{1200} = 2.33 \times 10^{-8}$

SPEC # 5 @ 100 HRS $\frac{(.000808 - 0)}{(400 + 150)} = \frac{.000808}{550} = 1.47 \times 10^{-6}$
 500 HRS $\frac{(.000878 - .0004)}{(1200 + 100)} = \frac{.000478}{1300} = 3.68 \times 10^{-7}$
 1400 HRS $\frac{(.00098 - .0006)}{(1600 - 600)} = \frac{.00038}{1000} = 3.8 \times 10^{-7}$

SINCE THE CURVES IN THE STRESS RANGE (300 TO 400 PSI) CLOSELY PARALLEL THE UPPER RANGE CURVES, THE CREEP RATES SHOULD BE SIMILAR AND WILL NOT BE CALCULATED.

SIGNIFICANCE OF THE ABOVE RESULTS FOR EGCR GRAPHITE

COMPARING THE ABOVE VALUES OF CREEP RATE WITH THAT QUOTED IN II-227, APP 4, P. 5 (I.E. $.64 \times 10^{-9}$ IN/IN/MIN) AS THE RATE NECESSARY IN ORDER THAT NON-STRESS-PRODUCING EXTENSION (OR CONTRACTION) OF FIBERS DUE TO CREEP JUST EQUAL THE SHORTENING (OR LENGTHENING) OF FIBERS DUE TO IRRADIATION-INDUCED SHRINKAGE, THEREFORE PRODUCING NO STRESS, ONE FINDS:

REQ'D RATE = $.64 \times 10^{-9}$ IN/IN/MIN OR 3.84×10^{-8} IN/IN/HR

WHICH IS MAXIMUM RATE OF ACCUMULATING STRAIN IN EARLY CORE LIFE (6 MONTHS)

ACTUAL RATE = 2.33×10^{-8} IN/IN/HR (COLD) FOR 3 MONTHS

OR

= 3.8×10^{-7} IN/IN/HR (HOT) FOR 2 MONTHS

BOTH OF THESE ACTUAL RATES ARE FOR STRESS IN THE 550 TO 750 PSI RANGE. SINCE THEY ARE ROUGHLY EQUAL TO THE REQUIRED RATE, IT DOES

EGCR CREEP TEST ANALYSIS

TASK 227
APP 8

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SIMILAR TO

DR'N	RRN	CH'D	PUG 6/12/60	APP'D	[Signature]	SCALE	= 12	SHEET 41	OF 45	ISSUE
PROPERTY OF ALLIS-CHALMERS MFG. CO.						DEPT.		NPD - W		6/12/60

NOT APPEAR THAT THE STRESS IN EGCR WILL EVER VERY MUCH EXCEED 1000 PSI (MAKING ALLOWANCE FOR EXPERIMENTAL ERROR AND INACCURACY IN THE MATHEMATICAL TREATMENT). THIS CONFIRMS THE ESTIMATE MADE IN II-227, APP. 4 THAT THE MAXIMUM STRESS IN EGCR GRAPHITE WOULD NOT EXCEED 900 TO 1300 PSI. FURTHER, THIS INDICATES THAT MAXIMUM STRESS IS NOT THE CRITERION OF FAILURE IN EGCR GRAPHITE, BUT THAT MAXIMUM STRAIN, AS EXPLAINED IN PART II, IS.

EGCR CREEP TEST ANALYSIS

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APP 8

SIMILAR TO

DR'N RRN

CH'D PUG 6/17/60

APP'D *[Signature]*

SCALE = 12

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ISSUE

6/12/60

Property of ALLIS-CHALMERS MFG. CO.

DEPT. NPD-W

A

B

A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

218

DEFLECTION RELATIVE TO POINT #1 LOCATED
AT ORIGIN OF 115/60 - INCHES

Fig I

SPECIMEN # 1 - COLD

POINT #1 OF 115/60 TEST
PLACED AT ORIGIN AND ALL TEST
DATA MADE RELATIVE TO THIS POINT.
FITTED CURVES SHOWN DOTTED

RRN 6/12/60

EG&G CREEP TEST ANALYSIS
TASK 227 - App. 8.

SHEET #3 OF 45
WFO-LW

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FIG III
CREEP STRAIN VS TIME

R.R.N.
4/12/60

EGGE CREEP TEST ANALYSIS
TASK 227 - APP. 8

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APPENDIX 9

SUPPLEMENTARY CALCULATIONS OF GRAPHITE BOWING

(SEE APPENDIX 7)

APPENDIX 9

1. This Appendix includes supplementary calculations which determine:

a. An estimate of gaps between EGCR graphite columns after 3, 5, 10, and 15 years of reactor operation.

b. An estimate of stresses induced in core-graphite columns (due to restrained bowing and internal shrinkage effects) after at 3, 5, 10, and 15 years of reactor operation.

c. An estimate of the redistribution of gaps and stresses if any particular column should fail.

Additional work performed under this same task and concerned with analysis of creep-test data obtained by Allis-Chalmers laboratory personnel is contained in Appendix 8. Analyses of stresses in graphite columns, and in top and bottom restraints, due to restraint of bowing by the peripheral-restraint bands, are included in Appendix 6 of A-C Study No. II-229.

2. The following general conclusions are noted:

a. The gaps between columns at operating temperatures exceed, on the average, those in the cold condition. However, the tendency of the columns to bow causes many gaps to be zero in both cases. Gaps as high as 1/2 in. can occur in some locations on the core mid-plane. Gaps at the top of every column will be restricted to about 0.09 in. and to about 0.07 in. at the bottom (roughly the original installation clearance plus thermal expansion effects).

b. The stresses in the columns were calculated in this report on a stepwise basis, taking into account the linear or non-linear variation with time of all gaps, bows, and internal effects. These stresses do not significantly differ from the stress values reported in Appendix 7, which have a more approximate basis, treating some non-linear effects as linear. Maximum core stress occurs during the cold condition. Stress varies from column to column at any one time during core life, and no "maximum" stress can be explicitly stated.

c. The lives of individual columns, based on the maximum allowable flexural stress, do not significantly differ from those calculated in Appendix 7. The minimum life of any column is about 6 years, and the average life for all 120 columns is about 13.8 years (see Paragraph g below) neglecting effects of creep.

d. The maximum net bow which will occur in any one column is about 1/2 in. and will occur after 15 years of reactor operation.

e. Should those columns with the shortest predicted lives all rupture, they will be prevented from gross lateral displacements by concentric rings of columns which have longer lives. Displacement following rupture will be limited to the gaps which exist around the ruptured columns at the time; in some cases, this could be as high as a quarter-inch. Although the structural integrity of the core structure would not disappear as a result of these early ruptures, the possibility of levitation of half-columns and consequent dislocation of fuel and control-rod channels would probably impair the core functions. Any redistribution of gaps upon early failure would be random.

f. Generally speaking, the rupture of columns with shortest predicted lives will not produce significant redistribution of stress. Later and more extended ruptures have not been considered, since the early ruptures would probably have already so impaired core functions as to require some repair operations to the core. Because of the generally outward bowing tendency of all columns it is believed that further rupture would effect no great stress redistributions.

g. The calculated column lives, and the conclusions drawn from them, must be regarded as very conservative, since they are based on the criterion that when maximum allowable flexural stress is once reached at any one point in a column, the column is considered to have reached the end of its useful life. Obviously, this is ultra-conservative with regard to lifetime predictions.

3. Gaps between core columns are calculated for two general conditions:

a. The core is at operating temperature, so as to cause maximum open spaces between columns, and therefore is critical from the standpoint of coolant bypass leakage between columns (based upon coolant distribution given in Study II-179-1 and 2).

b. The core is in the cold state so as to cause minimum open spaces between columns (at any time in core life) and therefore is critical from the standpoint of the amount of stress induced in columns by restrained bow.

All gaps calculated in this report include the effect of nominal erection clearances between columns, as required by the contract drawings; similar preliminary calculations in Appendix 7 included only an estimate of this clearance. Calculation of open spaces between columns (exclusive of the tendency of bowed columns to close these spaces) also includes: (1) The effects of the hot and cold clearance between peripheral restraint bands and the outermost core columns; (2) The transverse shrinkage of column cross-sections due to fast-neutron irradiation; and (3) Separation of adjacent columns due to thermal expansion of the top restraint lattice and the bottom core-support plate.

4. For any specific column, the sum of all spaces between columns, from the peripheral restraint inward to the column in question, due to all the above factors, minus the bowing tendency of the column, results in either a net gap (if gap exceeds bow) or a restrained bow (if potential bow exceeds gap).

Net gaps between columns are shown for the operating condition in Figures I and IV; the net bow and the restrained bow for this condition are shown for all columns in Tables VII to X. These represent the critical conditions for coolant leakage.

For the cold condition, the net and restrained bows of all columns are found as above, except that available spaces between adjacent columns (and consequently the cumulative space inward from the peripheral restraint bands to any column) are reduced from those of the hot condition by the amount of space previously contributed by thermal expansion of the restraint lattice and the bottom plate. These bows are summarized in Tables XI to XIV. The restrained bow causes stress in the graphite columns. This stress is computed by treating the amount of restrained bow as a known deflection of an originally slightly curved (and isotropic) beam caused by an unknown, uniformly distributed load along the whole beam length (i.e., column height). Stress is computed directly from the known "deflections" and known physical dimensions of "beams," using an average value of Young's Modulus over the range of stress. Use of the average was shown in Appendix 7 to give approximately the same final result as would the more accurate process of using the Young's Modulus appropriate to any stress level at the end of any time interval for finding the increment of stress in the next time interval. Upon the bowing stresses are superimposed the internally generated stresses at any time from the beginning of the core life. The superimposed stresses are calculated as in Appendix 7, taking into account variation in Young's Modulus with changing stress levels. Combined stresses, shown in Table XV, are used to estimate the life of various columns, based upon a maximum-allowable-stress criterion neglecting effects of creep.

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TEMPERATURES ARE FAIRLY UNIFORM ON ANY HORIZONTAL CORE CROSS-SECTION, THE SEPARATION CAN BE COMPUTED AS UNIFORM FOR ALL COLUMNS, AT THE MIDPLANE.

$$\text{TOP STEEL EXPANSION: } (16)(1200-70)(7.4 \times 10^{-6}) = .134$$

$$\text{BOTTOM STEEL EXPANSION: } (16)(500-70)(6.4 \times 10^{-6}) = .044$$

TOP STEEL IS 502

BOTTOM STEEL IS 212B

$$\text{GAP AT MIDPLANE} = \frac{.134 + .044}{2} = .089"$$

THIS IS REDUCED BY EXPANSION OF THE MIDPLANE GRAPHITE WHICH IS APPROXIMATELY AT 850F TO 900F.

$$\text{GRAPHITE EXPANSION: } (16)(875-70)(3.6 \times 10^{-6}) = .046"$$

$$\text{THE MAXIMUM RESULTANT GAP IS: } .089 - .046 = .043$$

4. TRANSVERSE SHRINKAGE OF THE GRAPHITE DUE TO IRRADIATION:
SHRINKAGE RATE IS .013 % PER 1000 MWD/AT (MEMO: ^{AC} DAVIDSON TO BANKS, APRIL 8, 1960)

EXPOSURES CAN BE PROPORTIONED FROM VALUES AT THE MIDPLANE OF EACH COLUMN LISTED IN APPENDIX 6 OF AC REPORT 227-II (PROPORTIONED FOR UTILIZATION FACTOR = 0.8)

THE SHRINKAGES ARE LISTED IN TABLE I (FOR X & Y DIRECTIONS) FOR SEVERAL TIMES IN CORE LIFE.

5. TRANSVERSE BOWING OF COLUMNS DUE TO NON-UNIFORM IRRADIATION:

THESE ARE CALCULATED IN ACCORD WITH APPENDIX 7 OF ^{AC} REPORT 227-II AND LISTED IN TABLE II (FOR X & Y DIRECTIONS) FOR SEVERAL TIMES IN CORE LIFE AND WITH A UTILIZATION FACTOR OF 0.8.

FROM STANDPOINT OF SHOWING MAXIMUM GAPS THAT WILL OCCUR BETWEEN COLUMNS IN EGCR, THE HOT (OPERATING) VALUES WILL BE SOUGHT. THIS SHOULD GIVE CRITICAL VALUE BECAUSE LEAKAGE WILL BE GREATEST BETWEEN COLUMNS THEN. FOR CALCULATING MAXIMUM

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COLUMN STRESSES DUE TO RESTRAINED BOWING, THE COLD CONDITION SHOULD BE CRITICAL BECAUSE GAPS FOR ACCEPTING BOWS ARE LESS AND GRAPHITE IS WEAKEST AT LOW TEMPERATURE. THIS IS A QUITE POSSIBLE CASE, SINCE REACTOR COULD BE SHUT DOWN AT ANY TIME WITH ALL ITS ACCUMULATED POTENTIAL BOWS AND ACTUAL GAPS.

FOR THE HOT CONDITION GAPS BETWEEN COLUMNS (AT 3 YEARS):

COL. 72 TO PERIPHERAL RESTRAINT — X DIRECTION

$$\begin{array}{rcl} \text{FACTOR \#1} & = & 0 \\ \text{\#2} & = & 0 \\ \text{\#3} & = & 0 \\ \text{\#4} & = & \frac{.0001}{2} \\ & & \hline & & \text{NEGLIGIBLE} \end{array}$$

COL. 71 TO 72 — X DIRECTION

$$\begin{array}{rcl} \text{\#1} & = & .045 \\ \text{\#2} & = & 0 \\ \text{\#3} & = & .043 \\ \text{\#4} & = & \frac{.0033 + .0001}{2} \\ & & \hline & = & .089 \end{array}$$

COL. 70 TO 71 — X DIRECTION

$$\begin{array}{rcl} \text{\#1} & = & .045 \\ \text{\#2} & = & 0 \\ \text{\#3} & = & .043 \\ \text{\#4} & = & .01 \quad \frac{.0033 + .0167}{2} \\ & & \hline & = & .089 \\ & & \hline & = & .187 \end{array}$$

COL. 69 TO 70 — X DIRECTION

$$\begin{array}{rcl} \text{\#1} & = & .045 \\ \text{\#2} & = & 0 \\ \text{\#3} & = & .043 \\ \text{\#4} & = & .019 \quad \frac{.0167 + .0224}{2} \\ & & \hline & = & .187 \\ & & \hline & = & .294 \end{array}$$

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Col 68 To 69

X DIRECTION

1 = .045

2 = 0

3 = .043

4 = .023

$$\begin{array}{r} .294 \\ \hline .405 \end{array}$$

$$\frac{.0324 + .0239}{2}$$

Col 67 To 68

X DIRECTION

1 = .045

2 = 0

3 = .043

4 = .023

$$\begin{array}{r} .405 \\ \hline .516 \end{array}$$

$$\frac{.022 + .0239}{2}$$

Col 67 To Col. 67

X DIRECTION

1 = $\frac{.045}{2} = .0225$

2 = 0

3 = $\frac{.043}{2} = .0215$

4 = $\frac{.011}{2} = .0055$

$$\frac{.022}{2}$$

Col 84 To PERIPHERAL RESTRAINT — X DIRECTION

NEGLECTIBLE

Col. 83 To 84

X DIRECTION

1 = .045

2 = 0

3 = .043

4 = $\frac{.001}{2} = .0005$

$$\frac{.0027 + .0001}{2}$$

Col 82 To 83

X DIRECTION

1 = .045

2 = 0

3 = .043

4 = .008

$$\begin{array}{r} .089 \\ \hline .185 \end{array}$$

$$\frac{.0027 + .0185}{2}$$

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Col 81 To 82

#1 = .045
#2 = .0
#3 = .043
#4 = $\frac{.016}{.185}$
 .289

X DIRECTION

$\frac{.0135 + .0194}{2}$

Col 80 To 81

#1 = .045
#2 = .0
#3 = .043
#4 = $\frac{.021}{.289}$
 .298

Y DIRECTION

$\frac{.0194 + .0231}{2}$

Col 79 To 80

#1 = .045
#2 = .0
#3 = .043
#4 = $\frac{.024}{.398}$
 .510

X DIRECTION

$\frac{.0231 + .0239}{2}$

Col 78 To 79

#1 = $\frac{.045}{2} = .0225$
#2 = .0
#3 = $\frac{.043}{2} = .0215$
#4 = $\frac{.019}{.0559}$

X DIRECTION

$\frac{.021 + .0239}{2}$

PERIPHERAL RESTRAINT TO COL # 96

NEGLECTABLE

X - DIRECTION

Col 95 To 96

#1 = .045
#2 = .0
#3 = .043
#4 = $\frac{.007}{.095}$

X - DIRECTION

$\frac{.0001 + .0012}{2}$

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Col 94 To 95

1 = .045
2 = 0
3 = .043
4 = .004
 .095

 .187

X DIRECTION

$$\frac{.0012 + .0059}{2} =$$

Col 93 To 94

1 = .045
2 = 0
3 = .043
4 = .009
 .187

 .284

X DIRECTION

$$\frac{.0059 + .0123}{2}$$

Col 92 To 93

1 = .045
2 = 0
3 = .043
4 = .016
 .284

 .388

X DIRECTION

$$\frac{.0123 + .0194}{2}$$

Col 91 To 92

1 = .045
2 = 0
3 = .043
4 = .031
 .388

 .497

X DIRECTION

$$\frac{.0194 + .0224}{2}$$

Q To Col 91

1 $\frac{.045}{2} = .0225$
2 0
3 $\frac{.043}{2} = .0215$
4 $\frac{.0112}{2} = .0056$
 .0552

$$\frac{+ .0224}{2}$$

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PERIPHERAL RESTRAINT TO COL 106

NEGLECTIBLE

X DIRECTION

COL 105 TO 106

$$\begin{array}{rcl}
 \# 1 & = & .045 \\
 \# 2 & = & 0 \\
 \# 3 & = & .043 \\
 \# 4 & = & .001 \\
 & & \hline
 & & .089
 \end{array}$$

X DIRECTION

$$\frac{.0002 + .001}{2}$$

COL 104 TO 105

$$\begin{array}{rcl}
 \# 1 & = & .045 \\
 \# 2 & = & 0 \\
 \# 3 & = & .043 \\
 \# 4 & = & .004 \\
 & & \hline
 & & .089 \\
 & & \hline
 & & .181
 \end{array}$$

X DIRECTION

$$\frac{.001 + .0059}{2}$$

COL 103 TO 104

$$\begin{array}{rcl}
 \# 1 & = & .045 \\
 \# 2 & = & 0 \\
 \# 3 & = & .043 \\
 \# & = & .009 \\
 & & \hline
 & & .181 \\
 & & \hline
 & & .278
 \end{array}$$

X DIRECTION

$$\frac{.0059 + .0135}{2}$$

COL 102 TO 103

$$\begin{array}{rcl}
 \# 1 & = & .045 \\
 \# 2 & = & 0 \\
 \# 3 & = & .043 \\
 \# 4 & = & .015 \\
 & & \hline
 & & .278 \\
 & & \hline
 & & .381
 \end{array}$$

X DIRECTION

$$\frac{.0135 + .0167}{2}$$

Q TO COL 102

$$\begin{array}{rcl}
 \# 1 & = & \frac{.045}{2} = .0225 \\
 \# 2 & = & 0 \\
 \# 3 & = & \frac{.043}{2} = .0215 \\
 \# 4 & = & .0084 \\
 & & \hline
 & & .0524
 \end{array}$$

$$\frac{.0135 + .0167}{2}$$

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PERIPHERAL RESTRAINT TO COL 114
NEGUGIBLE

X DIRECTION

Col 113 To 114

X DIRECTION

$$\begin{array}{rcl} \#1 & = & .045 \\ \#2 & = & 0 \\ \#3 & = & .043 \\ \#4 & = & .001 \\ & & \hline & & .089 \end{array}$$

$$\frac{.0002 + .0012}{2}$$

Col 112 To 113

X DIRECTION

$$\begin{array}{rcl} \#1 & = & .045 \\ \#2 & = & 0 \\ \#3 & = & .043 \\ \#4 & = & .002 \\ & & \hline & & .089 \\ & & \hline & & .179 \end{array}$$

$$\frac{.0012 + .0027}{2}$$

Col 111 To 112

X DIRECTION

$$\begin{array}{rcl} \#1 & = & .045 \\ \#2 & = & 0 \\ \#3 & = & .043 \\ \#4 & = & .003 \\ & & \hline & & .199 \\ & & \hline & & .270 \end{array}$$

$$\frac{.0027 + .0033}{2}$$

Q To Col # 111

X DIRECTION

$$\begin{array}{rcl} \#1 & .045 & = .0225 \\ \#2 & 0 & \\ \#3 & .043 & = .0215 \\ \#4 & & .0016 \\ & & \hline & & .0456 \end{array}$$

$$\frac{.0012 + .0033}{2}$$

PERIPHERAL RESTRAINT TO COL # 120
NEGUGIBLE

X DIRECTION

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COL 119 TO 120

$$\#1 = .045$$

$$\#2 = 0$$

$$\#3 = .043$$

$$\#4 = \frac{.0001}{2} = .00005$$

X DIRECTION

$$\frac{.0001 + .0001}{2}$$

COL 118 TO 119

$$\#1 = .045$$

$$\#2 = 0$$

$$\#3 = .043$$

$$\#4 = \frac{.0001}{2} = .00005$$

X DIRECTION

$$\frac{.0001 + .0001}{2}$$

Q TO COL 118

$$\#1 = \frac{.045}{2} = .0225$$

$$\#2 = 0$$

$$\#3 = \frac{.043}{2} = .0215$$

$$\#4 = \frac{.00005}{2} = .000025$$

BECAUSE OF SYMMETRY, AVAILABLE GAPS IN THE Y DIRECTION CAN BE TAKEN FROM THE FOREGOING X-GAPS BY SELECTING ANY COLUMN AND ITS MIRROR IMAGE ABOUT THE OCTANT LINE. THESE VALUES ARE LISTED IN TABLE III.

FOR YEARS 5, 10, & 15, A SIMILAR PROCESS IS FOLLOWED, USING APPROPRIATE SHRINKAGE VALUES, AND THE RESULTING GAPS ARE LISTED IN TABLES IV, V, & VI

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COLUMNS AT MIDHEIGHT - (UTILIZATION FACTOR = 0.9)

* ESTIMATED

A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

UNRESTRAINED BOW OF EGCR GRAPHITE COLUMNS (@ U=0.8)

Col #	X		Y		X		Y		K _z (3)	K _z (5)	K _z (10)	K _z (15)	MAXIMUM POTENTIAL BOW AT COLUMN MID-HEIGHT							
	E ₁	E ₂	E ₁	E ₂	E ₁ -E ₂	E ₁ -E ₂	δX (in)						δY (in)							
	MWD/AT 1000YR	MWD/AT 1000YR	MWD/AT 1000YR	MWD/AT 1000YR	MWD/AT 1000YR	MWD/AT 1000YR	N=3	N=5					N=10	N=15	N=3	N=5	N=10	N=15		
	in-YR 1000 MWD/AT																			
67	3.63	3.38	3.63	3.38	0.30	0.30	.182	.303	.606	.91	.0545	.0909	.182	.273	.0545	.0909	.182	.273		
68	3.33	3.68	3.76	3.58	-0.35	0.18	.182	.303	.606	.91	-.0635	-.106	-.212	-.318	.033	.0545	.109	.164		
69	3.68	3.15	3.50	3.30	0.53	0.20	.182	.303	.606	.91	.0964	.16	.321	.482	.036	.0606	.121	.181		
70	3.15	1.29	2.80	2.29	1.86	0.21	.182	.303	.606	.91	.338	.563	1.13	1.69	.039	.063	.126	.191		
71	1.29	0.05	0.40	0.38	1.24	0.02	.182	.303	.606	.91	.226	.376	.752	1.13	.0036	.006	.013	.018		
72	.05	~0	.075	.015	0.05	0.002	.182y	.303y	.606y	.91y	.01	.016	.034	.046	.0004	.0006	.0013	.0018		
80	3.58	3.35	3.58	3.35	0.23	0.23	.201x	.335x	.670x	1.0x	.182	.303	.606	.91y	.0418	.07	.14	.21		
81	3.35	2.57	3.30	2.62	0.78	0.68	.182	.303	.606	.91	.142	.236	.473	.71	.124	.206	.412	.618		
82	2.57	1.03	2.29	1.66	1.54	0.63	.182	.303	.606	.91	.280	.467	.934	1.40	.114	.191	.382	.572		
83	1.03	.045	0.38	0.25	0.98	0.13	.182	.303	.606	.91	.178	.297	.595	.891	.024	.039	.079	.118		
84	.045	~0	0.015	.0126	0.045	0.002	.182y	.303y	.606y	.91y	.011	.018	.036	.056	.0004	.0006	.0013	.0018		
93	2.62	1.44	2.62	1.44	1.18	1.18	.242x	.403x	.806x	1.21x	.182	.303	.606	.91	.215	.359	.719	1.08		
94	1.44	0.50	1.66	0.25	0.94	1.41	.182	.303	.606	.91	.170	.283	.570	.855	.256	.428	.856	1.28		
95	0.50	0.02	0.25	.038	0.48	0.21	.182	.303	.606	.91	.087	.145	.291	.437	.038	.064	.127	.191		
96	0.02	0	.0126	0	0.02	0.01	.182y	.303y	.606y	.91y	.01	.016	.032	.049	.002	.003	.006	.009		
105	0.25	.042	0.25	.042	0.21	0.21	.480x	.810x	1.62x	2.43x	.182	.303	.606	.91	0.104	0.06	0.13	0.19		
106	.042	0	.038	0	.042	.038	.182	.303	.606	.91	.0076	.013	.025	.038	.007	.012	.023	.035		

$K_x = K_y$ EXCEPT
AS NOTED

SHRINKAGE RATE PARALLEL TO GRAIN = .02% PER 1000 MWD/AT
FOR IRREGULARLY SHAPED COLUMNS AT THE PERIPHERY, BOWING VALUES ARE
APPROXIMATE, SINCE IN GENERAL LOAD DO NOT PASS THROUGH SHEAR CENTER
OR PERPENDICULAR TO THE TRUE NEUTRAL AXIS.

TABLE II

CONC. STRUCTURE

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MAXIMUM CUMULATIVE SPACE AVAILABLE BETWEEN COLUMNS FOR ACCOMMODATING BOWING

TABLES III, IV, V & VI ON THE FOLLOWING PAGES INDICATE, FOR ANY COLUMN, THE AMOUNT OF SPACE (IN X AND Y DIRECTIONS) WHICH WOULD BE AVAILABLE TO ACCEPT THE COLUMN'S BOWING TENDENCY IF ALL THE VOIDS AND SPACES BETWEEN THE SUBJECT COLUMN AND THE MIDPLANE PERIPHERAL RESTRAINT WERE CLOSED. SUCH CLOSURE IS ASSUMED TO HAVE OCCURRED BY EVERY INTERVENING COLUMN BOWING SO AS TO CLOSE UP ALL SPACES BETWEEN COLUMNS AND FORCE THE OUTERMOST COLUMN AGAINST THE PERIPHERAL RESTRAINT.

THE TABLES SHOULD BE READ AS FOR COL. 92 (TABLE III) FOR EXAMPLE

THAT IS, THE CUMULATIVE X-DIRECTION GAPS WHICH EXIST UP TO THE PARTY LINE BETWEEN 92 AND 93 CAN BE READ FROM THE TABLE ~~AT~~ ^{AT THE PARTY LINE BETWEEN 92 AND 103} THE LINE BETWEEN THESE COLUMNS. THE CUMULATIVE Y-DIRECTION GAPS CAN BE READ FROM THE TABLE AS THE y-VALUE BETWEEN THESE TWO NUMBERS. THIS RULE HOLDS FOR ALL COLUMNS. THE ONLY EXCEPTIONS ARE THE GAPS WHICH EXIST BETWEEN THE INNERMOST COLUMNS OF ROWS AND THE CORE Φ ; THE y-VALUES OF SUCH GAPS CAN BE READ AS THE UPPERMOST VALUE IN ANY ROW, THE x-VALUES CAN BE READ AS THE LEFTMOST x-MARKED VALUE IN ANY ROW. ARROWS ~~BE~~ ^{OUTSIDE OF TABLE OUTLINE MERELY INDICATE THE DIRECTION OF GAP AND NOT THAT TABULAR VALUES ARE MISPLACED.}

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DR'N <u>R.R.N</u>	CH'D	APP'D <u>(Signature)</u>	SCALE = 12	SHEET <u>11A</u> OF <u>33</u>	ISSUE
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TABLE III

MAXIMUM AVAILABLE SPACES BETWEEN COLUMNS AT THREE YEARS (HOT CONDITION)

CORE Φ

Y .055	Y .056	Y .055	Y .052**	Y .046	Y .044
67	68	69	70	71	72
X .055	X .516	X .405	X .294	X .187	X .089
Y .516	Y .510	Y .497	Y .381	Y .270	Y .176
79	80	81	82	83	84
X .056**	X .510	X .598	X .289	X .185	X .089
Y .405	Y .398	Y .388	Y .278	Y .179	Y .088
91	92	93	94	95	96
X .055	X .497	X .388**	X .284	X .187	X .095
Y .294	Y .289**	Y .284	Y .181	Y .089	
102	103	104	105	106	
X .052	X .381	X .278	X .181	X .089	
Y .187	Y .185	Y .187	Y .089		
111	112	113	114		
X .046	X .270	X .179	X .089		
Y .089	Y .089	Y .095			
118	119	120			
X .044	X .176	X .088			

TABLE IV

MAXIMUM AVAILABLE SPACES BETWEEN COLUMNS AT FIVE YEARS (HOT CONDITION)

CORE Φ

Y .062	Y .064	Y .063	Y .057	Y .047	Y .044
67	68	69	70	71	72
X .062	X .570	X .444	X .317	X .196	X .091
Y .570	Y .559	Y .523	Y .400	Y .273	Y .176
79	80	81	82	83	84
X .064	X .559	X .432	X .308	X .192	X .090
Y .444	Y .432	Y .400	Y .287	Y .180	Y .088
91	92	93	94	95	96
X .063	X .523	X .400	X .286	X .183	X .089
Y .317	Y .308	Y .286	Y .183	Y .089	
102	103	104	105	106	
X .057	X .400	X .287	X .183	X .089	
Y .196	Y .192	Y .183	Y .089		
111	112	113	114		
X .047	X .273	X .180	X .089		
Y .091	Y .090	Y .089			
118	119	120			
X .044	X .176	X .088			

CORE STRUCTURE
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TABLE V

MAXIMUM AVAILABLE SPACES BETWEEN COLUMNS AT TEN YEARS (HOT CONDITION)

CORE Φ →

y .081	y .084	y .081	y .072	y .049	y .044
67	68	69	70	71	72
x .091	x .698	x .533	x .368	x .215	x .094
y .698	y .677	y .607	y .449	y .282	y .176
79	80	81	82	83	84
x .084	x .677	x .510	x .351	x .208	x .093
y .533	y .510	y .449	y .311	y .184	y .058
91	92	93	94	95	96
x .081	x .607	x .449	x .308	x .190	x .090
y .368	y .351	y .308	y .190	y .090	
102	103	104	105	106	
x .072	x .449	x .311	x .190	x .090	
y .315	y .208	y .190	y .090		
111	112	113	114		
x .049	x .282	x .184	x .090		
y .094	y .093	y .090			
118	119	120			
x .044	x .176	x .088			

TABLE VI

MAXIMUM AVAILABLE SPACES BETWEEN COLUMNS AT FIFTEEN YEARS (HOT CONDITION)

CORE Φ →

y .099	y .103	y .100	y .086	y .052	y .044
67	68	69	70	71	72
x .099	x .828	x .625	x .421	x .235	x .097
y .828	y .712	y .691	y .496	y .293	y .178
79	80	81	82	83	84
x .103	x .712	x .589	x .393	x .223	x .095
y .625	y .589	y .498	y .332	y .190	y .089
91	92	93	94	95	96
x .100	x .691	x .498	x .331	x .197	x .091
y .421	y .393	y .331	y .196	y .092	
102	103	104	105	106	
x .086	x .496	x .332	x .196	x .091	
y .235	y .223	y .197	y .091		
111	112	113	114		
x .052	x .243	x .190	x .092		
y .097	y .095	y .091			
118	119	120			
x .044	x .198	x .089			

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A

0 10 20 30 40 50 60 70 80 90 100 110 120

10 min baseline 10 min treatment 90 min post-treatment

B

H A

C

H A

Legend: $\square$ Baseline, $\square$ Treatment, $\square$ Post-treatment

II). ON THE ASSUMPTION THAT ANY PARTICULAR COLUMN WILL BOW (GENERALLY OUTWARD) UNTIL ^{EITHER} ALL AVAILABLE SPACE OUT TO THE RESTRAINT IS CLOSED OR ALL OF ITS BOWING POTENTIAL IS EXHAUSTED BEFORE THE NEAREST NEIGHBOR (IN ITS FINAL POSITION DUE TO ITS OWN PARTICULAR COMBINATION OF SPACE & BOWING) IS CONTACTED. BOWING TENDENCIES ARE SHOWN IN TABLE II FOR THREE, FIVE, TEN, AND FIFTEEN YEARS, AND THE AVAILABLE GAPS ARE TAKEN AT OPERATING TEMPERATURE TO GIVE THE SUPPOSEDLY CRITICAL CASE FOR COOLING.

FOR INSTANCE, AT THREE YEARS:

Col 72 POTENTIAL X-Bow = .01"
 " Y-Bow = .0004"

AVAILABLE $\times$ GAP = NEGLIGIBLE OUT TO RESTRAINT

$.01 > .00$ $\therefore$ No Gap At 3 yr. BETWEEN
72 & RESTRAINT

AVAILABLE Y GAP MUST BE COMPUTED (IN GENERAL) BY WORKING INWARD (IN THE Y DIRECTION) FROM THE RESTRAINT. **EVEN** IN THIS COLUMN, WHERE THE BOW IS SO MUCH LESS THAN THE GAP WHICH EXIST BETWEEN 72 AND 84, EVEN WITHOUT ANY BOWING OF 84, THE GAP MUST BE COMPUTED BY WORKING INWARD FROM 96. THIS WILL BE DONE SEPARATELY FOR ALL COLUMNS IN Y DIRECTION (NOTE THAT THE AMOUNT OF RESTRAINED BOW COULD BE SEEN FOR COL. 72 AT ONCE BECAUSE THE GAP, NOT COUNTING BOWING OF 84, EXCEEDS THE BOWING).

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C

COL 71

Pot. Bow = .226"

AVAILABLE X-GAP .089 FROM RESTRAINT TO 71

.226 > .089 $\therefore$ No GAP 71 TO 72

NET BOW OF 71 = .089

COL 70

Pot. Bow = .338

AVAILABLE GAP = .187

(GAPS CLOSED OUT TO RESTRAINT)

.338 > .187 $\therefore$ No GAP 70 TO 71

NET BOW OF 70 = .187

COL 69

Pot Bow = .0964

AVAILABLE GAP = .294

(GAPS CLOSED OUT TO RESTRAINT)

.0964 < .294 $\therefore$ GAP 69 TO 70 = .293
$$\begin{array}{r} -.096 \\ \hline .197 \end{array}$$

NET BOW OF 69 = .0964"

(ALL OTHER GAPS MUST NOW BE MEASURED FROM NET BOW OF 69)

COL 68

Pot. Bow = -.0635"

 $\therefore$ THE GENERAL FORE GOING

METHOD OF COMPUTING GAPS CAN-

NOT BE USED, SINCE THIS IS AN

INWARD BOW.

THE GAP AVAILABLE BETWEEN 67 & 68 IS:

FACTOR # 1 .045

2 0

3 .043

4 .023

$$\begin{array}{r} .111 \end{array}$$

$$\frac{.022 + .024}{2} = .023$$

THE SIMULTANEOUS OUTWARD BOW OF 67 IS .0545

 $\therefore$ TOTAL TENDENCY TO CLOSE THE GAP IS .118" $\therefore$ No GAP 67 TO 68

NET. Gap 68 TO 69 IS THEN:

FACTOR 1+3 = .088

FACTOR 4 = .023

NET OUTWARD BOW OF 69 = .096

NET INWARD BOW OF 68 = $\frac{.111}{2}$

(Approx.)

TOTAL .263

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SIMILAR TO

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GMS

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Col 67

NET GAP OF 67 TO ϕ IS.

FACTOR 1+3

$$\frac{.088}{2} = .044$$

FACTOR 4

$$\frac{.022}{2} = .011$$

NET BOW OF 67

$$\frac{.111}{2} = .056$$

.111

CHECKING:

TOTAL FACTOR (1+3) FROM ϕ TO RESTRAINT = $5.5 (.088) = .484$
 SHRINKAGE OF BRICKS

.022
 .024
 .022
 .017
 .003
 .572

TOTAL GAPS NET :

.111
 .263
 .197
 .571

3 YEAR GAPS ARE SHOWN IN FIG. I. OTHER YEARS ARE SHOWN IN FIGS. II, III, IV.

	.111	.089	.091	.091	.050	.044
.111	(67) 0	(68) .263	(69) .197	(70) 0	(71) 0	(72) 0
0	0	.121	.197	.178	.111	.088
.089	(79) .121	(80) .209	(81) .147	(82) 0	(83) 0	(84) 0
.263	.263	.209	.149	.165	.104	.088
.091	(91) .197	(92) .149	(93) .053	(94) .009	(95) .108	(96) 0
.197	.197	.147	.053	0	.051	0
.091	(102) .178	(103) .145	(104) 0	(105) 0	(106) 0	0
0	0	0	.009	0	0	0
.050	(111) .111	(112) .104	(113) .052	(114) 0	0	0
0	0	0	.008	0	0	0
.044	(118) .088	(119) .088	(120) 0	0	0	0
0	0	0	0	0	0	0

FIG I

NET GAPS BETWEEN COLUMNS
 AT OPERATING TEMPERATURE

3 YEARS

CORE STRUCTURE
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APP'D

G M

SCALE

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FIG. II
NET GAPS BETWEEN COLUMNS
AT OPERATING TEMPERATURE
5 YEARS

CORE STRUCTURE
II-246

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SIMILAR TO

DR'N R.R. IV

CH'D PVG 6/14/60

APP'D *gwm*

SCALE = 12

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FIG. III
NET GAPS BETWEEN COLUMNS
AT OPERATING TEMPERATURE
10 YEARS

	.164	.193	.202	.198	.062	.045
.164	(67) 0	(68) .569	(69) .047	(70) 0	(71) 0	(72) 0
	0	.198	.449	.323	.164	.089
.193	(79) .198	(80) .370	(81) 0	(82) 0	(83) 0	(84) 0
	.569	.370	.037	0	.105	.087
.202	(91) .449	(92) .037	(93) 0	(94) 0	(95) 0	(96) 0
	.047	0	0	0	0	0
.198	(102) .323	(103) 0	(104) 0	(105) 0	(106) 0	0
	0	0	0	0	0	0
.062	(111) .164	(112) .105	(113) 0	(114) 0	0	0
	0	0	0	0	0	0
.045	(119) .089	(117) .087	(120) 0	0	0	0
	0	0	0	0	0	0

CONCRETE STRUCTURE
II-246

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SIMILAR TO

DR'N RRN

CH'D PHG 9/16/60

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FIG. IV
NET GAPS BETWEEN COLUMNS
AT OPERATING TEMPERATURE
15 YEARS

CORE STRUCTURE
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SIMILAR TO

DR'N RRN

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A

B

C

TABLE VII
NET & RESTRAINED BOW AT FIVE YEARS (HOT CONDITION)
X DIRECTION

	67	68	69	70	71	72
NET	.063	-.063 **	.16	.196	.091	0
RESTR.	.028	-.043 *	0	.367	.285	.016
	79	80	81	82	83	84
NET	-.055	.07	.236	.192	.090	0
RESTR.	0	0	0	.275	.207	.018
	91	92	93	94	95	96
NET	.061	.206	.286	.153	.089	0
RESTR.	0	0	.073	.100	.056	.016
	102	103	104	105	106	
NET	.063	.191	.183	.089	0	
RESTR.	0	0	.245	-.029 *	.013 "	
	111	112	113	114		
NET	.006	.039	.064	0		
RESTR.	0	0	0	.012		
	118	119	120			
NET	.001	.001	0			
RESTR.	0	0	.003			

TABLE VIII
NET & RESTRAINED BOW AT THREE YEARS (HOT CONDITION)
X DIRECTION

	67	68	69	70	71	72
NET	.056	-.056 **	.096	.186	.088	0
RESTR.	0	-.008 *	0	.152	.138	.01
	79	80	81	82	83	84
NET	.033	.042	.142	.185	.089	0
RESTR.	0	0	0	.095	.089	.011
	91	92	93	94	95	96
NET	.036	.124	.215	.170	.088	0
RESTR.	0	0	0	.000	-.000	.01
	102	103	104	105	106	
NET	.039	.114	.181	.089	0	
RESTR.	0	0	.075	-.049 *	.008	
	111	112	113	114		
NET	.004	.024	.038	0		
RESTR.	0	0	0	.007		
	118	119	120			
NET	.0004	.0004	0			
RESTR.	0	0	.002			

* PUSHED OUTWARD (By Bow Of INNER COLUMNS) BEYOND IS NORMAL ^(INWARD OR OUTWARD) Bow.
 ** NORMAL INWARD BOW

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TABLE IX
NET & RESTRAINED Bow AT TEN YEARS (HOT CONDITION)
X DIRECTION

	67	68	69	70	71	72
NET	.083	-.083 **	.321	.215	.094	0
RESTR.	.099	-.129 *	0	.915	.658	.034
	79	80	81	82	83	84
NET	.109	.14	.251	.208	.093	0
RESTR.	0	.0	.122	.387	.502	.036
	91	92	93	94	95	96
NET	.121	.412	.308	.190	.090	0
RESTR.	0	.0	.411	.880	.201	.032
	102	103	104	105	106	
NET	.126	.311	.190	.090	0	
RESTR.	0	.071	.666	.040	.025	
	111	112	113	114		
NET	.013	.079	.090	0		
RESTR.	0	0	.037	.023		
	118	119	120			
NET	.001	.001	0			
RESTR.	0	0	.006			

TABLE X
NET & RESTRAINED Bow AT FIFTEEN YEARS (HOT CONDITION)
X DIRECTION

	67	68	69	70	71	72
NET	.101	-.101 **	.421	.235	.097	0
RESTR.	.172	-.217 *	.061	1.455	1.033	.046
	79	80	81	82	83	84
NET	.164	.21	.393	.223	.095	0
RESTR.	0	.0	.317	1.177	.796	.056
	91	92	93	94	95	96
NET	.151	.498	.331	.197	.091	0
RESTR.	0	.120	.749	.658	.346	.049
	102	103	104	105	106	
NET	.191	.322	.196	.091	0	
RESTR.	0	.250	1.084	.099	.038	
	111	112	113	114		
NET	.018	.118	.092	0		
RESTR.	0	0	.099	.035		
	118	119	120			
NET	.002	.002	0			
RESTR.	0	0	.009			

INWARD OR

* PUSHED OUTWARD (By Bow Of INNER COLUMNS) BEYOND ITS NORMAL OUTWARD BOW

** NORMAL INWARD BOW

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CALCULATION OF MAXIMUM RESTRAINED BOWS IN EGCR COLUMNS

PREVIOUS CALCULATIONS HAVE OBTAINED THE MAXIMUM NET GAPS BETWEEN COLUMNS AT VARIOUS TIMES IN CORE LIFE AS WELL AS THE MAXIMUM NET BOWS THAT OCCUR SIMULTANEOUSLY AT THE CORE MIDPLANE. THE HOT CONDITION WAS USED. HOWEVER, THE RESTRAINED BOWS PREVIOUSLY CALCULATED FOR THE HOT CONDITION ARE NOT THE MAXIMUM TO BE EXPECTED. SINCE THE REACTOR COULD BE SHUT DOWN TO ROOM TEMPERATURE AT ANY TIME WITH ITS THEN ^{CURRENT} BOWING TENDENCIES (ASSUMING NO CREEP RELAXATION), THE DISAPPEARANCE OF GAPS CAUSED BY DIFFERENTIAL THERMAL EXPANSION OF THE TOP & BOTTOM CORE SUPPORTS WOULD MEAN GREATER RESTRAINED BOWING FOR ANY COLUMN. FROM THE STANDPOINT OF MAXIMUM STRESS DUE TO RESTRAINT OF BOWING, THE CRITICAL CASE IS AT ROOM TEMPERATURE. NO ACCOUNT WILL BE TAKEN OF THE INITIAL PERIOD OF GROWTH ^{of the graphite} IN COMPUTING RESTRAINED BOWS AT ANY TIME. THE MATERIALS OF PERIPHERAL RESTRAINT BANDS ARE CHOSEN AND THE BANDS ARE TO BE ERECTED SO THAT ESSENTIALLY NO GAPS EXIST BETWEEN THE EXTERIOR COLUMNS AND THE BANDS IN BOTH HOT AND COLD CONDITIONS. (EGCR Study No. II-240)

MAKING USE OF TABLE II FOR BOWING TENDENCY OF EACH COLUMN, AND BY SUBTRACTING FROM TOTAL HOT GAPS (TABLES III TO VI) THE AMOUNTS CONTRIBUTED BY THERMAL EXPANSION (SEE TYPICAL CALCULATIONS FOR TOTAL HOT GAPS ON PP 3 et seq.) THE RESTRAINED AND NET BOWS (COLD) CAN BE CALCULATED. A FEW TYPICAL CALCULATIONS FOR THESE VALUES AT 3 YEARS (COLD) IN THE X DIRECTION ARE:

COL 72 TO PERIPHERAL RESTRAINT

GAP = 0
(ASSUMPTION)

BOWING TENDENCY
OF 72 = .001
(TABLE II)

RESTRAINED BOW
.01

Net Bow
0

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Col. 71 to 72

GAP
 .088
 -.043
 .045

(TABLE III
 MINUS THERMAL
 EFFECT)

BOWING TENDENCY
 OF 71
 .226

RESTRAINED BOW
 .226
 -.045
 .181

NET BOW
 .045

Col 70 To 71

GAP
 .186
 .086
 .100

(TABLE III
 MINUS THERMAL
 EFFECT FROM
 PERIPHERY UP TO
 COL. 70)

BOWING TENDENCY
 OF 70
 .338

RESTRAINED BOW
 .338
 -.100
 .238

NET BOW
 .100

Col 69 To 70

GAP
 .293
 .029
 .164

BOWING TENDENCY
 OF 69
 .0964

RESTRAINED BOW
 0

NET BOW
 .096

BECAUSE OF THE INWARD BOWING TENDENCY OF COL 67 THE GENERAL
 PROCEDURE ABOVE MUST BE MODIFIED:

Col 67 to 68

GAP
 .045 (INSTALLED)
 .023 (SHRINKAGE)
 .068

INWARD TENDENCY OF 68 = -.0635
 OUTWARD TENDENCY OF 67 = .0545
 .1180

∴ THE GAP BETWEEN 67 & 68 WILL CLOSE AND ASSUMING
 $x_{I67} \approx x_{I68}$ THE NET BOW OF EACH WILL APPROACH HALF THE GAP.

AND RESTRAINED BOW 67 = .0545
 .034
 .020
 NET BOW 67 .034
 68 .0635
 .034
 -.029
 68 -.034

WHERE (-) IS ATTACHED TO NET BOW₍₆₈₎ BECAUSE OF ITS DIRECTION AND
 TO RESTRAINED BOW₍₆₈₎ BECAUSE IT IS PUSHED OUTWARD BEYOND ITS

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SIMILAR TO

DR'N RRN

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APP'D *gms*

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NORMAL BOWING BY COLUMNS FURTHER WITHIN THE CORE (THIS WILL ALSO APPLY TO COLUMNS WHOSE NORMAL BOWS ARE OUTWARD BUT ARE PUSHED BEYOND THIS NORMAL BOW).

Col 84 to Restraint

GAP = 0

BOWING TEND. $_{84} = .011$

RESTRAINED
Bow
.011

NET BOW
0

Col 83 To 84

GAP .089
-.043

.046

BOWING TEND. $_{83} = .178$

RESTE. Bow.
.178
-.046

.132

NET BOW
.046

Col 82 To 83

GAP .185
-.086

.099

BOWING TEND. $_{82} = .280$

RESTE. Bow
.280
.099

.181

NET BOW
.099

Col 81 To 82

GAP .289
-.129

.160

BOWING TEND. $_{81} = .142$

RESTE. Bow
0

NET BOW
.160

Col 80 To 81

GAP .045 (ERECT.)
.021 (SHRINK)
.160 (NET BOW $_{81}$)

.226

BOWING TEND. $_{80} = .0418$

RESTE. Bow
0

NET BOW
.042

Col 79 To 80

GAP .045
.024
.042

.111

BOWING TEND. $_{79} = .033$

RESTE. Bow
0

NET BOW
.033

VALUES FOR OTHER COLUMNS ARE SIMILARLY CALCULATED. ALL VALUES ARE SUMMARIZED IN TABLES XI TO XIV, FOR X DIRECTION. VALUES FOR Y DIRECTION CAN BE FOUND BY SYMMETRY.

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TABLE XI
NET & RESTRAINED BOWS AT THREE YEARS (COLD CONDITION)
X DIRECTION

	67	68	69	70	71	72
NET	.034	-.034 **	.096	.100	.045	0
RESTR.	.020	-.029 *	0	.238	.181	.01
	79	80	81	82	83	84
NET	.033	.042	.142	.099	.046	0
RESTR.	0	0	0	.181	.132	.011
	91	92	93	94	95	96
NET	.036	.124	.155	.101	.052	0
RESTR.	0	0	.060	.069	.035	.01
	102	103	104	105	106	
NET	.039	.114	.095	.046	0	
RESTR.	0	0	.161	-.006 *	.008	
	111	112	113	114		
NET	.004	.024	.038	0		
RESTR.	0	0	0	.007		
	118	119	120			
NET	.0004	.0004	0			
RESTR.	0	0	.002			

TABLE XII
NET & RESTRAINED BOW AT FIVE YEARS (COLD CONDITION)
X DIRECTION

	67	68	69	70	71	72
NET	.042	-.042 **	.188	.110	.048	0
RESTR.	.049	-.064 *	0	.453	.328	.016
	79	80	81	82	83	84
NET	.055	.07	.179	.106	.047	0
RESTR.	0	0	.057	.361	.250	.018
	91	92	93	94	95	96
NET	.061	.206	.157	.097	.046	0
RESTR.	0	0	.202	.186	.099	.016
	102	103	104	105	106	
NET	.063	.158	.097	.046	0	
RESTR.	0	.033	.331	.014	.013	
	111	112	113	114		
NET	.006	.039	.046	0		
RESTR.	0	0	.018	.012		
	118	119	120			
NET	.001	.001	0			
RESTR.	0	0	.006			

* PUSHED OUTWARD (BY COLUMNS NEARER $\frac{1}{2}$) BEYOND ITS NORMAL OUTWARD OR INWARD BOWING-

** NORMAL INWARD BOW

CORE STRUCTURE
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 APP. 9

SIMILAR TO

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TABLE XIII
NET & RESTRAINED BOW AT TEN YEARS (COLD CONDITION)
X DIRECTION

	67	68	69	70	71	72
NET	.061	-.061 **	.239	.129	.051	0
RESTR.	.121	-.151 *	.082	1.001	.701	.034
	79	80	81	82	83	84
NET	.109	.14	.222	.122	.050	0
RESTR.	0	0	.251	.812	.545	.036
	91	92	93	94	95	96
NET	.121	.272	.179	.104	.047	0
RESTR.	0	.140	.540	.464	.248	.032
	102	103	104	105	106	
NET	.126	.182	.104	.047	0	
RESTR.	0	.200	.752	.083	.025	
	111	112	113	114		
NET	.013	.079	.047	0		
RESTR.	0	0	.080	.023		
	118	119	120			
NET	.001	.001	0			
RESTR.	0	0	.006			

TABLE XIV
NET & RESTRAINED BOW AT FIFTEEN YEARS (COLD CONDITION)
X DIRECTION

	67	68	69	70	71	72
NET	.080	-.080 **	.292	.149	.054	0
RESTR.	.193	-.238 *	.190	1.541	1.076	.046
	79	80	81	82	83	84
NET	.164	.21	.264	.137	.052	0
RESTR.	0	0	.446	1.263	.839	.056
	91	92	93	94	95	96
NET	.151	.326	.204	.111	.048	0
RESTR.	0	.292	.876	.844	.389	.049
	102	103	104	105	106	
NET	.192	.193	.110	.048	0	
RESTR.	0	.379	1.17	1.42	.038	
	111	112	113	114		
NET	.018	.104	.049	0		
RESTR.	0	.014	.142	.035		
	118	119	120			
NET	.002	.002	0			
RESTR.	0	0	.009			

* PUSHED OUTWARD (BY COLUMN CLOSER TO $\frac{1}{2}$) BEYOND ITS NORMAL OUTWARD OR INWARD BOW

** NORMAL INWARD BOW

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SIMILAR TO

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CALCULATION OF STRESSES IN COLUMNS
DUE TO RESTRAINED BOWING AT VARIOUS YEARS

~~IN REPORT II-227 (REV. 1)~~ ^{Appendix 1} THE STRESSES INDUCED IN COLUMNS BY RESTRAINED BOWING IS CALCULATED FROM STANDARD DEFLECTION FORMULAS BY TREATING THE RESTRAINED BOW AS A DEFLECTION OF AN INITIALLY CURVED BEAM AND FINDING STRESSES DUE TO KNOWN DEFLECTION AS THE INDEPENDENT VARIABLE. SUCH STRESSES WERE FOUND FOR TWO YEAR INTERVALS (UP TO 20 YEAR CORE LIFE) BY ^{LINEARLY} PROPORTIONATING THE AMOUNT OF RESTRAINED BOW (DEFLECTION) FOR ANY YEAR FROM THE AMOUNT PRESENT AT 20 YEARS. THIS WAS KNOWN TO BE SLIGHTLY INACCURATE BECAUSE OF ERECTION GAPS AND THERMAL GAPS WHICH ARE NOT TIME DEPENDENT; IN THIS ANALYSIS THE ACTUAL GAPS AT 3, 5, 10 & 15 YEARS HAVE BEEN FOUND FOR CALCULATING STRESS. THE ASSUMPTION, OF ^{Appendix 7} ~~II-227 (REV. 1)~~, THAT THE REACTIONS BETWEEN COLUMNS ARE MORE OR LESS UNIFORMLY DISTRIBUTED OVER THE COLUMN HEIGHT IS USED HERE, ALTHOUGH IT IS BELIEVED THAT CONTACT BETWEEN COLUMNS DOES NOT EXTEND THE FULL HEIGHT. IN VIEW OF THE APPROXIMATE NATURE OF THE FORMULAS EMPLOYED (IN RELATION TO ANISOTROPIC GRAPHITE) THE UNIFORM LOAD IS TAKEN. THE OTHER EXTREME OF A COMPLETELY CONCENTRATED LOAD GIVES STRESSES DIFFERING BY ONLY 20%.

THE FORMULA IS

$$S = \frac{5 w l^4}{384 EI}$$

$$M_{MAX} = \frac{w l^2}{8}$$

$$\sigma = \frac{M_{MAX}}{I}$$

$$\frac{w l^2}{8} = \frac{48 S EI}{5 l^2}$$

$$\sigma = \frac{9.6 S E C}{l^2}$$

WHERE E IS E_{II} AND IS TAKEN AS AN AVERAGE OF 1.5×10^6 THROUGH THE RANGE OF STRESSES DUE TO RESTRAINT; WHERE $Q = 232$

$\therefore \sigma = 268 S C = K S$

WHERE S IS TAKEN FROM TABLES XI TO XIV. & K FROM ^{Appendix 7} ~~II-227 (REV. 1)~~ App. 7, p. 20

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STRESSES DUE TO RESTRAINED BOW ARE TO BE ADDED TO STRESSES DUE TO INTERNAL SHRINKAGE EFFECTS MORE OR LESS SYMMETRICAL AROUND FUEL CHANNEL ϕ . AS IN ~~APPENDIX 7~~ ^{APPENDIX 7}, TOTAL STRESS WILL BE FOUND AT THE WORST COLUMN CORNER (AT MIDHEIGHT) AND AT THE CORRESPONDING FUEL CHANNEL SURFACE. STRESSES DUE TO INTERNAL RESTRAINT WILL BE APPROXIMATED FROM VALUES ON PAGES 25 AND 26 OF ~~APPENDIX 7~~ ^{APPENDIX 7} SINCE THESE EFFECT ARE ROUGHLY LINEAR WITH TIME ASSUMING UNIFORM REACTOR OPERATION.

STRESS LOCATIONS ARE TABULATED (IN TABLE XV) FOR ALL COLUMNS, AT MIDHEIGHT AT LOCATIONS "A" AND "B"

AT "A" COMPRESSIVE STRESS DUE TO INTERNAL EFFECTS ARE SUBTRACTED FROM TENSILE STRESSES DUE TO RESTRAINT. AT "B" BOTH STRESSES ARE TENSILE (RESTRAINT EFFECTS DERIVED FROM "A" ON THE BASIS OF $\frac{\sigma_B}{\sigma_A}$) AND ARE ADDED. RESTRAINED BOWING EFFECTS ARE ALWAYS TAKEN OF SAME SIGN IN X AND Y DIRECTION REGARDLESS OF LOCATION OF CHANNEL USED FOR INTERNAL EFFECT.

IT IS ASSUMED IN ALL STRESS CALCULATIONS THAT THE X AND Y COMPONENTS ON RESTRAINT LOADS PASS APPROXIMATELY THROUGH THE CENTROID OF EACH COLUMN CROSS-SECTION. THE VARIOUS MOMENTS OF INERTIA FOR EACH COLUMN ARE TAKEN FROM THE APPROXIMATE VALUES USED IN ESTIMATING LOAD ON TOP LATTICE (A.C. REPORT II-229-APP. 7, P. 5).

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DR'N R.R.N.

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APP'D *[Signature]*

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TABLE XV
COMBINED STRESSES DUE TO (1) RESTRAINTS
BOWING AND (2) INTERNAL STRESS EFFECTS
COLD CONDITION

COL	K _x	K _y	S _x				S _y				S							
			C								3		5		10		15	
			3	5	10	15	3	5	10	15	A	B	A	B	A	B	A	B
67 (1) x	2140	2140	.020	.049	.121	.193	.020	.049	.121	.193	43	31	105	77	259	189	413	302
(1) y											43	31	105	77	259	189	413	302
(2) x											-306	548	-508	898	-988	1670	-1418	2155
(2) y											-220	610	-298	1052	-470	2048	-592	2759
68 (1) x	2140	2140	.029	.064	.151	.238	0	0	0	0	62	43	137	100	323	236	510	372
(1) y											0	0	0	0	0	0	0	0
(2) x			(-)	(-)	(-)	(-)					-318	563	-528	931	-1026	1718	-1464	2216
(2) y											-256	606	-391	1081	-703	1954	-954	2588
69 (1) x	2140	2140	0	0	.082	.190	0	0	0	0	0	0	0	176	128	406	296	
(1) y											0	0	0	0	0	0	0	0
(2) x											-309	602	-513	905	-998	1674	-1431	2172
(2) y											-309	502	-513	905	-822	1802	-1025	2468
70 (1) x	2140	2140	.238	.453	1.001	1.541	0	0	0	0	509	371	970	707	2140	1560	3300	2410
(1) y											0	0	0	0	0	0	0	0
(2) x											-243	436	-405	721	-797	1363	-1155	1864
(2) y											266	807	565	1428	1343	2923	2145	4294
71 (1) x	2140	2140	.181	.328	.701	1.076	0	0	0	0	387	282	702	512	1500	1093	2300	1676
(1) y											0	0	0	0	0	0	0	0
(2) x											0	0	0	0	0	0	0	0
(2) y											387	282	702	512	1500	1093	2300	1676
72 (1) x	2010	2140	.01	.016	.034	.046	0	0	0	0	20	15	32	23	68	50	92	67
(1) y											0	0	0	0	0	0	0	0
(2) x											0	0	0	0	0	0	0	0
(2) y											20	15	32	23	68	50	92	67
80 (1) x	2140	2140	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(1) y											0	0	0	0	0	0	0	0
(2) x											-306	546	-508	895	-988	1666	-1418	2156
(2) y											-306	546	-508	895	-988	1666	-1418	2156
81 (1) x	2140	2140	0	.057	.251	.446	0	0	.140	.292	0	0	122	89	536	391	955	695
(1) y											0	0	0	0	300	219	539	394
(2) x											-282	504	-469	840	-916	1552	-1319	2068
(2) y											-282	504	-469	840	-916	1552	-1319	2068
82 (1) x	2140	2140	.181	.361	.812	1.263	0	.033	.200	.379	387	283	722	527	1738	1265	2700	1970
(1) y											0	0	71	52	428	312	911	592
(2) x											-213	381	-355	631	-702	1209	-1023	1692
(2) y											174	664	438	1210	1464	2786	2488	4254
83 (1) x	2140	2140	.132	.250	.545	.839	0	0	0	.014	282	206	534	389	1163	850	1790	1306
(1) y											0	0	0	0	0	0	30	22
(2) x											0	0	0	0	0	0	0	0
(2) y											282	206	534	389	1163	850	1790	1306
84 (1) x	1600	2140	.011	.018	.036	.056	0	0	0	0	18	13	29	21	58	42	90	66
(1) y											0	0	0	0	0	0	0	0
(2) x											0	0	0	0	0	0	0	0
(2) y											18	13	29	21	58	42	90	66
93 (1) x	2140	2140	.060	.202	.540	.876	.060	.202	.540	.876	128	179	433	316	1152	840	1880	1380
(1) y											128	179	433	316	1152	840	1880	1380
(2) x											-213	381	-355	631	-702	1209	-1023	1692
(2) y											+43	569	511	1263	1802	2809	2731	4432
94 (1) x	2140	2140	.069	.186	.464	.744	.161	.331	.752	1.17	148	108	548	290	892	725	1590	1160
(1) y											344	253	795	580	1690	1232	2500	1820
(2) x											-129	228	-215	379	-457	745	-665	1081
(2) y											263	589	511	1263	1802	2809	2731	4432
95 (1) x	2140	2140	.035	.099	.248	.389	0	.018	.088	.142	75	55	212	155	530	386	832	601
(1) y											0	0	39	28	171	125	304	222
(2) x											0	0	0	0	0	0	0	0
(2) y											75	55	251	183	701	511	1136	829
96 (1) x	668	2140	.01	.016	.032	.049	.002	.006	.006	.009	7	5	11	8	21	15	33	24
(1) y											4	3	12	9	12	9	20	15
(2) x											0	0	0	0	0	0	0	0
(2) y											11	8	23	17	33	24	53	39

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TABLE XV
(CONT)

Col	K _x	K _y	S _x				S _y				σ							
			3		5		10		15		3		5		10		15	
			A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
105 (1) x	2140	2140	.006	.014	.083	.142	.006	.014	.083	.142	13	10	30	22	178	130	304	222
(1) y			(-)				(-)				13	10	30	22	178	130	304	222
(2)											0	0	0	0	0	0	0	0
106 (1) x	2140	2140	.008	.013	.025	.032	.007	.012	.023	.035	26	20	60	44	356	260	608	444
(1) y											17	12	28	20	53	39	81	59
(2)											15	11	26	19	49	36	75	55
											0	0	0	0	0	0	0	0
											32	23	54	39	102	75	156	114

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REDISTRIBUTION OF STRESS AND OTHER EFFECTS
IN THE EVENT SOME COLUMNS BREAK COMPLETELY

FROM EXAMINATION TABLE XV IT WOULD APPEAR THAT VARIOUS COLUMNS REACH THEIR SPECIFIED MAXIMUM FLEXURAL TENSILE STRESS IN ROUGHLY THE NUMBER OF YEARS SHOWN BELOW:

(67) 8 YR	(68) 8 YR	(69) 10 YR	(70) 6 YR	(71) 20 YR	(72) 20 YR
(79) 8 YR	(80) 11 YR	(81) 8 YR	(82) 6 YR	(83) 20 YR	(84) 20 YR
(91) 10 YR	(92) 8 YR	(93) 7 YR	(94) 6 YR	(95) 20 YR	(96) 20 YR
(102) 6 YR	(103) 6 YR	(104) 6 YR	(105) 20 YR	(106) 20 YR	
(111) 20 YR	(112) 20 YR	(113) 20 YR	(114) 20 YR		
(118) 20 YR	(119) 20 YR	(120) 20 YR			

FIG V
NUMBER OF YEARS TO
REACH MAXIMUM ALLOWABLE
FLEXURAL TENSILE STRESS
(I.E. 1800 PSI)

ON THE CONSERVATIVE ASSUMPTION THAT 1800 psi AT ANY POINT MEANS CONSEQUENT COMPLETE RUPTURE, EACH QUADRANT CONTAINS A BAND OF COLUMNS (SUCH AS 70, 82, 93, 94, 102, 103, & 104) WHICH TEND TO RUPTURE IN SIX OR SEVEN YEARS. COMPARING THESE COLUMNS WITH THE RESULTANT GAPS BETWEEN COLUMNS SHOWN IN FIG. II FOR FIVE YEARS, IT CAN BE SEEN THAT, EVEN IF ALL THESE COLUMNS BREAK, THEY ARE STILL SUR-

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ROUNDED BY TWO RINGS OF COLUMNS WHICH SERVE TO ROUGHLY POSITION THEM. (IT SHOULD BE NOTED THAT COMPLETE RUPTURE GIVES RISE TO POTENTIAL LEVITATION AND POSSIBLE ^{RELATIVE} LATERAL DISPLACEMENT OF PARTS OF BROKEN COLUMNS. GAPS BETWEEN COLUMNS ARE SUCH THAT DISPLACEMENTS COULD BE ^{LARGE} ~~TOO GREAT~~. DISPLACEMENTS AND SUBSEQUENT SHUTDOWN COULD BE ~~HEAVY~~ INJURIOUS TO GRAPHITE. ~~THEFORE, ASIDE FROM OTHER CONSIDERATIONS, THE SHORT LIVES OF THIS MANY COLUMNS APPEAR TO LIMIT THE CORE LIFE.~~ THEREFORE, GROSS LATERAL DISPLACEMENT OF BROKEN COLUMNS WOULD NOT OCCUR, ALTHOUGH SOME COLUMNS COULD DISPLACE BY AS MUCH AS A QUARTER-INCH. REDISTRIBUTION OF GAPS WOULD OCCUR RANDOMLY, BUT THE TOTAL OF SPACES BETWEEN COLUMNS WOULD NOT CHANGE.

NO SPECIAL REDISTRIBUTION OF STRESS WOULD OCCUR OTHER THAN IN THE RUPTURED COLUMNS. COLUMNS ^{OUTSIDE THE RUPTURE RING} GENERALLY BOW OUTWARD SUFFICIENTLY SO THAT ALL AVAILABLE SPACE AT ANY TIME OUT TO THE PERIPHERAL RESTRAINT IS OCCUPIED BY ANY ONE COLUMN REGARDLESS OF HOW MUCH COLUMNS FURTHER IN TEND TO BOW. HENCE, GENERALLY, RUPTURE OF A COLUMN ~~AT~~ 6 YEARS WILL NOT AFFECT OTHER COLUMNS; WITHIN THE RUPTURE RING, GAPS EXIST SO THAT COLUMNS DO NOT TOUCH EACH OTHER AND NO REDISTRIBUTION WOULD OCCUR. ONE SPECIAL CASE EXISTS AT 5 YEARS: COL. 105 IS PUSHED OUTWARD BEYOND ITS NORMAL BOW (HOT CONDITION) AND SHOULD COL. 104 FAIL AT SIX YEARS, COL. 105 WOULD SPRING BACK TO AN UNSTRESSED POSITION. THIS CASE MARKS THE ONLY PREDICTABLE STRESS REDISTRIBUTION.

SINCE, IF NO CREEP OCCURS, THE FAILURE OF SEVEN COLUMNS AT SIX OR SEVEN YEARS CONSTITUTES A POTENTIAL END TO CORE LIFE, NO EXAMINATION OF FURTHER FAILURES AT EIGHT OR ELEVEN YEARS HAS BEEN MADE, BUT THE GENERAL CONCLUSION OF MINOR STRESS REDISTRIBUTION APPEARS TO REMAIN VALID. THE POSSIBILITY OF SERIOUS DISLOCATION OF PARTS OF COLUMNS INCREASES AS FURTHER FAILURES OCCUR (67, 68, 79, 81, & 92) AND FREEDOM FOR RANDOM LATERAL MOVEMENT OF COLUMNS INCREASES. LOAD ON PERIPHERAL RESTRAINT WILL, OF COURSE,

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DECREASE AS TIME GOES ON, AND SO WILL LOADS ON TOP LATTICE
RESTRAINT,

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$$C_1 = - \frac{\Delta T \alpha}{w} \left[\frac{l^2}{2} + \frac{l^3}{6l} \right]$$

From $y=0$ @ $z=l$

$$= - \frac{50 \times 2.4 \times 10^{-6}}{16} \times 232 \left[\frac{2}{3} \right] = - .00115$$

$$y\left(\frac{l}{2}\right) = \frac{50 \times 2.4 \times 10^{-6}}{16} \left[\frac{116^2}{2} + \frac{116^3}{6 \times 232} \right] - .00115 \times 116$$

$$= .059 - .134$$

$$= - .075$$

$$\sigma = 2140 y = 2140 \times .075 = 160 \text{ psi}$$

FOR BENDING IN ONE DIRECTION

$$\sigma_{\text{point}} = 160 + 160 = 320$$

WORST POINT STRESS AT COLUMN CORNER

$$\sigma_{\text{CHANNEL SURF}} = .73 \times 320 = 234 \text{ psi (+)}$$

TENSILE STRESS PROPORTED TO CHANNEL SURFACE.

ON THE ASSUMPTION THAT THE RADIAL GRADIENTS, ^{STRESSES} WILL BE INFLUENCED IN A WAY SIMILAR TO ^{THOSE DUE TO} THE OVERALL GRADIENTS WHICH HAVE BEEN REDUCED BY ABOUT $\frac{234}{394}$ FROM THEIR ORIGINAL VALUES, THE RADIAL GRADIENT (AT THE COLUMN MIDHEIGHT) CONSISTENT WITH OVERALL GRADIENTS OF 50F AND 100F AT BOTTOM AND TOP OF CORE WILL CAUSE STRESS OF

$$\sigma = \frac{234}{394} (385) = 169 \text{ psi (+) AT THE CHANNEL SURFACE}$$

TOTAL WORST STRESS IS THEN

$$\sigma_{\text{TOTAL}} = 234 + 169 \approx 400 \text{ psi AS REQUIRED.}$$

THE RADIAL GRADIENT AT CORE MIDPLANE AROUND ANY FUEL CHANNEL DUE TO UNLOADING ONE FUEL CHANNEL SHOULD THEREFORE BE APPROXIMATELY

$$\Delta T_{\text{(RADIAL)}} = \frac{234}{394} (75) \approx 45^\circ\text{F}$$

THESE ^{GRADIENT} VALUES SHOULD BE VERY SAFE.

THERMAL STRESS IN EGCR GRAPHITE

SEPTEMBER 8, 1960

STUDY II-227

APPENDIX 10

REFER TASK NO. 250

SIMILAR TO

DR'N R.M.

CH'D Rm.

APP'D

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SINCE THIS IS CONSERVATIVELY CALCULATED AND IS LESS THAN THE EXCESS ALLOWABLE (800 PSI) WHICH IS ITSELF CONSERVATIVE (BASED ON ROOM TEMPERATURE ALLOWABLE AND NOT COUNTING GRAPHITE'S INCREASE IN STRENGTH WITH TEMPERATURE), IT APPEARS THAT THE TEMPERATURES SHOWN FOR THE WORST CONDITIONS OF REPORT II-226 WILL NOT CAUSE CRACKING OF BLOCK.

REDUCTION OF TEMPERATURE GRADIENTS

ALTHOUGH IT DOES NOT SEEM NECESSARY FROM THE FOREGOING CALCULATIONS, IF A SAFETY FACTOR IS DESIRED ON THE THERMAL STRESS TO EXCESS ALLOWABLE RATIO, THE THERMAL GRADIENTS MUST BE REDUCED. SINCE THE STRESSES CALCULATED ARE LINEAR WITH THE GRADIENTS USED, THE FOLLOWING MAXIMUM GRADIENTS WOULD BE NECESSARY FOR SAFETY FACTORS AS NOTED:

FOR SAFETY FACTOR OF 2.

TOTAL STRESSES MUST BE APPROX 400 PSI

TOTAL MAX. OVERALL GRADIENT FROM SIDE TO SIDE OF COLUMN

AT BOTTOM OF CORE 50°F (TWO MAJOR DIRECTIONS)

AT TOP OF CORE 100°F (" " ")

TOP GRADIENT ^{WAS} FOUND BY TRIAL AND ERROR USING FOLLOWING METHOD:

ASSUME ΔT AT CORE TOP = 100°F

THEN $\Delta T_3 = \Delta T_{\text{BOTTOM}} \left(1 + \frac{\gamma}{2}\right)$

$$\frac{dy}{dz} = \frac{\Delta T}{W} \left[1 + \frac{\gamma}{2}\right]$$

$$\frac{dy}{dz} = \frac{\Delta T}{W} \left[3 + \frac{\gamma^2}{2}\right] + C_1$$

$$y = \frac{\Delta T}{W} \left[\frac{3}{2}z + \frac{\gamma^2}{6}z^2\right] + C_1 z + C_2$$

WHERE $C_2 = 0$

THERMAL STRESS IN LGEE GRAPHITE.

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APPENDIX 10

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IF ALL THIS BOW WERE RESTRAINED, THE AXIAL STRESS WOULD BE (USING METHOD OF A.C. REPORT II-227, APP 7, P20 AND NEGLECTING THE ANISOTROPIC PROPERTIES OF GRAPHITE)

$$\sigma = 2140 y$$

$$= 2140 (.126)$$

$$= 270 \text{ psi } (\pm)$$

(FOR THE 16X16, FOUR CHANNEL, CRITICAL COLUMN)

THIS STRESS IS A RESULT OF BOWING IN ONLY ONE DIRECTION AND EXISTS ALONG OPPOSITE SIDES OF A COLUMN. TABLES II TO IV OF II-227 SHOW APPROXIMATELY EQUAL OVERALL GRADIENTS TO EXIST ON BOTH MAJOR AXES OF THE COLUMN CROSS-SECTION. CONSEQUENTLY, ^{EQUAL} BOWING IN TWO PERPENDICULAR DIRECTIONS SHOULD OCCUR SIMULTANEOUSLY, CAUSING A POINT STRESS AT ONE CORNER OF CROSS-SECTION OF

$$\sigma = 270 + 270 = 540 \text{ psi } (\pm)$$

THE DIRECTIONS OF BOWING IN THIS UNUSUAL CONDITION OF ONE FUEL CHANNEL UNLOADED ARE OPPOSITE TO THE UNLOADED CHANNEL. SINCE WE HAVE ASSUMED ALL THE BOW TO BE RESTRAINED, THIS AMOUNTS TO DEFLECTION OF THE COLUMN TOWARD THE UNLOADED CHANNEL. CONSEQUENTLY, IT IS CONSISTENT TO ADD THE TENSILE STRESS THAT PRODUCED NEAR THE UNLOADED CHANNEL (PROPORTIONED ON BASIS OF DISTANCE FROM CENTER OF COLUMN) TO THAT CAUSED BY THE RADIAL THERMAL GRADIENTS.

THEREFORE, PROPORTIONING THE CORNER POINT STRESS TO THE NEAREST EDGE OF FUEL CHANNEL FOR WHICH RADIAL-GRADIENT-STRESSES HAVE BEEN FOUND (I.E. THE UNLOADED CHANNEL):

$$\sigma = .73 \times 540$$

$$= 394 \text{ psi}$$

AT THE FUEL CHANNEL SURFACE, THE TOTAL WORST COMBINED STRESS IS (CONSERVATIVELY)

$$\sigma_{\text{TOTAL}} = 394 + 285 = 679 \text{ psi} \quad \text{AT COLUMN MIDHEIGHT}$$

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FOLLOWING THE METHOD OF II-227 App 7
WE CAN DEVELOP THE DIFFERENTIAL EQUATION
OF THE COLUMN:

$$\frac{E dz}{w} = d\theta$$

WHERE E IS THE OVERALL
STRAIN FROM SIDE TO SIDE OF
BEAM

$$E = \Delta T \alpha$$

AND FROM THE DIRECTION OF BOW SHOWN

$$\frac{d\theta}{dz} = \frac{d^2 y}{dz^2} = \frac{E}{w}$$

$$\frac{d^2 y}{dz^2} = \frac{\Delta T \alpha}{w} \left(1 + \frac{3y^2}{l^2}\right)$$

when $z=0$ $y=0$
 $z=l$ $y=0$

$$\frac{dy}{dz} = \frac{\Delta T \alpha}{w} \left[z + \frac{3y^2}{2l^2}\right] + C_1$$

$$y = \frac{\Delta T \alpha}{w} \left[\frac{z^2}{2} + \frac{3y^3}{6l^2}\right] + C_1 z + C_2$$

From $z=0$ $y=0$

$$0 = \left[0 + 0\right] + 0 + C_2$$

$$\therefore C_2 = 0$$

From $z=l$ $y=0$

$$0 = \frac{\Delta T \alpha}{w} \left[\frac{l^2}{2} + \frac{l^2}{2}\right] + C_1 l$$

$$C_1 = -\frac{\Delta T \alpha l^2}{lw} = -\frac{\Delta T \alpha l}{w}$$

$$= -50 \frac{(2.4 \times 10^{-6})(232)}{16}$$

$$= -0.00174$$

WHERE α IS TAKEN PARALLEL
TO EXTRUSION AND AVERAGED
OVER THE CORE HEIGHT
FOR SIMPLICITY

$$y\left(\frac{l}{2}\right) = \frac{50(2.4 \times 10^{-6})}{16} \left[\frac{116^2}{2} + \frac{116^3}{2 \times 232}\right] - 0.00174 \times 116$$

$$= \frac{50(2.4 \times 10^{-6})}{16} \left[\frac{3 \times 116^2}{4}\right] - 0.202$$

$$= 0.0755 - 0.202$$

$$= -0.126"$$

(WHICH CHECKS WITH DIRECTION OF ASSUMED
BOW)

THERMAL STRESS IN EGCK GRAPHITE

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REFER TASK NO. 250

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THE FLATNESS OF THE OVERALL ^{CORE} TEMPERATURE DISTRIBUTION AT ANY ELEVATION WOULD INDICATE THAT THERMAL BOWING IN THE USUAL CASE WOULD BE SMALL AND, CONSEQUENTLY, THE INDUCED STRESSES ALSO SMALL. THE THERMAL GRADIENTS DUE TO UNLOADING ONE CHANNEL ARE MUCH LARGER AND WILL BE USED IN CALCULATING STRESS.

IN THE UNUSUAL CASE OF UNLOADING A FUEL CHANNEL, THE OVERALL GRADIENTS ^{IN} ANY COLUMN WILL BE MUCH LARGER THAN WHEN ALL CHANNELS OF A COLUMN ARE LOADED. INSPECTION OF TABLES 11, 12, 13, & 14 OF II-226 GIVES THE FOLLOWING AVERAGES, APPROXIMATE OVER-ALL GRADIENTS:

AT BOTTOM OF ACTIVE CORE : $106 - 55 = 51^{\circ}\text{F}$ (LEFT TO RIGHT)
 4.25' ABOVE BOTTOM OF ACTIVE CORE : $175 - 20 = 155^{\circ}\text{F}$
 10.25' " " " " " $150 + 80 = 230^{\circ}\text{F}$
 13.25' " " " " " $70 + 150 = 220^{\circ}\text{F}$
 (I.E. TOP OF ACTIVE CORE)

AS NOTED IN II-226 THE AXIAL TEMPERATURE GRADIENT OF THE CORE IS ROUGHLY LINEAR IN THE USUAL CASE. THEREFORE, IF WE ASSUME (CONSERVATIVELY) THAT THE TOP OF FULL CORE HAS SAME GRADIENT AS TOP OF ACTIVE CORE AND VICE VERSA FOR THE BOTTOM OF FULL CORE, IT DOES NOT SEEM UNREASONABLE TO EXPRESS THE GRADIENT AT ANY CORE ELEVATION AS

$$\Delta T_z = \Delta T_{(\text{BOTTOM OF CORE})} \left[1 + \frac{3z}{2l} \right]$$

WHERE T_z = TEMP. AT ANY ELEVATION z
 ABOVE THE BOTTOM OF THE CORE

BECAUSE ANY CHANNEL IN A COLUMN CAN BE UNLOADED AT AN ADVERSE TIME, WE CONSERVATIVELY ASSUME THAT ANY BOWING DUE TO THE ABOVE THERMAL GRADIENT WILL BE COMPLETELY RESTRAINED (I.E. THE THERMAL AND SHRINKAGE EFFECTS ACT IN THE SAME DIRECTION). CONSEQUENTLY, WITH THIS CONSERVATIVE ASSUMPTION WE CAN AGAIN LIMIT OUR CONSIDERATION TO THE "CRITICAL" COLUMN ALREADY SELECTED. SINCE THE BOWING EFFECTS CAN BE ^{IN} ANY DIRECTION, WE WILL CONSERVATIVELY ADD RESULTING STRESSES TO THOSE OF INTERNAL EFFECTS.

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IS ABOUT 70°F. CONSEQUENTLY, FROM THE FOREGOING CALCULATION IT WOULD APPEAR THAT THE THERMAL STRESS DUE TO RADIAL GRADIENT IS ABOUT 285 psi (TENSION AT THE FUEL CHANNEL), SINCE THE GRADIENTS AT TOP OF ACTIVE CORE AND AT MIDHEIGHT ARE EQUAL.

A PLOT OF TEMPERATURES AT GRID POINTS OF TABLES 12 & 13 DOES NOT REVEAL THE STEEPEST GRADIENTS PER INCH TO BE SIGNIFICANTLY DIFFERENT FROM THOSE PLOTTED PREVIOUSLY FOR THE TOP OF ACTIVE CORE. CONSEQUENTLY, IT DOES NOT SEEM PROBABLE THAT, AS A ROUGH CHECK ON THE 285 psi, THE TENSILE STRESS AT THE CHANNEL SURFACE WILL EXCEED 455 psi, AS PREVIOUSLY CONSERVATIVELY CALCULATED, AND MOST PROBABLY WILL BE IN THE NEIGHBORHOOD OF 285 psi, LONGITUDINALLY AND CIRCUMFERENTIALLY.

THE FINAL SOURCE OF THERMAL STRESS WHICH CAN BE EXPECTED AT THE COLUMN MIDPLANE IS RESTRAINED BOW. IN EARLY CORE LIFE, THE INSTALLATION GAPS BETWEEN COLUMNS AND GAPS DUE TO THERMAL EXPANSION OF TOP AND BOTTOM COLUMN SUPPORTS WILL PROVIDE SPACE INTO WHICH AT LEAST SOME OF THE THERMALLY-INDUCED BOW MAY OCCUR WITHOUT GENERATING STRESS. LATER IN CORE LIFE, WHEN SHRINKAGE-INDUCED BOW HAS, IN MOST COLUMNS, ALREADY PRODUCED SOME RESTRAINED BOW EITHER ALL OR NONE OF THE THERMAL BOW MAY PRODUCE STRESS, DEPENDING ON THE RELATIVE DIRECTION OF THERMAL AND SHRINKAGE INDUCED BOW.

UNDER ORDINARY CONDITIONS, I.E. ALL CHANNELS LOADED, THE DIRECTION OF OVERALL GRADIENT (FROM SIDE TO SIDE) IN A COLUMN IS SUCH, AS TO KEEP INWARD FACES AT THE HIGHER TEMPERATURES AT ALL ELEVATIONS IN CORE. THE CONSEQUENT BOW WOULD BE CONVEX INWARD. SINCE THE STRESSES DUE TO PERSISTENT BOWING TENDENCIES RESULT FROM POTENTIAL OUTWARD BOW, IT APPEARS THAT THIS THERMAL EFFECT WOULD TEND TO RELIEVE STRESS AND CANNOT, THEREFORE, BE CONSIDERED THE CRITICAL CASE. FURTHER,

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By Inspection, The Steepest Gradient Is Approximately 300°F IN SIX INCHES, ROUGHLY LINEAR, I.E. ABOUT 50°F/IN.

Using, For Maximum Circumferential Stress At The Column End

$$\sigma_{\theta} = \frac{E\alpha(\Delta T)}{2(1-\nu)} \left[1 - \nu + \frac{\sqrt{1-\nu^2}}{\sqrt{3}} \right] \quad \text{TIMOSHENKO "PLATES \& SHELLS" p. 423}$$

WHERE ΔT IS TAKEN AS 150° FOR THE CYLINDER WALL THICKNESS OF 3"

$$\begin{aligned} \therefore \sigma_{\theta} &= \frac{(1.15 \times 10^6)(3.8 \times 10^6)(150)}{2(1-.28)} \left[1 - .28 + \sqrt{\frac{1-.078}{3}} \right] \\ &= 455 [1 - .28 + .55] \\ &= 580 \text{ psi } (\pm) \quad (\text{TENSION AT FUEL CHANNEL SURFACE}) \end{aligned}$$

EVEN THIS VERY CONSERVATIVE NUMBER, WHICH APPLIES ONLY TO THE VERY END OF THE COLUMN, SEEMS WELL WITHIN THE ^{EXCESS} ALLOWABLE STRESS AT THAT LOCATION. EXCESS ALLOWABLE, AT THAT POINT, IS THE FULL ALLOWABLE, TAKEN CONSERVATIVELY AS THE ROOM TEMPERATURE ALLOWABLE FLEXURAL TENSILE STRESS. (GRAPHITE INCREASES IN STRENGTH WITH TEMPERATURE.) THIS VALUE IS 1800 psi PER SPECIFICATION. SINCE THE TEMPERATURE GRADIENTS USED APPLY TO THE TOP OF THE ACTIVE CORE, THE ACTUAL STRESSES (FOLLOWING TIMOSHENKO, p 422) COULD BE MORE LIKE 455 psi THERE RATHER THAN 580 AT THE VERY TOP OF COLUMN.

CONDITION (b) STRESSES

AT COLUMN MID HEIGHT IT IS ASSUMED THAT, AT THE FUEL CHANNEL SURFACE, PRE-EXISTENT, CREEP-LIMITED TENSILE STRESS OF 1000 psi HAS ALREADY ACCUMULATED AT THE TIME OF THE UNLOADING CONDITIONS AND TEMPERATURE GRADIENTS OF REPORT II-226. THE EXCESS ALLOWABLE IS, THEREFORE, 1800 - 1000 = 800 psi.

FROM TABLES 12 AND 13 OF II-226 (INTERPOLATING) IT APPEARS THAT THE RADIAL GRADIENT (OR AS NEAR AS THE ACTUAL TEMPERATURES COME TO PRODUCING A UNIFORM RADIAL GRADIENT) ABOUT A FUEL CHANNEL

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AS A ROUGH CHECK ON THE STRESS PREVIOUSLY COMPUTED FROM THE ESTIMATED OVERALL TEMPERATURE GRADIENT IN THE WALL OF THE UNIT CELL, WE DETERMINE THE MAXIMUM GRADIENT PER INCH (BY PLOTTING THE DATA FROM TABLE 14 AND ASSUME THAT (CONSERVATIVELY) THIS GRADIENT APPLIES ACROSS THE FULL CELL WALL EVERYWHERE.

PLOT OF GRID TEMPERATURES FROM
TABLE 14 OF REPORT II-226

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TWO CELLS:		← CHANNEL SURFACE				→ CHANNEL SURFACE		
		CELL # 1				CELL # 2		
"UNCONNECTED" LENGTHS		8	8	9	10	8	6	5
AVERAGED "CONNECTED" LENGTHS		8	8.33	9	9	8	6.33	5.5
		8.16	8.51	8.78	8.67	7.78	6.61	5.92
		9.34	8.48	8.65	8.41	7.69	6.77	6.27
		9.41	8.49	8.51	8.25	7.62	6.91	6.52
		9.45	8.47	8.42	8.13	7.59	7.02	6.72

HERE CELL #2 REPRESENTS A CELL WITH STEEP RADIAL GRADIENTS SUCH AS ARE USED IN COMPUTING THE 285 psi TENSILE STRESS. CELL #1 REPRESENTS AN ADJACENT, LOWER-GRADIENT CELL SUCH AS OCCURS IN THE CRITICAL COLUMN BEING CONSIDERED. AVERAGES REPRESENT THE COMBINED ACTION OF BOTH CELLS.

ONE CELL:		CELL # 2			
"UNCONNECTED" LENGTHS		10	8	6	5
AVERAGED "CONNECTED" LENGTHS		9	8	6.33	5.5
		8.5	7.78	6.61	5.91
		8.14	7.43	6.77	6.26
		7.89	7.51	6.89	6.51
		7.70	7.43	6.97	6.70

FOR TWO CELLS, THE TENSILE STRAIN AT THE CHANNEL SURFACE OF CELL #2 IS

$$\frac{6.72 - 5}{5} = .543 \text{ IN/IN}$$

FOR ONE SINGLE CELL THE STRAIN IS

$$\frac{6.70 - 5}{5} = .540 \text{ IN/IN}$$

ALTHOUGH THIS APPROXIMATION IS NOT AN ACCURATE ANALOGY OF THE ACTUAL GENERATION OF STRAIN, IT DOES INDICATE A SMALL ENOUGH EFFECT DUE TO COMBINING ADJACENT CELLS TO ALLOW SIMPLY ONE SINGLE CELL TO BE EXAMINED FOR STRESS.

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THE RADIAL DIFFERENCES ARE

224	335	322	237
150	316	300	170
74	19	22	67

IT APPEARS THAT THE WORST GRADIENT IS ABOUT 75°F ACROSS THE WALL OF THE UNIT CELL. OTHER FUEL CHANNELS HAVE LESSER GRADIENTS. BY INSPECTION, TENSILE STRESSES WILL OCCUR ON THE CHANNEL SURFACES. THESE WILL BE THE CRITICAL STRESSES TO BE COMPUTED. THEN TAKING THE WORST GRADIENT AS EXISTING EVERYWHERE

$$\sigma = \frac{(75)(3.8 \times 10^{-4})(1.15 \times 10^6)}{2(1-.28) \ln \frac{5.63}{2.63}} \left[1 - \frac{2 \times 5.63^2}{5.63^2 - 2.63^2} \ln \frac{5.63}{2.63} \right]$$

$$= -300 [1 - 1.95]$$

$$= +285 \text{ psi tension}$$

IT APPEARS THAT THE WORST GRADIENT CAN BE EASILY ACCOMMODATED IN A SINGLE, ISOLATED UNIT CELL. BECAUSE THE VARIOUS RADIAL GRADIENTS ARE FOUND BY USING TEMPERATURES AT INTERIOR POINTS COMMON TO ADJACENT CELL, THE CONSEQUENT SIMILAR CHANGES IN FIBER LENGTHS IN ADJACENT CELLS IS ASSUMED TO HAVE SMALL EFFECT ON THE STRESS VALUES IN THE WORST CELL, IF THE FOUR CELLS IN AN ACTUAL CROSS-SECTION ARE RECOMBINED TO GET THE COMPOSITE STRESS EFFECT. THIS BELIEF IS BORNE OUT BY THE FOLLOWING APPROXIMATION:

- 1) ASSUME A SERIES OF NUMBERS THAT REPRESENT THE LENGTHS THAT "UNCONNECTED" FIBERS IN A BLOCK TAKE DUE TO THERMAL EXPANSION
- 2) ASSUME THAT EACH FIBER WHEN IN THE ACTUAL CROSS-SECTION TENDS TO ASSUME THE AVERAGE LENGTH OF ITSELF AND ITS NEIGHBORS
- 3) COMPARE THE EFFECT OF A SINGLE CELL AND TWO ADJACENT CELLS.

ESTIMATE OF THERMAL STRESSES IN
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THE COMBINATION OF THERMAL AND PRE-EXISTENT STRESS MAY BE CRITICAL.

BOTH CONDITIONS WILL BE EXAMINED

CONDITION (A) STRESSES

ANY STRESSES THAT WOULD BE CAUSED BY RESTRAINED THERMAL BOW (DUE TO THE INTEGRATED EFFECT OF OVERALL GRADIENTS FROM SIDE TO SIDE OF A COLUMN) WILL NOT BE SIGNIFICANT NEAR THE TOP OF COLUMN. THE STRESSES DUE TO RADIAL GRADIENT CAN BE CALCULATED USING THE FORMULAS OF A.C. TITLE I REPORT 3-230-6.2 AS APPLIED TO A UNIT, THICK-WALLED CYLINDRICAL CELL APPROXIMATING A QUARTER CROSS-SECTION OF A COLUMN. THE CIRCUMFERENTIAL STRESS IS THEN (AT THE CHANNEL SURF):

$$\sigma_{\theta} = \frac{(\Delta T) \alpha E}{2(1-\nu)} \ln \frac{r_o}{r_i} \left(1 - \frac{2r_o^2}{r_o^2 - r_i^2} \ln \frac{r_o}{r_i} \right)$$

(LONGITUDINAL STRESSES SHOULD BE ABOUT THE SAME) FROM ROARK p 338 CASE 16

THIS FORMULA DOES NOT INCLUDE EFFECTS OF INTERNAL HEAT GENERATION IN THE GRAPHITE, BUT ITS RESULTS ARE NOT SIGNIFICANTLY DIFFERENT FROM THOSE OF A FORMULA WHICH DOES (cf. 3-230-6.2 pp 15 & 57) IN THE UNIT CELL.

$$r_i = 2.625$$

$$r_o = 5.63$$

$$E_{1000F} = 1.15 \times 10^6$$

$$\alpha = 3.8 \times 10^{-6}$$

$$\nu = .28$$

PERP. TO EXTRUSION

" " "

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FROM EXAMINATION OF TABLE 14, IT CAN BE SEEN THAT FOR ANY FUEL CHANNEL, THE GRADIENTS ALONG VARIOUS RADII DIFFER WIDELY. HOWEVER, TAKING THE LOWER RIGHT-HAND FUEL CHANNEL FOR EXAMPLE AND FINDING THE ^{APPROXIMATE} GRADIENTS ALONG THE QUADRANT LINES:

FOR THE UNLOADED CHANNEL, WHICH HAS HIGHEST GRADIENTS (BY INSPECTION)

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EXAMINATION OF THERMAL STRESSES IN EGCR GRAPHITE

DETERMINING MOST CRITICAL COLUMN

CROSS-SECTION

ON THE ASSUMPTION THAT TEMPERATURE DIFFERENCES IN ANY BLOCK, WILL BE ROUGHLY PROPORTIONAL TO THE AVERAGE TEMPERATURE OF THAT CROSS-SECTION IT APPEARS FROM TABLES 1 TO 9 OF A.C. REPORT II-226 THAT MAXIMUM GRADIENTS SHOULD BE EXPECTED IN BLOCKS NO. 79 & 68 OF THE SOUTH EAST QUADRANT (AND IN SIMILAR BLOCKS OF OTHER QUADRANTS). FROM A.C. REPORT II-227 APPENDIX 6, THE HIGHEST FAST FLUX IS FOUND IN COLUMN 68; THIS MEANS THAT INTERNALLY GENERATED SHRINKAGE-INDUCED STRESSES SHOULD BE HIGHEST (OR ACCUMULATE FASTEST) IN THIS COLUMN. ~~ALTHOUGH~~ BOWING-INDUCED STRESSES MAY BE CRITICAL IN OTHER COLUMNS, THE FACT THAT CREEP LIMITS THE ACCUMULATION OF ANY TYPE OF STRESS TO 1000 PSI OR LESS (SEE A.C. REPORT II-227, APP. B), MAKE COLUMN 68 (AND SIMILAR COLUMNS) APPEAR CRITICAL FOR THERMAL STRESS.

WITHIN THE CRITICAL COLUMN, THERE SEEM TO BE TWO CASES TO CONSIDER.

- (a) FROM II-226, TABLES 11-14, IT APPEARS THAT THE HIGHEST GRADIENTS FROM SIDE-TO-SIDE OF A BRICK OCCUR NEAR THE TOP OF THE ACTIVE CORE. ALSO, THE HIGHEST ^{RADIAL} GRADIENTS SYMMETRICAL ABOUT CENTER LINES OF FUEL CHANNELS OCCUR ~~NEAR~~ ^{MINIMAL} 3 FEET OF THE TOP OF ACTIVE CORE. CONSEQUENTLY THE HIGHEST ^{THERMAL} STRESSES WILL PROBABLY OCCUR NEAR THE ^{VARIOUS} TOP OF CORE (WITH EXCEPTION OF THOSE DUE TO RESTRAINED THERMAL BOW). HOWEVER, PRE-EXISTENT STRESSES DUE TO SHRINKAGE EFFECTS WILL PROBABLY BE LOW HERE AND THESE THERMAL STRESSES MAY NOT BE CRITICAL.
- (b) AT THE COLUMN MID-HEIGHT, WHERE PRE-EXISTENT STRESSES MAY EASILY BE AT THEIR CREEP-LIMITED, MAXIMUM VALUE OF 1000 PSI, THE ^{VARIOUS} THERMAL GRADIENTS IN ANY ONE COLUMN MAY CAUSE LESS THAN MAXIMUM THERMAL STRESSES BUT

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285 psi	due to radial gradient
<u>394 psi</u>	due to restraint of thermal bow
679	Total local stress

Since a conservative approach has been used throughout, it is concluded that the thermal stress of 679 psi will not cause cracking (based on an allowable thermal stress of 800 psi).

If a larger safety factor is desired for the thermal stress (despite the conservatism of the previously calculated stresses), the radial and overall gradients must be reduced.

For a safety factor of two (i.e., total thermal stress of approximately 400 psi) temperature gradients should be limited as follows:

- (a) Overall gradient from side-to-side of column:
50 F at bottom of core (in two major perpendicular directions of column cross-section).
100 F at top of core.
- (b) Radial gradient from channel surface to nearest side of column:
45 F at core mid-height.

For comparison the gradients estimated from Report No. II-266 and used in the calculations are:

- (a) Overall gradient:
50 F at bottom of core.
200 F at top of core.
- (b) Radial gradient:
75 F at core mid-plane - from channel surface to outer surface of a hollow cylindrical unit cell approximately one-quarter of a column cross-section.

APPENDIX 10

ESTIMATE OF THERMAL STRESS IN CORE GRAPHITE

Thermal stress calculations are based on thermal gradients derived in A-C Report No. II-226 for the extreme case in which one fuel channel of a column contains no fuel but has undiminished coolant flow. Considering the relatively flat temperature distribution at any one core elevation, this case will most likely represent the severest condition for thermal stresses in the EGR core graphite. Thermal stress conditions are analyzed using the same mathematical model as used for analysis of the radiation induced stresses, viz., a thick walled circular cylinder approximately equivalent to one quadrant of the graphite column.

Thermal stress results from two basic causes:

- (a) Radial temperature gradients about any fuel channel.
- (b) Overall temperature gradients from side-to-side of a column which produce a bowing tendency (restraint of any potential bow causes stresses in the column).

Stresses of both types are considered in the analysis. Because of the relatively high strength of graphite in compression, tensile stresses are given most consideration.

At the top of any column, thermal stresses are primarily due to the radial temperature gradient. Stresses from other causes at this location (due to such factors as irradiation-induced radial shrinkage gradients or restraint of shrinkage-induced bowing) have been shown to be small; consequently the full allowable strength (in flexural tension) is available to accommodate thermal stresses. Tension at the critical fuel channel surface at the top of any column will not exceed 580 psi and for the average channel will be close to 285 psi. Compared with the allowable strength of 1800 psi, these stresses at the tops of the columns are acceptable.

At the column mid-height, tensile stresses may already exist at the channel surface when the severest thermal gradient stresses are developed. It is expected that these stresses will never exceed 1000 psi due to the effects of creep. Subtracting this saturation stress from the allowable stress leaves 800 psi for accommodating the short-term thermal stresses.

With the thermal gradients as derived from A-C Report No. II-226, tensile stresses at the channel surface at column mid-height are conservatively calculated to be as follows:

APPENDIX 10

ESTIMATE OF THERMAL STRESS IN CORE GRAPHITE