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**THE H - 3 IRRADIATION EXPERIMENT:
IRRADIATION OF EGCR GRAPHITE --
INTERIM REPORT NO. 2**

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MASTER

SEPTEMBER 1964

HANFORD LABORATORIES

HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

GENERAL ELECTRIC

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September 1964

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RICHLAND, WASHINGTON

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INTRODUCTION

An experimental program, underway since May, 1960, is being conducted to determine the long-term irradiation stability of the graphite used as the moderator in the Experimental Gas Cooled Reactor (EGCR) at Oak Ridge. The EGCR is a power reactor that has a moderator of large graphite blocks, approximately 16 in. square and 20 ft long, arranged vertically into a structure approximately 16 ft in diameter.⁽¹⁾

During operation of the EGCR the properties of the graphite moderator will be changed by the neutron irradiation. The property changes depend on the type of graphite, the temperature of irradiation, and the neutron exposure. Flux intensity and temperature variations through the large blocks will result in differential distortion. This will give rise to stress gradients which, during the lifetime of the EGCR, may be sufficient to rupture the blocks. Assessment of the potential problems of stress fracture and bowing, therefore, depends on a knowledge of the radiation effects on the graphite.

To provide this information a series of capsules, designated H-3, are being irradiated in the General Electric Test Reactor (GETR). Seven successive capsules have been completed to date. Results of the H-3-1 and H-3-2 irradiations were reported in HW-71500 A, Interim Report No. 1.⁽²⁾ The results from the next five capsules, H-3-3 through H-3-7, are presented in this report. For completeness, all applicable data, including some previously published in HW-71500 A, are presented. Detailed interpretations and mechanisms of graphite damage will be discussed in the future in various separate reports.

SUMMARY

Irradiations are being performed in the GETR to determine the long-term stability of EGCR graphite. The results from the first seven experiments with a maximum peak neutron exposure equivalent to 70,000 MWd/adjacent ton in the EGCR are now available. This is the largest known exposure on graphite.

The capsules H-3-1 through H-3-7 contained samples of EGCR graphite and reference CSF graphite. All seven capsules were basically the same design; however, modifications were made in later capsules to change irradiation temperatures. The samples were irradiated sequentially to increase the neutron exposure on the samples. To minimize the effect of the loss to the program of increasingly valuable samples due to the possible failure of any individual capsule in the series, only a predetermined fraction of previously irradiated samples were reirradiated. This fraction varied from capsule to capsule.

The basic H-3 capsule design utilizes the gamma heating in the E7 position of the GETR to achieve the desired operating temperatures. Samples were irradiated in a temperature range of 375 to 850 C. The mean sample temperatures on intra- and inter-capsule irradiations were within ± 50 C.

The graphite tested was obtained from a full-size cross section of an EGCR block. The contraction of the graphites tested continued to show a dependence on the temperature of irradiation. The parallel samples contracted at an increasing rate with increasing exposure. Results indicated no differences in contraction rate for parallel samples taken from several positions in the large block. The transverse samples contracted less than the parallel samples and one sample, at 800 C irradiation temperature, expanded back past the original length in the last two irradiation periods. Data on the changes with continued irradiation of volume, crystallite parameters, Young's modulus and electrical resistivity are presented.

DESIGN AND CONSTRUCTION OF EXPERIMENT

Sample Selection and Preparation

At the time of construction of the H-3-1 capsule, production-run EGCR graphite was not available. However, a graphite electrode, produced from raw materials and manufactured by processes similar to those specified for EGCR bars, was supplied by the National Carbon Company. The prototype material had a somewhat larger grain size and a slightly lower graphitization temperature than that specified for the production-run material. The prototype bar (designated NC7) was 16 in. square in cross section, approximately the same as the production-run bars. All the EGCR-type graphite for the H-3-1 capsule was taken from this NC7 bar. In the H-3-2 and subsequent capsules, samples of graphite (designated NC8) from a broken production-run bar comprised the bulk of the loading. Because of previous exposure on the NC7 graphite, a few samples were included in succeeding capsules.

The graphites irradiated are described in Table I.

TABLE I
GRAPHITE DESCRIPTION

<u>Hanford Designation</u>	<u>Supplier</u>	<u>Coke Source and Type</u>	<u>Extrusion Cross Section, in.</u>	<u>Remarks</u>
CSF	National Carbon Co.	Cleves (conventional type)	4 x 4	Reactor grade; F-purified at 2700 C; density: 1.66 g/cm ³
NC7	National Carbon Co.	Continental-Lake Charles (needle type)	16-3/8 x 16-3/8	Electrode stock; similar to graphite used for EGCR; density: 1.70 g/cm ³
NC8	National Carbon Co.	Continental-Lake Charles (needle type)	17-1/2 x 17-1/2	Reactor grade: AGOT; EGCR graphite; density: 1.72 g/cm ³

The sampling scheme for the EGCR graphites is shown in Figure 1 and for the CSF reference graphite in Figure 2. (See HW-71500 A⁽²⁾ for discussion of orientation and anisotropy.)

After machining to a quarter-round shape, the individual samples were annealed at 1800 C for 1 hr at a pressure of 3×10^{-4} mm Hg to remove a small, thermally annealable strain present in fabricated samples.⁽³⁾ Tests were made to determine if deleterious effects were introduced by this procedure. The effect on mechanical moduli, crystallite parameters, and

length changes caused by varying heating rates, dwell times, and cooling rates were studied. No effects on these properties were noted. Further studies are presently under way on samples subjected to these varying heating and cooling times and then subsequently irradiated to identical neutron exposures.

FIGURE 1
 Sampling Scheme
 Needle Coke Graphites

FIGURE 2
Sampling Scheme
CSF Reference Graphite

Preirradiation Measurements

Several measurements were made on the samples before irradiation. Lengths were measured optically and physically on all samples. A Bausch and Lomb DR-25 Optical Gage (Type 33- 14-23) was used for end-to-end length measurements, and a Bausch and Lomb Bench Comparator (Type 33- 12-11) was used for measurements of the distances between spaced holes drilled in the samples. These length measurements have a standard deviation of 2×10^{-5} and 12×10^{-5} in., respectively,

Crystallite parameters were measured on some of the samples by X-ray diffraction. Electrical resistivity was measured on a few samples by passing a measured current through the sample and measuring the voltage drop between two precisely spaced knife edges in contact with the sample surface. Young's modulus was measured on some samples using the resonance or sonic technique.⁽⁴⁾

Capsule Design

Seven capsules, H-3-1 through H-3-7, have been constructed and irradiated. They were basically of similar design; and, except as noted hereafter, can be considered identical. As discussed in HW-71500 A, substantial features from the design of the H-1 Experiment⁽⁵⁾ were used in the design of the H-3 capsule series. The original heat-transfer calculations for the early capsules in the series were presented in Appendix A of HW-71500 A. These have since been supplemented by use of an IBM 7090 computer program, STHTP - A Steady-State Heat-Transfer Program for the IBM 7090 Computer.⁽⁶⁾ The temperatures of all capsule parts are now determined in considerable detail with these calculations. (See Appendix A for a detailed discussion of the techniques used.) Design modifications made in the H-3-6, *et seq.* capsules were based on calculations using this program.

The basic H-3 design as used for the H-3-1 and H-3-2 capsules is shown in Figure 3. All capsules after H-3-1 contained between 50 and 100%

FIGURE 3
Preassembly View
(H-3-1 and H-3-2 Capsules)

Neg. 061871-2

FIGURE 4
Preassembly View
(H-3-3, et seq. Capsules)

radioactive samples (up to 2 rem/hr at 4 in.) from previous capsules. This necessitated special handling and generally made construction more difficult. The basic design principles and the assembly technique are presented in HW-71500 A in some detail.

Modifications to the basic design were made for capsules H-3-3, et seq. The new design is shown in Figure 4. The cooling tabs at the midspan positions of the connecting tubes were replaced with additional cooling rings. These provided the necessary thermal grounds and also allowed the insertion of 30 additional flux monitors. An additional slight modification was made in capsules H-3-4 et seq. to facilitate disassembly of the capsules after irradiation. This consisted of use of stainless steel socket-head cap screws instead of aluminum slotted-head screws to hold the molybdenum centering disks onto the cooling rings. Also in capsules H-3-4 et seq., the seal cover, Figure 5, containing the primary seal for the capsule and the junction plug for the Geminol N-P thermocouples was filled with Scotchcast epoxy resin, which proved to be a very satisfactory secondary sealant.

An important design change was made in capsule H-3-6. Positions 5 and 6 were modified so that data could be obtained at lower temperatures in positions of higher flux intensity where exposures were generated more rapidly. The modification consisted of a graphite collar as shown in

Neg. 0621362-5

FIGURE 5

Seal Cover
(Capsule Primary Seal)

Figure 6. This collar thermally grounded the center of the sample to the midspan cooling ring. Several minor modifications were made at various times to external capsule components to improve reliability and integrity in-reactor. These included such items as wear pins on the capsule upper end, protection tubes on the lower end, seal covers, flanges, spacer knobs, and connections. Complete as-built blueprints for capsules H-3-1 through H-3-7 are given on drawings H-3-9479 Rev. 2, H-3-20572, H-3-20573, H-3-20576 Rev. 1, H-3-20685, H-3-20849, and H-3-20583.

Neg. 0630569-1

FIGURE 6

Graphite Collar

EXPERIMENTAL PROCEDURE

Installation

The H-3-3 capsule was installed in the E-7 position of the GETR⁽⁷⁾ in July, 1961. The installation was made as described in HW-71500 A for H-3-1 with the exception that the original guide tube was replaced by a 2 in. diameter, schedule 80 aluminum-pipe guide tube.

The H-3-4 capsule was installed in the E-7 position in February, 1962. At that time, modifications to the GETR spool piece and addition of a flow deflector made obsolete the original bracketing for the guide tube. Consequently, a new bracket was made which attached the guide tube to the edge of the flow deflector. The old funnel tubes were also removed and the external thermocouples exited through a flexible stainless steel hose. The capsule was constructed with an integral 1.5 in. OD by 0.188 in. wall support tube to provide additional protection for the thermocouple leadout tube. A diagram of the experiment installation is given in Figure 7.

Installation was repeated in September, 1962, with the H-3-5 capsule; in April, 1963, with the H-3-6 capsule; and in September, 1963, with the H-3-7 capsule,

FIGURE 7
Experiment Installation

Irradiation

Initially all nine thermocouples were operable in each of the five capsules, H-3-3 through H-3-7. All nine thermocouples in H-3-3 operated satisfactorily for the entire irradiation period of 2570 hr. H-3-4 thermocouple 7 failed after 2360 hr of operation while the remaining eight functioned properly for the entire irradiation period of 2600 hr. All nine thermocouples in H-3-5 operated satisfactorily for the entire irradiation period of 2050 hr. Thermocouple 5 in H-3-6 failed after only 211 hr of operation while the other eight operated satisfactorily for the entire 2160 hr irradiation period. Thermocouple 2 in H-3-7 failed just after initial reactor startup while the other eight operated satisfactorily for the entire irradiation of 2300 hr.

After completion of the irradiation each capsule was transported to a radioactive materials laboratory for disassembly. The respective effective days of full reactor power and removal dates are given in Table II.

TABLE II
CAPSULE HISTORY

<u>Capsule</u>	<u>Effective Days</u>	<u>Removal Date</u>
H-3-3	106.7	November, 1961
H-3-4	105.5	July, 1962
H-3-5	84.1	February, 1963
H-3-6	88.5	August, 1963
H-3-7	95.2	February, 1964

Disassembly

The disassembly procedure for each of the capsules was the same as for H-3-1. The interiors of the capsules immediately after opening are shown in Figures 8 through 12. (The apparent capsule curvature is due to refraction through the lead-glass viewing window.) The interior surfaces were relatively clean except for some carbon deposits at the lower end. This is thought to be a form of carbon suboxide and analyses of the deposit are being made. Two bent spacer rods are seen in Figure 8. The displacement of the center ring in capsule H-3-4, Figure 9, took place during insertion of the sample subassembly into the aluminum shell. Capsules H-3-5, Figure 10; H-3-6, Figure 11; and H-3-7, Figure 12, show no evidence of warped rods and very little carbon deposit.

FIGURE 8
Postirradiation View
H-3-3

FIGURE 9
Postirradiation View
H-3-4

FIGURE 10
Postirradiation View
H-3-5

FIGURE 11
Postirradiation View
H-3-6

FIGURE 12
Postirradiation View
H-3-7

There was no visible indication of the cause of the failure of H-3-4 thermocouple 7 or of H-3-7 thermocouple 2. H-3-6 thermocouple 5 failed due to a poor weld at the junction. All samples from all five capsules were recovered intact and in excellent condition. The appearance of a sample which has been irradiated successively in five of the seven H-3 capsules is shown in the top section of Figure 13; in the bottom section is an unirradiated sample. Slightly more crack structure is visible in the irradiated sample, but no gross effects have taken place. The sample ends are still in excellent condition. All 65 flux monitors were recovered from H-3-3, -5, -6, and -7, and 63 were recovered from H-3-4.

Irradiated
(Five Capsules)

Unirradiated

FIGURE 13
Typical Samples

Postirradiation Measurements

Lengths of the irradiated samples were measured both physically and optically (see section on Preirradiation Measurements). Results reported are based on the end-to-end measurements. Crystallite parameters, electrical resistivity, and Young's modulus were measured on those samples on which preirradiation measurements were taken plus other selected samples.

Thermocouple Calibration

Several thermocouples from each capsule were calibrated after irradiation to check their accuracy. A new thermocouple of the same materials was used as a reference at several temperatures. The results of the calibration are shown in Table III.

TABLE III
CALIBRATION OF IRRADIATED GEMINOL N - P THERMOCOUPLES

Capsule	Thermocouple	Exposure, ^(a) nvt x 10 ⁻²¹ , E > 0.18 MeV	Irradiation Temperature, (a)	Calibration Temperature,		
H-3-1	Reference	0.0	---	772		
	2	0.81	590	---		
	5	1.36	800	---		
H-3-2	Reference	0.0	---	898	885	
	3	1.61	710	882	869	
	5	1.77	785	869	859	
	7	1.28	625	865	851	
H-3-3	Reference	0.0	---	402	799	
	6	1.55	795	---	---	
	7	1.44	765	392	782	
H-3-4	Reference	0.0	---	319	696	910
	3	0.99	575	305	---	---
	5	1.52	770	301	657	860
H-3-5	Reference	0.0	---	301		
	2	0.61	440	---		
	4	1.28	760	---		
	6	1.44	805	---		
H-3-6	Reference	0.0	---	294	740	904
	4	1.38	760	---	---	---
	6	1.46	510	288	682	---
	9	1.00	390	288	682	---
H-3-7	Reference	0.0	---	200	499	805
	3	1.39	765	184	474	---
	7	1.54	540	173	458	763
	9	1.17	420	174	458	763

(a) At the thermocouple junction

A graph of the true temperature as a function of the indicated temperature is given in Figure 14. The figure includes all Geminol N - P thermocouple calibration data obtained to date including those from the N-Reactor graphite irradiation program.⁽⁸⁾ The temperature difference is taken into account when sample mean irradiation temperatures are determined (see Appendix A).

FIGURE 14
Calibration of Irradiated Geminol N - P Thermocouples

EXPOSURE DETERMINATION

The neutron exposure to the samples irradiated in the H-3 series of experiments was determined experimentally. Consequently the exposures reported in HW-71500 A have been revised so that all results are on a consistent basis. The exposure to high energy neutrons was of primary interest and was measured by the nickel, iron, and titanium flux monitor foils contained in the capsule cooling rings. The reactions occurring are $\text{Ni}^{58} (n, p) \text{Co}^{58}$, $\text{Fe}^{54} (n, p) \text{Mn}^{54}$, and $\text{Ti}^{46} (n, p) \text{Sc}^{46}$.

Burnout of the Co^{58} and Co^{58m} by thermal neutrons presents problems in the use of the Ni^{58} reaction. The current values for the (n, γ) cross sections are 1650 barns for Co^{58} ($T_{1/2} = 71.3$ days) and 170,000 barns for Co^{58m} ($T_{1/2} = 9.1$ hr).⁽⁹⁾

The activation cross section for Ni^{58} is known reasonably accurately as a function of neutron energy. The lethargy-dependent activation cross section used for the Ni^{58} reaction is shown in Figure 15.⁽¹⁰⁾ Lethargy is defined as $u = \ln (10 \text{ MeV}/E)$.

Much less is known about the activation cross section for the Fe^{54} reaction. The estimated lethargy-dependent activation cross section used for the Fe^{54} reaction is shown in Figure 16.⁽¹¹⁾

Nothing is known about the lethargy-dependent activation cross section for the Ti^{46} reaction, so an average cross section based on a ratio to the nickel and iron results was used. The relative values from the several flux monitor locations provide a check on the orientation of the capsule in-reactor and will be normalized to a measured value when they become available.

The neutron spectrum in the graphite samples located in the E7 testing position used for the irradiations is shown in Figure 17. This spectrum was calculated by use of the 2DXY computer code.⁽¹²⁾ This is a two-dimensional multiregion transport theory code which is set up with 18 energy groups, 16 of which are greater than 0.183 MeV. A grid spacing of 1 by 1 in. was used, and the results give the neutron flux as a function

FIGURE 15
Activation Cross Section
 $\text{Ni}^{58} (n, p) \text{Co}^{58}$

FIGURE 16
Activation Cross Section
 $\text{Fe}^{54} (n, p) \text{Mn}^{54}$

FIGURE 17
Neutron Spectrum
Center of Graphite Sample

of space and energy.⁽¹³⁾ For the nickel and iron monitors, for which at least an approximate lethargy-dependent activation cross section, $\sigma(u)$, is known, the computer calculation gives an effective cross section, $\bar{\sigma}$, defined by:

$$\bar{\sigma} = \frac{\int_{\infty}^0 \varphi(u) \sigma(u) du}{\int_{u_1}^0 \varphi(u) du}$$

where $\varphi(u)$ is the neutron-flux distribution.

The effective cross section calculated for each monitor foil position was used to determine the neutron exposure, and then the relative flux intensities calculated for the foil positions and the samples were used to determine the exposure to the samples. Even with the inaccuracies in activation cross sections, these exposures are more accurate than the previous ones⁽²⁾ based strictly on theoretical physics calculations. They can also be revised as more information on cross sections becomes available. (See Appendix B for a detailed discussion of the methods and calculations.)

EXPOSURE EQUIVALENCE

The exposure equivalence of 1.5×10^{17} nvt, $E > 0.18 \text{ MeV} = 1 \text{ MWd/}$ adjacent ton in the EGCR as reported in HW-71500 A is still the current value. However, it must be emphasized that this value applies only to a comparison between the E-7 position of the GETR and EGCR moderator and may be revised in the future.

IRRADIATION RESULTS

The H-3 series of graphite irradiations extends the knowledge of physical distortion effects induced by neutron irradiation to the highest exposures known. Data have been obtained to exposures equivalent to 70,000 MWd/adjacent ton, EGCR. Complete results from the samples in all seven capsules are presented in Tables IV through X. All data obtained including those reported in HW-71500 A, are presented by capsule number. Length changes are given for all samples, ΔL and L_c . X-ray parameter changes for nearly all, and ΔL_a , Young's modulus, and electrical resistivity for part of the samples. All percent changes are cumulative and are based on the initial unirradiated value and the final or total change through the capsule being tabulated. Sample weights, although not tabulated for each sample, did not vary more than 0.05% during each irradiation period.

All the data tabulated are presented graphically in the several figures discussed in the following subsections. For the CSF graphite all data presently available, including those obtained from the N-Reactor graphite irradiation program,⁽⁸⁾ are presented. Data obtained from more than one sample at any particular exposure are presented as a mean point, with a bar indicating the maximum and minimum values and not the standard deviation. The small number by the mean data point indicates the number of individual data points which were averaged.

TABLE IV
H-3-1 EXPERIMENTAL RESULTS

Capsule Position	Temperature, C	Exposure, nvt x 10 ⁻²¹ (E > 0.18 Mev)	Sample Code	Sample Number	Capsules In	Length Change,		Crystallite Parameters, Å										Young's Modulus		Electrical Resistivity																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
						Per Cent ΔL/L ₀		c		Per Cent Δc/c ₀	L _c		Per Cent ΔL _c /L _{c0}	a		Per Cent Δa/a ₀	L _a		Per Cent ΔL _a /L _{a0}	psi x 10 ⁻⁶		Per Cent ΔE/E ₀	ohm-cm x 10 ⁴		Per Cent Δρ/ρ ₀																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																			
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1	450	0.50	CSF ⊥	141-1	1	-0.058	±0.001	6.718	6.732	+0.208	700	320	-54.3																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
			NC7 ⊥	NC7-31	1	-0.040	±0.001	6.722	6.735	+0.193	645	320	-50.4																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
			CSF	141-201	1	-0.105	±0.001	6.722	6.733	+0.163	720	305	-57.6																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
			NC7 (1)	NC7-1	1	-0.112	±0.001	6.732	6.732	0	610	310	-49.2																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
2	575	0.81	CSF ⊥	141-2	1	-0.067	±0.001	6.718	6.728	+0.149	685	475	-30.7																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
			NC7 (1)	NC7-2	1	-0.114	±0.001	6.715	6.725	+0.149	685	365	-46.6																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
			NC7 (2)	NC7-11	1	-0.123	±0.002	6.717	6.732	+0.213	720	420	-41.7																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
			NC7 (3)	NC7-21	1	-0.124	±0.001	6.702	6.730	+0.418	440	355	-19.3																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
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TABLE V
H-3-2 EXPERIMENTAL RESULTS

Capsule Position	Temperature, C	Exposure, nvt x 10 ⁻²¹ (E >0.18 Mev)	Sample Code	Sample Number	Capsules In	Length Change		Crystallite Parameters, Å										Young's Modulus		Electrical Pesistivity				
						Per Cent		L _c		Per Cent		L _a		Per Cent		L _b		Per Cent		psi x 10 ⁻⁶		ohm-cm x 10 ⁻⁴		
						Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	ΔE/E ₀	Initial	Final
1	475	1.28	CSF I	141-1	1,2	-0.223	±0.001	6.718	6.758	+0.595	700	199	-71.6											
		1.28	NC7 L	NC7-31	1,2	-0.186	±0.001	6.722	6.760	+0.565	645	240	-62.8											
		0.76	CSF II	141-206	1,2	-0.143	±0.002	6.720	6.748	+0.416		260	-54.4										3.15	
		1.28	NC7 II (1)	NC7-1	1,2	-0.363	±0.002	6.732	6.755	+0.342	610	230	-62.3	2.461	2.459	-0.081	400	310	-22.5					
2	575	2.04	CSF L	141-2	1,2	-0.283	±0.001	6.718	6.739	+0.312	685	220	-68.9										2.95	
		2.04	NC7 II (1)	NC7-2	1,2	-0.438	±0.001	6.715	6.752	+0.550	685	250	-63.5											
		1.23	NC8 II (2)	NC8-11	2	-0.203	±0.001	6.719	6.742	+0.342		280	-53.0											
		1.23	NC8 II (3)	NC8-21	2	-0.212	±0.002	6.707	6.738	+0.461	595	283	-41.6	2.462	2.461	-0.041	485	287	-40.8					
3	700	1.61	CSF L	141-7	2	-0.120	±0.001	6.725	6.738	+0.193	560	270	-51.9											
		1.61	NC8 L	NC8-31	2	-0.144	±0.001	6.722	6.732	+0.149	762	279	-63.4										2.71	
		1.61	CSF II	141-207	2	-0.228	±0.001	6.730	6.738	+0.119	420	248	-41.0											
		1.61	NC8 II (1)	NC8-1	2	-0.231	±0.001	6.725	6.740	+0.223	680	243	-64.3	2.464	2.461	-0.122	775	773	-0.3					
4	800	1.77	CSF L	141-9	2	-0.114	±0.002	6.731	6.728	-0.045	560	261	-53.4										1.29	
		1.77	NC8 II (1)	NC8-2	2	-0.227	±0.001	6.723	6.728	+0.074	735	243	-67.0										29.96	
		3.10	NC7 II (2)	NC7-12	1,2	-0.662	±0.001	6.736	6.732	-0.059	620	213	-65.6										19.80	
		3.10	NC7 II (3)	NC7-22	1,2	-0.634	±0.001	6.756	6.733	-0.340	600	189	-68.5										24.01	
5	775																						21.07	
		3.02	CSF L	141-5	1,2	-0.324	±0.001	6.739	6.732	-0.104	630	219	-65.3										35.62	
		3.02	NC7 L	NC7-33	1,2	-0.222	±0.001	6.722	6.738	-0.238	645	224	-65.3										27.20	
		3.02	CSF II	141-204	1,2	-0.643	±0.001	6.734	6.735	+0.015	580	217	-62.6											
6	625																							
		3.02	NC7 II (1)	NC7-5	1,2	-0.653	±0.001	6.732	6.736	+0.059	720	210	-70.8											
		2.28	CSF L	141-6	1,2	-0.253	±0.001	6.722	6.724	+0.030	595	232	-61.0											
		2.28	NC7 L	NC7-34	1,2	-0.227	±0.002	6.736	6.745	+0.133	700	258	-63.2											
		2.28	CSF II	141-208	1,2	-0.399	±0.001	6.722	6.744	+0.328	685	292	-57.4											
		2.28	NC7 II (1)	NC7-6	1,2	-0.397	±0.001	6.736	6.742	+0.089	635	250	-60.6											

TABLE VII
H-3-4 EXPERIMENTAL RESULTS

Capsule Position	Temperature, C	Exposure, nvt x 10 ⁻²¹ (E > 0.18 Mev)	Sample Code	Sample Number	Capsules In	Length Change,		Crystallite Parameters, $\bar{\rho}$										Young's Modulus			Electrical Resistivity		
						Per Cent		Per Cent		Per Cent		Per Cent		Per Cent		Per Cent		Per Cent		psi x 10 ⁻⁶		ohm-cm x 10 ⁴	
						$\Delta L/L_0$	$\Delta c/c_0$	$\Delta L_c/L_{c_0}$	$\Delta a/a_0$	$\Delta L_a/L_{a_0}$	$\Delta E/E_0$	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	$\Delta \rho/\rho_0$	
1	475	2.59	CSF $\perp$	141-1	1,2,3,4	-0.588	± 0.001	6.718	6.777	+0.877	700	160	-77.1	2.4643		233							
	425	0.60	NC8 $\perp$	NC8-33	4	-0.081	± 0.002	6.720	6.761	+0.610	695	263	-62.2	2.4619		349							
	450	1.81	CSF $\parallel$	141-201	1, 3,4	-0.590	± 0.001	6.722	6.780	+0.864	720	180	-75.0	2.4648		223							
	425	0.60	NC8 $\parallel$ (1)	NC8-3	4	-0.142	± 0.001	6.730	6.761	+0.461	545	262	-51.9	2.4628		478							
2	575	0.99	CSF $\perp$	141-8	4	-0.112	± 0.001	6.738	6.772	+0.505	530	268	-49.5	2.462	+0.162	950	351	-63.0					
	600	2.09	NC8 $\perp$	NC8-34	3,4	-0.302	± 0.002	6.720	6.759	+0.580	748	231	-69.1	2.4637		274							
	575	0.99	CSF $\parallel$	142-220	4	-0.182	± 0.001	6.733	6.767	+0.505	510	278	-45.5	2.464	0	486	447	-8.0					
	575	2.22	NC8 $\parallel$ (3)	NC8-21	2, 4	-0.508	± 0.002	6.707	6.761	+0.805	485	264	-45.6	2.462	+0.041	485	343	-29.3					
3	700	2.42	CSF $\perp$	141-3	1, 4	-0.232	± 0.001	6.707	6.754	+0.700	600	225	-62.5	2.4631		405			1.33		38.04		
	725	4.32	NC8 $\perp$	NC8-31	2,3,4	-0.601	± 0.001	6.722	6.759	+0.550	762	230	-69.9	2.4650		262							
	700	2.42	CSF $\parallel$	141-202	1, 4	-0.411	± 0.001	6.720	6.759	+0.580	680	210	-69.1	2.4648		268			2.84				
	700	1.32	NC8 $\parallel$ (1)	NC8-5	4	-0.159	± 0.001	6.728	6.759	+0.461	592	285	-51.8	2.4640		285							
4	775	3.29	CSF $\perp$	141-9	2, 4	-0.338	± 0.001	6.731	6.759	+0.416	560	250	-55.4	2.4639		295			1.38		38.38		
		3.06	NC8 $\perp$	NC8-32	3,4	-0.256	± 0.001	6.718	6.756	+0.565	469	227	-51.6	2.4640		319							
		4.83	NC8 $\parallel$ (1)	NC8-2	2,3,4	-1.157	± 0.001	6.723	6.753	+0.446	735	189	-74.4	2.4628		542			2.63		24.79		
		1.52	NC8 $\parallel$ (1)	NC8-6	4	-0.190	± 0.001	6.719	6.755	+0.535	700	255	-63.6	2.4645		330							
5	775	6.01	CSF $\perp$	141-5	1,2,3,4	-0.757	± 0.001	6.739	6.765	+0.386	630	190	-69.9	2.4621		277					41.07		
	775	6.01	NC7 $\perp$	NC7-33	1,2,3,4	-0.388	± 0.001	6.722	6.770	+0.713	645	186	-71.2	2.4635		672							
	775	6.01	CSF $\parallel$	141-204	1,2,3,4	-1.967	± 0.001	6.734	6.767	+0.342	580	160	-69.7	2.4635		293					27.62		
	750	1.51	NC8 $\parallel$ (3)	NC8-22	4	-0.198	± 0.002	6.724	6.753	+0.432	535	253	-52.8	2.4632		432					24.14		
6	675	1.19	CSF $\perp$	141-11	4	-0.089	± 0.001	6.734	6.754	+0.297	620	266	-57.1	2.463	+0.081	950	325	-65.8					
	625	4.52	NC7 $\parallel$ (1)	NC7-6	1,2,3,4	-1.148	± 0.001	6.736	6.770	+0.505	635	207	-67.5	2.4640		418			2.84				
	675	1.19	NC7 $\parallel$ (1)	NC7-7	4	-0.168	± 0.001	6.718	6.753	+0.520	590	296	-49.8	2.4656		313							
	675	1.19	NC8 $\parallel$ (1)	NC8-8	4	-0.151	± 0.001	6.729	6.759	+0.445	509	300	-41.4	2.4647		590							

TABLE VIII
H-3-5 EXPERIMENTAL RESULTS

Capsule Position	Temperature, C	Exposure nvt x 10 ⁻²¹ (E > 0.18 Mev)	Sample Code	Sample Number	Capsules In	Length Change		Crystallite Parameters, Å										Young's Modulus			Electrical Resistivity					
						Per Cent ΔL/L ₀	c		Per Cent Δc/c ₀	L _c		Per Cent ΔL _c /L _{c0}	a		Per Cent Δa/a ₀	L _a		Per Cent ΔL _a /L _{a0}	psi x 10 ⁻⁶		Per Cent ΔE/E ₀	ohm-cm x 10 ⁴		Per Cent Δρ/ρ ₀		
							Initial	Final		Initial	Final		Initial	Final		Initial	Final		Initial	Final		Initial	Final			
1	450	3.17	CSF ⊥	141-1	1,2,3,4,5	-0.754	+0.001	6.718	6.754	+0.535	700	158	-77.5													
	425	1.18	NC8 ⊥	NC8-33	4,5	-0.236	'0.002	6.720	6.727	+0.104	695	220	-68.3													
	450	2.39	CSF	141-201	1, 3,4,5	-0.837	'0.001	6.722	6.749	+0.402	720	170	-76.4													
	425	1.18	NC8 (1)	NC8-3	4,5	-0.355	'0.002	6.730	6.744	+0.208	545	200	-63.4													
2	575	1.93	CSF ⊥	141-8	4,5	-0.301	'0.002	6.738	6.733	-0.074	530	235	-55.6	2.462	2.462	0	950	293	-69.1							
	600	3.03	NC8 ⊥	NC8-34	3,4,5	-0.550	'0.002	6.720	6.741	+0.312	748	205	-72.6													
	575	1.93	CSF	142-220	4,5	-0.481	+0.001	6.733	6.731	-0.028	510	205	-59.8	2.464	2.460	-0.163	486	235	-51.6							
	600	3.27	NC8 (2)	NC8-11	2,3, 5	-0.818	'0.002	6.719	6.719	0	595	210	-64.7													
3	725	4.27	CSF ⊥	141-7	2,3, 5	-0.522	0.001	6.725	6.737	+0.179	560	188	-66.4													
	725	5.59	NC8 ⊥	NC8-31	2,3,4,5	-0.742	+0.001	6.722	6.738	+0.238	762	162	-76.1													
	725	2.88	CSF	141-207	2, 5	-0.546	+0.001	6.730	6.716	-0.208	420	205	-51.2													
	750	1.27	NC8 (2)	NC8-221	5	-0.121	'0.001	6.746	6.716	-0.445	451	240	-46.7	2.4653	2.4619	-1.38	758	319	-57.8	1.47	2.68 2.24	+52.4	6.65	20.12	+202.6	
4	800	1.44	CSF ⊥	142-49	5	-0.064	+0.001	6.753	6.714	-0.665	418	212	-49.4	2.4656	2.4628	-1.14	1700	382	-77.5							
	800	1.44	NC8 ⊥	NC8-62	5	-0.053	'0.001	6.750	6.731	-0.282	566	300	-47.0	2.4660	2.4616	-1.79	653	330	-40.3				10.10	29.67	+193.8	
	800	6.27	NC8 (1)	NC8-2	2,3,4,5	-1.742	'0.002	6.723	6.738	+0.223	735	175	-76.2													
	775	2.96	NC8 (1)	NC8-6	4,5	-0.582	'0.001	6.719	6.727	+0.119	700	200	-71.4									2.54		24.53		
5	775	7.41	CSF ⊥	141-5	1,2,3,4,5	-0.822	0.001	6.739	6.743	+0.053	630	157	-75.0													
	775	7.41	NC7 ⊥	NC7-33	1,2,3,4,5	-0.218	'0.001	6.722	6.739	+0.253	645	158	-75.5													
	775	7.41	CSF	141-204	1,2,3,4,5	-2.688	'0.001	6.734	6.740	+0.089	580	165	-71.6													
	800	1.40	NC8 (1)	NC8-4	5	-0.149	'0.001	6.727	6.727	0	531	278	-47.7									1.67	2.55	+52.7	6.52	26.08 20.21
6	675	2.28	CSF ⊥	141-11	4,5	-0.309	0.001	6.734	6.742	+0.124	620	248	-60.0	2.463	2.461	-0.081	950	333	-64.9							
	650	1.09	NC8 ⊥	NC8-57	5	-0.084	'0.001	6.746	6.755	+0.134	555	275	-50.4	2.4653	2.4614	-1.58	746	270	-63.9	0.79	1.25	+58.2	11.75	35.10	+198.7	
	675	2.28	NC8 (1)	NC8-8	4,5	-0.462	'0.001	6.729	6.728	-0.015	509	238	-53.3													
	650	1.09	NC8 (3)	NC8-216	5	-0.149	'0.001	6.749	6.729	-0.297	468	332	-29.1	2.4655	2.4601	-2.19	637	453	-28.9	1.47	2.30	+56.5	6.78	22.80	+236.3	

TABLE IX
H-3-6 EXPERIMENTAL RESULTS

Capsule Position	Temperature, °C	Exposure, nvt x 10 ⁻²¹ (E > 0.18 Mev)	Sample Code	Sample Number	Capsules In	Length Change		Crystallite Parameters, Å												Young's Modulus			Electrical Resistivity		
						Per Cent		c		Per Cent	L _c		Per Cent	a		Per Cent	L _a		Per Cent	psi x 10 ⁻⁶		Per Cent	ohm-cm x 10 ⁴		Per Cent
						ΔL/L ₀		Initial	Final		Initial	Final		Initial	Final		Initial	Final		Initial	Final		Initial	Final	
1	450	3.82	CSF ⊥	141-1	1,2,3,4,5,6	-0.903	±0.001																		
	450	1.83	NC8 ⊥	NC8-33	4,5,6	-0.414	±0.003																		
	475	2.64	NC7 (1)	NC7-1	1,2,3, 6	-0.981	±0.001																		25.96
	475	1.82	NC8 (1)	NC8-3	1,2,3, 4,5,6	-0.608	±0.003																		
2	600	4.17	CSF ⊥	141-2	1,2,3, 6	-0.722	±0.002																		
	600	4.06	NC8 ⊥	NC8-34	3,4,5,6	-0.782	±0.002																		
	600	2.96	CSF	142-220	4,5,6	-0.851	±0.001	6.733	6.734	+0.015	510	198	-61.2	2,464	2,4584	-0.227	486	512	+5.33						26,45
	600	4.30	NC8 (2)	NC8-11	2,3, 5,6	-1.197	±0.002																		
3	725	5.64	CSF ⊥	141-7	2,3, 5,6	-0.758	±0.001																		
	725	6.96	NC8 ⊥	NC8-31	2,3,4,5,6	-0.902	±0.001																		
	725	4.37	NC8 (1)	NC8-1	2,3, 6	-1.064	±0.001																		
	750	2.64	NC8 (2)	NC8-221	5,6	-0.457	±0.001													1.47	2.39	+62.6	6.65	24.32	+265.7
4		8.93	CSF ⊥	141-5	(1,2,3,4,5)*6	-0.800	±0.001	6,739	6,723	-0.237	630	168	-73.3												44.61
	775	8.93	NC7 ⊥	NC7-33	(1,2,3,4,5)*6	+0.095	±0.002	6,722	6,759	+0.550	645	158	-75.5												
	775	8.93	CSF	141-204	(1,2,3,4,5)*6	-3.534	±0.002	6,734	6,738	+0.059	580	180	-69.0												30.28
	800	7.79	NC8 (1)	NC8-2	2,3,4,5,6	-2.486	±0.002	6,723	6,724	+0.014	735	160	-78.2							2.47					26.85
5	450	1.43	CSF ⊥	142-44	6	-0.268	±0.001	6,763	6,753	-0.147	421	223	-47.0	2,4654	2,4587	-0.271	661	435	-34.2	0.77	1.38	+79.2	12.01	39.29	+227.1
	450	1.43	NC8 ⊥	NC8-53	6	-0.269	±0.001	6,751	6,734	-0.251	550	220	-60.0	2,4658	2,4603	-0.223	905	625	-30.9	0.81	1.42	+75.3	7.45	39.30	+293.3
	450	1.43	NC8 (3)	NC8-214	6	-0.400	±0.001	6,755	6,729	-0.384	520	240	-53.8	2,4655	2,4596	-0.239	867	478	-44.9	1.48	2.33	+57.4	6.34	26.10	+294.2
	450	1.43	NC8 (2)	NC8-222	6	-0.408	±0.001	6,728	6,723	-0.074	532	215	-59.6	2,4632	2,4603	-0.117	1000	465	-53.5	1.25	2.34	+87.2	7.45	29.37	+294.2
6	375	1.04	CSF ⊥	142-56	6	-0.149	±0.001	6,728	6,732	+0.059	523	220	-57.9	2,4616	2,4581	-0.142	635	263	-58.6	0.76	1.26	+65.8	13.12	43.33	+230.2
	375	1.04	NC8 ⊥	NC8-55	6	-0.155	±0.001	6,746	6,736	-0.148	512	230	-55.1	2,4665	2,4587	-0.316	747	325	-56.5	0.81	1.45	+79.0	3.83	37.89	+889.3
	375	1.04	CSF	142-235	6	-0.295	±0.001		6,737			212		2,4573						1.72	2.65	+54.1	7.12	26.33	+269.8
	375	1.04	NC8 (3)	NC8-223	6	-0.316	±0.001	6,755	6,736	-0.281	502	193	-61.6	2,4652	2,4584	-0.275	1520	505	-66.8	1.40	2.29	+63.6	6.91	26.92	+289.6

*In position 5

TABLE X
H-3-7 EXPERIMENTAL RESULTS

Capsule Position	Temperature, C	Exposure, nvt x 10 ⁻²¹ (E >0.18 Mev)	Sample Code	Sample Number	Capsules In	Length Change, Per Cent ΔL/L ₀		Crystallite Parameters, Å												Young's Modulus			Electrical Resistivity		
								c		Per Cent Δc/c ₀	L _c		Per Cent ΔL _c /L _{c0}	a		Per Cent Δa/a ₀	L _a		Per Cent ΔL _a /L _{a0}	psi x 10 ⁻⁶		Per Cent ΔE/E ₀	ohm-cm x 10 ⁴		Per Cent Δρ/ρ ₀
						Initial	Final	Initial	Final		Initial	Final		Initial	Final		Initial	Final		Initial	Final		Initial	Final	
1	450	2.01	CSF ⊥	142-44	(6)*,7	-0.397	±0.001	6.763	6.747	-0.236	421	225	-46.6	2.4654	2.4588	-0.268	661	430	-34.9	0.77	1.44	+87.0	12.01	40.35	+236.0
	450	2.01	NC8 ⊥	NC8-53	(6)*,7	-0.411	±0.001	6.751	6.746	-0.074	550	230	-58.2	2.4658	2.4569	-0.361	905	482	-46.7	0.81	1.41	+74.1	7.45	37.94	+409.3
	450	2.97	CSF	141-201	1, 3,4,5, 7	-1.067	±0.002	6.722	6.749	+0.402	720	200	-72.2												
	450	2.01	NC8 (2)	NC8-222	(6)*,7	-0.618	±0.001	6.728	6.730	+0.030	532	232	-56.4	2.4632	2.4514	-0.479	1000	395	-60.5	1.25	2.20	+76.0	7.45	30.43	+308.4
2	600	2.91	CSF ⊥	141-8	4,5, 7	-0.551	±0.001	6.738	6.732	-0.089	530	230	-56.6	2.462	2.4607	-0.053	950	440	-53.7						
	600	5.04	NC8 ⊥	NC8-34	3,4,5,6,7	-0.979	±0.001	6.720	6.731	+0.164	748	205	-72.6												
	600	3.94	CSF	142-220	4,5,6,7	-1.259	±0.001	6.733	6.735	+0.030	510	192	-62.4	2.464	2.4593	-0.191	486	365	-24.9						
	575	3.20	NC8 (3)	NC8-21	2, 4, 7	-0.866	±0.001	6.707	6.738	+0.462	485	235	-51.5	2.462	2.4589	-0.126	485	362	-25.4						
3	750	7.03	CSF ⊥	141-7	2,3, 5,6,7	-0.941	±0.001	6.725	6.734	+0.134	560	183	-67.3												
	725	8.35	NC8 ⊥	NC8-31	2,3,4,5,6,7	-0.973	±0.001	6.722	6.731	+0.136	762	192	-74.8												
	725	3.81	CSF	141-202	1, 4, 7	-0.842	±0.002	6.720	6.726	+0.089	680	210	-69.1								2.93				
	750	5.76	NC8 (1)	NC8-1	2,3, 6,7	-1.619	±0.001	6.725	6.734	+0.134	680	185	-72.8												
4	775	10.61	CSF ⊥	141-5	(1,2,3,4,5)*,6,7	-0.517	±0.006	6.739	6.737	-0.030	630	158	-74.9												
	775	10.61	NC7 ⊥	NC7-33	(1,2,3,4,5)*,6,7	+0.866	±0.004	6.722	6.742	+0.298	645	132	-79.5												
	775	10.61	CSF	141-204	(1,2,3,4,5)*,6,7	-4.537	±0.001	6.734	6.741	+0.104	580	149	-74.3												
	800	9.47	NC8 (1)	NC8-2	2,3,4,5, 6,7	-3.390	±0.005	6.723	6.732	+0.134	735	152	-79.3								2.49				
5	475	5.39	CSF ⊥	141-1	(1,2,3,4,5,6)*,7	-1.200	±0.001	6.718	6.746	+0.417	700	146	-79.1												
	475	3.40	NC8 ⊥	NC8-33	(4,5,6)*,7	-0.936	±0.002	6.720	6.743	+0.342	695	175	-74.8												
	475	3.40	NC8 (1)	NC8-3	(4,5,6)*,7	-1.420	±0.001	6.730	6.733	+0.044	545	179	-67.2												
	525	3.00	NC8 (3)	NC8-214	6, 7	-1.115	±0.001	6.755	6.732	-0.340	520	175	-66.3	2.4655	2.4595	-0.244	867	255	-70.6	1.48	2.48	+67.5	6.34	25.63	+304.2
6	425	2.26	CSF ⊥	142-56	6,7	-0.512	±0.001	6.728	6.749	+0.312	523	200	-61.8	2.4616	2.4587	-0.118	635	300	-52.8	0.76	1.46	+92.1	13.12	41.46	+216.0
	425	2.26	NC8 ⊥	NC8-55	6,7	-0.507	±0.002	6.746	6.751	+0.074	512	218	-57.4	2.4665	2.4580	-0.345	747	370	-50.5	0.81	1.70	+109.9	3.83	35.98	+839.4
	425	2.26	CSF	142-235	6,7	-0.818	±0.001													1.70	2.28	+87.2	7.12	25.46	+257.6
	425	2.26	NC8 (3)	NC8-223	6,7	-0.811	±0.001	6.755	6.748	-0.104	502	190	-62.2	2.4652	2.4595	-0.231	1520	732	-51.8			+75.7	6.91	28.43	+311.4

* Position 5
† Position 1

Length Change

The length change data from Tables IV through X are presented graphically as a function of exposure in Figures 18 through 21. Data for the samples taken transverse and parallel to the extrusion axis of the bar are shown on separate figures to reduce the number of curves per graph, but both orientations for one graphite type should be considered together. The isotherms show that for both orientations of the graphites tested the samples irradiated at the higher temperatures contract less than those irradiated at lower temperatures.

The data for the CSF samples cut transverse to the extrusion axis are presented in Figure 18. The contraction of the sample irradiated at the maximum temperature, 775 to 800 C, has reached a maximum and the sample is expanding with increasing exposure. Both the 425 to 475 C and 700 to 725 C isotherms appear to show a decreasing contraction rate indicating they may also be approaching a maximum contraction.

The data from the CSF parallel samples are presented in Figure 19. The figure is to the same scale as Figure 18 so that the large differences between the transverse and parallel data are readily apparent. All isotherms indicate an increasing contraction with increasing exposure and for all data except the 425 to 475 C the contraction rate is increasing,

Figure 20 presents the data from the EGCR samples cut transverse to the extrusion axis. The NC7 sample irradiated at 775 to 800 C has also reached a maximum contraction and is now expanding with increasing exposure. The sample now exhibits over twice as much net growth as the maximum contraction it attained. The growth rate is approximately the same as the contraction rate of the parallel EGCR samples irradiated at 775 to 800 C. There continues to be a significant difference between the NC8 and NC7 graphites, with the NC7 showing less contraction, although it had originally been thought they would be quite similar. (See Sample Selection and Preparation section for differences.) The NC7 contracts less than the CSF while the NC8 contracts slightly more than the CSF at the lower temperatures and slightly less at the higher temperatures.

The data from the EGCR parallel samples are presented in Figure 21. There is no statistical difference among the three types of parallel samples (N1, M2, N3 or P1, P2, P3) and consequently all the data are plotted as either NC8 or NC7. The isotherms indicate the parallel orientation is not as temperature sensitive as the transverse at irradiation temperatures above 575 C. The contraction of the NC7 samples is nearly the same as that of the CSF parallel samples. The NC8 samples contract less at 800 C than the CSF and about the same at the lower temperatures. The rate of contraction continues to increase with increasing exposure, with the exception of the 575 to 625 C NC8 samples.

The length data from Figures 18 through 21 are also presented in Figures 22 through 25 with length-change parameters as a function of exposure and irradiation temperature. From these curves information can readily be obtained on expected length changes for any combination of exposure and temperature. Comparison of transverse and parallel data quickly shows the much larger contraction in the parallel direction. Figures 22 and 24 show the difference in behavior between CSF and EGCR graphites in the transverse direction.

FIGURE 13
Physical Distortion of CSF Graphite (Transverse) as a Function of Exposure

FIGURE 19
Physical Distortion of CSF Graphite (Parallel) as a Function of Exposure

FIGURE 20

Physical Distortion of EGCR Graphite (Transverse) as a Function of Exposure

FIGURE 21
Physical Distortion of EGCR Graphite (Parallel) as a Function of Exposure

FIGURE 22

Physical Distortion of CSF Graphite (Transverse) as a Function of Temperature and Exposure

FIGURE 23

Physical Distortion of CSF Graphite (Parallel) as a Function of Temperature and Exposure

FIGURE 24

Physical Distortion of EGCR Graphite (Transverse) as a Function of Temperature and Exposure

FIGURE 25

Physical Distortion of EGCR Graphite (Parallel) as a Function of Temperature and Exposure

Volume Change

Using the length-change data presented in the previous figures, an analysis of the resultant sample volume change was made. The model used was a sample of square cross section with both the width and thickness taken as transverse directions and the length taken as the parallel direction. The equation used is:

$$\frac{\Delta V}{V_0} = \left(1 + \frac{\Delta L}{L_{0\perp}}\right)^2 \left(1 + \frac{\Delta L}{L_{0\parallel}}\right) - 1$$

where V = volume

$L_{\perp}$ = length transverse to the extrusion axis

$L_{\parallel}$ = length parallel to the extrusion axis.

The calculated volume changes are shown in Figures 26 and 27 as a function of exposure and in Figures 28 and 29 as a function of irradiation temperature and exposure. The CSF data, Figure 26, show a nearly constant rate of change of volume with increasing exposure except at 775 to 800 C where the rate is rapidly decreasing and appears to be nearing a maximum contraction.

The volume changes for NC8 and NC7 are presented in Figure 27. NC7 shows less volume change than NC8 except at the lowest temperature where the changes are the same. The NC8 volume changes are about the same as the CSF while the NC7 are less. At 675 to 800 C the NC7 volume change has gone through a maximum contraction of 3.4% and is expanding with increasing exposure. At the other irradiation temperatures the rate is nearly constant and contraction is continuing. Comparison of Figures 28 and 29 points out the different behavior of the two graphite types as a function of temperature.

FIGURE 26
Volume Distortion of CSF Graphite as a Function of Exposure

FIGURE 27

Volume Distortion of EGCR Graphite as a Function of Exposure

FIGURE 28
Volume Distortion of CSF Graphite as a Function of Temperature and Exposure

FIGURE 29

Volume Distortion of EGCR Graphite as a Function of Temperature and Exposure

Crystallite Parameters

The effect of continued neutron exposure on the crystal parameters $\underline{c}$ and L_c are presented in Figures 30 through 33, $\underline{c}$ being the distance between alternate layer planes and L_c the apparent crystallite size in the $\underline{c}$ direction. Data on $\underline{c}$ from both the transverse and parallel orientations of CSF graphite are shown in Figure 30. As indicated by the length of the bars, in some cases there is considerable scatter among several samples irradiated at the same temperature to the same exposure. Although there is a large variation in $\underline{c}$, with increasing exposure the data tend to fall into a pattern of an increase in $\underline{c}$ followed by a decrease in $\underline{c}$ followed by an increase. With increasing exposure $\underline{c}$ seems to be approaching a value approximately the same as the initial unirradiated $\underline{c}$ value. The isotherms do not seem to fall into a regular temperature pattern.

The $\underline{c}$ data for the EGCR transverse and parallel samples are presented in Figures 31a (NC8) and 31b (NC7). An increase in $\underline{c}$ followed by a decrease is again apparent. The variations of the NC8 data appear to be damping out at approximately the initial $\underline{c}$ value but the NC7 data continue to show large variations even at the highest exposures.

The data on apparent crystallite size in the $\underline{c}$ direction, L_c , are presented in Figure 32 for CSF graphite. The data fall on two distinct curves with the 425 to 475 C data lying below the data obtained from samples irradiated at 575 to 800 C. The L_c decreases rapidly with increasing exposure and then tends to reach a relatively constant value with a possible slight further decrease at the highest exposure.

The L_c data for the EGCR graphites are presented in Figure 33. Again for both graphites N68 and NC7, the L_c decreases rapidly, tends to a constant, and decreases slightly at the highest exposures. The lower temperature data fall below all the remaining data.

The effect of neutron exposure on the crystallite parameters $\underline{a}$ and L_a are shown in Figures 34 through 37, $\underline{a}$ being the unit cell dimension in the layer plane and L_a the apparent crystallite size in the $\underline{a}$ direction. Data on $\underline{a}$ for CSF graphite are presented in Figure 34. A slight decrease is

followed by a rapid decrease to a relatively constant value. The data at 425 to 475 C fall below the data at all other temperatures.

The a data for the EGCR graphites are presented in Figure 35. There is considerable spread in the data but the a parameter appears to decrease to a value of $2.459 \text{ \AA}$, which is nearly the same as that for the higher temperature CSF data.

The data on L_a for CSF graphite are presented in Figure 36. Extremely large variations, some as large as a factor of 5, are noted in several cases. A general decrease in L_a is observed, although the 575 to 625 C data show a decrease followed by an increase.

The L_a data for the EGCR graphites are presented in Figure 37. Again large spreads in individual datum points are observed, but a general decrease in L_a is suggested.

FIGURE 30

Crystallite Layer Spacing (Δ) of CSF Graphite as a Function of Exposure

FIGURE 31a

Crystallite Layer Spacing (c) of EGCR (NC8) Graphite as a Function of Exposure

FIG RE 31b
Crystallite Layer Spacing (c) of EGCR (NC7) Graphite as a Function of Exposure

FIGURE 32

Apparent Crystallite Size (L_c) of CSF Graphite as a Function of Exposure

FIGURE 33

Apparent Crystallite Size (L_c) of EGCR Graphite as a Function of Exposure

FIGURE 34
Crystallite Layer Spacing (a_c) of CSF Graphite as a Function of Exposure

FIGURE 35

Crystallite Layer Spacing (a) of EGCR Graphite as a Function of Exposure

FIGURE 36

Apparent Crystallite Size (L_a) of CSF Graphite as a Function of Exposure

FIGURE 37

Apparent Crystallite Size (L_a) of EGCR Graphite as a Function of Exposure

Young's Modulus of Elasticity

The data obtained on Young's modulus of elasticity, E, as a function of neutron exposure are presented in Figures 38 through 41. All data indicate a rapid increase in Young's modulus upon initial irradiation, followed by a leveling off or a decrease with increased exposure.

The data for the CSF transverse samples are presented in Figure 38. There is a spread of approximately 15% for individual samples irradiated at the same temperature to identical exposures. A rapid increase in E at low exposures is followed by a smaller rate of increase as exposure is continued. The isotherms indicate that the lowest irradiation temperatures, 425 to 475 C, cause the largest increase; however, 575 to 600 C data show the least, while the highest temperatures, 700 to 800 C, exhibit an intermediate change.

The data for the CSF parallel samples are presented in Figure 39. The spread for individual samples as indicated by the bars is much larger than for the transverse samples. However, the isotherms through the mean values indicate a more regular behavior than for the CSF transverse data, with the 425 to 475 C samples showing the largest increase, 73%, those at 575 to 725 C an intermediate, and those at 775 to 800 C the least, 48%. The last also exhibits a slight decrease in E from a maximum of 2.46×10^6 psi with increasing exposure.

Figure 40 presents the few points for the EGCR transverse samples.

The data from the EGCR parallel samples are presented in Figure 41. The same trends are apparent; a large initial increase, a maximum, a decrease, and for the 800 C NC8 samples, an apparent leveling out at a change of 70%. The NC7 data which have a higher initial E show about the same change as the NC8 data so that the absolute values of E for NC7 samples are greater. The isotherms again show an irregular behavior.

The Young's modulus data are presented in Figures 42 through 45 as a function of temperature and exposure to make the data more useful to reactor designers.

FIGURE 38

Young's Modulus of CSF Graphite (Transverse) as a Function of Exposure

FIGURE 39

Young's Modulus of CSF Graphite (Parallel) as a Function of Exposure

FIGURE 40

Young's Modulus of EGCR Graphite (Transverse) as a Function of Exposure

FIGURE 41
Young's Modulus of EGCR Graphite (Parallel) as a Function of Exposure

FIGURE 42
Young's Modulus of CSF Graphite (Transverse) as a Function of Temperature and Exposure

FIGURE 43

Young's Modulus of CSF Graphite (Parallel) as a Function of Temperature and Exposure

FIGURE 44

Young's Modulus of EGCR Graphite (Transverse) as a Function of Temperature and Exposure

FIGURE 45

Young's Modulus of EGCR Graphite (Parallel) as a Function of Temperature and Exposure

Electrical Resistivity

The data on the effect of increased neutron exposure on electrical resistivity, ρ , are presented in Figures 46 through 49. All the data show a rapid increase in ρ upon initial irradiation followed by a smaller rate of increase, and then another rapid increase with exposure.

The data for CSF transverse samples are presented in Figure 46. The isotherms indicate a fairly regular behavior with the 425 to 475 C samples showing the largest initial increase, the 575 to 625 C samples and 700 to 725 C samples intermediate changes, and the 775 to 800 C samples the smallest increase. The data then show a leveling off at a change of 216 to 250% and for the 800 C samples show another increase.

The CSF parallel sample data are presented in Figure 47. The 425 to 475 C isotherm shows an initial change of 271% while all the other isotherms show an increase of 214%. All then level off until at the highest exposure the 775 to 800 C data again show an increase.

The small amount of data for the EGCR transverse samples are presented in Figure 48. The isotherms again indicate a regular behavior.

The data for the EGCR parallel samples are presented in Figure 49. These isotherms also show a regular behavior with the largest initial changes at 375 to 475 C and the smallest at 800 C.

The data on ρ are presented as a function of temperature and exposure in Figures 50 through 53.

FIGURE 46

Electrical Resistivity of CSF Graphite (Transverse) as a Function of Exposure

FIGURE 47

Electrical Resistivity of CSF Graphite (Parallel) as a Function of Σ_{exposure}

FIGURE 48

Electrical Resistivity of EGCR Graphite (Transverse) as a Function of Exposure

FIGURE 49

Electrical Resistivity of EGCR Graphite (Parallel) as a Function of Exposure

FIGURE 50

Electrical Resistivity of CSF Graphite (Transverse) as a Function of Temperature and Exposure

FIGURE 51

Electrical Resistivity of CSF Graphite (Paraffin) as a Function of Temperature and Exposure

FIGURE 52

Electrical Resistivity of EGCR Graphite (Transverse) as a Function of Temperature and Exposure

FIGURE 53

Electrical Resistivity of EGCR Graphite as a Function of Temperature and Exposure

CONCLUSIONS

At the temperatures of primary interest to the EGCR operators (375 to 475 C) data are presented to neutron exposures equivalent to approximately one-third the predicted EGCR lifetime exposure (74,000 MWd/adjacent ton). The H-3 irradiation program is continuing and these low-temperature samples are being exposed at the maximum capsule exposure of approximately 1.5×10^{21} nvt, $E > 0.18$ MeV or 10,000 MWd/adjacent ton EGCR per capsule.

In applying the length-change data reported to reactor conditions, consideration should be given to the difference between small samples and large blocks. At present the largest block on which length data have been obtained was 4 by 4 by 24 in.⁽¹⁴⁾ For both transverse and parallel orientations, this large block showed contractions approximately twice the contraction of small, 0.43 in. diam by 4 in., samples. Consequently, such a factor should be kept in mind when applying these data to changes expected in the EGCR.

The possible effect of neutron flux intensity differences on the contraction and other properties is apparently of no significance at the temperatures studied. The 425 to 475 C data obtained at the minimum flux (Capsule Position 1) and those obtained at the maximum flux (Capsule Position 5) show no statistical difference and fall on the same curve.

It is readily apparent that the concept of saturation of length change as discussed in HW-71500 A is no longer valid. At the highest irradiation temperatures, the results from the transverse samples indicate that a mechanism causing growth with continued irradiation has become controlling. It does not appear that this mechanism can be entirely explained by crystal-lite expansion as measured by ϵ -spacing changes, since the ϵ -spacing levels out at approximately the initial value. However, the interstitials may form new planes indistinguishable from the former planes by the ϵ -spacing measurement. This might also explain the apparent variations in ϵ that may be caused by a buildup of interstitials followed by formation of a new layer and an apparent decrease in ϵ . It appears the oscillations in ϵ are too regular to be purely random.

The neutron exposure at which the high-temperature contraction passes through a maximum, $6 \text{ to } 8 \times 10^{21} \text{ nvt}$, $E > 0.18 \text{ MeV}$, appears to be a critical point for other parameters also. The mechanism causing the increase in length also causes a decrease in apparent crystallite size, L_c , and an increase in electrical resistivity, indicating that the crystallite disorder is becoming greater.

Data on length change and crystallite parameters will continue to be taken on all samples, and data on electrical resistivity and Young's modulus will be obtained on all samples from future capsules in the program so that a more complete picture of graphite behavior under irradiation can be drawn in the future.

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REFERENCES

1. R. E. Nightingale (Ed.). Nuclear Graphite, Academic Press, New York, 1962.
2. J. M. Davidson and J. W. Helm. The H-3 Irradiation Experiment: Irradiation of EGCR Graphite, Interim Report No. 1, HW-71500 A. October 16, 1961.
3. J. M. Davidson. Unpublished Data, General Electric Co., Richland, June 24, 1960.
4. D. E. Cooley. Sonic Determination of Elastic Constants in Graphite, HW-75654. July 13, 1962.
5. J. M. Davidson and J. W. Helm. The H-1 High Temperature Graphite Irradiation Experiment, HW-64286. April 1961.
6. F. J. Mollerus, Jr. User's Manual for STHTP - A Steady State Heat Transfer Program for the IBM 7090 Computer, HW-73668. May 21, 1962.
7. Complete Irradiation Services at Vallecitos, GE-APED, San Jose, California.
8. J. W. Helm. Irradiation of N-Reactor Graphite: The H-4, -5, -6 Irradiation Program, Interim Report No. 1, HW-81250 A. October 1964.
9. C. H. Hogg, L. D. Weber, and E. C. Yates. Thermal Neutron Cross Sections of the Co^{58} Isomers and the Effect on Fast Flux Measurements Using Nickel, IDO-16744. Phillips Petroleum Co., June 1960.
10. T. O. Passell. "The Use of Ni^{58} and Fe^{54} as Integrators of Fast-Neutron Flux," Neutron Dosimetry, vol. 1, p. 501. Proceedings of the International Atomic Energy Symposium on Neutron Detection, Dosimetry and Standardization, Harwell, England, December 1962.
11. J. J. Van Loef. Nuclear Physics, vol. 24, pp. 340-345. 1961. R. G. Johnson, S. Salsbury, and F. J. Vaughn, LMSC-4-50-62-1. October 1962.
12. J. Bengston, et al. 2DXY Two-Dimensional, Cartesian Coordinate Sn Transport Calculation, AGN-TM-392. June 1961.
13. R. E. Dahl and H. H. Yoshikawa. "Neutron Spectra Calculations for Radiation Damage Studies," Nucl. Sci. and Eng. vol. 17, pp. 398-403, 1963.
14. R. E. Nightingale and E. M. Woodruff. Radiation-Induced Dimensional Changes in Large Graphite Bars, HW-SA-2996. December 18, 1963.
15. Atomic Energy Commission. The Reactor Handbook, vol. 2, AECD-3646. May 1955.

16. W. H. McAdams. Heat Transmission, McGraw-Hill, New York, 1954. 3rd ed.
17. P. D. Bush, et al. Engineering Test Reactor Engineering Design and Safeguards Report, IDO-24020. Phillips Petroleum Company, July 1956.
18. Alcoa Structural Handbook, Aluminum Company of America, Pittsburgh, 1956.
19. L. S. Marks (Ed.). Mechanical-Engineers' Handbook, McGraw-Hill, New York, 1961. 5th ed.
20. H. H. Yoshikawa and W. H. Zimmer. Fast-Neutron Dosimetry: Intercalibration of Counting Facilities, HW-81871. April 1964.
21. H. H. Yoshikawa. Flux Monitoring for Radiation Damage Studies, HW-64251. March 3, 1960.
22. W. C. Morgan. FOILS: A Program for Computing Neutron Exposures from Foil-Activation Data, HW-81367. April 1964.

APPENDIX A

DESIGN AND HEAT TRANSFER CALCULATIONS

APPENDIX ASUMMARY OF DESIGN AND HEAT TRANSFER CALCULATIONS

Results of coolant flow and heat transfer calculations for the capsules are summarized in Table A-I.

TABLE A-I

FLUX MAXIMUM VALUES (design)	
Neutron, nv:	
10-0.18 MeV	3.7×10^{14}
0.18 MeV-0.17 eV	3.5×10^{14}
Less than 0.17. eV	2.2×10^{14}
Gamma Heating	
W/g	12
Btu/(hr)(g)	41.0
SAMPLE DESCRIPTION	
Assembly Size:	
Graphite Cylinder	1 in. in diam 3 7/8 in. long
Weight:	
Sample, g	76.1
Assembly, g/ft	570
HEAT GENERATION	
Graphite Core, Btu/(hr)(ft)	13,550
Total Assembly, Btu/(hr)(ft)	31,450
HEAT FLUX	
Capsule Surface, Btu/(hr)(ft ²)	59,200
COOLANT CONDITIONS	
Water Flow Past Capsule, gal/min	44
Water Velocity Past Capsule, ft/sec	22
TEMPERATURES	
Capsule Surface Temperature, F (Maximum, Node 5)	187
Sample Temperature Range, F C	800 to 1500 400 to 850
GAS ATMOSPHERE	
Helium Pressure, psia at 1000 C	65
MECHANICAL STRENGTH	
Collapsing	840 psia

A. COOLANT FLOW CALCULATIONS

1. Design Parameters

Water temperature	130 F
Pressure drop through core	25 psi
Dimensions of capsule and facility	
Capsule	2.030 in. OD
Protection Tube	1.100 in. OD
Filler Piece	2.20 in. ID
Flow Restrictor	2.12 in. ID x 2.437 in. OD

$$\begin{aligned}
 \Delta P &= \frac{f L \rho V^2}{D_e^2 g_c} \\
 &= \frac{f L \rho V^2 [\text{ft}^2 / \text{sec}^2]}{D_e (2) (32.2) [\text{ft} / \text{sec}^2]} \times \frac{61.7 [\text{lb} / \text{ft}^3]}{144 [\text{in.}^2 / \text{ft}^2]} \\
 &= 0.00665 \frac{f L V^2}{D_e} \text{ psi}
 \end{aligned}$$

Contraction

$$\Delta P = \frac{K_c V_2^2}{2g_c}$$

$$= 0.00665 K_c V_2^2 \text{ psi}$$

K_c from Figure 1.5.7, p. 67 of Reference 15

Enlargement

$$\Delta P = \frac{K_e V_1^2}{2g_c}$$

$$= 0.00665 K_e V_1^2 \text{ psi}$$

K_e from Figure 1.5.6, p. 66 of Reference 15

3. Water Velocity, V :

$$V = F \frac{\text{gal}}{\text{min}} \times 0.1337 \frac{\text{ft}^3}{\text{gal}} \times \frac{[\text{min}]}{60[\text{sec}]} \times \frac{144[\text{in.}^2]}{[\text{ft}^2]} \times \frac{1}{A[\text{in.}^2]}$$

$$= \frac{0.321 F}{A} \text{ ft/sec}$$

4. Water Flow, F :

Location	Area, in. ²	Coefficient	Pressure Drop, psi x 10 ⁴ F ⁻²
A ₁	Large		0
		$K_c = 0.40$	0.02
A ₂	10.134		0
		$K_c = 0.38$	0.68
A ₃	1.917		0.38
		$K_c = 0.35$	5.97
A ₄	0.634		82.34
		$K_e = 0.60$	10.22
A ₅	2.749		0.01
		$K_e = 0.36$	4.49
A ₆	0.745		0.68
		$K_e = 0.34$	4.19
A ₇	1.784		2.70
		$K_c = 0.33$	4.17
A ₈	0.735		3.69
		$K_e = 0.48$	6.09
A ₉	2.405		0.13
		$K_e = 1.0$	1.18
A ₁₀	Large		0
Total			126.94
Thus 0.01269 F ² = 25 F = 44 gal/min			

5. Coolant Conditions Past Capsule

Water Flow	44 gal/min
Velocity Past Capsule	22 ft/sec
Equivalent Diameter	$D_e = 0.190 \text{ in.} = 0.0158 \text{ ft}$

6. Data for Water at 130 F

Viscosity, μ	1.36 lb/(hr)(ft) (Ref. 16, p. 484)
Thermal Conductivity, k	0.372 Btu/(hr)(ft ²)(F°) per ft (Ref. 16, p. 484)
Heat Capacity, c	1.0 Btu/(lb)(F°) (Ref. 16, p. 462)

7. Water Film Coefficient, h :

$$h = 0.020 \frac{k}{D} (N_{RE})^{0.8} (N_{PR})^{0.33} \quad (\text{Ref. 17, p. 150})$$

Reynolds Number, N_{RE}

$$N_{RE} = \frac{D_e V \rho}{\mu}$$

$$= \frac{0.0158 [\text{ft}] \times 22 [\text{ft/sec}] \times 61.7 [\text{lb/ft}^3] \times 3600 [\text{sec/hr}]}{1.36 [\text{lb/(hr)(ft)}]}$$

$$= 0.568 \times 10^5$$

Prandtl Number, N_{PR}

$$N_{PR} = \frac{c \mu}{k}$$

$$= \frac{1.0 [\text{Btu/(lb)(F°)}] \times 1.36 [\text{lb/(hr)(ft)}]}{0.372 [\text{Btu/(hr)(ft)(F°)}]}$$

$$= 3.65$$

$$h = 0.020 \frac{k}{D} (0.568 \times 10^5)^{0.8} (3.65)^{0.33}$$

$$= \frac{0.372 [\text{Btu/(hr)(ft)(F°)}]}{0.0158 [\text{ft}]} (0.020)(0.636 \times 10^4)(1.54)$$

$$= 4700 \text{ Btu/(hr)(ft}^2\text{)(F°)}$$

Therefore, the water film coefficient is 4700 Btu/(hr)(ft²)(F°).

B. HEAT TRANSFER CALCULATIONS

The temperatures of all capsule parts are calculated by a steady-state computer program⁽⁶⁾ using heat-transfer calculations. The capsule is set up with a three-dimensional geometry and the calculation includes internal heat generation, constant or temperature-dependent thermal conductivity, constant contact or film coefficients, and heat transfer by conduction and radiation. The calculation includes

- 142 nodes, or regions where heat is generated or transferred
- 1 sink, or boundary temperature, 130 F
- 9 material-property tables
- 5 contact or film coefficients.

Temperatures for ten heat-generation rates are calculated by changing the heat generation contained in the material-property tables and adding a new case card for each new set.

The technique used by the program consists of an iterative solution of the heat transfer through all the nodes in the problem. An acceptable solution is obtained when the error in heat flux across any node boundary is less than an arbitrary value of 10 Btu/hr. Output from the program consists of:

- Temperature at each node
- Conductance through each of the eight sides of each node
- Temperature of and heat transferred to each sink
- Total heat generation in the capsule.

Calculation Details—

Momenclature

- A = heat-transfer area, or area of node face
- U = thermal conductance
- T = temperature
- Q = heat-generation rate
- ϵ_N = heat-balance error for node N
- ϵ_T = absolute value of heat-transfer error
- a = accelerator factor

Subscripts

N = node number

K = number of node adjacent to node N

J = number of node side

The temperature of any node, N, is found in terms of the node heat-generation rate, Q_N , and the adjacent node temperature, T_K , from the following equation:

$$T_N = \frac{Q_N + \sum_{J=1}^8 A_{N,J} U_{N,J} (T_K)}{\sum A_{N,J} U_{N,J}}$$

The computer solves a set of N equations of this type by an iterative process. After 20 iterations the accuracy of the calculated temperatures is checked by making heat balances on each node. This heat-balance error is given by the equation:

$$\epsilon_N = Q_N + \sum_{J=1}^8 U_{N,J} A_{N,J} (T_K - T_N).$$

Then the absolute value $\epsilon_T = \sum_{N=1}^8 \epsilon_N$.

If ϵ_T is less than 10 Btu/hr the temperatures are considered accurate and the iteration procedure is terminated.

To speed up the iterative process the program uses an acceleration factor, a . The calculated node temperature, T_N , is compared with the calculated temperature from the previous iteration, T'_N , or

$$\Delta T_N = T_N - T'_N.$$

A corrected node temperature is then calculated from $T_N = T'_N + a\Delta T_N$. An extrapolation procedure is also used to eliminate some iterations and

bring the calculated temperature asymptotically to the correct temperature. Ratios of the ΔT_N are taken for the four previous iterations and used for the extrapolation. A history of a calculated node temperature is shown in Figure 54.

FIGURE 54

Calculated Node Temperature

The areas, A , and distances, d , used for the computer input for a typical node in radial symmetry are shown in Figure 55. The nodal structure for the capsule is shown in Figure 56.

FIGURE 55

Typical Node in Radial Symmetry

FIGURE 56
Heat Transfer Node Diagram

The results of the calculations for typical capsule positions are shown in Figure 57. The 8 and 6 W/g thermally grounded cases apply to Capsule Positions 5 and 6, respectively, and the 8 and 6 W/g ungrounded cases apply to Positions 3 and 4, respectively. The calculated temperature distribution agrees within ± 25 C of the temperatures as measured by thermocouples in the capsule.

The computer output for the 12 W/g thermally grounded case is shown in Table A-II. The total heat generation in the assembly (10 in. length) is 26,210 Btu/hr and in the graphite is 11,290 Btu/hr.

FIGURE 57

Calculated Axial Temperatures of Sample Sections
H-3 Capsule

TABLE A-II

DEBUG PRINT OUT OF INTER NODE CONDUCTANCES - CASE NUMBER					306 AFTER ITERATION CYCLE NUMBER			64
1	0.	0.	0.	0.	6.756E 02	8.176E 01	0.	1.212E 01
2	0.	0.	0.	0.	7.230E 02	8.750E 01	1.212E 01	1.173E 01
3	0.	0.	0.	0.	7.230E 02	8.750E 01	1.173E 01	7.822E 00
4	0.	0.	0.	0.	1.446E 03	1.750E 02	7.822E 00	7.822E 00
5	0.	0.	0.	0.	1.353E 01	8.750E 01	7.822E 00	1.173E 01
6	0.	0.	0.	0.	7.230E 02	8.750E 01	1.173E 01	1.173E 01
7	0.	0.	0.	0.	7.230E 02	8.750E 01	1.173E 01	1.173E 01
8	0.	0.	0.	0.	7.230E 02	8.750E 01	1.173E 01	1.173E 01
9	0.	0.	0.	0.	7.230E 02	8.750E 01	1.173E 01	1.173E 01
10	0.	0.	0.	0.	1.353E 01	8.750E 01	1.173E 01	1.173E 01
11	0.	0.	0.	0.	7.230E 02	8.750E 01	1.173E 01	1.173E 01
12	0.	0.	0.	0.	7.230E 02	8.750E 01	1.173E 01	7.822E 00
13	0.	0.	0.	0.	1.446E 03	1.750E 02	7.822E 00	7.822E 00
14	0.	0.	0.	0.	1.353E 01	8.750E 01	7.822E 00	1.173E 01
15	0.	0.	0.	0.	7.230E 02	8.750E 01	1.173E 01	1.173E 01
16	0.	0.	0.	0.	7.230E 02	8.750E 01	1.173E 01	1.173E 01
17	0.	0.	0.	0.	7.230E 02	8.750E 01	1.173E 01	1.212E 01
18	0.	0.	0.	0.	9.481E 02	1.148E 02	1.212E 01	0.
19	0.	0.	0.	0.	8.610E 00	1.353E 01	0.	4.777E 00
20	0.	0.	0.	0.	8.638E 00	1.353E 01	4.915E 00	4.915E 00
21	0.	0.	0.	0.	8.610E 00	1.353E 01	0.	4.789E 00
22	0.	7.599E-01	7.635E-01	0.	3.980E 00	0.	4.777E 00	0.
23	0.	7.646E-01	7.651E-01	0.	4.202E 00	0.	4.789E 00	0.
24	0.	0.	0.	0.	1.795E-01	6.756E 02	0.	1.750E-02
25	0.	0.	0.	0.	1.861E-01	7.230E 02	1.750E-02	1.694E-02
26	0.	0.	0.	0.	1.740E-01	7.230E 02	1.694E-02	1.130E-02
27	0.	0.	0.	0.	3.597E-01	1.446E 03	1.130E-02	0.
28	0.	0.	0.	0.	1.641E-01	7.230E 02	0.	1.696E-02
29	0.	0.	0.	0.	1.295E-01	7.230E 02	1.696E-02	1.691E-02
30	0.	0.	0.	0.	1.202E-01	7.230E 02	1.691E-02	1.693E-02
31	0.	0.	0.	0.	1.017E-01	7.230E 02	1.693E-02	0.
32	0.	0.	0.	0.	3.379E 01	8.638E 00	9.225E-01	9.225E-01
33	0.	0.	0.	0.	9.696E-02	7.230E 02	0.	1.692E-02
34	0.	0.	0.	0.	1.089E-01	7.230E 02	1.692E-02	1.128E-02
35	0.	0.	0.	0.	2.920E-01	1.446E 03	1.128E-02	0.
36	0.	0.	0.	0.	1.589E-01	7.230E 02	0.	1.695E-02
37	0.	0.	0.	0.	1.517E-01	7.230E 02	1.695E-02	1.693E-02
38	0.	0.	0.	0.	1.692E-01	7.230E 02	1.693E-02	1.465E-02
39	0.	0.	0.	0.	2.365E-01	9.481E 02	1.465E-02	0.
40	0.	0.	0.	0.	2.095E 01	1.795E-01	0.	2.768E-02
41	0.	0.	0.	0.	2.222E 01	1.861E-01	2.768E-02	2.649E-02
42	0.	0.	0.	0.	2.222E 01	1.740E-01	2.649E-02	0.
43	0.	0.	0.	0.	9.260E 01	3.597E-01	0.	0.
44	0.	0.	0.	0.	4.622E 01	1.641E-01	0.	0.
45	0.	0.	0.	0.	2.222E 01	1.295E-01	0.	2.362E-02
46	0.	0.	0.	0.	2.222E 01	1.202E-01	2.362E-02	2.260E-02
47	0.	0.	0.	0.	2.222E 01	1.017E-01	2.260E-02	0.
48	0.	0.	0.	0.	1.562E 01	2.484E 01	2.018E 0	2.018E 00
49	0.	0.	0.	0.	2.222E 01	9.696E-02	0.	2.200E-02

50	0.	0.	0.	0.	2.222E 01	1.089E-01	2.200E-02	0.
51	0.	0.	0.	0.	9.269E 01	2.920E-01	0.	0.
52	0.	0.	0.	0.	4.622E 01	1.589E-01	0.	0.
53	0.	0.	0.	0.	2.222E 01	1.517E-01	0.	2.561E-02
54	0.	0.	0.	0.	2.222E 01	1.692E-01	2.561E-02	2.276E-02
55	0.	0.	0.	0.	2.968E 01	2.365E-01	2.276E-02	0.
56	0.	0.	0.	0.	6.114E 00	2.095E 01	0.	2.027E 00
57	0.	0.	0.	0.	6.523E 00	2.222E 01	2.027E 00	1.967E 00
58	0.	0.	0.	0.	6.523E 00	2.222E 01	1.967E 00	1.197E 00
59	0.	0.	0.	0.	1.142E 01	2.553E 01	1.197E 00	1.376E 00
60	0.	0.	0.	3.744E 00	2.854E 00	6.379E 00	1.376E 00	2.447E 00
61	0.	0.	0.	0.	5.708E 00	1.273E 01	2.293E 00	1.836E 00
62	0.	0.	0.	0.	6.523E 00	2.222E 01	1.836E 00	1.967E 00
63	0.	0.	0.	0.	6.523E 00	2.222E 01	1.967E 00	1.967E 00
64	0.	0.	0.	0.	6.523E 00	2.222E 01	1.967E 00	1.967E 00
65	1.010E 01	5.052E 00	5.052E 00	1.010E 01	6.523E 00	1.562E 01	1.967E 00	1.967E 00
66	0.	0.	0.	0.	6.523E 00	2.222E 01	1.967E 00	1.967E 00
67	0.	0.	0.	0.	6.523E 00	2.222E 01	1.967E 00	1.197E 00
68	0.	0.	0.	0.	1.142E 01	2.553E 01	1.197E 00	1.376E 00
69	0.	0.	0.	3.744E 00	2.854E 00	6.379E 00	1.376E 00	2.447E 00
70	0.	0.	0.	0.	5.708E 00	1.273E 01	2.293E 00	1.836E 00
71	0.	0.	0.	0.	6.523E 00	2.222E 01	1.836E 00	1.967E 00
72	0.	0.	0.	0.	6.523E 00	2.222E 01	1.967E 00	1.701E 00
73	0.	0.	0.	0.	8.573E 00	2.968E 01	1.701E 00	0.
74	0.	0.	0.	0.	0.	6.114E 00	0.	6.735E-01
75	0.	0.	0.	0.	0.	6.523E 00	6.735E-01	6.533E-01
76	0.	0.	0.	0.	0.	6.523E 00	6.533E-01	3.977E-01
77	0.	0.	0.	0.	0.	1.142E 01	3.977E-01	4.573E-01
78	0.	0.	0.	0.	0.	2.854E 00	4.573E-01	2.287E 00
79	0.	0.	0.	0.	0.	5.708E 00	7.622E-01	6.098E-01
80	0.	0.	0.	0.	0.	6.523E 00	6.098E-01	6.533E-01
81	0.	0.	0.	0.	0.	6.523E 00	6.533E-01	6.533E-01
82	0.	0.	0.	0.	0.	6.523E 00	6.533E-01	6.533E-01
83	0.	0.	0.	0.	0.	6.523E 00	6.533E-01	6.533E-01
84	0.	0.	0.	0.	0.	6.523E 00	6.533E-01	6.533E-01
85	0.	0.	0.	0.	0.	6.523E 00	6.533E-01	3.977E-01
86	0.	0.	0.	0.	0.	1.142E 01	3.977E-01	4.573E-01
87	0.	0.	0.	0.	0.	2.854E 00	4.573E-01	2.287E 00
88	0.	0.	0.	0.	0.	5.708E 00	7.622E-01	6.098E-01
89	0.	0.	0.	0.	0.	6.523E 00	6.098E-01	6.533E-01
90	0.	0.	0.	0.	0.	6.523E 00	6.533E-01	5.652E-01
91	0.	0.	0.	0.	0.	8.573E 00	5.652E-01	0.
92	0.	0.	0.	0.	2.553E 01	9.269E 01	0.	1.027E 00
93	0.	0.	0.	0.	6.379E 00	1.925E 01	1.027E 00	5.133E 00
94	0.	0.	0.	0.	1.273E 01	4.622E 01	1.711E 00	0.
95	0.	0.	0.	0.	2.553E 01	9.269E 01	0.	1.027E 00
96	0.	0.	0.	0.	6.379E 00	1.925E 01	1.027E 00	5.133E 00
97	0.	0.	0.	0.	1.273E 01	4.622E 01	1.711E 00	0.
98	0.	0.	0.	0.	0.	-0.	2.287E 00	1.906E 01
99	0.	0.	0.	0.	0.	4.661E-01	1.906E 01	1.906E 01
100	0.	0.	0.	0.	0.	-0.	1.906E 01	2.287E 00

101	0.	0.	0.	0.	0.	2.854E 00	2.287E 00	7.622E-01
102	0.	0.	0.	0.	0.	-0.	2.287E 00	1.906E 01
103	0.	0.	0.	0.	0.	4.661E-01	1.906E 01	1.906E 01
104	0.	0.	0.	0.	0.	-0.	1.906E 01	2.287E 00
105	0.	0.	0.	0.	0.	2.854E 00	2.287E 00	7.622E-01
106	0.	0.	0.	0.	-0.	-0.	2.447E 00	2.382E 01
107	0.	0.	0.	0.	4.661E-01	5.674E-01	2.382E 01	2.382E 01
108	0.	0.	0.	0.	-0.	-0.	2.382E 01	2.447E 00
109	0.	0.	3.744E 00	0.	2.854E 00	6.379E 00	2.447E 00	2.293E 00
110	0.	0.	0.	0.	-0.	-0.	2.447E 00	2.382E 01
111	0.	0.	0.	0.	4.661E-01	5.691E-01	2.382E 01	2.382E 01
112	0.	0.	0.	0.	-0.	-0.	2.382E 01	2.447E 00
113	0.	0.	3.744E 00	0.	2.854E 00	6.379E 00	2.447E 00	2.293E 00
114	0.	0.	3.744E 00	0.	-0.	-0.	0.	3.475E 00
115	0.	0.	0.	0.	5.674E-01	7.787E-01	3.475E 00	3.475E 00
116	0.	0.	0.	3.744E 00	-0.	-0.	3.475E 00	0.
117	0.	0.	3.744E 00	0.	-0.	-0.	0.	3.507E 00
118	0.	0.	0.	0.	5.691E-01	8.068E-01	3.507E 00	3.507E 00
119	0.	0.	0.	3.744E 00	-0.	-0.	3.507E 00	0.
120	0.	0.	0.	0.	-0.	0.	5.133E 00	5.908E 00
121	0.	0.	0.	0.	7.787E-01	3.980E 00	5.908E 00	5.908E 00
122	0.	0.	0.	0.	-0.	0.	5.908E 00	5.133E 00
123	0.	0.	0.	0.	6.379E 00	0.	5.133E 00	1.711E 00
124	0.	0.	0.	0.	-0.	0.	5.133E 00	5.918E 00
125	0.	0.	0.	0.	8.068E-01	4.202E 00	5.918E 00	5.918E 00
126	0.	0.	0.	0.	-0.	0.	5.918E 00	5.133E 00
127	0.	0.	0.	0.	6.379E 00	0.	5.133E 00	1.711E 00
128	7.599E-01	0.	0.	0.	1.925E 01	6.314E 01	0.	0.
129	7.646E-01	0.	0.	0.	1.925E 01	6.314E 01	0.	0.
130	0.	0.	0.	7.635E-01	6.314E 01	8.610E 00	0.	0.
131	0.	0.	0.	7.651E-01	6.314E 01	8.610E 00	0.	0.
132	0.	1.010E 01	0.	0.	0.	0.	0.	7.667E 00
133	5.052E 00	0.	0.	0.	0.	1.094E 00	7.667E 00	2.018E 00
134	0.	0.	0.	5.052E 00	0.	1.094E 00	2.018E 00	7.667E 00
135	0.	0.	1.010E 01	0.	0.	0.	7.667E 00	0.
136	0.	0.	0.	0.	1.094E 00	1.200E 01	0.	1.994E 00
137	0.	0.	0.	0.	2.484E 01	3.379E 01	1.994E 00	1.994E 00
138	0.	0.	0.	0.	1.094E 00	1.200E 01	1.994E 00	0.
139	0.	0.	0.	0.	1.200E 01	8.213E 00	0.	9.225E-01
140	0.	0.	0.	0.	1.200E 01	8.213E 00	9.225E-01	0.
141	0.	0.	0.	0.	8.213E 00	0.	0.	4.915E 00
142	0.	0.	0.	0.	8.213E 00	0.	4.915E 00	0.
HEAT BALANCE NUMBER 6 AFTER ITERATION 306 ABSOLUTE ERROR= 3.179E 00 POSITIVE ERROR= 1.410E 00								

MAIN OUTPUT STEADY STATE HEAT TRANSFER PROGRAM

CASE NUMBER 306 NUMBER OF NODES 142 ITERATION LIMIT 500 ERROR LIMIT 1.000E 01
 TEMPERATURE OF SINK 1 = 1.300E 02 HEAT TRANSFERRED TO THIS SINK = -2.621E 04
 TOTAL INTERNAL HEAT GENERATION IN PROBLEM = 2.621E 04 BTU/HR
 ACCELERATION FACTOR = 1.600E 00 NUMBER OF ITERATION CYCLES = 64 HEAT BALANCE ERROR = 3.179E 00

NODE TEMPERATURES DEG F											CASE NUMBER 306
NODE	01	02	03	04	05	06	07	08	09	10	
0	1.396E 02	1.394E 02	1.392E 02	1.406E 02	1.867E 02	1.433E 02	1.382E 02	1.378E 02	1.402E 02	1.672E 02	02
10	1.401E 02	1.375E 02	1.389E 02	1.709E 02	1.415E 02	1.387E 02	1.389E 02	1.392E 02	5.808E 02	4.175E 02	02
20	4.424E 02	1.057E 03	6.738E 02	1.401E 02	1.399E 02	1.396E 02	1.409E 02	1.435E 02	1.385E 02	1.380E 02	02
30	1.403E 02	6.139E 02	1.402E 02	1.377E 02	1.392E 02	1.418E 02	1.390E 02	1.393E 02	1.396E 02	1.925E 03	03
40	1.889E 03	1.808E 03	1.557E 03	1.431E 03	1.458E 03	1.370E 03	1.171E 03	7.350E 02	1.114E 03	1.254E 03	03
50	1.271E 03	1.388E 03	1.644E 03	1.775E 03	1.853E 03	1.940E 03	1.904E 03	1.821E 03	1.585E 03	1.212E 03	03
60	1.448E 03	1.466E 03	1.377E 03	1.175E 03	8.276E 02	1.119E 03	1.260E 03	1.288E 03	1.002E 03	1.420E 03	03
70	1.654E 03	1.787E 03	1.867E 03	1.953E 03	1.916E 03	1.832E 03	1.600E 03	1.300E 03	1.456E 03	1.472E 03	03
80	1.383E 03	1.184E 03	8.962E 02	1.126E 03	1.265E 03	1.297E 03	1.097E 03	1.435E 03	1.663E 03	1.798E 03	03
90	1.879E 03	1.562E 03	1.025E 03	1.435E 03	1.275E 03	8.129E 02	1.393E 03	1.326E 03	1.329E 03	1.333E 03	03
100	1.365E 03	1.153E 03	1.159E 03	1.167E 03	1.230E 03	1.278E 03	1.285E 03	1.291E 03	1.348E 03	1.098E 03	03
110	1.108E 03	1.117E 03	1.207E 03	1.242E 03	1.273E 03	1.312E 03	1.041E 03	1.082E 03	1.147E 03	1.089E 03	03
120	1.144E 03	1.226E 03	1.321E 03	8.480E 02	8.784E 02	1.011E 03	1.164E 03	9.112E 02	7.100E 02	8.742E 02	02
130	6.784E 02	8.145E 02	7.953E 02	7.953E 02	8.145E 02	6.161E 02	6.640E 02	6.161E 02	5.861E 02	5.861E 02	02
140	5.354E 02	5.354E 02									

MAXIMUM TEMPERATURE IS 1.953E 03 DE(; F AT NODE 74

SUPPLEMENTAL OUTPUT STEADY STATE HEAT TRANSFER PROGRAM

MATERIAL TYPE				VOLUME		AVERAGE TEMPERATURE		TOTAL HEAT GENERATION		CASE NUMBER 306
				CU INCHES		DEG F		BTU/HR		
1				0.		0.		0.		
2				5.192E 00		1.466E 03		5.919E 03		
3				4.928E 00		1.363E 03		5.372E 03		
4				4.735E 01		9.537E 02		3.239E 03		
5				6.454E 00		1.908E 02		1.168E 04		
6				0.		0.		0.		
7				0.		0.		0.		
8				0.		0.		0.		
9				1.507E 01		7.436E 02		0.		

$$q_a = 26,210 \text{ Btu/hr} \times \frac{12 \text{ in./ft}}{10 \text{ in.}} = 31,450 \text{ Btu/(hr)(ft)}$$

$$q_g = 11,290 \text{ Btu/hr} \times \frac{12 \text{ in./ft}}{10 \text{ in.}} = 13,550 \text{ Btu/(hr)(ft)}$$

$$\text{Heat Flux } \frac{q_a}{A} = \frac{31,450 \text{ Btu/(hr)(ft)}}{(\pi)(2.030/12) \text{ ft}} = 59,200 \text{ Btu/(hr)(ft}^2\text{)}$$

C. SAMPLE MEAN IRRADIATION TEMPERATURES

The sample mean irradiation temperatures are determined from the capsule thermocouple readings, the thermocouple calibration curve, and the heat-transfer distribution. The mean thermocouple temperatures are obtained by graphically integrating the temperature history for the entire irradiation period. These temperatures are corrected to the true temperature by use of Figure 14. The mean temperatures along the samples are then determined by locating the thermocouple on the temperature distribution given in Figure 57 and taking the ratio to the sample mean temperature.

D. MECHANICAL STRENGTH

Collapsing Pressure, Ignoring the Support of the Cooling Rings

Shell	2 in. OD x 0.065 in. wall	
Material	3003-H14 aluminum	
Minimum Mechanical Properties		
Yield Strength (Compression)	15,000 psi	(Ref. 18, p. 55)
Rating for Temperature, YS	100% at 75 F	(Ref. 18, p. 70)
	89% at 212 F	

$$P = 2S_c \left[\frac{t}{D} - \left(\frac{t}{D} \right)^2 \right] \quad \text{when } \frac{t}{D} \geq 0.03 \quad (\text{Ref. 19, p. 422})$$

$$P = 2 \times 15,000 \times 0.89 [0.0325 - (0.0325)^2]$$

$$= 840 \text{ psia}$$

Reactor Pressure	140 psia
------------------	----------

Safety Factor	$\frac{840}{140} = 6.0$
---------------	-------------------------

HW-71500 B

APPENDIX B

DETERMINATION OF EXPOSURE

APPENDIX B

DETERMINATION OF EXPOSURE

A. EXPERIMENTAL PROCEDURE

Four types of flux monitor foils were inserted in small holes in each of the cooling rings before the irradiation of each capsule. These were nickel, iron, and titanium (wire form, 0.020 in. diam by 0.250 in. long) for the measurement of fast flux and 0.1% cobalt in aluminum (wire form 0.040 in. diam by 0.250 in. long) for thermal flux. Approximate weights were 0.010, 0.006, 0.011, and 0.013 g respectively. Upon completion of the irradiation period the wires were removed, weighed, and the following gamma energies counted on a 256 channel analyzer:⁽²⁰⁾

<u>Isotope Counted</u>	<u>MeV of γ</u>	<u>γ/disintegration</u>
Ni ⁵⁸ (n, p) Co ⁵⁸	0.81	1.01
Fe ⁵⁴ (n, p) Mn ⁵⁴	0.83	1.00
Ti ⁴⁶ (n, p) Sc ⁴⁶	0.89	1.00
	1.12	1.00
Co ⁵⁹ (n, γ) Co ⁶⁰	1.17	1.00
	1.33	1.00

B. EQUATIONS

Fast Flux, Ni⁵⁸ (n, p) Co⁵⁸

The activation and decay scheme for Co⁵⁸ production from Ni⁵⁸ is as follows:

The number of Co^{58} atoms, n , present at any time, t , is found by integration of the following differential equation:

$$\frac{dn}{dt} = \text{number formed} - \text{number disintegrated} - \text{number burned out}$$

$$\frac{dn}{dt} = '_{\text{act}} N\phi_f + \lambda'n' - \lambda n - '_{\text{abs}} \phi_{\text{th}} n$$

n = number of Co^{58} atoms per milligram foil

n' = number of Co^{58m} atoms per milligram foil

N = number of Ni^{58} atoms per milligram foil = 6.94×10^{18} atoms Ni^{58} per mg

t = time

'effective' = effective activation cross section determined by neutron spectra calculations as discussed in the following section

σ = activation cross section, Ni^{58} to Co^{58} = 66.3%(9)
effective

σ_m = activation cross section, Ni^{58} to Co^{58m} = 33.7%(9)
of effective

σ_f = average fast flux

λ_1 = disintegration constant for Co^{58m} = 1.85 day^{-1}

λ_2 = disintegration constant for Co^{58} = $9.72 \times 10^{-3} \text{ day}^{-1}$

σ_1 = absorption cross section, Co^{58m} = 170,000 barns(9)

σ_2 = absorption cross section, Co^{58} = 1650 barns(9)

ϕ_{th} = average thermal flux.

Assuming ϕ_f to be a square wave with a magnitude equal to a constant during each operating period and equal to zero during each shutdown one can obtain the following:

$$\phi_f^{t_{\text{op}}} = \frac{A^*}{\sigma N} \left[(\lambda_2 + \sigma_2 \phi_{\text{th}}) t_{\text{op}} \right] E \left[\sum_{j=1}^m \frac{1 - e^{-(\lambda_2 + \sigma_2 \phi_{\text{th}}) t_{ij}}}{\left(e^{\lambda_2 t_{sj}} \right) \left(e^{\lambda_2 + \sigma_2 \phi_{\text{th}} t_{ij+1}} \right) \left(e^{\lambda_2 t_{sj+1}} \right)} \right]^{-1}$$

where $t_{\text{op}} = \sum_{j=1}^m t_{ij}$ is the total operating time

$j = 1, 2, 3, \dots, m$ each operating time

t_{ij} = operating time for the j^{th} operating period

A^* = specific activity of foil at time of reactor shutdown, T_0
(Corrected for decay from T_0 to time of counting)

$$E = \frac{\lambda_1 + \sigma_1 \Phi_{th}}{\lambda_1 \sigma_m + (\sigma)(\lambda_1 + \sigma_1 \Phi_{th})} \quad \text{(This term is solved graphically as a function of } \Phi_{th} \text{.)}$$

Fast Flux, $Fe^{54}(n, p) Mn^{54}$

The activation and decay scheme for Mn^{54} production from Fe^{54} is as follows:

The number of Mn^{54} atoms, n , present at any time, t , is found by integration of the following differential equation:

$$\frac{dn}{dt} = \text{number formed} - \text{number disintegrated}$$

$$\frac{dn}{dt} = \sigma N \Phi_f - \lambda n$$

n = number of Mn^{54} atoms per milligram foil

N = number Fe^{54} atoms per milligram foil = 6.36×10^{17} atoms Fe^{54} per mg

t = time

σ = activation cross section, Fe^{54}

Φ_f = average fast flux

λ_2 = disintegration constant for $Mn^{54} = 2.21 \times 10^{-3} \text{ day}^{-1}$

$\sigma_m, \sigma_1, \sigma_2$ are negligible.

The basic equation derived in the same manner as the one for nickel with no $\sigma_{abs} \Phi_{th}$ term, becomes

$$\phi_f^{t_{op}} = \frac{A^*}{\sigma N \lambda_2} \left[\lambda_2 t_{op} \right] \left[\sum_{j=1}^m \frac{1 - e^{-(\lambda_2 t_{ij})}}{e^{\lambda_2 t_{oj}}} \right]^{-1}$$

Fast Flux, Ti^{46} (n, p) Sc^{46}

The activation and decay scheme for the production of Sc^{46} from Ti^{46} is as follows:

The number of Sc^{46} atoms, n , present at any time, t , is found by integration of the following differential equation:

$$\frac{dn}{dt} = \text{number formed} - \text{number disintegrated}$$

$$\frac{dn}{dt} = \sigma N \phi_f - \lambda n$$

n = number of Sc^{46} atoms per milligram foil

N = number of Ti^{46} atoms per milligram foil = 1.01×10^{18} atoms
 Ti^{46} per mg

t = time

σ = activation cross section Ti^{46}

ϕ_f = average fast flux

λ_2 = disintegration constant for $Sc^{46} = 8.25 \times 10^{-3} \text{ day}^{-1}$

$\sigma_m, \sigma_1, \sigma_2$ are negligible.

The basic equation is the same as that derived for iron

$$\phi_f^{t_{op}} = \frac{A^*}{\sigma N \lambda_2} \left[\lambda_2 t_{op} \right] \left[\sum_{j=1}^m \frac{1 - e^{-(\lambda_2 t_{ij})}}{e^{\lambda_2 t_{oj}}} \right]^{-1}$$

Thermal Flux. $\text{Co}^{59} (n, \gamma) \text{Co}^{60}$

The activation and decay scheme for the $\text{Co}^{59} (n, \gamma) \text{Co}^{60}$ reaction is:

The number of Co^{60} atoms, n , present at any time, t , is found by integration of the following differential equation:

$$\frac{dn}{dt} = \text{number formed} - \text{number disintegrated} - \text{number burned out}$$

$$\frac{dn}{dt} = \sigma N \Phi e^{-\sigma_a \Phi t} - n(\lambda_2 + \sigma_2 \Phi) + \sigma_m N \Phi (e^{-\sigma_a \Phi t} - e^{-\lambda_1 t})$$

n = number of Co^{60} atoms per milligram of foil

N = number of Co^{59} atoms per milligram of foil = 1.022×10^6 atoms Co^{59} per mg

t = time

σ = activation cross section Co^{59} to Co^{60}
= activation cross section Co^{59} to Co^{60m}

$$\sigma_a = \sigma + \sigma_m = 36 \text{ barns}$$

Φ = average thermal (cobalt) flux

$$\lambda_1 = \text{disintegration constant } \text{Co}^{60m} = 95 \text{ day}^{-1}$$

$$\lambda_2 = \text{disintegration constant } \text{Co}^{60} = 3.61 \times 10^{-4} \text{ day}^{-1}$$

$$\sigma_2 = \text{absorption cross section } \text{Co}^{60} = 6 \text{ barns}$$

$$\sigma_1 = \text{absorption cross section } \text{Co}^{60m}.$$

Due to the relatively long half life of Co^{60} , the t_{ij} terms may be summed to a t_i term and the equation becomes:

$$\Phi_{th} t_{op} = \left[\frac{A * e^{\lambda_2 t}}{\sigma_a N \lambda_2} \right] \left[\frac{\lambda_2 + (\sigma_2 - \sigma_a) \Phi t}{e^{-\sigma_a \Phi t} - e^{-(\lambda_2 + \sigma_2 \Phi) t}} \right].$$

The equation can be simplified to the following if the Co^{59} and Co^{60} burnup corrections are not made:

$$\phi_{\text{th op}}^t = \left[\frac{A^* e^{\lambda_2 t}}{\sigma_a N \lambda_2} \right] \left[\frac{\lambda_2 t}{1 - e^{-\lambda_2 t}} \right].$$

This gives a thermal flux that is approximately 5% low. (21)

C. COMPUTER PROGRAM

All exposure calculations from monitor foils contained in the capsules through H-3-5 were made on a desk calculator using the previous equations. At the time of irradiation of the H-3-6 capsule a computer program was made available to perform this calculation, and this program⁽²²⁾ has been used for calculation of exposures since that time. The program uses the same equations for the fast flux calculations with the exception that the summation term is taken as one operating period and no shutdowns are accounted for. The ratios of the fluxes calculated for the three monitor materials without corrections for reactor shutdown are presented in Table B-I.

TABLE B-I
FLUX RATIOS^(a)

<u>Days Used in Computation^(b)</u>	<u>Nickel</u>	<u>Iron</u>	<u>Titanium</u>
Effective days at power	0.88	0.92	0.90
Operating days	0.92	0.95	0.94
Total days including shutdowns	0.96	0.99	1.01
Adjusted total days including shutdowns	1.00	0.99	1.01

(a) Ratio of flux calculated without reactor shutdown correction to the shutdown corrected flux.

(b) For nonshutdown calculation

D. NEUTRON SPECTRA CALCULATIONS

The effective neutron cross sections used in the above calculations are obtained by use of a computer computation. The reactor spectrum for the E7 testing position, shown in Figure 17, is calculated by the 2DXY

computer code.⁽¹²⁾ A grid spacing of 1 x 1 in. is used for the entire GETR core, and the results give the neutron flux as a function of space and energy.

The effective cross section is computed by averaging the energy-dependent activation cross section, $\sigma(E)$, for the monitor, over the calculated spectra. The effective cross section, σ_{eff} , is given by

$$\sigma_{\text{eff}} = \frac{\int_0^{10 \text{ MeV}} \Phi(E) \sigma(E) dE}{\int_{0.18 \text{ MeV}}^{10 \text{ MeV}} \Phi(E) dE}$$

where $\Phi(E)$ is the flux distribution.

E. EXPOSURE CALCULATIONS

The effective cross section from the above computation is used in conjunction with the equations given in Section B to determine the neutron exposure at each flux monitor location. Relative flux intensities from the computation are then used to determine the neutron exposure at the graphite sample. Results from the monitors irradiated in the H-3-6 capsule are shown in Table B-II.

TABLE B-II

NICKEL AND IRON FLUX MONITOR RESULTS

Location(a) of Monitor in Capsule	Effective Cross Section. mb		Neutron Exposure ^(b) H-3-6 Capsule nvt x 10 ⁻²¹ , E > 0.18 MeV	
	E7 Position			
	Ni ⁵⁸	Fe ⁵⁴	Ni	Fe
NW	80.3	51.4		1.40
N	76.4	48.9	1.41	
NE	81.1	51.9		
E	83.0	53.2	1.38	
SE	81.0	51.8		
S	76.2	48.8		1.42
SW	80.2	51.4	1.40	
W	82.6	52.9		1.41
C	80.3	51.4		1.40

(a) 1 x 1 in. grid location as set up for the 3 x 3 in. E7 position

(b) Exposure at the center (graphite sample) determined from monitors located in the listed positions

As shown in the table the effective cross section for the E7 position varied by a maximum of 9% while the neutron exposure varied by only 3%.

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