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**REACTOR PHYSICS STUDIES IN THE
GCFR PHASE III CRITICAL ASSEMBLY**

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

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REACTOR PHYSICS STUDIES IN THE
GCFR PHASE III CRITICAL ASSEMBLY

Edited by

J. A. Morman

Applied Physics Division

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March 1980

PREFACE

The GCFR Program described herein was planned jointly by ANL and the General Atomic Company. R. Moore and A. Hess of General Atomic were instrumental in planning the GCFR/ZPR program and in the exchange of information and suggestions during the course of the program. The results reported here are compiled from a series of internal memoranda based on the efforts of the following persons during the program: R. G. Bucher, M. M. Bretscher, R. D. McKnight, J. A. Morman, I. K. Olson, R. B. Pond, W. R. Robinson, D. M. Smith and D. C. Wade.

Design and implementation of the special equipment needed during the program, especially steam simulation materials and the special voided/steam-filled calandria, was provided by E. F. Groh and his staff of machinists.

Operational support for the ZPR-9 facility was provided by G. K. Rusch, F. H. Martens, and the supervisors and operators of ZPR-9.

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REACTOR PHYSICS STUDIES IN THE
GCFR PHASE III CRITICAL ASSEMBLY

edited
by

J. A. Morman

ABSTRACT

The third phase of the gas cooled fast reactor (GCFR) program, ZPR-9 Assembly 30, is based on a multi-zoned core of PuO_2 - UO_2 with radial and axial blankets of UO_2 . Studies performed in this assembly will be compared to the previous phases of the GCFR program and will help to define parameters in this power-flattened demonstration plant-type core.

Measurements in the Phase III program included small sample reactivity worths of various materials, central reaction rates and reaction rate distributions, absorption-to-fission ratios and the central point conversion ratio and the worth of steam entry into a small central zone. The reactivity change associated with the construction of a central pin zone in the core and axial blanket was measured. Reaction rate and steam entry measurements were repeated in the pin environment.

Standard analysis methods using ENDF/B-IV data are described and the results are compared to measurements performed during the program.

1. THE GCFR PHASE III ASSEMBLY

A. Introduction

The GCFR Phase III assembly is the third in the series of critical assemblies in support of the gas cooled fast reactor design. The assembly was constructed in the ZPR-9 facility at Argonne, Illinois and was designated as Assembly 30. The objective of this final phase of the program was to characterize a multi-zoned GCFR core of varying enrichments in preparation for a possible future Engineering Mockup Critical of the 300 MWe GCFR Demonstration Plant. Also, the effects of the loading environment were studied by measuring central reaction rates, foil reaction rate traverses, and steam zone reactivity worths in both a normal plate and a central pin zone loading.

This report contains the detailed description of the Phase III reference assembly and the pin zone loading, along with the results of the measurements performed in both the plate-loaded configuration and pin-loaded zone. Calculational techniques are described and analytical results are compared to the measurements. The results reported here include ZPR-9 operational measurements, the approach-to-critical, small sample reactivity worths, central reaction rates and reaction rate distributions in plate and pin environments, absorption-to-fission ratios and the central point conversion ratio and the worth of steam entry into a small central zone for both plate and pin environments. Some comparisons with results from Phases I and II of the GCFR program^{1,2,3} are also included.

B. Description of the Reference Assembly

The GCFR Phase III assembly contains a multi-zoned core more characteristic of the 300 MWe Gas Cooled Fast Reactor Demonstration Plant than previous GCFR assemblies in the ZPR series. The plutonium enrichment in the outer zones is increased in order to provide a flatter power distribution in the core. Figure I-1 shows the configuration of the radially zoned core. The enrichments* in Zones I, II, and III were 13.1%, 17.3%, and 25.5%, respectively. Figure I-2 shows the radial and axial dimensions of the assembly. The core height is 122.08 cm (48.06 inches); the height-to-diameter ratio is 0.86. The axial and radial blanket thicknesses are 30.48 cm (12 inches) and 28.99 cm (11.4 inches), respectively. The reactor is surrounded by a stainless steel reflector, ~6-in. thick.

All unit cell structures, drawer masters, and matrix loading configurations introduced below are the stationary-half diagrams; the corresponding movable-half diagrams are the mirror images.

The unit cell loadings for the zone I core and axial blanket are given in Fig. I-3. Core zone II consists of a three-drawer unit cell identical to the Phase II core loading. The axial blanket loading is, however, slightly modified from the Phase II blanket in order to make the average composition of all Phase III axial blanket zones nominally the same. The unit cell structures for zone II are shown in Fig. I-4. The core and axial blanket

---

*Enrichment denotes the ratio of the fissile plutonium ($^{239}\text{Pu} + ^{241}\text{Pu}$) atom density to the heavy metal (all Pu and U) atom density.

loadings for zone III, presented in Fig. I-5, are symmetric, single-drawer unit cells. All three core and axial blanket zones have a void fraction of approximately 43 v/o. The Phase III radial blanket, shown in Fig. I-6, is identical to the Phase II loading with a void fraction of 37 v/o. The radial and axial reflectors consist of stainless steel blocks as shown in Fig. I-7.

The void columns in the core and axial blanket loadings for each zone are aligned so as to maintain the axial streaming paths throughout the assembly. However, void columns in adjacent zones are not, in general, aligned. Vertical streaming paths are therefore disrupted at zone and region interfaces as shown in Fig. I-8.

The stationary-half drawer masters for the core and axial blanket of each zone and for the radial blanket and reflector are shown in Figs. I-9 through I-15. The homogeneous atom densities for each region are presented in Table I-1. Due to limited availability of specific fuel-plate sizes, core zone III is composed of 3 drawer types. The type 1 drawer master is represented in Fig. I-13, and types 2 and 3 differ only in the lengths of the individual fuel plates. The zone III atom densities in Table I-1 are the weighted averages for the zone. The atom densities, the fuel plate loading, and the number per half for each zone III drawer type are given in Table I-2.

Each radial blanket matrix tube has two drawers -- a front drawer containing a 24-in. loading of blanket material, and a back drawer containing the last 12 inches. An approximate 3/8-in. gap between the two sections of radial blanket loading contains the drawer ends and a leaf spring to prevent the front 24-in. of the loading from shifting. The back 12 in. is held in position by a 1/4-in. high by 2-in. wide stainless steel column positioned against the plate ends and lying along the bottom of the back drawer.

The radial reflector is composed of stainless steel blocks loaded to an axial half-height of 36 in. in the standard 36.25-in. long stainless steel drawer. The axial reflector stainless steel blocks are loaded directly in the matrix tubes behind the core-plus-axial-blanket drawers. A gap of approximately 1/4 in. between the blanket and reflector contains the drawer end and leaf spring. No axial reflector is loaded behind the radial blanket.

The stationary-half matrix loading established for the GCFR Phase III reference configuration is given in Fig. I-1. The drawer types for zones II and III are specified for the lower portion of the assembly half. Zone II drawers in the same vertical column are of the same type and the zone III drawer pattern in the upper half is a reflection of that for the lower half. Each zone or region boundary is symmetric about both the horizontal and vertical axes and also about a set of axes rotated 45° with respect to these. However, the asymmetric zone II drawer loading destroys the quarter-core symmetry of the assembly.

Also indicated in Fig. I-1 are the locations of the experimental thermocouple drawers (T) and the operational fuel rods and ¹⁰B blades. Fuel rod positions that are not symmetric about the assembly midplane are marked with an S (for stationary half only) or an M (for movable half only).

Table I-3 contains a summary of the number of drawers per half, the corresponding equivalent radius calculated by preserving cross-sectional area, and the fissile plutonium mass for each zone or region. Figure I-2 illustrates the RZ geometry of the reference configuration. The 61.04 cm core half-height includes the 32-mil thick stainless steel drawer front.

C. Description of the Pin Zone Assembly

The final configuration in the GCFR program consisted of a central pin zone loaded within zone I of the multi-zoned GCFR Phase III assembly. The pin zone provided a close compositional match with the zone I plate loading but afforded markedly different heterogeneity and streaming characteristics. The limited experimental program in the Phase III pin zone assembly included the following measurements:

1. eigenvalue of the reference assembly,
2. central cavity measurements of fission rates for ^{239}Pu , ^{235}U , and ^{238}U and of ^{238}U capture,
3. unit cell reaction rates for ^{239}Pu , ^{235}U , and ^{238}U fission and ^{238}U capture,
4. axial fission rate distribution for ^{239}Pu , and
5. worths of central 5×5 drawer (simulated) steam-filled pin zones of incremental axial half-heights.

The pin zone, loaded within zone I of the GCFR Phase III assembly, was composed of 85 matrix locations per half, corresponding to an equivalent radius of 28.74 cm. The central 5×5 locations contained special calandria into which CH_2 foam could be loaded, and the remaining 60 locations contained the normal sodium-voided calandria. The matrix configuration for the pin zone reference assembly is shown in Fig. I-16. The zone and region boundaries are identical to those of the plate geometry Phase III reference configuration (Fig. I-1) except for the zone III/radial blanket boundary. Locations S/M-12/17 and S/M-34/17 were zone III, type 3 core-plus-axial-blanket drawers in the plate reference but were radial blanket drawers in the pin zone reference.*

The central 5×5 locations in the pin zone were loaded with calandria specifically designed for the pin zone steam entry experiment. Each calandria was composed of a 4×4 array of stainless steel tubes, 12 inches in length, supported by two drilled end assemblies and two interior-positioned rectangular grids. Three such special calandria, two loaded with mixed oxide fuel rods (15% PuO_2 and 85% UO_2 , core region) and one with depleted uranium oxide rods (axial blanket region) were placed end-to-end axially in standard 36.25-in. long stainless steel drawers and inserted into the central

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*Matrix locations denoted by I/J refers to row I, column J; S refers to stationary half, and M refers to movable half.

5 × 5 matrix positions. The resulting stainless steel density in the special calandria region was only slightly greater than that in the surrounding normal calandria region.

The masses of the individual special calandria were recorded and accumulated to produce a distribution of calandria masses. An apparently significant variation in the 3/8-in. ID stock stainless steel tubing produced a pronounced double-lobed distribution with approximately 50 calandria peaked about 348.5 grams and approximately 85 calandria peaked about 340 grams. Fifteen additional calandria had masses scattered in the 356 gram to 362 gram region. The calandria were sorted according to mass -- the minor lobe in the distribution being used in the axial blanket region and the major lobe plus the large mass "stragglers" being used in the core region.* The mean special calandria mass in the axial blanket was 348.28 ± 0.10 grams and that for the core was 343.07 ± 0.63 grams.

Table I-4 lists the atom densities for the normal and special calandria in the core and axial blanket regions.

D. Approach to Critical

The experimental procedure for the GCFR Phase III approach to the delayed-critical configuration was basically the source multiplication technique. In this technique the inverse neutron count rate, $1/C$, or equivalently the inverse multiplication, is plotted as a function of some measure of the reactivity, such as the fissile plutonium mass, M_f . Extrapolation of the inverse neutron count rate to zero (corresponding to infinite multiplication) gives an estimate of the critical mass for the assembly. To account for neutrons emitted by the spontaneous fission of ^{240}Pu , an examination of M_f/C vs. M_f has been demonstrated in the earlier GCFR assemblies to be a more reliable, yet conservative, indicator of criticality, as detailed in Ref. 1.

The as-planned GCFR Phase III assembly configuration is outlined in Fig. I-17. The numbers at each location summarize the drawer loading steps in the approach-to-critical. All the inner zone and the dual purpose (DP) rods were included in the first loading step. The approach-to-critical was completed in six loading steps, with a seventh step required to establish the reference configuration shown in Fig. I-1. All fuel loading steps were symmetric about the assembly midplane and, with the single exception of S/M-15/29, were symmetric also about both the horizontal and vertical axes. The correlation between the assembly loading numbers and the approach-to-critical loading step number is given in Table I-5. Also tabulated is the fissile plutonium mass after each loading step. The ^{241}Pu mass is decay-corrected to the date that the reactivity excess of the reference assembly** was measured, 7/1/76. Details of the loading steps are given below.

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*The large mass "stragglers" were placed in the 16 corner positions of the 5 × 5 array and 84 calandria from the major lobe filled the remainder of the central zone. This symmetric loading of the special calandria in the core region was not accounted for in the calculational modeling.

**The reference assembly is characterized by specifying the reference configuration (the assembly geometry) and the operational parameters (excess at reference temperature, power level, etc.).

The Phase III approach-to-critical began with the final subcritical reference configuration of the Phase II steam entry program.³ The Phase II drawers in the region designated as zone I were converted to Phase III, zone I drawers. The ring of Phase II core-plus-axial-blanket drawers that remained became the initial loading of the Phase III, zone II drawers. The axial blanket of the Phase II, type 1 drawers were modified by replacing one 1/8-in. depleted uranium column with uranium oxide. Fuel rod loadings were modified to match the composition of the zone in which they were located and installed in the assembly. Twelve single-bladed ^{10}B rods were also installed. To accommodate the 0.5-in. wide ^{10}B -blade sheaths in the indicated locations, the normal zone I drawer contents, except the 0.5-in void column nearest the ^{10}B blade, were loaded into a special three-quarter width drawer. Finally, the radial reflector was moved outward to its anticipated final location, leaving voided tubes in the outer areas of the radial blanket region. All the above modifications constituted the first step in the approach-to-critical.

For all subsequent steps in the approach-to-critical, the added core drawers replaced radial blanket drawers. These blanket drawers were moved to the voided tubes in the outer radial blanket region. The Phase III, zone II loading was completed in the second loading step. For the additional steps toward criticality, the radial blanket inner-edge drawers indicated in Fig. I-17 were replaced with zone III core-plus-axial-blanket drawers. Pre-analysis calculations for the assembly over-estimated the critical mass, requiring that four radial blanket drawers per half remain within the as-planned zone III region. The final loading step was required to complete the outer radial blanket region, to load additional radial reflector, and to symmetrize the drawer types in core zone III. Fission counters used to accumulate approach-to-critical data were also removed at this time. The resulting reference configuration has been presented in Fig. I-1.

The subcriticality of the assembly during approach-to-critical was monitored by the six reactor operational channels and the two experimental channels, SP-10 and SP-11. Count rate data were also accumulated from ^{235}U fission counters loaded into the axial blanket portion of S/M-23/23. Data were collected at each loading step with all ^{10}B and DP rods in their most reactive and also in their least reactive positions.

The estimated critical masses using the $1/C$ and M_f/C techniques are reported in Tables I-6 and I-7, respectively. These numbers were calculated using the most-reactive configuration data. Estimates for the total rod worth were obtained by subtracting the most-reactive from the least-reactive critical mass estimates.

Plots of $1/C$ vs. M_f and M_f/C vs. M_f for representative detection systems are shown in Figs. I-18 through I-21. Both fission counters (e.g., as shown in Fig. I-18), historically considered to be reliable early indicators of the critical mass, provided extremely low initial estimates while successive steps did yield more consistent results. The data from the experimental and reactor operational channels were quite good. The $1/C$ technique produced the expected conservative critical mass estimates and the M_f/C technique gave more accurate, though generally conservative estimates.

E. Corrections to the Reference Assembly Critical Mass

The reference assembly as shown in Fig. I-1 has a critical mass of 888.1 ± 0.2 fissile kg and an excess reactivity of 214.5 ± 1.7 Ih. A series of corrections was made to the fissile plutonium mass of the reference assembly to obtain the critical mass of a hypothetical zero-excess, delayed-critical, cylindrical assembly. The more significant of these reactivity adjustments corrected for the built-in excess reactivity of the reference configuration, the adjustment of the measured excess to a reference temperature, the source subcriticality at the reference power level due to ^{240}Pu spontaneous fission neutrons, and the reactivity effects due to the stepwise region/zone boundaries. Each of these corrections is discussed in detail in the following paragraphs. The measurements of the experimental quantities used for these analyses are described in Section I.F.

The quoted value of the critical mass of the reference assembly (shown in Fig. I-1), 888.1 ± 0.2 kg, includes only the fissile plutonium isotopes ^{239}Pu and ^{241}Pu . Since ^{241}Pu β^- decays with a half-life of 14.5 years to ^{241}Am , it was necessary to re-evaluate the critical mass of the assembly to reflect this decrease. Consequently, all fuel loading figures quoted in this report are adjusted to the date that the reactivity excess of the reference configuration was measured, 7/1/76.

1. Excess Reactivity and Temperature Correction

The reference Phase III assembly had a built-in apparent excess reactivity of 217.2 ± 1.7 Ih.* This measured excess has been adjusted to correspond to the reference temperature, 25.0°C , through the use of a measured temperature coefficient of -3.00 ± 0.03 Ih/ $^\circ\text{C}$. Based upon the experimental value of the worth of a core edge drawer relative to a radial blanket drawer, the excess reactivity is equivalent to 7.78 ± 0.08 kg of "edge fuel". This reduction in the critical mass would be required for a zero-excess configuration of the Phase III assembly.

2. Source Subcriticality Correction

The spontaneous fission of ^{240}Pu constitutes a built-in neutron source in all plutonium-fueled assemblies. The effect of this source is to make an apparently critical assembly actually subcritical. The magnitude of this effect is given by

$$\Delta k = - \frac{S\ell}{n}$$

where S is the effective neutron source per unit volume, ℓ is the neutron lifetime and n is the neutron density. For ^{240}Pu spontaneous fission, S is equal to 4.30×10^{12} neutrons/sec per gm of ^{240}Pu . The experimental value of the source subcriticality at the reference power level, $\Delta k = -2.7 \pm 0.2$ Ih, translates into an increase in the critical mass of 0.10 ± 0.01 kg. Normally, both the temperature coefficient and source subcriticality are combined with the measured excess and reported as the assembly excess. Thus, the excess of the GCFR Phase III reference assembly is 214.5 ± 1.7 Ih.

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*This value does not include the source subcriticality discussed below.

3. Edge Smoothing Corrections

The actual zone and region interfaces of the reference assembly are not cylindrical boundaries as represented in RZ eigenvalue calculations, but rather step-wise boundaries produced by the drawer-loading geometry.

Consider, for example, the core/radial blanket boundary of the Phase III reference configuration. The radius of a cylindrical core region with an equal-area cross section is readily computed from the expression

$$R_c \text{ (cm)} = [(\text{number of core drawers per half}) \times (5.5245 \text{ cm})^2/\pi]^{1/2}.$$

Both the step-wise and the equal-area circular boundaries are shown in Fig. I-22 for one quadrant of the assembly. Since the reactivity worth of fuel at this interface has a negative radial gradient, the worth of the fuel located outside the circular boundary is less than the worth of the equal quantity of fuel displaced from inside the circular boundary. Consequently, a calculated smoothing of the core/radial blanket boundary would increase the excess of the as-built assembly and thus reduce the zero-excess critical mass.

A numerical algorithm was coded to calculate the reactivity worth of the edge-smoothing correction. The radial dependence of the edge core drawer worth was assumed to be that given by the preanalysis value for the axially-averaged worth distribution of Pu fuel at the core/radial blanket interface. This radial dependence was then normalized to the experimental value of the core edge-drawer worth of 36.9 ± 0.3 lh/drawer, at the mean radial position of 69.22 cm. The resulting radial gradient was 0.74 lh/drawer per cm. The numerical routine divides the regions between the step-wise and circular boundaries into a grid of approximately square elements. The worth of each element is calculated relative to the equal-area circular boundary and summed over all elements. Since the circular boundary is an equi-reactivity line, this sum is the net worth of the edge-smoothing effect. The numerical calculation for one quadrant of the reference assembly (full core height) computed that 2.47 drawers displaced a mean distance of 1.94 cm produced a reactivity change of 7.12 lh. Assuming a $\pm 10\%$ uncertainty in the value for the radial gradient of the core edge drawer worth, the total edge-smoothing correction for the Phase III reference assembly is 28.5 ± 2.9 lh with a corresponding reduction in the critical mass of 1.02 ± 0.10 kg.

These reactivity corrections and the corresponding adjustments to the as-built critical mass are summarized in Table I-8. Applying these corrections yielded a zero-excess delayed-critical fissile plutonium mass for the Phase III reference assembly operating at 25°C of 879.4 ± 0.2 kg.

F. Operational Measurements

After establishing the reference configuration of the GCFR Phase III assembly, a series of measurements was made to determine operational characteristics of the assembly such as excess reactivity, control rod worths and the temperature coefficient of reactivity. Tables I-9 and I-10 summarize the operational measurements and include some calculated parameters such as the conversion from $\Delta k/k$ to inhours (calculations are discussed in Section II).

1. Measurement of the Reactivity Excess of Reference Assembly

The measured reactivity excess for the GCFR Phase III reference assembly was 214.5 ± 1.7 lh. This figure includes the reactivity adjustments for the assembly temperature and source subcriticality that are discussed below. The quoted excess was determined from two consecutive startups from the complete shutdown configuration. For each startup, the excess was measured by positioning the 10B rod at M-19/30 full in, the DP rod at S-15/20 full out, and controlling on the DP rod at S-27/26.

The uncertainty associated with a single measurement of the reactivity excess for a given configuration is taken to be the sum, added in quadrature, of three components: (1) configuration reproducibility uncertainty, (2) rod calibration uncertainties, and (3) statistical uncertainties of the measurement. Other sources of uncertainty, such as the temperature correction, the ^{240}Pu source correction, and the ^{241}Pu decay correction are less significant and contribute negligibly to the uncertainty of the measured excess. If several independent determinations of the reactivity excess are made, the final uncertainty in the excess is obtained by adding in quadrature the uncertainties from each measurement.

The first of these uncertainties in k_{eff} reflects the difficulties in precisely reproducing the assembly configuration. The major source of this uncertainty is attributed to table closure reproducibility, although errors in positioning the 10B and DP rods in their most or least reactive configurations also contribute. Configuration reproducibility, determined for the Phase III reference assembly from the two excess reactivity measurements results in a value of one standard deviation in the measured excess of 0.7 lh. Consequently, an uncertainty of ± 1 lh was assigned to k_{eff} .

The accuracy of the control rod calibrations (reactivity worth as a function of position) and the control rod worths (reactivity worth at most reactive versus least reactive positions) used to measure the configuration excess represent a second source of possible uncertainty. The mechanical linkages, limit switches, and electro-mechanical position readouts introduce uncertainties during both the rod-worth and configuration-excess measurements. Furthermore, use of high-worth poison (or fuel) control rods may contribute to appreciable distortions in the space- and energy-dependent spectrum, resulting in systematic errors associated with changing detector efficiency. To consider an extreme example, the reactivity excess of the reference configuration, measured with the 10B rod at S-19/30 full-in and controlling on the DP rod at S-16/29, was 220.3 ± 2.6 lh. Thus the effect of using over two hundred inhours of control located in a small section of the assembly was to increase the apparent excess by 5.8 ± 3.1 lh, a significant systematic deviation. Since the rod-worth component of the uncertainty in the measured excess is dependent on the amount of reactivity control that is introduced, it is represented by a percentage of the apparent excess. Experience indicates that a value of 1% is a reasonable first approximation. Obviously, the systematic deviations caused by flux distortions are not included.

The third component of the uncertainty in the measurement of the configuration excess is the statistical uncertainty associated with the measuring process. The repeated measurement of the control rod position and the assembly temperature provides a spread about the mean which reflects this contribution to the uncertainty.

2. Measurement of Temperature Coefficient

In order to compare reactivity excesses measured at different operating temperatures, it is necessary to adjust the measured values to the same reference temperature. A measured temperature coefficient of reactivity is used for this correction, and is equivalent to measuring the excess at the reference temperature. The temperature coefficient was determined for the Phase III reference configuration by measuring the reactivity excess as a function of the assembly temperature. The experimental technique was as follows. After start-up, the assembly was operated at standard power until thermal equilibrium had been reached; at that point the reactor cooling system was shut down and the assembly temperature allowed to rise from 27.5°C to 32°C. The rate of rise, approximately 3.5°C/hr, was sufficiently low so as to roughly maintain thermal equilibrium. No data were accumulated as the assembly temperature was decreasing, since previous GCFR measurements had shown the cooling-down data to be inconsistent with the heating-up data. This inconsistency is attributed to the large void channels in a GCFR assembly allowing the cooling process to proceed too rapidly.

For experimental purposes the assembly temperature was monitored by a network of 16 Copper-Constantan (type T) thermocouples. The thermocouples were positioned at axial heights of approximately 0, 6, 12, and 18 inches from the assembly midplane in each of the matrix locations S/M-29/19 and S/M-17/27. The TC reference junction was maintained at 150°F. A least-squares fit to tabulated millivolt-to-°C conversion values over the range $15 \leq T(^{\circ}\text{C}) \leq 40$ produced the calibration equation,

$$T(^{\circ}\text{C}) = 2.2411584 \times 10^{-2} + 2.5785378 \times 10^{-1} \times R - 6.0465744 \times 10^{-1} \times R^2$$

where R is the thermocouple reading in millivolts plus the reference constant 2.711 mV. The assembly temperature was taken to be the arithmetic mean of the 16 thermocouple temperatures. The reactivity excess of the assembly was determined by recording the position of a calibrated dual purpose rod, and the position data were converted to reactivity excesses using a fourth order fit to the inverse-kinetics calibration data for the rod.

A linear least-squares fit of the measured excess as a function of the assembly temperature established a temperature coefficient of -3.00 ± 0.03 $\Delta k/k$ /°C. The experimental data and the resulting least-squares linear fit are shown in Fig. I-23. The quoted uncertainty is the quantity calculated from the error matrix of the least-squares fitting procedure. The effects of systematic errors in the determination of the temperature and the excess are reduced since only the slope of the linear fit is of interest.

3. Measurement of ^{10}B and DP Rod Worths

The worths of the ZPR-9 ^{10}B and DP control and safety rods are needed in order to satisfy administrative reactivity requirements for each startup. These rod worths were obtained while operating in a critical configuration by scrambling each rod individually from its most reactive position. Flux data were accumulated on the SP-10 and SP-11 channels as a function of time and analyzed using inverse kinetics. The worths of the rods as determined from

the data of each detection system are reported in Table I-10. The worths of the DP rods at S-16/29 and S-27/26 were determined from the rod calibration data using SP-11 only.

The ^{10}B rods at M-30/23, M-16/23, and S-16/23 were dual-bladed rods installed during the Phase III approach-to-critical. A dual-bladed ^{10}B rod is composed of two standard ^{10}B blades separated by a normal 2-in. drawer and a special 3/4-width drawer, a total distance of 11.05 cm center-to-center. The actual positions of the ^{10}B blades are shown in Fig. I-1 and I-17. Additional rods of this design replaced several of the remaining single-bladed ^{10}B rods as the experimental program progressed.

The agreement between the SP-10 and SP-11 results for the DP rod worths is quite good, less than 0.5% discrepancy. The agreement for the ^{10}B rods, though good, shows evidence of systematic errors. These deviations are best illustrated by the sketch in Fig. I-24. The boxes indicate the relative positions of the ^{10}B rods in the stationary and movable halves, and the numbers are the differences (in inhours) between the worths as measured by the two detectors, that is, SP-11 minus SP-10. The boxes labeled SP-11 and SP-10 indicate which detector is above each half of the assembly. The agreement for the three ^{10}B rods in the lower portion of either half of the assembly is very good and does not indicate any systematic trends. However, the worths as determined by SP-11 for the ^{10}B rods in the upper portion of the stationary half are more than the corresponding worths as determined by SP-10, and the converse applies to the movable half. The worths of the ^{10}B rods nearest the detectors (that is, in row 16) differ by 2-1/2%. The worths of the ^{10}B rods in row 19, though only disagreeing by 1/2%, definitely reflect systematic errors. These results indicate that a ^{10}B rod inserted in the upper portion of one half of the assembly tends to shield the detector above that half. Though these discrepancies are minor and insignificant in regards to operational measurements, the systematic effect is of consequence to experimental measurements.

The inverse-kinetics analysis of the rod drops also yielded values of the degree of subcriticality prior to the rod drop. This initial subcriticality is caused by the presence of ^{240}Pu spontaneous fission neutrons and is commonly referred to as the source subcriticality. The magnitude of this effect as determined from the ^{10}B rod drops using SP-11 data is 2.7 ± 0.2 Ih at a power level designated as standard for the assembly.

4. Measurement of Edge Drawer Worth

The reactivity worth of a core edge drawer relative to a radial blanket drawer is needed to evaluate the reactivity change associated with a change in the core/radial blanket boundary. This value is not only useful in estimating reactivity effects of loading changes, but also necessary for the experimental steam zone worth measurements. To determine the edge drawer worth, eight symmetrically-positioned type 3, zone III core-plus-axial-blanket drawers were removed from the Phase III reference assembly and replaced with radial blanket drawers. The eight drawers S/M-12/17, -34/17, -12/29, and -34/29 contained 10.61 ± 0.02 kg of fissile plutonium ($^{239}\text{Pu} + ^{241}\text{Pu}$), and each drawer was located 69.22 cm radially from the assembly center. The subcriticality of the assembly was determined from the SP-10 and SP-11 data

for three rod drops to be -81.0 ± 1.4 Ih. Each rod drop consisted of a single-bladed ^{10}B rod scrambled from its most reactive configuration. The worth of a core edge drawer relative to a radial blanket drawer is thus 36.9 ± 0.3 Ih/drawer, or 27.9 ± 0.2 Ih/kg of fuel at the edge of the core.

5. Determination of ^{241}Pu Decay Coefficient

The ^{241}Pu in the core, representing approximately 1-1/4% of the fissile plutonium mass, decays by β^- emission with a half-life of 14.5 years to ^{241}Am . Consequently, there is a decrease in the excess reactivity of the reference configuration as the experimental program progresses. Because of the rather large uncertainty associated with a single measurement of the reactivity excess and of the short Phase III experimental program, it would have been difficult to measure the decay coefficient with any confidence.* Consequently, a calculated value of 0.12 Ih/day was established as the ^{241}Pu decay coefficient. The details of the calculation are presented in the discussion of the RZ analysis model.

II. CALCULATIONAL METHODS

A. Introduction

The calculational methods used for the analysis of the GCFR Phase III assembly are presented below. The half-height RZ and quarter-core XY two dimensional calculations of the reference configuration are based on 29-group diffusion theory with Benoist anisotropic diffusion coefficients. The space- and energy-independent transverse buckling of the XY model was chosen so that the XY and RZ models produced the same eigenvalue. The cross sections were generated using the ENDF/B-IV data base and the ETOE-II/MC²-2/SDX cross section processing codes,⁴⁻⁶ accounting for spatial and energy self-shielding.

B. Generation of Atom Densities

Atom densities for the analysis of the Phase III assembly were generated from the standard ZPR materials inventory data. Heterogeneous or "plate" number densities represent the physical density of the plate materials and are used in the cross section shielding calculations. The homogeneous or "cell-averaged" atom densities listed in Table I-1 are used in the diffusion theory calculations. A set of "stretched plate" number densities were generated by assuming that all plates were stretched to the full height of the unit cell, 2.175 in., for the calculation of directional diffusion coefficients. The stainless steel from the matrix tube top and bottom, drawer bottom, fuel plate cladding ends, etc., was distributed into the plates in the

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*The attempt to experimentally determine the ^{241}Pu decay coefficient was abandoned when the digital voltmeter that reads the experimental thermocouples failed. The replacement DVM, though compatible, was not intercalibrated with the initial unit, producing a discrete shift in the measured assembly temperature.

one dimensional representation of the unit cell.⁷ In each set of atom densities, the trace elements Cu, P, S and Co were added to Fe while C, Si and Al were added to O.

Atom densities for the normal calandria core and axial blanket unit cells as well as the special calandria unit cells were also calculated using standard ZPR materials inventory data. The mean special calandria mass for the specific region was used, and calculational techniques were consistent with those used to generate plate atom densities. The resulting pin zone atom densities are listed in Table I-4 where it can be seen that only the atom densities for the components of stainless steel differ for the special versus normal calandria. For comparison, the atom densities for the Phase III zone I plate-geometry unit cell are also included in Table I-4.

The composition match for the fissile and fertile isotopes in the plate-loaded and pin-loaded core unit cells is quite good. The atom densities for the components of stainless steel show greater deviations but are, on the whole, well matched. The plutonium oxide/depleted uranium oxide rods do not contain molybdenum. The atom densities for the axial blanket region contain significant deviations for both the fertile and structural isotopes.

C. Broad-group Cross Sections

The 29 broad-group, flux-weighted cross section set for the Phase III analysis was generated from ENDF/B Version IV data using the ETOE-2/MC²-2/SDX cross-section processing codes.⁴⁻⁶ The 226 fine-group base library input to the SDX calculations was initially generated by MC²-2 for the critically-buckled, homogenized GCFR Phase I unit cell. An additional MC²-2 calculation for the stainless steel reflector was made to add energy self-shielded reflector cross sections to this base library. The thermal group cross sections represented ENDF/B version III rather than version IV data and were 2200 m/sec values. The SDX calculations were set up to generate three types of broad-group cross sections -- "self-shielded", "detector", and "plate."

1. "Self-shielded" cross sections include the effects of plate spatial self-shielding and resonance energy self-shielding in such a way that cell-averaged reaction rates are correctly predicted using a diffusion theory model in which the unit cell composition is homogenized.

2. "Detector" cross sections, which do not include the plate spatial self-shielding effects, correctly predict infinitely-dilute, spatially-homogeneous detector reaction rates in the diffusion theory model.

3. "Plate" cross sections are used in the generation of Benoist anisotropic diffusion coefficients.

Radial and axial (one dimensional) SDX calculations produced broad-group cross sections for each unit cell composition collapsed over appropriate asymptotic and/or transition fine-group spectra. The twelve unit cell compositions and associated alphanumeric labels are:

- A - Core Zone I Unit Cell
- B - Core Zone II Three-Drawer Unit Cell
- 1 - Core Zone II Drawer Type 1
- 2 - Core Zone II Drawer Type 2
- 3 - Core Zone II Drawer Type 3
- C - Core Zone III Drawer Type 1 Unit Cell
- 4 - Core Zone III Drawer Type 2 Unit Cell
- D - Radial Blanket Unit Cell
- E - Axial Blanket Zone I Unit Cell
- F - Axial Blanket Zone II Three-Drawer Unit Cell
- G - Axial Blanket Zone III Unit Cell
- R - Reflector Unit Cell.

The core and axial blanket zone II three-drawer unit cells were the models developed for the Phase II analysis.² The eleven spectrum-collapse regions and associated alphanumeric labels are:

- A - Asymptotic Core Zone I
- B - Outer Core Zone I
- C - Core Zone II
- D - Core Zone III
- E - Core Near Axial Blanket
- F - Radial Blanket Near Core
- G - Asymptotic Radial Blanket
- H - Axial Blanket Near Core
- I - Asymptotic Axial Blanket
- R - Radial Reflector
- S - Axial Reflector.

The broad-group energy/lethargy structure, the same as used in both the Phase I and Phase II analyses, is tabulated in Table II-1.

"Self-shielded" and "detector" cross sections were generated for each isotope in the unit cell composition in each appropriate spectrum-collapse region. "Detector" cross sections were also generated for infinitely-dilute, spatially-uniform "trace" isotopes in each core and blanket unit cell composition and associated spectrum-collapse region. The trace isotopes were:

H	⁹ Be	²³ Na	¹⁸¹ Ta
³ He	¹⁰ B	Si	²³² Th
⁴ He	¹¹ B	²⁷ Al	²³³ U
⁶ Li	¹² C	¹⁵¹ Eu	²³⁴ U
⁷ Li	¹⁴ N	¹⁵³ Eu	²³⁶ U.

The five principle plutonium isotopes plus ^{241}Am and Mo were included as trace elements in the radial and axial blanket regions. "Plate" cross sections were calculated only for the heavy metal plates in each unit cell of the assembly and for the isotopes ^{239}Pu , ^{240}Pu , ^{241}Pu , ^{241}Am , ^{235}U , and ^{238}U .

Cross sections for the pin zone were generated with ENDF/B-IV data using the standard processing codes described above. An axial SDX calculation produced broad-group cross sections for the core and axial blanket special calandria unit cells collapsed over asymptotic and transition spectra. The four unit cell, spectrum-collapse regions are:

- PA - Special Calandria Asymptotic Core
- PE - Special Calandria Core Near Axial Blanket
- QH - Special Calandria Axial Blanket Near Core
- QI - Special Calandria Asymptotic Axial Blanket,

where the unit cell composition labels are defined as

- P - Special Calandria Core Unit Cell
- Q - Special Calandria Axial Blanket Unit Cell.

D. Benoist Anisotropic Diffusion Coefficients

In ZPR assemblies of a gas cooled fast reactor design, the coolant channels are simulated with air-filled "void cans." Within a given unit cell these "void cans" align to form essentially-voided vertical planes that pass axially through the unit cell (see Figs. I-9 to I-15). The existence of these streaming paths required the use of anisotropic diffusion coefficients. Energy-dependent Benoist modifiers⁸ were generated for directions parallel, $M_{\parallel}$, and perpendicular, $M_{\perp}$, to the streaming channels. Using the normal isotropic diffusion coefficient, $1/3\Sigma_{tr}$, and the Benoist modifiers, the anisotropic diffusion coefficients for directions parallel to the void slots are

$$D_{\parallel} = M_{\parallel}/3\Sigma_{tr}$$

and for the direction perpendicular to the slots are

$$D_{\perp} = M_{\perp}/3\Sigma_{tr}.$$

In RZ geometry diffusion theory models, the radial direction coefficients are taken to be the average of the two directions,

$$D_R = (M_{\perp} + M_{\parallel})/6\Sigma_{tr}.$$

The broad-group Benoist modifiers were generated for seven plate-loaded unit cell, spectrum-collapse region combinations:

- AA - Asymptotic Core Zone I Unit Cell
- BC - Core Zone II Three-Drawer Unit Cell
- CD - Core Zone III Drawer Type I Unit Cell
- DG - Asymptotic Radial Blanket Unit Cell
- EI - Asymptotic Axial Blanket Zone I Unit Cell
- FI - Asymptotic Axial Blanket Zone II Unit Cell
- GI - Asymptotic Axial Blanket Zone III Unit Cell.

The two-character alphanumeric label indicates, respectively, the unit cell composition and the spectrum-collapse region. Although generated for a specific collapse region within the unit cell, the resulting anisotropic diffusion coefficients were applied to the entire zone or region. The 29-group Benoist modifiers, M_{I} and M_{II} , are listed for each plate zone or region in Tables II-2 and II-3.

Broad-group Benoist diffusion coefficient modifiers were generated for the special calandria asymptotic core (PA) and axial blanket (QI) regions. The zone I plate- and pin-geometry Benoist modifiers, M_{Z} and M_{R} are tabulated in Table II-4. A much smaller degree of anisotropy in the diffusion coefficients is evidenced for the pin case.

E. The RZ Model and the Eigenvalue of the Reference Configuration

The cylindrical version of the Phase III plate-loaded reference configuration given in Fig. I-2 was represented for calculational purposes by the RZ model shown in Fig. II-1. The solid lines, other than the R and Z axes, indicate composition boundaries. The dashed lines distinguish the spectrum-collapse regions within a given composition. A two-character label identifies each area. The first character indicates the unit cell composition, and the second, the spectrum-collapse region -- both according to the labeling convention defined above. A mesh spacing of approximately 2 cm was maintained in the core and blanket regions in both the R and Z directions. A homogenized matrix tube composition, MT, filled the remainder of the cylindrical assembly except for the region behind the radial blanket. In this region the drawer and additional stainless steel that are required to position the back 12 in. of the radial blanket is included in the composition labeled MT'. Logarithmic boundary conditions, with an extrapolation distance of $0.71 \lambda_{\text{tr}}$ were applied to the R and Z exterior boundaries, and symmetry required that zero-current boundary conditions be used at the R and Z axes.

The three-drawer unit cell cross sections were used in the zone II core and axial blanket regions. Core zone III used the broad-group cross sections for the type 1 drawer, but the composition was the drawer-weighted average for the zone as reported in Table I-1. Reflector cross sections were used in the matrix tube regions.

The anisotropic diffusion coefficients in the Z direction were the products of the isotropic D's and the Benoist multipliers, $M_{\parallel}$, for the appropriate region and broad group. The anisotropic diffusion coefficients in the R direction were the products of the isotropic D's and the average of the appropriate Benoist multipliers in the parallel and perpendicular directions, that is, $(M_{\parallel} + M_{\perp})/2$. Isotropic diffusion coefficients were used in both the reflector and matrix tube regions.

The Phase III eigenvalue calculated using the RZ model with Benoist anisotropic diffusion coefficients is 0.9856. Using isotropic diffusion coefficients in the RZ model produced an eigenvalue of 0.9990, corresponding to a δk due to streaming of -1.34%. The RZ calculations of the GCFR Phase II reflected assembly² produced a with-streaming eigenvalue of 0.9994 and a δk due to streaming of -1.53%. Although the δk 's due to streaming are in reasonable agreement for the two assemblies, the Phase III eigenvalue has a rather large negative bias relative to that for Phase II. The following possible sources of the bias were investigated:

- a) disruption of the vertical streaming paths at zone and region boundaries,
- b) selection of reflector cross sections,
- c) reflection from ZPR structural material, and
- d) arrangement of transition regions in the RZ model.

The results are discussed below.

As pointed out in the description of the Phase III reference assembly and as illustrated in Fig. I-8, the vertical streaming paths are disrupted at zone interfaces, requiring a decrease in the radial anisotropic diffusion coefficients. Although the decrease in the radial Benoist multipliers cannot be calculated, the upper limit on the magnitude of this effect can be established by assuming isotropic diffusion coefficients in the radial direction for all regions in the assembly. The eigenvalue calculated using the RZ model with axial streaming only is 0.9916, corresponding to a δk due to axial streaming of -0.74%; the δk due to radial streaming is therefore -0.60%. Consequently, the increase in k_{eff} due to the disruption of the vertical streaming paths at all zone or region boundaries in the assembly must be less than 0.60%. Since the physical decrease in radial streaming is greater in the narrower zones, the impact on k_{eff} was computed for zones II and III individually. Using an RZ model with isotropic radial diffusion coefficients in the zone II core and axial blanket produced a δk due to radial streaming in zone II of 0.17%. Similarly, a δk due to radial streaming in zone III was calculated as 0.15%.

The use of asymptotic blanket cross sections in the reflector regions, rather than the specifically-generated reflector cross sections, increased k_{eff} by 0.09%. Blanket cross sections have normally been used in the reflector regions for previous GCFR analyses.

Reflection from the radial and axial ZPR structural components, most notably the bed and knees, was scoped by filling the unoccupied regions of the assembly with reflector composition. This corresponded to a 160% increase in the thickness of the radial reflector and a 100% increase in that of the axial reflector. The change in the eigenvalue was 0.14%, with the radial portion of this increased reflector accounting for 0.09%.

The arrangement of the core zone I transition regions were altered such that the outer core zone I (region AB in Fig. II-1) extended the full 61 cm half-height of the core rather than only 40 cm. Consequently, the zone I core-near-axial-blanket (AE) region was located only behind the asymptotic core zone I (AA). No change (0.00%) in k_{eff} was calculated. In summary, none of these model variations produced a significant change in k_{eff} .

F. Kinetics Parameters and the ^{241}Pu Decay Coefficient

The GCFR Phase III kinetics parameters were generated using the RZ model for the three streaming cases introduced above -- with streaming, with axial streaming, and without streaming. The values are summarized in Table II-5. The delayed neutron fractions, expressed as a function of family and isotope, and the effective decay constants are reported for the with-streaming case in Table II-6. The decay constants are given in Table II-7 as a function of family and isotope.

The ^{241}Pu decay coefficient for Phase III was calculated using the with-streaming RZ model of the reference assembly. For each zone the ^{241}Pu atom densities were decreased by 1%, this decrease being added to the ^{241}Am atom densities. Using the 14.5 year half-life for ^{241}Pu , a 1% decay corresponds to 76.8 days. The decrease in the eigenvalue associated with these changes in compositions was 0.0099%, with a k_{eff} convergence criterion for each RZ calculation of 0.0001%. The resulting calculated ^{241}Pu decay coefficient was 0.12 1h/day. Since the data available on the materials library inventory as given in Table I-1 reflect the plutonium isotopic concentrations on 7/1/75, the ^{241}Pu number densities in the physical reference assembly (7/1/76) are approximately 5% less than the values used in the analysis. The calculated ^{241}Pu decay coefficient can be used to adjust the value of k_{eff} computed for the RZ model to more accurately reflect the composition on the day the reference assembly was defined. This adjustment to the calculated k_{eff} was 0.05% -- on the order of the δk 's associated with the model variations discussed above.

G. The RZ Model and Eigenvalue of the Pin-Loaded Reference Configuration

The RZ calculational model of the GCFR Phase III pin zone reference configuration is given in Fig. II-2. The two-character alphanumeric label identifies each area according to the notation defined above. The solid lines, other than the R and Z axes, indicate composition boundaries. The dashed lines distinguish the spectrum collapse regions within a given composition. The pin zone, as indicated by the dotted/dashed line, is composed of the central 5×5 special calandria zone and the outer 60-drawer-per-half normal calandria zone. The pin zone cross sections, though collapsed specifically for the special calandria composition, were also used in the normal calandria zone. However, the number densities in the two zones represent the actual special or normal

calandria values. In addition, the Benoist diffusion coefficient modifiers generated for the special calandria asymptotic core and axial blanket unit cells were also applied to the special calandria transition regions and to the normal calandria asymptotic and transition regions.

Other zones of the RZ calculational model are identical to those of the plate-geometry reference configuration model, except for the zone III/radial blanket boundary which has been reduced to reflect the removal of two edge core drawers per half. A mesh spacing of approximately 2 cm was maintained in the core and blanket regions in both the R and Z directions. Logarithmic boundary conditions, with an extrapolation distance of $0.71 \cdot \lambda_{tr}$, were applied to the R and Z exterior boundaries. Symmetry required that zero current boundary conditions be used at the R and Z axes.

The eigenvalue for the RZ model of the pin zone reference configuration, calculated using 29-group diffusion theory with Benoist diffusion coefficients, was 0.98455. The use of isotropic diffusion coefficients in the pin zone only produced an eigenvalue of 0.98511, or a δk due to streaming in the pin zone of -0.056%.

H. The XY Model of the Plate-Loaded Reference Configuration

The matrix loading configuration for the Phase III reference assembly given in Fig. I-1 was represented for calculational purposes by the quarter-core XY model shown in Fig. II-3. As with the RZ model, a two-character alphanumeric label identifies each area. The first identifies the unit cell composition, and the second the spectrum-collapse region, both according to the labeling convention given above. A cross-sectional area equivalent drawer loading pattern was defined for the asymptotic core zone I and asymptotic radial blanket region. A homogeneous matrix tube composition filled the unoccupied assembly perimeter. The mesh spacings in both the X and Y directions are precisely two mesh points per drawer. Logarithmic boundary conditions, with an extrapolation distance of $0.71 \cdot \lambda_{tr}$, were applied to the X and Y exterior boundaries. Symmetry required that zero-current boundary conditions be used at the X and Y axes.

The asymmetric three-drawer loading pattern in zone II does not destroy the quarter-core symmetry of the XY model since the three-drawer unit cell cross sections are used for each drawer type in the zone and since an equal number of each drawer type is present. The three core drawer types in zone III are represented by two cross section sets -- one each for types 1 and 2. The set generated for drawer type 1 is also applied to drawer type 3 (see Section I.B). However, the number densities assigned to each drawer type are the values computed for the specific composition. Reflector cross sections were used in the matrix tube region.

The anisotropic diffusion coefficients in the X direction were the products of the isotropic D's and the Benoist multipliers M_1 ; those in the Y direction were the products of the isotropic D's and M_2 . Isotropic diffusion coefficients were used in both the reflector and matrix tube regions.

The space- and energy-independent transverse buckling, $B^2 = 4.031 \times 10^{-4} \text{ cm}^{-2}$, corresponding to an extrapolated height of 78.24 cm, was selected so that the eigenvalue for the XY model would agree with that for the RZ model.

The XY model calculations were used in analyses of the foil reaction rate and small sample reactivity worth traverses to be described in subsequent sections.

I. Comparison of Plate and Pin Geometry Eigenvalues and Streaming Corrections

As reported above, the eigenvalue for the pin zone reference configuration, computed using Benoist diffusion coefficients in all core and blanket regions, was 0.98455. The δk due to streaming in the pin zone, computed using isotropic diffusion coefficients in the central pin zone, was -0.056%.

The RZ calculational model of the Phase III plate reference configuration was modified in order to compute the corresponding δk due to streaming in plate geometry; the modified RZ model is shown in Fig. II-4. The radius of the asymptotic core zone I, region AA, was increased to equal that of the pin zone. The two areas labeled AE are identical in both cross sections and number densities, but can be assigned different sets of diffusion coefficients. This also applies to the areas labeled EH and EI. The plate reference eigenvalue with Benoist diffusion coefficients in all core and blanket regions was 0.98564. Inserting isotropic diffusion coefficients in the central zone yielded an eigenvalue of 0.98753, corresponding to a δk due to streaming in the plate-geometry central zone of -0.189%.

The calculated streaming in the pin zone is 30% of the value calculated for an equivalent plate-geometry zone. The results of the calculations on the plate and pin zone reference configurations are summarized in Table II-8.

In order to compare the calculated and experimental δk for the plate-to-pin conversion of the central zone, all differences between the two reference configurations must be accounted for. The two differences between the plate reference configuration and pin zone reference configuration, other than the central zone itself, were:

1. the absence of the zone III drawers S/M-12/17 and -34/17 in the pin zone reference configuration and
2. the change in ^{241}Pu and ^{241}Am atom densities due to ^{241}Pu β^- decay.

Consider the experimental determination of the δk for the plate-to-pin conversion outlined in Table II-9. The excess reactivity of the plate reference configuration, ZPR-9 Loading 45/1, was measured on 8/18/76 to be $193.1 \pm 2.2 \text{ Ih}^*$ at 25°C. This is step 1 of Table II-9. The excess reactivity of the pin zone reference configuration, L 48/1, was measured on 8/28/76 to be $12.6 \pm 1.2 \text{ Ih}$ at 25°C. This is step 5 of Table II-9.

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*The matrix configuration for the plate reference, loading 45/1, is identical to that established for the GCFR Phase III reference configuration of Section I. The difference in the measured excess is attributed to ^{241}Pu β^- decay, no intercalibration of the replacement thermocouple DVM, and possible minor variations in the individual plate loadings.

The operationally-motivated differences between the two reference configurations (edge drawer configuration and ^{241}Pu decay) can be corrected through the use of the Phase III operational measurements. The reactivity associated with the two zone III core-plus-axial-blanket drawers per half is four times the operational value of the edge drawer worth, 36.94 ± 0.28 lh/drawer (Step 2 of Table II-9). The four drawers in question constituted half of the drawers removed for the edge drawer worth measurement (the other half were the symmetrically located zone III drawers) and as such remove possible systematics in the measured value.

The reactivity change due to ^{241}Pu decay during the nine-day interval between the reference configurations is nine times the calculated ^{241}Pu decay coefficient, -0.12 ± 0.01 lh/day (Step 3 of Table II-9).

The results of the adjustments yield a hypothetical reactor existing on 8/27/76 which is the pin zone reference configuration just before the replacement of plates by pins (Step 4 of Table II-9). Its excess at 25°C is 44.3 ± 2.5 lh. The difference between this and the excess ($+12.6 \pm 1.2$ lh) of the pin zone is the reactivity change caused by the pin-for-plate replacement in the zone (Step 6 of Table II-9), -31.7 ± 2.8 lh.

This pin-for-plate replacement worth consisted of three components:

- a. the worth due to different zone-averaged compositions between the plate and pin zones,
- b. the worth due to the different heterogeneity effects of the plate and relatively more homogeneous pin unit cells, and
- c. the worth due to the different streaming effects in the plate and pin unit cells.

While these individual components could not be measured, they can be calculated along with the net result of the pin-for-plate replacement. The calculational sequence is outlined in Table II-10 and makes use of the computed eigenvalues displayed in Table II-11.

Starting with the plate reference core whose $k_{\text{eff}} = 0.98564$, the components of a pin-for-plate replacement in the plate reference core are:

composition change	+157.80 lh
heterogeneity change	-250.96 lh
streaming change	+122.63 lh
net change	+29.47 lh.

These components were computed for the plate reference core outer boundary, but are expected to apply as well to the pin reference core outer boundary. Both the plate and pin zone models had ^{241}Pu atom densities adjusted to the same date, 7/1/75, so that no correction was required for ^{241}Pu β^- decay in this comparison of calculations.

Thus, comparing the calculated and measured pin-for-plate replacement worth, it is seen that the calculation slightly overpredicts the net result.

calculated (C)	+29.47	Ih
measured (E)	-31.7	± 2.8 Ih
C-E	61.2	± 2.8 Ih (0.0006 Δk).

In view of the fact that the individual components are two to three times this value, the calculational prediction is taken to be quite good. At present, it is not possible to further determine which of the components is in error.

The data in Table II-11 permit a calculational determination of the edge drawer worth for the pin zone reference core. This computation is shown (Step 6) in Table II-10. The C/E value for edge drawer worth is found to be 0.90, and the C-E is -15.13 Ih.

J. Summary

In summary, the critical mass of the GCFR Phase III plate-loaded reference assembly is 888.1 ± 0.2 kg with an excess reactivity of 214.5 ± 1.7 Ih. This reactivity value includes corrections for the assembly temperature and the source subcriticality, but does not include edge-smoothing effects of the zone/region interfaces. The eigenvalue of the reference assembly calculated using 29-group diffusion theory with Benoist anisotropic diffusion coefficients is 0.9856 with a δk due to streaming of -1.34%.

The calculated eigenvalue of the pin zone reference configuration is 0.98455, with a δk due to streaming in the pin zone of -0.056%.

The change in eigenvalue for the plate-to-pin conversion of the central zone is the sum of the following competing processes:

- 1) the δk due to the compositional changes in the zone,
- 2) the δk_{∞} due to the conversion from plate-to-pin, and the resulting change in spatial plate/pin and energy resonance self shielding, and
- 3) the change in leakage probability due to the different streaming characteristics of plate versus pin geometry.

The magnitudes of each of these effects are several tenths of a percent in $\Delta k/k$, and the algebraic sum of these positive and negative contributions has been shown to agree with experiment to within 0.06% $\Delta k/k$.

III. SMALL SAMPLE WORTHS

A. Introduction

Central reactivity worths and radial reactivity worth traverses were measured in the Phase III plate-loaded assembly. The measurements of the worths were made using the sample-oscillation, reactivity difference technique. In order to examine in detail the worths of materials in a spectrum characteristic of the zone I composition, central reactivity worths were measured for a variety of fissile and fertile isotopes, for scattering, structural and control materials, and simulated steam. Reactivity worth traverse data were accumulated in each of the three core zones and in the radial blanket region. In addition, radial reactivity worth traverses were conducted for ^6Li and ^{252}Cf in order to determine the central core conversion ratio (see Section V).

B. Assembly Configuration

The basic matrix loading configuration for these measurements was the GCFR Phase III plate-loaded reference assembly described in Section I. This reference loading was modified to include the following: (1) the radial insertion hole for the sample changer traverse tube, (2) the fine autorod (FAR), and (3) adjustments to the core zone III/radial blanket interface.

To accommodate the sample changer traverse tube, specially-drilled drawers and materials were loaded into the stationary half of the assembly along row 23, from columns 21 through 43. Although drilled iron oxide plates, depleted uranium oxide plates and stainless steel void cans were loaded into the drawers in these matrix locations, drilled fuel plates were not available. Consequently, no fuel material was loaded into the fuel columns adjacent to the sample changer traverse tube from the axial distances of 1 inch to 3 inches from the assembly midplane. Stainless steel void frames were placed in the fuel columns at 1 to 3 inches to position the remaining fuel plates. The resulting radial insertion hole was 1-1/4 inches in diameter and was vertically centered in row 23, 1-3/4 inches axially from the assembly midplane. The zone II, type 2 drawers in S/M-23/14 were removed and the fine autorod (FAR) installed in this location. To compensate for the reactivity losses accompanying these modifications to the reference assembly, two radial blanket drawers at the core zone III/radial blanket interface (S/M-14/32) were replaced with zone III, type 1 fuel drawers.

The resulting small sample reactivity worth experimental matrix configuration, shown in Fig. III-1, had an excess of approximately 120 lh at 25°C. The control rod configuration during the measurement was as follows: the dual-bladed boron rod at M-30/22-24 was parked at approximately 60% out and the DP rod at S-16/29, being used for control, was positioned near 50 to 55 cm (60 cm is the nominal full-out position.)

C. Experimental Methods

The worths of the sample capsules and the associated dummy (empty) capsules and capsule holders (rabbits) were measured using the sample-oscillation, reactivity difference technique. With this technique the reactivity difference (worth) is obtained by noting the change in the mean equilibrium position of a calibrated autorod as an encapsulated sample is pneumatically oscillated radially in and out of the assembly. The detailed experimental procedure for measuring sample worths has been documented previously.¹⁻³

The samples used in the GCFR Phase III series of worth measurements are described in Tables III-1 and III-2.

The FAR was calibrated using both the oscillation and single-pass techniques, as discussed in Ref. 1. From the oscillation technique, the mean total linear worth of the FAR was measured to be 4.966 ± 0.010 lh. The total linear worth is twice the coefficient of the first order Legendre polynomial resulting from a least squares fit of the FAR worth vs. position data.

The experimental data and reduced data are presented in Tables III-3 through III-6.

D. Calculational Methods

The central reactivity worths and radial reactivity worth traverses were calculated using the RZ and XY models, respectively, of the GCFR Phase III reference assembly. The fluxes and adjoints were generated as described in Section II, and the worths were then calculated using first order perturbation theory with the detector cross sections which simulate an infinitely dilute sample spanning the unit cell. Details of these models and of the cross section preparation are given in Section II. Note that the standard ARC processing codes use flux-weighting rather than bilinear-weighting⁹ for cross section collapse. No sample size correction factors were applied.

Sample and isotopic central worths were calculated using first order perturbation theory and a 29-group RZ diffusion theory model of the reference assembly. The sample compositions used in the calculations are reported in Table III-2. The calculated sample central worths are listed in Table III-7. These calculated central worths correspond to the worths at the central mesh point which extends radially from 0.00 to 2.12 cm and axially from 0.00 to 2.00 cm. Sample reactivity worths were also calculated at the radially-centered mesh point extending axially from 4.00 to 6.00 cm since sample worths are actually measured 4.45 cm axially from the assembly midplane. The percentage deviations of the worths at this mesh point from that at the central mesh point are given in parentheses beside the calculated value in Table III-7. For all fissile and absorbing materials, whose worth curves behave essentially as cosine squared, these deviations are on the order of -0.8 to -0.9%. For all scattering materials, the axial worth distribution falls off more rapidly and the deviations vary from -1.0 to -1.8%.

The isotopic central worths, listed in Table III-8 by increasing atomic number, were calculated at the central mesh point for every isotope for which

infinitely dilute detector cross sections were available. Because of the lack of available experimental values for the worths of the minor isotopes and elements in the reactivity samples, no determination of the isotopic or elemental reactivity worths was attempted by the unfolding of experimental data. Previous experience¹⁻³ has shown that, for the samples measured in the GCFR assemblies, the isotopic and elemental C/E's are in precise agreement with the sample C/E for the corresponding reactivity sample (only the ²⁴⁰Pu C/E deviates from this behavior*). Consequently, the C/E's in Table III-8 are the C/E's of the smallest sample for which the specified isotope or element is the predominant component.

Radial reactivity worth traverses were calculated using first order perturbation theory and a 29-group XY diffusion theory model of the reference assembly. The calculated worth distributions, normalized to the calculated RZ worth at the central mesh point, are presented in Tables III-9 through III-12. These calculated distributions renormalized to 1.00 at the central mesh point, are plotted in Figs. III-2 through III-8. A cubic spline interpolation routine was used to remove the piece-wise appearance of the calculated curve. For XY model calculations, the axial displacement of the samples from the assembly midplane requires that the worths be integrated over a transverse integration half-height. Assuming that the shape of the axial worth distribution is given by a cosine squared function, the transverse integration half-height (T) was selected such that the average of the cosine squared from 0 to T was equal to the value of the cosine squared at the axial position of the sample (S). This condition is approximated by the relation $T = \sqrt{3} S$. For GCFR Phase III, this technique reduces the calculated midplane (Z=0) worths by a factor of 0.9921. All points in the radial traverse were calculated in this manner. For CH₂, SST, and ²³⁸U, the assumption of a cosine squared axial worth distribution is less applicable, (see Ref. 2 or Table III-7) and consequently, the absolute value of these central worths calculated with an XY model is more uncertain.

Given the adjustments discussed above in both the RZ and XY calculations in order to correct for the axially off-center position of the sample in the central worth measurement, there remains a discrepancy in the central worths calculated using the XY and RZ models. For all samples used in radial traverses, except CH₂(F)-6, the central worths calculated using the XY model are 2-1/2 to 3-1/2% larger than those calculated using the RZ model. For the fissile isotopes ²³⁹Pu and ²³⁵U, the discrepancy is 3.12 and 3.11%, respectively, and for the absorber isotopes ¹⁰B and ⁶Li, the discrepancy is 3.45 and 3.43%, respectively. For all comparisons of calculated and experimental central worths, the RZ model results are used. For all comparisons of the calculated and experimental reactivity worth traverses, the calculated traverse is normalized to the calculated RZ worth at the central mesh point.

E. Central Reactivity Worth Results

The calculated and experimental central reactivity worths of the samples and the corresponding C/E's are summarized in Table III-7. To be consistent

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*The ²⁴⁰Pu sample is an oxide, PuO₂, and the reduction to isotopic ²⁴⁰Pu worth requires an experimental value of the oxygen worth which was not available.

with previous GCFR small sample reports ¹⁻³, the reported calculated central worths are the values obtained at the central RZ mesh point, with the deviations (see Section III.D) in the worths calculated at the approximate sample position given in parentheses. The effects of sample size and local environment are not included in the calculations. The uncertainties associated with the C/E's reflect only the uncertainties in the experimental values. The central C/E's are typical of the observed central worth discrepancy -- C/E's of ~1.15 to ~1.20 for fissile material, C/E of 1.05 for ¹⁰B, and C/E's of ~1.30 for scatterers.

F. Radial Reactivity Worth Traverse Results

The calculated and experimental radial reactivity worth traverses and the corresponding C/E's and C-E's are summarized in Tables III-9 through III-12. The calculated spatial distributions of the worths were computed using an XY model and normalized at the central mesh point to the RZ central worth. Plots of the reactivity worth traverses are presented in Figs. III-2 through III-8, where the horizontal axis is the radial position of the sample with zone/region boundaries indicated, and the vertical axis is the normalized reactivity worth. These normalized, calculated and experimental traverses are computed for point i by $C_i/|C_o|$ and $E_i/|E_o|$, respectively, where C_o and E_o are the values at the central point. With this normalization, each traverse has a magnitude of 1.0 at the central point. Due to the behavior of the experimental $CH_2(F)-6$ reactivity worth traverse, the normalization $E_i/10|E_o|$, corresponding to a magnitude of 0.1 at the center, is more appropriate.

Because of the plot normalization technique, neither the C/E ratio nor C-E difference is preserved. For example, the actual C/E equals the apparent C/E from the plot times the absolute value of the actual central C/E,

$$\frac{C_i}{E_i} = \frac{|C_o|}{|E_o|} \times \frac{[C_i/|C_o|]}{[E_i/|E_o|]}$$

where the quantities in brackets [ ] are the normalized reactivity worths and where the apparent C/E is the ratio of the normalized quantities. In addition, the actual C-E is not directly proportional to the apparent C-E from the plot. One form of the relationship is given by

$$C_i - E_i = |E_o| \left\{ [C_i/|C_o|] - [E_i/|E_o|] + \left(\frac{|C_o|}{|E_o|} - 1 \right) \times [C_i/|C_o|] \right\}$$

where the apparent C-E is the difference in the normalized quantities. In each case, the additional factor or term is required because the calculated and experimental traverses have distinct normalization factors, that is, because the absolute value of the central C/E, $|C_o|/|E_o|$, is not 1.0. Consequently, caution must be used in interpreting the plotted traverse data.

Table III-9 and Figs. III-2 and III-3 contain the reactivity worth distributions of the fissile samples, MB-10 (²³⁹Pu) and MB-21 (²³⁵U). For the ²³⁹Pu sample, the C/E increases approximately 3% from 1.16 ± 0.01 at the center to 1.17 ± 0.01 midway through the traverse of core zone I and decreases gradually to 1.06 ± 0.07 in the radial blanket region. For the ²³⁵U sample, the

C/E is nearly flat (within statistics) in the central region of core zone I and decreases gradually in the core region. In the radial blanket region, however, the C/E drops to 0.93 ± 0.03 , well below the corresponding C/E for the ^{239}Pu sample. This systematic variation in the misprediction is also revealed in the normalized plots.

The calculated and experimental reactivity worth distributions of the fertile sample, MB-25 (^{238}U), is presented in Table III-10 and Fig. III-4. The tabulated C-E shows only slight spatial variations, suggesting that the relative magnitude of the negative (positive) component of the worth is approximately uniformly overpredicted (underpredicted). A striking feature of the calculated distribution is that the worth is nearly zero throughout the entire radial blanket region.* In the earlier GCFR assemblies^{1,2} the normalized calculated reactivity worth became slightly positive (<0.1) near the core/blanket boundary, decaying to zero in the radial blanket region. In the present assembly, the calculated worth vanishes at the boundary and can therefore not decrease toward zero at larger radii.

The reactivity worth distributions of the structural sample, MB-19 (SST-304), are given in Table III-10 and Fig. III-5. In core zone I, the C/E, in general, increases slightly for increasing radius, although, except for the central point, the C-E decreases. These observations are not definitive since the magnitude of the uncertainties are comparable (within a factor of 2) to the magnitude of the variations. The plotted traverses and tabulated values indicate that the experimental central worth may be approximately 5% too large and that renormalization would improve the agreement in core zone I. However, the quoted experimental central value is the mean of two independent measurements which differed by only 1-1/2%. The poor C/E values in the outer core zones and radial blanket region indicate the difficulties in calculating the relative magnitudes of the positive and negative components of the worth and, hence, the position at which the worth changes sign.

For both MB-25 (^{238}U) and MB-19 (SST-304), the C-E is the largest in core zone II. The fact that the samples were centered in a type 3 drawer of the core zone II three-drawer unit cell is not considered in the analysis.

The calculated and experimental reactivity worth distributions of the absorber samples, B-7 (^{10}B) and LI-5 (^6Li), are presented in Table III-11 and Figs. III-6 and III-7. As is characteristic of pure absorbers, the agreement between calculations and experiments on radial shape is very good. The capture component of the central worth of B-7 is approximately 98% of the total worth, while for LI-5 it is approximately 95%. The minor deviations in the C/E comparisons for B-7 in the core region may be related to the fact that the dummy used to measure the reactivity effects of the SST capsule and capsule holder was, for this traverse, not ideally matched to the actual capsule of the sample.

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*Possible sources of calculational error have been investigated. The radial blanket detector cross sections (DDF and DDG) for ^{238}U in the sample were replaced with the shielded cross sections for the blanket (SDF and SDG) and with the detector cross sections for core zone I (DAA) and produced essentially identical results. In addition, the ARC input has been checked and found to be correct.

The results of the CH₂(F)-6 polyethylene foam measurements and analysis are presented in Table III-12 and Fig. III-8. The lack of agreement between the experimental and the calculated values may be attributable to the failure of first order perturbation theory to account for the large spectrum degradation resulting from even a 0.90 gm (24.5 cm³) sample of CH₂ foam. From the graph, however, the shape of the calculated curve does qualitatively follow the change in experimental value.

G. Comparison of Results to GCFR Phase I

Comparison of GCFR Phase I and Phase III central worth results reveals a systematic bias in the central C/E discrepancy for these two similar unit cells. The central C/E values of major isotopes are listed in columns 3 and 4 of Table III-13. The tabulated values represent the C/E's for the same samples in each assembly, thus minimizing any problems associated with uncertainties in composition.

The major component of the discrepancy is associated with errors in the calculation of the perturbation denominator. Normalized C/E's, obtained by dividing a given C/E by the C/E for ²³⁹Pu, are the C/E's for the ratios of the perturbation numerators, and are not affected by calculational errors in the perturbation denominator. These normalized C/E's are reported in columns 5 and 6 of Table III-13. With the exception of the ²⁴⁰PuO₂ and SST samples, these normalized C/E's are in good agreement for Phases I and III (the uncertainty in the normalized C/E of the ²³⁸U sample is on the order of 0.05).

An alternate approach to remove the calculational error in the perturbation denominator is to adjust the sample worth C/E with the C/E of the normalized perturbation denominator (its measurement is discussed in Section V). The C/E for the ²⁵²Cf measurement of the perturbation denominator in Phase I is 0.75¹ and for Phase III is 0.86. These adjusted C/E's are given in columns 7 and 8 of Table III-13. The normalized and adjusted C/E's for Phase III are identical since a perturbation denominator C/E of 0.86 removes the C/E bias in the ²³⁹Pu sample.

Discrepancies in the normalized C/E values may be attributable to varying fissile enrichment in the unit cell -- the Phase III core zone I unit cell contains a 1/4-in. wide U₃O₈ column that was a void in the Phase I core unit cell. This change in the ²³⁸U density may produce a systematic change in the ability to calculate the adjoint flux. The deviations in the normalized C/E may be due to errors in the calculated scattering component of the worth as is evidenced by the normalized C/E of ²⁴⁰PuO₂ and SST (the scattering component of the ²⁴⁰PuO₂ sample is ~20% of the total worth).

IV. REACTION RATE MEASUREMENTS

Three fission rates (²³⁹Pu, ²³⁵U and ²³⁸U) were measured in a 2-inch cubic cavity at the center of the Phase III assembly using Kirn-type fission counters. Cell-averaged reaction rates were determined at several locations in the core and blankets using foil irradiation techniques. Foil irradiations were also used to measure radial and axial reaction rate distributions (f^{49} ,

f^{25} , f^{28} and c^{28}) through the core and blanket regions. The ZPR-9 configuration for all reaction rate measurements is the reference assembly shown in Fig. I-1.

A. Central Fission Rate Measurements

Absolute fission rates were measured for ^{239}Pu , ^{235}U and ^{238}U in a 2-inch cubic cavity at the center of the assembly (location S-23/23) using a 5.1-cm diameter Kirn-type fission counter. A second counter was positioned in drawer S-23/18 to normalize successive reactor runs. Figure IV-1 shows the position of the detector within the drawers. The front two inches of drawer materials are removed to accommodate the detector, with the fission source positioned 1.91 cm from the front of the drawer.

In the pin zone measurements, the calandria within the two counter drawers were moved back two inches from the midplane to accommodate the detectors.

Scaler count rate data were accumulated for each of the counters along with the energy spectrum of each. The fission counters register counts from fissions, proton-recoil events and alpha-particle emissions. Energy resolution is good enough to allow rejection of nearly all of the low energy non-fission events, but a small data correction is still applied.

To eliminate this small fraction of low-energy counts, the minimum or valley of the spectrum below the fission events is found using an orthogonal polynomial fitting routine. The fitted data value, CTVL, at the valley channel, CHVL, is then extrapolated at constant value to channel zero, and a correction factor for the scaler data, α , is found according to

$$\alpha = \frac{\text{CHVL} * \text{CTVL} + \text{TCAVL}}{\text{TOTAL}}$$

where TCAVL is the sum of the counts in the spectrum above the valley channel and TOTAL is the sum of all counts in the spectrum. The correction $(1-\alpha)$ to the scaler data is normally less than 0.5%.

Using the monitor counter, all fission rates are normalized to the same reactor power level. The compositions listed in Table IV-1 are then used to derive isotopic rates from which ratios are calculated. For those isotopes whose fission rates are not measured, a calculated ratio, e.g., f^{26}/f^{25} , is used for isotopic corrections.

Table IV-2 lists the measured and calculated isotopic reaction rate ratios for the plate-loaded core at the central detector position. These values are normalized to a monitor count rate of 500 counts/sec., corresponding to a power level of approximately 120 watts. Included in the table are the central measured and calculated ratios for the pin zone.

B. Foil Data Analysis

Analysis of foil data is the same for intra-cell measurements and reaction rate distributions. A series of computer codes process the data to produce a relative capture or fission rate for each foil. The data are then used to derive the specific information which will be compared to calculations,

e.g., cell-averaged reaction rates or reaction rate distributions. The GCFR Phase III foil data was the first to be accumulated solely with new Ge(Li) detector-based sample changers, and was the first data analyzed with the new standard set of computer codes. Comparisons of reaction rate distributions measured in GCFR Phase II showed excellent agreement between the NaI and Ge(Li) systems. Because of this change, the analysis methods are presented here in some detail.

After irradiation, the foils are removed from the reactor and placed in an automatic sample changer system. Using this computer-controlled system, each foil is positioned above a Ge(Li) detector, and a gamma-ray spectrum is collected for a preset time. The typical counting electronics (preamplifier, amplifier, pulse-height analyzer, ADC) are set to accumulate a 1024-channel energy spectrum over the energy range of 0 to 1024 keV. The spectrum from each foil is accumulated and stored on magnetic tape a minimum of four times, usually six to eight times.

Figure IV-2 shows a typical multichannel analyzer spectrum for a depleted uranium foil. Four fission product gamma-ray peaks and one capture product peak are labelled, and these are used to determine reaction rates. Using a computer code SKEWGAUS¹⁰, somewhat modified from the original version, each photopeak of interest is fitted to a multi-parameter function. This function takes the form of a skewed Gaussian peak shape, and has the capability to fit unresolved multiplets within a spectrum. The area of each peak is found by numerically integrating the fitted function describing that peak. Thus, the contributions from the interfering peaks are not included in the result, and the background under the peak is subtracted as part of the fit. Four peaks are used for fission rate analysis and one for capture in ²³⁸U. Table IV-3 lists the photopeaks used and pertinent information about these gamma-ray peaks.

Two methods are used to obtain final results from this peak area integration data, depending on whether the fission or capture rate is being analyzed. For capture rates, the area of the one peak is corrected for decay subsequent to the irradiation, deadtime and counting cycle length. The corrected counts for each pass of each foil are then examined for anomalous counts, averaged and normalized for the power history of the run. For fission rates, the same corrections are applied to the integrated areas and the results for each foil are averaged as for capture rate data. Then the results from each of the four fission product peaks are averaged together to form one fission rate for each foil.

In order to form reaction rate ratios or to make isotopic corrections, the fission and capture rates must be put on an absolute basis. Absolute capture rates in foils are determined by calibrating the detector system with a standard source of ²⁴³Am for ²³⁸U capture. Fission foil data are normalized to absolute fission counter results. During the foil irradiation, a Kirn-type counter (the same type used in the central rate measurements) was placed in matrix location S-23/18 with two foils of the appropriate type (plutonium, enriched or depleted uranium, depending upon the foils being irradiated) on the face of the counter. The foils are in the same environment as the source on the Kirn counter, and should measure the same absolute rates as the fission counters. Thus, to get a normalization factor for each type of foil, the average value of the relative rates of each pair of foils on the

counter is equated to the absolute fission counter results. Isotopic compositions are accounted for, and the small change in spectral indices between the core center and the monitor counter location is also factored into the normalization.

This normalization technique assumes only that the foils placed on the front of the counter react to the same flux as the counter itself. While the detector cavity does perturb the local flux, no assumption is made that the detector samples a unit cell-averaged reaction rate or any drawer-averaged rate. Measurements of fission rates with and without the foils in place show that the foils do not affect the fission rate in the counter for non-threshold fissioning isotopes. Similarly, measurements of the ^{238}U capture rate in the counter cavity with and without the counter in place show that the counter does not affect the capture rate in the foils to any measurable extent.

Isotopic reaction rates are derived from the enriched and depleted uranium foil data using the compositions given in Table IV-4. The isotopic rates f^{25} and f^{28} are derived from the equations

$$\text{ENR} = f^{25} \left(N_E^{25} + \frac{f^{24}}{f^{25}} N_E^{24} + \frac{f^{26}}{f^{25}} N_E^{26} \right) + f^{28} N_E^{28}$$

$$\text{DEP} = f^{25} \left(N_D^{25} + \frac{f^{26}}{f^{25}} N_D^{26} \right) + f^{28} N_D^{28}$$

where N_j^i is the mass fraction of isotope i in foil type j as given in Table IV-4. The ratios f^{24}/f^{25} and f^{26}/f^{25} are calculated for each assembly, but their small contribution to the fission rate does not significantly change the equations from one core to the next.

No isotopic corrections are made to the ^{239}Pu fission rate data. Any corrections would have to be calculated, and such a technique would bias the experimental results. Instead, the absolute normalization factor derived from the fission counter data for ^{239}Pu assumes that the foils contain only ^{239}Pu and that the contributions from the other isotopes is a constant factor. This is an excellent approximation for ^{239}Pu fission measurements throughout the core, but may introduce some relative errors when traversing both the core and blanket. Since no plutonium foils were irradiated in the blanket, this problem does not arise except very near the edge of the core.

C. Cell-Averaged Reaction Rates

1. Plate-loaded Assembly

Detailed intra-cell reaction rates were measured in the core and both blankets of the assembly. These results provide cell-averaged reaction rate ratios and are also used to convert point reaction rate data to cell-averaged results.

In three of the one-drawer unit cell core locations, the normal 0.25-in. thick fuel plates were replaced by pairs of 0.125-in. thick plates, and foil packets placed between them. Wherever possible, the uranium oxide plates were replaced with 0.125-in. thick plates for a more detailed analysis. Table IV-4 describes the foils used for the unit cell measurements.

Intra-cell reaction rates were measured by placing foils between the plates of selected unit cells in the core, axial blanket, and radial blanket. Plutonium foils were used only in the core region, and only next to the fuel plates. Foils were held in 1-mil thick aluminum folders as shown in Fig. IV-3.

Data from the foils were analyzed and normalized as described above. In order to eliminate the effects of gross flux shapes through some of the unit cell regions, results within each unit cell region were corrected for positional differences in the radial direction. Multiparameter polynomial curves were fit to the experimental radial reaction rate distribution data (see Section IV.D). These curves were interpolated to give a value of each reaction rate at each foil location within the unit cells. The experimental reaction rate values at the foil locations within the unit cells were then corrected to a common radius by multiplying by the ratio of the fitted value at a reference location to the fitted value at each foil location.

Figures IV-4 to IV-7 show the distribution of plutonium fission reaction rates in the core region unit cells. Figures IV-8 to IV-13 show the distributions of the ^{235}U fission rate in the core, axial blanket and radial blanket regions. Figures IV-14 to IV-19 show distributions of the ^{238}U fission rate for these unit cells, and Figs. IV-20 to IV-25 show the ^{238}U capture rate distributions in the core, axial blanket and radial blanket regions. The intra-cell distributions in Figs. IV-6, IV-10, IV-16 and IV-22 are shown after the radial corrections discussed above were applied. The other unit cell locations were chosen such as to make the radial position difference corrections negligible. The notation at the tops of the figures define the matrix location and axial distance from the core midplane at which the measurement was made. The error bars on the plots indicate relative statistical uncertainty only.

Tables IV-5 to IV-10 summarize the foil data for each of the unit cell locations. Since individual data point uncertainties are very consistent, they have not been listed in the tables. For ^{239}Pu and ^{235}U fission and ^{238}U capture statistical uncertainties are approximately 0.75% in the core region and 1.0% in the blanket regions. The uncertainties for ^{238}U fission are somewhat higher, ranging from 1.0% in the core region to 2.0% in the blanket regions. These uncertainties include only the statistical uncertainties in the foil count-rate data and the uncertainty in the foil position. Positional uncertainties were estimated by calculating the change in the reaction rate results when the foil position was changed ± 0.125 in. according to the measured radial and axial distributions. The listed uncertainties do not include possible small uncertainties in the half-lives used to correct the counting data, in the dead time corrections to the data or other systematic uncertainties.

With the exception of the fuel plates, a plate-averaged reaction rate is taken to be the numerical average of the foil reaction rates on either side of the plate. These values for the foils are derived as described above. The cell-averaged reaction rate is an atom-density weighted average, defined by

$$CA_k = \frac{\sum_{i=1}^J (PA)_i^k N_i^k w_i}{\sum_{i=1}^J N_i^k w_i} .$$

In this expression, CA_k is the cell-averaged reaction rate of type k (where k is either ^{239}Pu , ^{235}U or ^{238}U fission or ^{238}U capture), $(PA)_i^k$ is the plate average of the k 'th reaction rate in plate i , N_i^k is the atom density of isotope k in plate i and w_i is the volume of plate i . The sum is over all plates within the unit cell.

Two corrections are normally applied to the plate-averaged rates for the fuel plates. The first accounts for the fact that the stainless steel clad (0.015-in. thick) on the fuel plates affects the values of the reaction rates measured next to the surface of the clad. Previous GCFR measurements have shown that the only reaction rate which is noticeably affected is ^{238}U capture. This stainless steel correction factor is relatively insensitive to spectral differences, so the values measured in the GCFR Phase II assembly² were used to correct the Phase III data. These factors were measured by placing extra stainless steel between the fuel plate and the foil (both outside the plate and between the half-width plates), then extrapolating the data to zero-thickness clad. The correction factor for foils on the outside of normal fuel plates is 0.999 ± 0.008 , and for foils between half-width plates is 0.984 ± 0.008 . These factors have not been applied to the data in Tables IV-5 to IV-11.

The second correction to the fuel plate data accounts for the dip in the capture rate and the peak in the fission rate within the plate. As part of the measurements, the normal (0.25 in.) fuel plate in the two central zone I unit cells and the two plates in one zone III unit cell were replaced by pairs of half-width (0.125 in.) plates in order to estimate the reaction rate peaking or depression. After applying the stainless steel corrections, the ratio of the plate average to the exterior surface foil average was formed. Only the values for the depleted uranium foils differed from essentially unity, but for consistency the factors were applied to all the reaction rates. The factors used to obtain in-fuel-plate reaction rates from the surface-foil averages are: for ^{238}U fission, 1.0151 ± 0.0043 ; for ^{238}U capture, 0.9640 ± 0.0032 ; for ^{239}Pu fission, 0.9963 ± 0.0064 ; for ^{235}U fission 0.9979 ± 0.0029 .

Table IV-11 lists the ratios of the cell averaged reaction rate to the "mapping foil" reaction rate. These numbers are used to convert reaction rate distribution data to cell-averaged values as discussed below.

Table IV-12 summarizes the unit cell measurements in the form of reaction rate ratios, which are also compared to calculated values in the table. Calculational methods are described below.

2. Pin Zone Assembly

Intra-cell reaction rates of f^{49} , f^{25} , f^{28} and c^{28} were also measured in the core and all except f^{49} were measured in the axial blanket region of the pin zone in the GCFR Phase III assembly.

In the core region (matrix location S-23/23, approximately three inches away from the stationary half/movable half boundary), special three-inch long stainless steel pins containing PuO_2/UO_2 pellets were used. The cladding on one end of these pins was reduced to a thickness of five mils to reduce the effect of stainless steel on the reaction rate measured in the adjacent measurement foil. Table IV-13 describes the foils used for the unit cell measurements.

The 0.20-inch diameter plutonium foils were centered, with silicon grease, on a five-mil thick, 0.346-inch diameter aluminum disc and then wrapped in one-mil thick aluminum. The package was then positioned between the special thin-end-capped fuel pins at locations A1, B6, and C2 (see Fig. IV-26). Enriched and depleted uranium foils, 0.346-inch diameter, were also wrapped in 1-mil aluminum foil and positioned between special pins at the locations A3, C1 and A2, B8, C3 respectively.

In the axial blanket region (matrix location S-23/23 approximately 27 inches away from the stationary half/movable half boundary), enriched and depleted uranium foils, 0.346-inch diameter, were wrapped in 1-mil thick aluminum and placed between the depleted UO_2 pellets within special six-inch long stainless steel clad open ended pins.

Enriched uranium foils were placed at locations A2, B8 and C3 and depleted uranium foils at locations A1, B6, and C2 (Fig. IV-26).

Foil data acquisition and analysis methods are described above. Table IV-14 lists the measured relative reaction rates at the various intra-cell positions in the pin zone.

Cell-averaged rates were formed by multiplying each positional rate times the number of pin positions it represents, e.g., $CA_{\text{DEP}} = 4(A1) + 8(B6) + 4(C2)$, referring to Fig. IV-26. No corrections to the data have been made for the effect of the stainless steel clad on the pins. Measurements in plate-loaded drawers have shown the effect is noticeable only for ^{238}U capture, and is on the order of one percent for foils placed next to the 15-mil thick clad on the plates. Based on this, no correction is made here for the 5-mil thick end caps. After normalization to the absolute rate measurements, ratios of the cell-averaged rates were calculated. Table IV-15 summarizes the intra-cell measurements in the form of measured and calculated cell-averaged ratios. Also given are the results of similar measurements in the plate-loaded GCFR Phase III assembly. The listed uncertainties are statistical only, resulting from counting statistics and normalization factors. No estimate of systematic uncertainties is included.

D. Reaction Rate Distributions

1. Plate-loaded Assembly

Radial and axial fission and capture rate distributions (f^{49} , f^{25} , f^{28} and c^{28}) were measured in the plate-loaded core and blanket regions of the GCFR Phase III assembly. The foils used are described in Table IV-4.

The radial traverses were made in the stationary half outward from the core center along column 23. Foils were placed in the front portion of the drawers in 1-mil aluminum folders as shown in Fig. IV-3. Each foil was placed at the mid-height of its drawer. In zone I of the core region, the foils were placed against the left side of the fuel plate in each drawer. In zones II and III of the core, the foils were placed against the left side of the right hand fuel column and in the radial blanket region, the foils were placed between uranium oxide plates 0.25 inch to the right of the drawer center.

The axial distributions of the uranium fission rates and the ^{238}U capture rate were measured in a central stationary half matrix location. Foils were placed at the mid-height of the drawer, held inside a folded length of 1-mil aluminum as shown in Fig. IV-27. The traverse holder was positioned against the right side of the fuel plates in drawer S-22/23.

Enriched uranium and plutonium foils were spaced at regular intervals through the core and axial blanket (enriched uranium only in the blanket) in one irradiation and depleted uranium foils were placed at the identical locations as the enriched uranium in a second irradiation.

Reaction rates in the distribution foils are determined using the analysis methods described in Section IV.B. Using the cell-averaged to mapping-foil ratios of Table IV-11, the traverse foil results are converted to cell-averaged reaction rates. In cases where these ratios vary across the core or blanket region (e.g., from S-23/23, 0-2 in. to S-23/23, 22-24 in. in Table IV-11) a linear fit was performed to obtain a correction factor for each foil position in the traverse.

The experimental fission rate data from the depleted and enriched uranium traverse foils were isotopically corrected to fission rates in ^{235}U and ^{238}U by normalizing to the absolute fission counter results, then solving the simultaneous equations for f^{28} and f^{25} .

Tables IV-16 and IV-17 list the measured radial and axial relative reaction rate distributions (reactions per gram). For each reaction rate in each direction, the experimental data were fit to a multiparameter polynomial function using a least-squares routine. Each traverse was then normalized to 1000. at the peak value given by the fit. The locations of the measured data points are the actual radial positions of the foils in the assembly. Tables IV-18 and IV-19 list the calculated reaction rate distributions (reactions per gram) in the radial and axial directions respectively. The locations of the calculated points are given as the center of the mesh region used in the flux calculation. Computational techniques are described below.

Figures IV-28 through IV-35 compare calculated and measured reaction rate distributions in both the radial and axial directions (both normalized to 1000 at the core center).

2. Pin Zone Assembly

The axial distribution of the ^{239}Pu fission rate was measured in the central matrix location at pin location C2 (Fig. IV-26). As for the unit cell measurements, the 0.20-in. diameter plutonium foils were centered, with silicon grease, on five-mil thick, 0.346-in. diameter aluminum discs and then wrapped in 1-mil aluminum. The packages were then positioned between special three inch stainless steel clad fuel pins over the total core height (stationary and movable halves). The special pins were arranged such that the thin-window ends of two pins were facing so that alternate foils on the axial traverse over the 48-in. core height were positioned between the thin ends of two special pins. The other foils were between the normal ends of two adjacent fuel pins.

Reaction rates in the plutonium foils were determined using the same techniques as those described above. The experimental data were fit using a least squares code and then normalized to 1000. at the peak value given by the fit.

Table IV-20 lists the measured axial reaction rate distribution in both the pin- and plate-loaded GCFR Phase III assemblies. Table IV-21 lists the calculated distribution for the pin-loaded configuration. Figure IV-36 compares the measured and calculated axial ^{239}Pu fission rate distribution in the pin zone.

E. Calculational Techniques

The calculated central reaction rate ratios in Table IV-2 are computed with the detector cross sections described in Section II. The XY model was used for the plate assembly rates and the pin zone RZ model for the pin assembly rates. While appropriate for the fission sources on the counters, these calculations do not in any way account for the fact that a 2-in. cubical void was created in the core, and that extra stainless steel (the counter) was placed around the source. In many cases, e.g., threshold fissioning isotope rates, the effects of these perturbations are non-negligible. Studies done in the GCFR Phase I assembly¹ indicate that threshold fission might be reduced by approximately 10% in the cavity environment.

Calculated values of the cell-averaged reaction rate ratios are derived from the shielded cross sections. For the plate-loaded assembly, the XY model flux was used for all unit cells at the reactor midplane and the RZ flux for all others. Pin zone ratios were calculated with the pin cross sections and RZ flux.

The XY model of the plate assembly has four mesh regions per drawer, and the RZ models have a mesh spacing of approximately 2 cm. To calculate unit cell reaction rate ratios, the ratio was formed for the mesh intervals adjacent to the unit cell location and the average value of the ratios was taken to be the cell-averaged ratio.

F. Results and Discussion

Both measured fission counter ratios at the core center of the plate assembly agree well with calculated values. The f^{25}/f^{49} ratio (1.040) is increased over the GCFR Phase II value of 0.992. The f^{28}/f^{49} ratio (0.0249) is lowered from the Phase II value (0.0309) indicating the softer spectrum in the central core zone of the Phase III assembly.

In the pin zone, for the two central spectral index ratios, f^{25}/f^{49} and f^{28}/f^{49} , excellent agreement was obtained between measurement and calculations, although corrections to account for the cavity in the calculation were not made.

Unit cell measurements of the f^{25}/f^{49} ratio are consistent in all core regions and agree well with calculated values. The c^{28}/f^{49} and c^{28}/f^{25} results are consistently higher than past measurements by approximately 3%. The two ratios at the outer limits of the blankets have C/E values of ~ 0.99 . In this region the c^{28}/f^{49} ratio is a rapidly changing function of position and these C/E values are not unexpected.

Similar results hold for the f^{28}/f^{49} and f^{28}/f^{25} ratios. Near region boundaries C/E values vary because of the rapidly changing f^{28}/f^{49} ratio, but the values away from the boundaries are typical of past measurements.

The in-core unit cell-averaged ratios from the pin zone are consistent with those obtained from the plate-loaded assembly. In both assemblies, the C/E value for the ratio c^{28}/f^{49} is 3%-5% higher than the GCFR Phase II results. C/E ratios for the unit cell-averaged reaction rate ratios, f^{28}/f^{25} and c^{28}/f^{25} in the axial blanket of the pin zone are higher than those for the plate loaded assembly. However, both reaction rate ratios undergo rapid changes as the distance into the axial blanket increases.

Calculated radial distributions of the f^{49} , f^{25} , f^{28} and c^{28} reaction rates in the plate assembly agree very well with measurements except for a slight under-prediction of the capture rate in the radial blanket. There is a noticeable discontinuity in the measured distribution of the f^{25} rate at approximately 30 cm. It should be noted that the f^{49} rate distribution matches the pattern in the f^{25} distribution. Its cause has not been identified.

The calculated axial distributions also agree very well with measurement for the plate-loaded assembly except for a slight underprediction of the ^{238}U capture rate in the blanket. Two features of the f^{28} distribution are noticeable. The depression of the central data point is due to the drawer front and gap between the reactor halves. This effect has been seen in previous measurements. The data point at 38.1 cm is low for the ^{238}U fission traverse, but high for the ^{238}U capture traverse. It was found that the one foil used to measure the fission and capture rate at this point was centered over the adjoining ends of two fuel plates. The high capture/low fission effect is attributed to a local perturbation caused by the relatively large amount of stainless steel at the junction of the two fuel plate claddings. The plutonium plate loading alongside this axial traverse was composed of lengths of 8-7-5-4 inches. The data point at 15 inches (38.1 cm) was the only foil position

point along the traverse that matched the location of the ends of two adjacent plutonium plates and this was the only point that showed the effect.

Normalization of the axial ^{239}Pu fission rate distribution near the core center results in calculated values which are underpredicted farther from the axial midplane (see Fig. IV-36). Previous studies have shown that Benoist diffusion coefficients can underpredict the amount of axial streaming in the pin zone, and it is probably such an effect which appears in Fig. IV-36. It should be noted that no systematic difference is evident among the data for foils placed between special pins and normal pins, indicating that the stainless steel has a negligible effect on the f^{49} fission rate measured next to the pin ends.

V. MEASUREMENT OF ABSORPTION-TO-FISSION RATIOS AND THE CENTRAL CORE CONVERSION RATIO

A. Introduction

Spectrum-averaged absorption (capture plus fission)-to-fission ratio measurements in fast critical assemblies are of considerable interest because they provide spectral indices which can be compared with calculations based on differential cross section data and because the value of the breeding ratio depends on these $(1 + \bar{\alpha})$ values. Because of the low fluxes characteristic of ZPR facilities, the reactivity-reaction rate method¹¹ was used to determine the $(1 + \bar{\alpha})$ values reported here. Measurements were made for ^{233}U , ^{235}U , ^{238}U , ^{239}Pu and ^{240}Pu . The central core conversion ratio has been obtained by combining these results with a measurement of the cell-averaged reaction rate ratio, c^{28}/f^{49} .

B. The Reactivity-Reaction Rate Method

The details of this method have been described previously (for example, see Ref. 2) and the final equation for the spectrum-averaged, position-dependent, absorption-to-fission ratio derived from perturbation theory is

$$1 + \bar{\alpha}(\underline{r}) = \frac{D(^6\text{Li})}{\bar{\phi}_a^*(\underline{r})} \left[\frac{\bar{v}(\underline{r}) \bar{\phi}_f^*(\underline{r})}{D(^{252}\text{Cf})} - \frac{\rho(\underline{r}) \text{RCF}}{R_{nf}(\underline{r})} \right] - \text{FCF} \quad (\text{V-1})$$

where

$$\bar{\phi}_f^*(\underline{r}) \equiv \sum_{i=1}^{NG} \phi_i^*(\underline{r}) \chi_i$$

$$\bar{\phi}_a^*(\underline{r}) \equiv \frac{\sum_{i=1}^{NG} \phi_i^*(\underline{r}) \sigma_{a_i} \phi_i(\underline{r})}{\sum_{i=1}^{NG} \sigma_{a_i} \phi_i(\underline{r})}$$

$$\bar{v}(\underline{r}) \equiv \frac{\sum_{i=1}^{NG} (v\sigma_f)_i \phi_i(\underline{r})}{\sum_{i=1}^{NG} \sigma_{fi} \phi_i(\underline{r})}$$

$$RCF \equiv [1 - (\rho_s + \rho_l)/\rho]$$

$$FCF \equiv (R_{np} + R_{n\alpha} - R_{n2n})/R_{nf}.$$

In these equations, ϕ_i and ϕ_i^* represent the flux and adjoint distributions, respectively, while σ_{ai} and σ_{fi} are the absorption and fission cross sections. The spectrum of prompt fission neutrons is given by χ_i and $\bar{v}$ is the average number of neutrons per fission event. The reactivity correction factor, RCF, adjusts the measured reactivity ρ for scattering and leakage effects in the sample. To account for neutron absorbing events other than capture and fission in the sample, the correction factor FCF is introduced. Two independent determinations of the perturbation denominator D are available from measurements made with samples of ${}^6\text{Li}$ and ${}^{252}\text{Cf}$:

$$D({}^6\text{Li}) = - \frac{\bar{\phi}_a^*({}^6\text{Li}) R_{n\alpha}({}^6\text{Li}) \text{ACF}({}^6\text{Li})}{\rho({}^6\text{Li}) \text{RCF}({}^6\text{Li})} \quad (\text{V-2})$$

$$D({}^{252}\text{Cf}) = \frac{\bar{\phi}_f^*({}^{252}\text{Cf}) S({}^{252}\text{Cf})}{\rho'({}^{252}\text{Cf})} \quad (\text{V-3})$$

The absolute specific absorption rate for the ${}^6\text{Li}(n,\alpha){}^3\text{H}$ reaction is denoted by $R_{n\alpha}$. Other types of absorption processes are accounted for by the small correction term ACF, where $\text{ACF} \equiv [1 + (R_{n\gamma} + R_{np})/R_{n\alpha}]$. The apparent reactivity, $\rho'(\text{Cf})$, of a calibrated ${}^{252}\text{Cf}$ spontaneous fission neutron source of strength S is evaluated at the power level used for the measurement of the absolute specific reaction rates R_{nf} and $R_{n\alpha}$. If the value of the perturbation denominator is insensitive to the local perturbation by the sample, $D({}^6\text{Li}) = D({}^{252}\text{Cf})$ and Eq. V-1 becomes

$$1 + \bar{\alpha}(\underline{r}) = \frac{1}{\bar{\phi}_a^*(\underline{r})} \left[\bar{v}(\underline{r}) \bar{\phi}_f^*(\underline{r}) - \frac{D\rho(\underline{r}) \text{RCF}}{R_{nf}(\underline{r})} \right] - \text{FCF}. \quad (\text{V-4})$$

The measured quantities are the relative specific reactivities $\rho({}^6\text{Li})$ and $\rho(\underline{r})$ for the fissile and fertile samples, the apparent reactivity $\rho'({}^{252}\text{Cf})$, the absolute specific reaction rates R_{nf} and $R_{n\alpha}({}^6\text{Li})$, and the neutron emission rate, $S(\text{Cf})$, from the extraneous source. The remaining terms in Eqs. V-1 to V-3 are calculated from fundamental nuclear data. If the measured reactivities and reaction rates are corrected for sample size effects, the flux and adjoint distributions in Eqs. V-1 to V-4 refer to the unperturbed reactor and so the corresponding $(1 + \bar{\alpha})$ results depend on reactivity ratios and are therefore independent of any absolute reactivity calibration.

C. Measured Quantities

Metallic lithium samples (99.2 w/o ^6Li) having a diameter of 0.309 in. and clad in 20-mil aluminum were used for both absorption rate and reactivity measurements. The neutron absorption rate in ^6Li is strongly dominated by the $^6\text{Li}(n,\alpha)^3\text{H}$ reaction. In fact, only a few hundredths of one percent of the absorptions result from (n,γ) and (n,p) processes. Thus, the ^6Li absorption rates were determined by measuring the tritium activity induced in irradiated samples using the methods described in Ref. 12.

Absolute ^{239}Pu fission rates were measured by gamma counting irradiated plutonium foils 0.0004-in. thick using $\text{Ge}(\text{Li})$ detectors. The gamma detectors were calibrated by counting foils irradiated on the face of a 5.1-cm diameter Kirn-type fission counter as discussed in Section IV.B. To determine the radial distribution of plutonium fission rates, foils were activated at numerous positions within the thin-walled stainless steel tube of the radial sample changer. A least squares polynomial fit of this distribution data was made, subject to the symmetry requirement $R_f(X) = R_f(-X)$, to determine the ^{239}Pu fission rates at the locations where small sample reactivities were measured. The fission rates for the other isotopes (^{233}U , ^{235}U , ^{238}U and ^{240}Pu) were obtained by combining measured fission ratios (see Table IV-2) with the ^{239}Pu fission rates. Unfortunately, f^{23}/f^{49} and f^{40}/f^{49} were not measured in the GCFR Phase III assembly. The values used for these ratios were obtained by dividing the calculated ratio by the corresponding C/E value obtained in the GCFR Phase II measurements (see Ref. 2, Table VI-3). Table V-1 summarizes the results of the fission ratio measurements.

Absolute reaction rate measurements for the $^6\text{Li}(n,\alpha)$ and the $^{239}\text{Pu}(n,f)$ processes, in units of events/sec-g, are shown in Table V-2. The measured rates were multiplied by a calculated sample size correction factor, R_0/R , which accounts for flux distortions due to the stainless steel tubes and cladding surrounding the sample and flux perturbations within the sample itself. To evaluate R_0/R , flux distortion factors were calculated using the perturbation integral transport code PIT.¹³ The errors shown in Table V-2 do not include uncertainties associated with the evaluation of R_0/R .

The small sample worth measurements have been described in Section III. A description of the reactivity samples used for these $(1 + \bar{\alpha})$ measurements is provided in Tables V-3 and V-4. The measured reactivities are shown in Table V-5. As with the R_0/R calculation, the PIT code was used to calculate distortion factors from which the sample size correction factor, ρ_0/ρ , was evaluated. The term $^i\rho_0/\rho_0$ converts the measured reactivity to that of the principal isotope (i) in the sample. Thus, $^i\rho_0$ (Table V-5) is the isotopic specific reactivity corrected for local disturbances in the flux and adjoint spectra. Since reactivities appear as ratios in the expression for $(1 + \bar{\alpha})$ (see Eqs. V-1 to V-3), the errors in Table V-5 do not include the approximately 1% uncertainty in the calibration of the autorod. Also, no error has been assigned to the calculated value of ρ_0/ρ .

A new californium source was used for the measurements made in the GCFR Phase III assembly. This source, designated as ORNL-NSD-56, was obtained from the Oak Ridge National Laboratory and has been calibrated by the

National Bureau of Standards and by the University of Michigan. At each radial position the worth of the ^{252}Cf source was measured at two power levels, differing by about an order of magnitude, in order to separate the apparent worth of the spontaneous fission neutrons from the reactivity of the source capsule. Table V-6 shows the measured apparent worth, $\rho'(E)$, at each radial position evaluated at the power level corresponding to the absolute reaction rates given in Table V-2. The source strength shown in Table V-6 corresponds to the time when the ^{252}Cf worth measurements were made. Again the PIT code was used to account for the distortion in the adjoint spectrum resulting from the stainless steel tubes surrounding the source and the source container itself. The PIT distortion factors were used to evaluate the correction term ρ_0'/ρ' shown in Table V-6. This correction assumes that the stainless steel surrounding the source absorbs a negligible number of source neutrons and does not significantly alter the spectrum of ^{252}Cf spontaneous fission neutrons. With these assumptions, $\rho_0'/\rho' = \phi_{f0}^*/\phi_f^*$, where ϕ_{f0}^* and ϕ_f^* are the spontaneous fission neutron importance terms calculated using undistorted and distorted adjoint distributions, respectively.

D. Calculated Quantities

Multigroup cross sections and appropriate flux and adjoint distributions are needed to calculate spectrum-averaged values of v , the importance terms ϕ^* and ϕ_f^* , and the correction factors RCF, FCF and ACF which appear in Eqs. V-1 to V-4. Section II describes the methods used to generate the 29 broad-group cross sections for the GCFR Phase III assembly beginning with ENDF/B Version IV data. Self-shielded cross sections, which include the effects of plate spatial self-shielding and resonance energy self-shielding, were used in a quarter-core XY model diffusion theory calculation (one mesh point per drawer - this model is identical to that described in Section II with the exception of the mesh interval) with Benoist anisotropic diffusion coefficients to determine the required flux and adjoint distributions (see Section II). These flux and adjoint distributions were used with 29 broad-group "detector" cross sections to calculate the required quantities in Eqs. V-1 to V-4. The "detector" cross sections do not include the effects of plate spatial self-shielding, but correctly predict infinitely-dilute and spatially homogeneous detector reaction rates within the framework of the diffusion theory model. Table V-7 summarizes the calculated quantities for infinitely-dilute samples.

The ^{252}Cf reactivity measurements were made with the point source displaced 1.95 cm from the center of the drawer toward the center of the assembly. However, the calculated values of ϕ_f^* (Cf) refer to the center of the drawer. Therefore, a least squares polynomial fit of ϕ_f^* (Cf), subject to condition that $\phi_f^*(X) = \phi_f^*(-X)$, was made for the purpose of interpolating the ϕ_f^* values to correspond to the locations where the ^{252}Cf reactivity measurements were made. These interpolated values are shown in Table V-6.

E. Perturbation Denominator Measurements

The ^{252}Cf data and the ^6Li data provide independent measurements of the perturbation denominator. $D(^{252}\text{Cf})$ and $D(^6\text{Li})$ were evaluated from Eqs. V-3 and V-2, respectively, using the data given in Tables V-2, V-5, V-6 and V-7.

The results are presented in Table V-8. It is seen that the mean value of the ^{252}Cf perturbation denominator, $\bar{D}(^{252}\text{Cf})$, is about 2.4% larger than $\bar{D}(^6\text{Li})$. For the GCFR Phase II measurements (see Ref. 2), $\bar{D}(^{252}\text{Cf})$ was .2% larger than $\bar{D}(^6\text{Li})$.

Since the magnitude of the perturbation denominator depends on the reactor power level, a normalization is required if the measured results are to be compared with calculation. A convenient normalization factor (NF) is

$$\text{NF} = \frac{S^*(0) S(0)}{I_h/(\delta k/k)} \quad (\text{V-5})$$

where

$$S^*(0) \equiv \sum_{i=1}^{\text{NG}} \chi_i^{\text{core}} \phi_i^*(0)$$

and

$$S(0) \equiv \sum_{j=1}^{\text{NI}} \sum_{i=1}^{\text{NG}} (\nu \Sigma_f)_{ij} \phi_i(0) = \frac{{}^{49}\text{R}_f}{N_0/{}^{49}\text{A}} \sum_{i=1}^{\text{NI}} i_V i_N (i_f/{}^{49}f).$$

NG and NI are the number of groups and the number of fissionable isotopes, respectively, N_0 is Avogadro's number, A is the atomic weight, i_N is the atom density of isotope i, and ${}^{49}\text{R}_f$ is the ^{239}Pu fission rate in fissions/sec-g, and ${}^{49}f$ is the calculated per-atom fission rate. $S^*(0)$ and $S(0)$ are $S^*(\underline{r})$ and $S(\underline{r})$ evaluated at the center of the reactor. The $I_h/\delta k/k$ term in Eq. V-5 is needed because the reactivities used in the expression for $\bar{D}(^6\text{Li})$ and $\bar{D}(^{252}\text{Cf})$ (Eqs. V-2 and V-3) are measured in inhours. To obtain the experimental values for the normalized perturbation denominator, $\bar{D}(^{252}\text{Cf})$ and $\bar{D}(^6\text{Li})$ are divided by the value of NF.

The normalized calculated perturbation denominator, $D_n(C)$, is

$$D_n(C) = \int_{\text{reactor}} S^*(\underline{r}) S(\underline{r}) dV / S^*(0) S(0). \quad (\text{V-6})$$

An RZ model calculation was used to evaluate $D_n(C)$. Table V-9 compares the measured and calculated perturbation denominators. The C/E ratio for the results based on the ^{252}Cf data is 0.857 ± 0.014 which is consistent with the value 0.850 ± 0.014 obtained in the GCFR Phase II measurement (Ref. 2).

F. Absorption-to-Fission Ratios

From Eq. V-1, the absorption-to-fission ratios, $(1 + \bar{\alpha})$, for ^{233}U , ^{235}U , ^{238}U , ^{239}Pu and ^{240}Pu were evaluated using the mean values of the perturbation denominator, $\bar{D}(^{252}\text{Cf})$ and $\bar{D}(^6\text{Li})$, given in Table V-8. The other data needed for these evaluations are given in Tables V-1, V-2, V-5 and V-7. Table V-10 shows the experimental (E) values of $(1 + \bar{\alpha})$ and the corresponding calculated (C) ones. These values refer to a very dilute detector spanning the width of the matrix drawer.

The errors (1σ) shown in Table V-10 include uncertainties in $\bar{v}$, the relative reactivity measurements, the absolute reaction rate determinations, and the calibration of the Cf neutron source strength. However, no error has been assigned to the calculation of the sample size effects, ρ_0/ρ and R_0/R , the importance terms, ϕ_f^* and ϕ_a^* , nor to the correction factors, RCF and FCF. For the Li measurements, samples of identical size were used for both reactivity and absorption rate determinations. Therefore, the value of $D(^6\text{Li})$ depends on the ratio $(R_0/R)/(\rho_0/\rho)$ which is very insensitive to the sample size corrections. In the expression for $(1 + \alpha)$, Eq. V-1, the importance terms enter as ratios of the form $\phi_a^*(^6\text{Li})/\phi_a^*(^{239}\text{Pu})$ and $\phi_f^*(^{240}\text{Pu})/\phi_f^*(^{252}\text{Cf})$. These ratios are thought to be quite insensitive to the details of the calculation. This argument is especially true for the ϕ_f^* terms which are calculated using a Maxwellian description of the spectrum of prompt fission neutrons. Table V-7 shows that the correction factors RCF and FCF are very small for all the isotopes except ^{238}U . Therefore, errors in the calculations of RCF and FCF contribute negligible uncertainties to the measured values of $(1 + \alpha)$, except for the case of ^{238}U .

Errors and error sensitivities are summarized in Tables V-11 and V-12. Table V-11 shows that the uncertainty in the fission rate contributes the largest uncertainty to $(1 + ^{233}\alpha)$ whereas almost all the uncertainty in $(1 + ^{240}\alpha)$ comes from the uncertainty in $\bar{v}$. From Table V-12 it can be seen that a 1.0% increase in $\bar{v}$, or a 1.0% decrease in $S(\text{Cf})$, will increase the $(1 + \alpha)$ values by 2.8%, 2.3%, 0.50%, 2.8% and 1.7% for ^{233}U , ^{235}U , ^{238}U , ^{239}Pu and ^{240}Pu , respectively. Similarly, a 1.0% increase in R_f , or a 1.0% decrease in ρ , will increase $(1 + \alpha)$ by 1.8%, 1.3%, -0.50%, 1.8% and 0.69% for ^{233}U , ^{235}U , ^{238}U , ^{239}Pu and ^{240}Pu , respectively.

Generally speaking, the measured $(1 + \bar{\alpha})$ values are in reasonably good agreement with the calculated ones. However, the C/E values are smaller at positions away from the center of the reactor than at the central location. After sample size corrections have been applied, the U-3 and MB-21 reactivity samples (see Tables V-3 and V-4) yield essentially the same values for $(1 + ^{235}\alpha)$, as Table V-10 indicates. The same is true for the ^{239}Pu reactivity samples, Pu-25 and MB-10. However, the reactivity measurement for the Pu-27 sample leads to an unusually large value of $(1 + ^{239}\alpha)$. Because of self-multiplication effects, one would expect the measured specific reactivity of the Pu-27 sample to be larger than that for the Pu-25 sample. This was indeed the case for the GCFR Phase II measurement (see Ref. 2), but was not observed in the present measurement, as Table V-5 shows. The unexpectedly low ρ -value for the Pu-27 sample is the reason for the correspondingly large value of $(1 + ^{239}\alpha)$. Because of the somewhat softer spectrum, the GCFR Phase III experimental $(1 + ^{239}\alpha)$ values are somewhat larger than the Phase II measurements (see Ref. 2).

Table V-13 lists C/E values for the position-dependent ratios $R_{\alpha 0}(^6\text{Li})/R_f(^{239}\text{Pu})$, $\rho_0(^6\text{Li})/\rho_0(^{239}\text{Pu})$ and $[\rho_0'(\text{Cf})/\rho_0(^{239}\text{Pu})] \times [R_f(^{239}\text{Pu})/S(\text{Cf})]$. The mean values of the C/E ratios are shown at the bottom of the table where they are compared with the corresponding quantities for the GCFR Phase II measurements (Ref. 2). The low C/E values for the Pu-27 sample and the MB-10 sample at the matrix location S-23/28 are consistent with the abnormally low $\rho(E)$ values (Table V-5) and the large $(1 + \bar{\alpha})$ values (Table V-10) for these samples and positions. This suggests the presence of a systematic error associated with these measurements and therefore these C/E values were not

included in the evaluation of $\overline{C/E}$. Table V-13 shows that the measured reaction rate ratio, $R_{\alpha_0}(^6\text{Li})/R_{f_0}(^{239}\text{Pu})$, agrees remarkably well with calculation and this observation is in agreement with the GCFR Phase II data. Also, the $\overline{C/E}$ value for the ratio $[\rho_0'(Cf)/\rho_0(^{239}\text{Pu})] \times [R_{f_0}(^{239}\text{Pu})/S(Cf)]$ is in reasonable agreement with the Phase II results. For the $^6\text{Li}/^{239}\text{Pu}$ reactivity ratio, however, the Phase III $\overline{C/E}$ value is nearly 4% larger than the Phase II result. This may be the primary reason why the perturbation denominator ratio, $\overline{D}(^{252}\text{Cf})/\overline{D}(^6\text{Li})$, was significantly greater in the Phase II measurement than in the Phase III experiment (see Section V.E).

G. The Central Core Conversion Ratio

The instantaneous central core conversion ratio, CR_p , may be defined as the rate of production of fissile material divided by its rate of loss evaluated at the center of the reactor. In terms of the central, cell-averaged reaction rates, CR_p may be written as

$$CR_p = \frac{^{28}\text{N}^{28}\text{c} + ^{40}\text{N}^{40}\text{c}}{^{49}\text{N}^{49}\text{f}(1 + ^{49}\overline{\alpha}) + ^{41}\text{N}^{41}\text{f}(1 + ^{41}\overline{\alpha}) + ^{25}\text{N}^{25}\text{f}(1 + ^{25}\overline{\alpha})}$$

$$= \frac{^{28}\text{N}^{28}\text{c}/^{49}\text{f}}{^{49}\text{N}(1 + ^{49}\overline{\alpha})} \left[\frac{1 + (^{40}\text{N}^{40}\overline{\alpha}^{40}\text{f}/^{49}\text{f})/(^{28}\text{N}^{28}\text{c}/^{49}\text{f})}{1 + \frac{^{41}\text{N}(1 + ^{41}\overline{\alpha})^{41}\text{f}/^{49}\text{f}}{^{49}\text{N}(1 + ^{49}\overline{\alpha})} + \frac{^{25}\text{N}(1 + ^{25}\overline{\alpha})^{25}\text{f}/^{49}\text{f}}{^{49}\text{N}(1 + ^{49}\overline{\alpha})}} \right] \quad (\text{V-7})$$

where ^iN is the atom density of isotope i and where ^ic and ^if are the cell-averaged, per-atom capture and fission rates. The $(1 + \overline{\alpha})$ values in Eq. V-7 are the cell-averaged absorption-to-fission ratios. These were obtained by dividing the calculated cell-averaged absorption-to-fission ratios by the corresponding thin sample $\overline{C/E}$ values given in Table V-10. The measurement of the cell-averaged $\text{c}^{28}/\text{f}^{49}$ ratio has been reported in Section IV. Since the $\text{f}^{40}/\text{f}^{49}$ and $\text{f}^{41}/\text{f}^{49}$ ratios were not measured in the GCFR Phase III assembly, these $\overline{C/E}$ values were taken from the GCFR Phase II data (see Ref. 2). Table V-14 summarizes the evaluation of CR_p at the center of the GCFR Phase III assembly. It is seen that the central conversion ratio is over-calculated by nearly 15%, mostly because of the over-calculation of the $\text{c}^{28}/\text{f}^{49}$ ratio.

Instead of using foil data, the $\text{c}^{28}/\text{f}^{49}$ ratio may be written in terms of the measured ^{238}U capture-to-fission ratio,

$$\text{c}^{28}/\text{f}^{49} = ^{28}\overline{\alpha} \text{f}^{28}/\text{f}^{49} . \quad (\text{V-8})$$

Table V-14 shows that when this evaluation is used there is excellent agreement between the measured and calculated central core conversion ratios. The $\overline{C/E}$ value now becomes 1.004 ± 0.039 . This same conclusion applies to the GCFR Phase II measurement for which the $\overline{C/E}$ value for the central core conversion ratio changes from 1.097 ± 0.032 to 0.993 ± 0.034 if Eq. V-8 is used. It should be remembered, however, that for ^{238}U , neutron scattering effects contribute a significant fraction to the total reactivity signal. Therefore, the ^{238}U $(1 + \overline{\alpha})$ values depend rather strongly on the calculated value of the

reactivity correction factor RCF (see Table V-7). For the GCFR Phase III measurements, $^{28}\rho_s/^{28}\rho = 1 - \text{RCF}$ would have to be increased by about 64% in order to make $^{28}\alpha^{28}\text{f}/^{49}\text{f}$ agree with the foil measurement of $^{28}\text{c}/^{48}\text{f}$.

H. Summary

Absorption-to-fission ratios ($1 + \bar{\alpha}$) have been measured in the core region of the GCFR Phase III assembly by the reactivity-reaction rate technique for ^{233}U , ^{235}U , ^{238}U , ^{239}Pu and ^{240}Pu . Generally speaking, the central values of ($1 + \bar{\alpha}$) are in favorable agreement with calculations based on the ENDF/B Version IV data.

The core conversion ratio was evaluated at the center of the GCFR Phase III assembly by combining the absorption-to-fission-ratio measurements with an independent determination of the cell-averaged $^{28}\text{c}/^{49}\text{f}$ reaction rate ratio. The central core conversion ratio is over calculated by nearly 15% mostly because of the 13% overprediction of the $^{28}\text{c}/^{49}\text{f}$ ratio. If the $^{28}\text{c}/^{49}\text{f}$ ratio is replaced by the measured value of $^{28}\alpha^{28}\text{f}/^{49}\text{f}$, however, excellent agreement is obtained between the measured and calculated central core conversion ratios.

VI. WORTH OF SMALL-ZONE STEAM ENTRY IN PLATE AND PIN ENVIRONMENTS

A. Introduction

The reactivity effects of steam entry into the coolant channels of a Gas Cooled Fast Reactor has been examined in each of the three GCFR assemblies built in ZPR-9. In Phase I, the worth of a small central steam zone was measured as a function of the steam density.¹ An extensive program in Phase II studied the effects of a full-core and blanket flooding with steam.³ The objective of the Phase III steam-entry program was to compare the reactivity worth of steam in a plate environment as used in the Phase I and II programs to that in the pin environment of Phase III that is more characteristic of a GCFR design. In each phase, steam entry was simulated by inserting polyethylene foam (CH_2) into the void regions (the simulated helium-coolant channels) of the assembly.

B. Measurement Techniques

In the Phase III program, polyethylene foam was loaded into the central 5×5 drawer array in three steps: 1) to an axial half-height of ± 12 in. relative to the axial midplane; 2) to an axial half-height of ± 24 in. (that is, to the core/axial blanket interface); 3) to an axial half-height of ± 36 in. (that is, to the axial blanket/reflector interface). For the plate loading, full-density polyethylene foam strips were inserted into the two 0.5-in. void cans of the zone I unit cell. This resulted in an average CH_2 density of 0.0136 g/cm^3 . Multiplying this density by the ratio of the molecular weights of H_2O and CH_2 conserves the hydrogen atom-number density and yields an equivalent steam density of 0.0174 g/cm^3 . For the pin loading, pre-drilled polyethylene foam blocks were inserted over the 4×4 pin array of the special calandria so that CH_2 completely filled the voids between the calandria pins.

The average CH_2 density in each calandria was 0.0149 g/cm^3 , corresponding to an equivalent steam density of 0.0191 g/cm^3 . Note that the average foam density is 9% greater in the pin environment than in the plate environment.

The steam-zone worths, relative to a steam-free reference configuration, are presented in Table VI-1 for both the plate and pin environments. The total worth of the steam zone at each loading step is 50-75% greater in the pin environment than in the plate environment, and the difference in the total worth increases as the axial half-height of the steam zone increases. The uncertainties reflect only the uncertainty in the measured excess of each loading step and of the steam-free reference. The uncertainty in the measured excess is estimated by adding in quadrature an uncertainty of 1 lh due to table closure and a 1% uncertainty in the excess reactivity as measured on the control rods. The worth (lh/kg) of the foam added at each of the three successive 12-in. loading steps and the total foam worth are given in Table VI-2, which also lists the ratio of the worth in the pin environment to that in the plate environment. This ratio of the worths is 1.42 for the first 12 in. of the steam zone, 1.60 for the second 12 in., and 1.11 in the axial blanket. For the full steam zone, the ratio is 1.59.

No calculations were made of the steam entry experiments in Phase III.

VII. REFERENCES

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Fig. I-1.

Matrix Loading for the GCFR
Phase III Reference Config-
uration.

ANL Neg. No. 116-80-43

Fig. I-2.

RZ Geometry for the GCFR
Phase III Reference Config-
uration.

ANL Neg. No. 116-80-35

Fig. I-3. Drawer Loading Patterns for Zone I Core (Upper) and Axial Blanket (Lower), GCFR Phase III.

ANL Neg. No. 116-80-30

Fig. I-5. Drawer Loading Patterns for Zone III Core (Upper) and Axial Blanket (Lower), GCFR Phase III. ANL Neg. No. 116-80-29

Fig. I-6. Drawer Loading Pattern for the Radial Blanket Region, GCFR Phase III. ANL Neg. No. 116-80-54

Fig. I-7. Drawer Loading Pattern for the Reflector Region, GCFR Phase III. ANL Neg. No. 116-80-53.

Fig. I-8.

Drawer Loading Patterns Illustrating the Disruption of Vertical Streaming Paths at Zone and Region Interfaces.
ANL Neg. No. 116-80-11

GCFR Phase III Core Zone I

Fig. I-9.

GCFR Phase III Stationary Half Drawer Master for Zone I Core Plus Axial Blanket.
ANL Neg. No. 116-80-10

GCFR Phase III Core Zone II Type 1

Fig. I-10. GCFR Phase III Stationary Half Drawer Master for Zone II, Type 1 Core Plus Axial Blanket. ANL Neg. No. 116-80-33

GCFR Phase III Core Zone II Type 2

Fig. I-11. GCFR Phase III Stationary Half Drawer Master for Zone II, Type 2 Core Plus Axial Blanket. ANL Neg. No. 116-80-32

GCFR Phase III Core Zone II Type 3

Fig. I-12. GCFR Phase III Stationary Half Drawer Master for Zone II, Type 3 Core Plus Axial Blanket.
ANL Neg. No. 116-80-31.

GCFR Phase III Core Zone III

Fig. I-13. GCFR Phase III Stationary Half Drawer Master for Zone III, Type 1 Core Plus Axial Blanket.
ANL Neg. No. 116-80-42.

GCFR Phase III Radial Blanket

Fig. I-14. GCFR Phase III Stationary Half Drawer
Master for the Radial Blanket.
ANL Neg. No. 116-80-41

GCFR Phase III Radial Reflector

Fig. I-15. GCFR Phase III Stationary Half Drawer
Master for the Radial Reflector.
ANL Neg. No. 116-80-57.

Fig. I-16.

Matrix Loading for the GCFR
Phase III Pin Zone Reference
Configuration.

ANL Neg. No. 116-80-51

Fig. I-17.

Drawer Loading Pattern in the
GCFR Phase III Approach-to-
Critical.

ANL Neg. No. 116-80-52

Fig. I-18. Approach-to-Critical Plots for U-235 Fission Counter in S-23/23 Axial Blanket.
ANL Neg. No. 116-80-18

Fig. I-19. Approach-to-Critical Plots for Experimental Channel SP-11.
ANL Neg. No. 116-80-36

Fig. I-20. Approach-to-Critical Plots for Reactor Channel No. 2.
ANL Neg. No. 116-80-55

Fig. I-21. Approach-to-Critical Plots for Reactor Channel No. 4.
ANL Neg. No. 116-80-21

Fig. I-22. Core Zone
III/Radial Blanket
Boundary.
ANL Neg. No.
116-80-77

Fig. I-23. Determination of GCFR
Phase III Temperature
Coefficient.
ANL Neg. No. 116-80-75

Fig. I-24.

Differences (SP-11
minus SP-10 in Inhours)
of ^{108}B Rod Worth as
Measured on Experi-
mental Flux Channels.
ANL Neg. No. 116-80-76

Fig. II-1. RZ Calculational Model of the
GCFR Phase III Plate Refer-
ence Configuration.
ANL Neg. No. 116-80-60

Fig. II-2. RZ Calculational Model of the
GCFR Phase III Pin Zone
Assembly.
ANL Neg. No. 116-80-62

Fig. II-3.

XY Calculational Model of
the GCFR Phase III Plate
Reference Configuration.
ANL Neg. No. 116-80-61

Fig. II-4.

Modified RZ Calculational
Model of the GCFR Phase
III Plate Reference Con-
figuration.
ANL Neg. No. 116-80-71

Fig. III-1. Matrix Configuration for the GCFR Phase III Small Sample Reactivity Worth Experiment.
ANL Neg. No. 116-80-22

MB-10 (^{239}Pu) REACTIVITY-WORTH TRAVERSE

Fig. III-2. MB-10 (^{239}Pu) Reactivity Worth Traverse.
ANL Neg. No. 116-80-13

MB-21 (^{235}U) REACTIVITY-WORTH TRAVERSE

Fig. III-3. MB-21 (^{235}U) Reactivity Worth Traverse.
ANL Neg. No. 116-80-12

MB-25 (^{238}U) REACTIVITY-WORTH TRAVERSE

Fig. III-4. MB-25 (^{238}U) Reactivity Worth Traverse.
ANL Neg. No. 116-80-23

MB-19 (SST-304) REACTIVITY-WORTH TRAVERSE

Fig. III-5. MB-19 (SST-304) Reactivity Worth Traverse.
ANL Neg. No. 116-80-24

B-7 (^{10}B) REACTIVITY-WORTH TRAVERSE

Fig. III-6. B-7 (^{10}B) Reactivity Worth Traverse.
ANL Neg. No. 116-80-19

LI-5 (^6Li) REACTIVITY-WORTH TRAVERSE

Fig. III-7. LI-5 (^6Li) Reactivity Worth Traverse.
ANL Neg. No. 116-80-20

$\text{CH}_2(\text{F})$ -6 (CH) REACTIVITY-WORTH TRAVERSE

Fig. III-8. $\text{CH}_2(\text{F})$ -6 Reactivity Worth Traverse.
ANL Neg. No. 116-80-56

Fig. IV-1. Position of Fission Chamber Within Stationary Half Zone I Core Drawer.
ANL Neg. No. 116-80-48

Fig. IV-2. Energy Spectrum of Gamma Rays Emitted Following Irradiation of Depleted Uranium Foils.
ANL Neg. No. 116-80-47

PACKET TYPE	FOIL DEP	LOCATION ENR	PU	PACKET USE
A	0.625			r28, c28 RADIAL TRAVERSE
B		0.625	1.250	r25, r49 RADIAL TRAVERSE
C	0.625	1.875		UNIT CELL MEASUREMENTS NEXT TO ALL BUT FUEL PLATES
D	0.625	1.875	1.250	UNIT CELL MEASUREMENTS NEXT TO FUEL PLATES

Fig. IV-3. Aluminum Foil Holders (1-mil thick) Used for Irradiations with Enriched and Depleted Uranium and Plutonium Foils.
ANL Neg. No. 116-80-46

Fig. IV-4.

Intra-cell ^{239}Pu Fission Rates in
Core Zone I:
S-23/23, $Z = 1.6$ cm;
S-15/23, $Z = 1.6$ cm;
S-23/23, $Z = 57.5$ cm.
ANL Neg. No. 116-80-49

Fig. IV-5.

Intra-cell ^{239}Pu Fission Rates in
Core Zone II:
S-13/22-24, $Z = 1.6$ cm.
ANL Neg. No. 116-80-52

Fig. IV-6. Intra-cell ^{239}Pu Fission Rates in Core Zone II:
S-23/32-34, $Z = 1.6$ cm.
ANL Neg. No. 116-80-7

Fig. IV-7. Intra-cell ^{239}Pu Fission Rates in Core Zone III:
S-11/23, $Z = 1.6$ cm.
ANL Neg. No. 116-80-8

Fig. IV-8. Intra-cell ^{235}U Fission Rates in Core Zone I:
S-23/23, Z = 1.6 cm; S-15/23, Z = 1.6 cm;
S-23/23, Z = 57.5 cm.
ANL Neg. No. 116-80-72

Fig. IV-9. Intra-cell ^{235}U Fission Rates in
Core Zone II:
S-13/22-24, Z = 1.6 cm.
ANL Neg. No. 116-80-73

Intra-cell ^{235}U Fission
Rates in Core Zone II;
S-23/32-34, Z = 1.6 cm.
ANL Neg. No. 116-80-74

Intra-cell ^{235}U Fission Rates in
Core Zone III: S-11/23, Z = 1.6 cm.
ANL Neg. No. 116-80-9

Fig. IV-12.

Intra-cell ^{235}U Fission
Rates in the Axial Blanket
Region: S-23/23,
 $Z = 62.5$ cm; S-23/23,
 $Z = 87.9$ cm.
ANL Neg. No. 116-80-63

Fig. IV-13.

Intra-cell ^{235}U Fission
Rates in the Axial Blanket
Region: S-6/23, $Z = 1.6$ cm;
S-10/23, $Z = 1.6$ cm.
ANL Neg. No. 116-80-64

Fig. IV-14. Intra-cell ²³⁸U Fission Rates in Core Zone I:
 S-23/23, Z = 1.6 cm; S-15/23, Z = 1.6 cm;
 S-23/23, Z = 57.7 cm.
 ANL Neg. No. 116-80-66

Fig. IV-15. Intra-cell ²³⁸U Fission Rates in Core Zone II: S-13/22-24, Z = 1.6 cm.
 ANL Neg. No. 116-80-65

Fig. IV-16.

Intra-cell ^{238}U Fission
Rates in Core Zone II:
S-23/32-34, $Z = 1.6$ cm.
ANL Neg. No. 116-80-70

Fig. IV-17.

Intra cell ^{238}U Fission Rates
in Core Zone III:
S-11/23, $Z = 1.6$ cm.
ANL Neg. No. 116-80-26

Fig. IV-20. Intra-cell ^{238}U Capture Rates in Core Zone I:
S-23/23, Z = 1.6 cm;
S-15/23, Z = 1.6 cm;
S-23/23, Z = 57.5 cm.
ANL Neg. No. 116-80-68

Fig. IV-21. Intra-cell ^{238}U Capture Rates in
Core Zone II:
S-13/22-24, Z = 1.6 cm.
ANL Neg. No. 116-80-14

Fig. IV-22.

Intra-cell ^{238}U Capture Rates in Core Zone II:
S-23/32-34, $Z = 1.6$ cm.
ANL Neg. No. 116-80-59

Fig. IV-23.

Intra-cell ^{238}U Capture Rates in Core Zone III:
S-11/23, $Z = 1.6$ cm.
ANL Neg. No. 116-80-28

Fig. IV-24.

Intra-cell ^{238}U Capture Rates in the Axial Blanket Region: S-23/23,
 $Z = 62.5$ cm: S-23/23,
 $Z = 87.9$ cm.
 ANL Neg. No. 116-80-58

Fig. IV-25. Intra-cell ^{238}U Capture Rates in the Radial Blanket Region: S-6/23,
 $Z = 1.6$ cm; S-10/23,
 $Z = 1.6$ cm.
 ANL Neg. No. 116-80-15

NOTE: GROUPS A, B, AND C DENOTE PINS WHICH ARE AT THREE DIFFERENT DISTANCES FROM THE CENTER OF THE CALANDRIA.

Fig. IV-26. Sixteen Pin Array Within Each Calandria Included in the Pin Zone of the GCFR Phase III Assembly.
 ANL Neg. No. 116-80-27

Fig. IV-27. Aluminum Foil Holder (1-mil thick) Showing Positions of Plutonium (X), Enriched Uranium (o), and Depleted Uranium Foils for Axial Reaction Rate Distributions.
ANL Neg. No. 116-80-16

Fig. IV-28.

Radial ^{239}Pu Fission Rate Dis-
tribution, Column 23.
ANL Neg. No. 116-80-17

Fig. IV-29.

Radial ^{235}U Fission Rate Dis-
tribution, Column 23.
ANL Neg. No. 116-80-44

Fig. IV-30.

Radial ^{238}U Fission Rate Distribution, Column 23.
ANL Neg. No. 116-80-45

Fig. IV-31

Radial ^{238}U Capture Rate Distribution, Column 23.
ANL Neg. No. 116-80-25

Fig. IV-32.

Axial ^{239}Pu Fission Rate Distribution.
ANL Neg. No. 116-80-2

Fig. IV-33.

Axial ^{235}U Fission Rate Distribution.
ANL Neg. No. 116-80-39

Fig. IV-34. Axial ^{238}U Fission Rate Distribution.
ANL Neg. No. 116-80-40

Fig. IV-35. Axial ^{238}U Capture Rate Distribution.
ANL Neg. No. 116-80-38

Fig. IV-36.

Axial ^{239}Pu Fission Rate Distribution in the Pin Zone.
ANL Neg. No. 116-80-37

TABLE I-1. Unit Cell Averaged Atom Densities for GCFR Phase III Plate Compositions (10^{21} atoms/cm³)

	Core Region			Axial Blanket Region			Radial Blanket	Reflector
	Zone I	Zone II ^a	Zone III ^b	Zone I	Zone II ^a	Zone III ^b		
Fe	13.2544	15.3744	18.9341	8.3648	8.8520	9.0957	8.6832	55.3173
Ni	1.2056	1.3240	1.4606	1.0667	1.1384	1.1743	1.1136	6.9735
Cr	2.6337	2.8669	3.1381	2.3563	2.4963	2.5663	2.4478	15.6724
Mn	0.2107	0.2291	0.2515	0.1870	0.1975	0.2027	0.1938	1.5646
O	14.8674	13.8595	11.8173	15.6918	15.8164	15.7200	18.5944	1.9709
Mo	0.2258	0.3022	0.4521	---	---	---	---	---
²³⁵ U	0.0126	0.0122	0.0111	0.0175	0.0176	0.0175	0.0198	---
²³⁸ U	5.8098	5.5423	4.9782	8.1763	8.2170	8.1763	9.2582	---
²³⁸ Pu	0.0006	0.0007	0.0008	---	---	---	---	---
²³⁹ Pu	0.8842	1.1832	1.7718	---	---	---	---	---
²⁴⁰ Pu	0.1171	0.1569	0.2351	---	---	---	---	---
²⁴¹ Pu ^c	0.0130	0.0163	0.0227	---	---	---	---	---
²⁴² Pu ^c	0.0019	0.0024	0.0032	---	---	---	---	---
²⁴¹ Am ^c	0.0052	0.0094	0.0178	---	---	---	---	---

^aThree-drawer unit-cell averaged atom densities.

^bDrawer-weighted averaged atom densities -- computed from unit-cell averaged atom densities and numbers of drawers per half for the three core drawer types in Zone III (Table I-2).

^cAtom densities corrected for ²⁴¹Pu decay to 7/1/75.

TABLE I-2. Number of Drawers Per Half, Fuel Plate Loading and Unit Cell Averaged Atom Densities for Each Type of Zone III Core Drawer

	Type 1	Type 2	Type 3
Number of Drawers per Half	34	50	8
Fuel Plate Loading (from midplane to axial blanket)	DOW 8" DOW 7" DOW 5" DOW 4"	DOW 7" DOW 5" DOW 4" DOW 4" NUMEC 4"	NUMEC 6" NUMEC 6" NUMEC 6" NUMEC 6"
Unit-Cell Averaged Atom Densities (10^{21} atoms/cm ³)			
Fe	18.8930	18.9727	18.8678
Ni	1.4546	1.4662	1.4510
Cr	3.1262	3.1493	3.1189
Mn	0.2505	0.2524	0.2498
O	11.8149	11.8187	11.8158
Mo	0.4558	0.4496	0.4518
²³⁵ U	0.0112	0.0111	0.0112
²³⁸ U	4.9999	4.9562	5.0236
²³⁸ Pu	0.0007	0.0008	0.0012
²³⁹ Pu	1.7836	1.7643	1.7684
²⁴⁰ Pu	0.2369	0.2341	0.2343
²⁴¹ Pu ^a	0.0221	0.0226	0.0260
²⁴² Pu	0.0031	0.0032	0.0038
²⁴¹ Am ^a	0.0195	0.0179	0.0104

^a Atom densities corrected for ²⁴¹Pu decay to 7/1/75.

TABLE I-3. Number of Drawers per Half, Corresponding Equivalent Radii and Fissile-Plutonium Mass for Each Zone or Region

Zone/ Region	Number of Drawers per Half	Equivalent Radius (cm)	Fissile Plutonium Mass (kg ²³⁹ Pu + ²⁴¹ Pu)
Zone I	229	47.17	303.7 ± 0.1
Zone II ^a	192	63.95	340.4 ± 0.1
Zone III ^b	92	70.60	244.0 ± 0.1
Radial Blanket	508	99.59	---
Radial Reflector	332	114.65	---

^a Zone II contains an equal number of Types 1, 2 and 3 drawers.

^b The numbers of Types 1, 2 and 3 drawers in Zone III are reported in Table I-2.

TABLE I-4. Atom Densities for the Pin Zone and Zone I Plate Unit Cells^a

Isotope \ Region	Core			Axial Blanket		
	Zone I Plate	Special Calandria	Normal Calandria	Zone I Plate	Special Calandria	Normal Calandria
Fe	13.254	12.491	12.226	8.365	12.545	12.240
Ni	1.206	1.593	1.589	1.067	1.601	1.591
Cr	2.634	3.540	3.487	2.356	3.556	3.492
Mn	0.2107	0.2596	0.2413	0.1870	0.2606	0.2416
O	14.867	14.201	14.145	15.692	14.305	14.247
Mo	0.2258	---	---	---	---	---
²³⁵ U	0.0126	0.0132	---	0.0175	0.0140	---
²³⁸ U	5.810	5.819	---	8.176	6.871	---
²³⁸ Pu	0.0006	0.0005	---	---	---	---
²³⁹ Pu	0.8842	0.8836	---	---	---	---
²⁴⁰ Pu	0.1171	0.1177	---	---	---	---
²⁴¹ Pu ^b	0.0130	0.0144	---	---	---	---
²⁴² Pu	0.0019	0.0020	---	---	---	---
²⁴¹ Am ^b	0.0052	0.0113	---	---	---	---

^a Units of 10²¹ atoms/cc.^b Atom densities corrected for ²⁴¹Pu decay to 7/1/75.

TABLE I-5. Fuel Loadings for the GCFR Phase III Approach-to-Critical

Loading Step	ZPR-9		Fissile Plutonium Mass ^a (kg ²³⁹ Pu + ²⁴¹ Pu)
	Loading Numbers	Date	
1	1-13	6/10/76	479.3
2	14-18	6/16/76	644.1
3	19-22	6/21/76	723.8
4	23,24	6/23/76	792.6
5	25	6/24/76	856.2
6	26	6/25/76	888.1

^a The values of the fissile plutonium mass have been adjusted to reflect ²⁴¹Pu decay as of 7/1/76.

TABLE I-6. Estimated Critical Mass of Fissile Plutonium, M_c (kg),
Using $1/C$ vs. M_f Technique^a

Channel Number	Description	Loading Step			
		No. 2	No. 3	No. 4	No. 5
1	^{235}U FC, S23/23-24"	707	853	871	884
2	^{235}U FC, M23/23-24"	708	854	873	884
3	SP-10, Movable Half	797	827	859	884
4	SP-11, Stationary Half	809	826	858	882
5	Reactor Channel No. 1	808	844	868	894
6	Reactor Channel No. 2	811	847	870	892
7	Reactor Channel No. 3	776	840	-	-
8	Reactor Channel No. 4	789	832	862	882
9	Reactor Channel No. 5	769	838	869	881
10	Reactor Channel No. 6	824	835	862	883

^a The data were accumulated with the assembly in the most reactive configuration.

TABLE I-7. Estimated Critical Mass of Fissile Plutonium, M_c (kg),
Using $1/C$ vs. M_f Technique^a

Channel Number	Description	Loading Step			
		No. 2	No. 3	No. 4	No. 5
1	^{235}U FC, S23/23-24"	724	905	888	887
2	^{235}U FC, M23/23-24"	725	907	891	887
3	SP-10, Movable Half	878	862	872	887
4	SP-11, Stationary Half	883	860	872	885
5	Reactor Channel No. 1	874	890	884	899
6	Reactor Channel No. 2	881	894	888	897
7	Reactor Channel No. 3	854	883	-	-
8	Reactor Channel No. 4	832	870	877	885
9	Reactor Channel No. 5	776	879	886	884
10	Reactor Channel No. 6	843	875	877	886

^a The data were accumulated with the assembly in the most reactive configuration.

TABLE I-8. Summary of the Reactivity Corrections and the Corresponding Adjustments to the GCFR Phase III Reference Assembly Critical Mass^a

Correction	Δk (lh)	Δm (kg) ^b
1. Excess Reactivity with Temperature Correction	-217.2 ± 1.7	-7.78 ± 0.08
2. Source Subcriticality Correction	2.7 ± 0.2	0.10 ± 0.01
3. Radial Blanket/Core Zone III Edge Smoothing Corrections ^c	-28.5 ± 2.9	-1.02 ± 0.10
Sum	-243.0 ± 3.4	-8.70 ± 0.13
Reference Configuration Critical Mass		888.1 ± 0.2 kg
Sum of Mass Corrections		-8.7 ± 0.1 kg
Zero-excess Critical Mass		879.4 ± 0.2 kg

^aAll values of the fissile-plutonium mass have been adjusted to reflect ²⁴¹Pu decay as of 7/1/76.

^bThe $\Delta\rho$ to Δm conversion is computed using the operational value of the edge-fuel worth of 27.9 ± 0.2 lh/kg.

^cSimilar corrections for the Zone I/Zone II and Zone II/Zone III boundaries are not included, but are expected to be of comparable magnitude.

TABLE I-9. Summary of ZPR-9 GCFR Phase III Operational Measurements

Measurement	Value
Reactivity Excess of Reference Configuration	214.5 ± 1.7 lh
Configuration Reproducibility	± 0.7 lh
Temperature Coefficient	-3.00 ± 0.03 lh/ ^o C
DP and ¹⁰ B Rod Worths	See Table I-10
Source Subcriticality at Reference Power Level	2.7 ± 0.2 lh
Core Edge Drawer Worth	36.9 ± 0.3 lh/drawer
Edge Fuel Worth	27.9 ± 0.2 lh/kg
Calculated ²⁴¹ Pu Decay Coefficient	0.12 ± 0.01^a lh/day

^aEstimated uncertainty.

TABLE I-10. Locations and Measured Worths of the ZPR-9 Control Rods for the GCFR Phase III Assembly

Identification	Location	Worth (lh)	
		SP-10	SP-11
DP # 1	M-19/26	34.4	34.3
2	M-22/29	32.2	32.2
3	M-28/26	33.0	33.0
4	M-24/17	33.7	33.7
5	M-18/20	33.5	33.5
6	S-16/29	-	64.3
7	S-22/29	33.1	33.2
8	S-27/26	-	34.9
9	S-24/17	33.5	33.6
10	S-15/20	28.7	28.7
¹⁰ B # 1 ^a	M-30/23	245.3	245.6
2	M-19/30	146.8	146.0
3	M-27/30	149.7	149.6
4 ^a	M-16/23	322.1	316.3
5	M-27/16	152.9	152.8
6	M-19/16	153.8	153.0
7	S-30/23	161.9	162.2
8	S-19/30	155.6	156.3
9	S-27/30	148.3	148.7
10 ^a	S-16/23	250.5	255.0
11	S-27/16	154.2	154.3
12	S-19/16	151.2	152.0

^aDual bladed assemblies with ¹⁰B blades in the drawers on both sides of the center drawer listed.

TABLE 11-1. Energy/Lethargy Group Structure
for the 29-Group Calculations

Group No.	Upper Energy, eV	Lethargy
1	1.4191×10^7	0.00
2	1.0000×10^7	0.35
3	6.0653×10^6	0.85
4	3.6788×10^6	1.35
5	2.2313×10^6	1.85
6	1.3534×10^6	2.35
7	8.2085×10^5	2.85
8	4.9787×10^5	3.35
9	3.0197×10^5	3.85
10	1.8316×10^5	4.35
11	1.1109×10^5	4.85
12	6.7379×10^4	5.35
13	4.0868×10^4	5.85
14	2.4788×10^4	6.35
15	1.5034×10^4	6.85
16	9.1188×10^3	7.35
17	5.5308×10^3	7.85
18	3.3546×10^3	8.35
19	2.0347×10^3	8.85
20	1.2341×10^3	9.35
21	7.4852×10^2	9.85
22	4.5400×10^2	10.35
23	2.7536×10^2	10.85
24	1.0130×10^2	11.85
25	3.7267×10^1	12.85
26	1.3740×10^1	13.85
27	5.0435×10^0	14.85
28	1.8554×10^0	15.85
29	4.1399×10^{-1}	17.35

TABLE 11-2. Benoist Anisotropic Diffusion Coefficient Multipliers, M_i ,
for the GCFR-III Plate Unit Cells

Group Number	Core			Axial Blanket			Radial Blanket
	Zone I	Zone II	Zone III	Zone I	Zone II	Zone III	
1	1.0408	1.0419	1.0402	1.0316	1.0269	1.0243	1.0246
2	1.0426	1.0440	1.0429	1.0319	1.0265	1.0250	1.0246
3	1.0483	1.0502	1.0492	1.0353	1.0298	1.0276	1.0276
4	1.0514	1.0544	1.0531	1.0358	1.0301	1.0288	1.0285
5	1.0644	1.0643	1.0628	1.0500	1.0428	1.0394	1.0398
6	1.0931	1.0867	1.0856	1.0822	1.0739	1.0712	1.0738
7	1.0830	1.0807	1.0803	1.0690	1.0606	1.0582	1.0591
8	1.1360	1.1256	1.1222	1.1234	1.1114	1.1090	1.1122
9	1.1229	1.1174	1.1158	1.1050	1.0922	1.0884	1.0902
10	1.1323	1.1267	1.1279	1.1142	1.1006	1.0975	1.0986
11	1.1380	1.1356	1.1360	1.1126	1.0971	1.0927	1.0928
12	1.1453	1.1445	1.1452	1.1156	1.0991	1.0943	1.0943
13	1.1493	1.1542	1.1509	1.1027	1.0856	1.0798	1.0775
14	1.1472	1.1413	1.1466	1.1253	1.1094	1.1054	1.1044
15	1.1438	1.1440	1.1430	1.1105	1.0929	1.0872	1.0857
16	1.1606	1.1772	1.1648	1.1054	1.0905	1.0912	1.0834
17	1.1496	1.1575	1.1519	1.1052	1.0878	1.0852	1.0797
18	1.1553	1.1657	1.1596	1.1047	1.0983	1.0847	1.0794
19	1.1668	1.1778	1.1738	1.1074	1.0906	1.0840	1.0809
20	1.1740	1.1884	1.1836	1.1067	1.0902	1.0841	1.0803
21	1.1779	1.1955	1.1896	1.1011	1.0842	1.0796	1.0758
22	1.1714	1.1944	1.1796	1.1017	1.1006	1.0901	1.0824
23	1.2094	1.2340	1.2313	1.1076	1.0894	1.0852	1.0808
24	1.2693	1.3121	1.3223	1.1001	0.0826	1.0796	1.0752
25	1.2616	1.2766	1.2953	1.1418	1.1164	1.1142	1.1099
26	1.3501	1.3600	1.3901	1.1138	1.0932	1.0918	1.0868
27	1.1847	1.2087	1.2025	1.1004	1.0830	1.0804	1.0758
28	1.4931	1.5417	1.7753	1.0928	1.0773	1.0753	1.0704
29	3.6353	4.2561	4.7431	1.0995	1.0835	1.0889	1.0808

TABLE II-3. Benoist Anisotropic Diffusion Coefficient Multipliers, $M_{\perp}$
for the GCFR-III Plate Unit Cells

Group Number	Core			Axial Blanket			Radial Blanket
	Zone I	Zone II	Zone III	Zone I	Zone II	Zone III	
1	1.0010	1.0013	1.0009	1.0007	1.0007	1.0006	1.0007
2	1.0011	1.0015	1.0011	1.0008	1.0007	1.0006	1.0008
3	1.0015	1.0020	1.0014	1.0010	1.0009	1.0008	1.0010
4	1.0017	1.0023	1.0016	1.0011	1.0010	1.0009	1.0012
5	1.0022	1.0028	1.0021	1.0017	1.0016	1.0013	1.0016
6	1.0032	1.0034	1.0030	1.0030	1.0031	1.0029	1.0035
7	1.0030	1.0036	1.0030	1.0025	1.0025	1.0022	1.0027
8	1.0065	1.0066	1.0061	1.0063	1.0066	1.0064	1.0075
9	1.0064	1.0071	1.0062	1.0056	1.0055	1.0049	1.0060
10	1.0073	1.0082	1.0075	1.0063	1.0063	1.0058	1.0070
11	1.0094	1.0110	1.0093	1.0074	1.0070	1.0062	1.0076
12	1.0108	1.0130	1.0107	1.0082	1.0076	1.0068	1.0083
13	1.0138	1.0175	1.0124	1.0096	1.0084	1.0072	1.0090
14	1.0101	1.0111	1.0105	1.0085	1.0081	1.0076	1.0090
15	1.0131	1.0159	1.0123	1.0097	1.0086	1.0075	1.0093
16	1.0237	1.0342	1.0213	1.0184	1.0157	1.0177	1.0186
17	1.0194	1.0256	1.0176	1.0148	1.0124	1.0125	1.0140
18	1.0202	1.0274	1.0184	1.0147	1.0136	1.0125	1.0140
19	1.0195	1.0263	1.0181	1.0118	1.0102	1.0091	1.0109
20	1.0218	1.0300	1.0201	1.0125	1.0107	1.0098	1.0116
21	1.0230	1.0321	1.0210	1.0120	1.0101	1.0094	1.0110
22	1.0268	1.0400	1.0240	1.0191	1.0183	1.0187	1.0193
23	1.0319	1.0441	1.0298	1.0136	1.0114	1.0109	1.0126
24	1.0509	1.0683	1.0503	1.0126	1.0105	1.0102	1.0117
25	1.0413	1.0531	1.0440	1.0179	1.0148	1.0147	1.0173
26	1.0786	1.0838	1.0682	1.0140	1.0116	1.0118	1.0135
27	1.0259	1.0374	1.0240	1.0128	1.0107	1.0106	1.0121
28	1.1415	1.1551	1.1954	1.0124	1.0104	1.0105	1.0117
29	2.4850	2.7449	2.7300	1.0163	1.0135	1.0168	1.0174

TABLE II-4. Comparison of Benoist Anisotropic Diffusion Coefficient Multipliers for the GCFR-III Central Pin and Plate Zones

Group	M_Z				M_R			
	Core		Axial Blanket		Core		Axial Blanket	
	Plate	Pin	Plate	Pin	Plate	Pin	Plate	Pin
1	1.0408	1.00725	1.0316	1.00841	1.0209	1.00368	1.0162	1.00427
2	1.0426	1.00633	1.0319	1.00739	1.0219	1.00322	1.0164	1.00376
3	1.0483	1.00723	1.0353	1.00819	1.0249	1.00369	1.0182	1.00419
4	1.0514	1.00710	1.0358	1.00768	1.0266	1.00363	1.0184	1.00393
5	1.0644	1.01327	1.0500	1.01507	1.0333	1.00680	1.0258	1.00773
6	1.0931	1.03180	1.0822	1.03461	1.0482	1.01627	1.0426	1.01769
7	1.0830	1.02330	1.0690	1.02632	1.0430	1.01194	1.0357	1.01348
8	1.1360	1.04949	1.1234	1.05464	1.0713	1.02556	1.0649	1.02821
9	1.1229	1.03727	1.1050	1.04168	1.0647	1.01934	1.0553	1.02163
10	1.1323	1.04132	1.1142	1.04663	1.0698	1.02147	1.0603	1.02422
11	1.1380	1.03502	1.1126	1.04016	1.0737	1.01841	1.0600	1.02110
12	1.1453	1.03423	1.1156	1.03888	1.0780	1.01808	1.0619	1.02055
13	1.1493	1.02129	1.1027	1.02533	1.0816	1.01141	1.0562	1.01357
14	1.1472	1.04436	1.1253	1.04857	1.0786	1.02329	1.0669	1.02551
15	1.1438	1.02435	1.1105	1.02773	1.0784	1.01306	1.0601	1.01488
16	1.1606	1.00268	1.1054	1.00382	1.0922	1.00148	1.0619	1.00210
17	1.1496	1.00793	1.1052	1.00950	1.0845	1.00435	1.0600	1.00521
18	1.1553	1.00953	1.1047	1.01016	1.0877	1.00522	1.0597	1.00557
19	1.1668	1.01795	1.1074	1.01871	1.0932	1.00976	1.0596	1.01016
20	1.1740	1.01679	1.1067	1.01647	1.0979	1.00916	1.0596	1.00897
21	1.1779	1.01598	1.1011	1.01359	1.1005	1.00872	1.0566	1.00739
22	1.1714	1.00372	1.1017	1.00203	1.0991	1.00205	1.0604	1.00112
23	1.2094	1.02070	1.1076	1.01441	1.1206	1.01140	1.0606	1.00788
24	1.2693	1.03007	1.1001	1.01126	1.1601	1.01664	1.0564	1.00614
25	1.2616	1.04455	1.1418	1.03327	1.1515	1.02483	1.0798	1.01843
26	1.3501	1.04147	1.1138	1.01809	1.2144	1.02309	1.0639	1.00992
27	1.1847	1.01328	1.1004	1.01044	1.1053	1.00727	1.0566	1.00570
28	1.4931	1.04085	1.0928	1.00674	1.3173	1.02278	1.0526	1.00366
29	3.6353	1.65612	1.0995	1.00359	3.0602	1.41827	1.0579	1.00197

TABLE II-5. Kinetics Parameters for the GCFR Phase III Assembly

Radial D's	With streaming	With axial streaming	Without streaming
	Benoist	Isotropic	Isotropic
Axial D's	Benoist	Benoist	Isotropic
Effective Delayed Neutron Fraction, β_{eff}	3.3743×10^{-3}	3.3701×10^{-3}	3.3623×10^{-3}
Prompt Neutron Lifetime, $\lambda_p(\text{sec})$	4.1765×10^{-7}	4.1906×10^{-7}	4.1981×10^{-7}
Neutron Generation Time, $\Lambda(\text{sec})$	4.2373×10^{-7}	4.2260×10^{-7}	4.2023×10^{-7}
Inhours per Percent Reactivity, $\text{Ih}/\%k$	9.5683×10^2	9.5695×10^2	9.5753×10^2
Inhours per Dollar Reactivity, $\text{Ih}/\$$	3.2286×10^2	3.2250×10^2	3.2195×10^2
Normalized Perturbation Denominator	4.2584×10^5	4.2250×10^5	4.1748×10^5
Effective Multiplication Factor, k_{eff}	0.9856	0.9916	0.9990

TABLE II-6. Delayed Neutron Fractions and Effective Decay Constants for the GCFR Phase III Assembly

Isotope (i)	Family (j)						Total, β_i^a	Effective Decay Constant, λ_i^c (sec ⁻¹)
	1	2	3	4	5	6		
²³⁵ U	2.22 ⁻⁶	1.38 ⁻⁵	1.12 ⁻⁵	2.45 ⁻⁵	7.71 ⁻⁶	1.57 ⁻⁶	6.10 ⁻⁵	7.71 ⁻²
²³⁸ U	2.15 ⁻⁵	2.49 ⁻⁴	2.73 ⁻⁴	6.57 ⁻⁴	3.78 ⁻⁴	1.26 ⁻⁴	1.70 ⁻³	1.27 ⁻¹
²³⁹ Pu	5.44 ⁻⁵	4.33 ⁻⁴	3.10 ⁻⁴	4.76 ⁻⁴	1.49 ⁻⁴	5.08 ⁻⁵	1.47 ⁻³	6.69 ⁻²
²⁴⁰ Pu	1.81 ⁻⁶	1.91 ⁻⁵	1.25 ⁻⁵	2.29 ⁻⁵	8.39 ⁻⁶	1.90 ⁻⁶	6.65 ⁻⁵	7.26 ⁻²
²⁴¹⁺²⁴² Pu	6.71 ⁻⁷	1.66 ⁻⁵	1.17 ⁻⁵	2.65 ⁻⁵	1.24 ⁻⁵	1.09 ⁻⁶	6.89 ⁻⁵	8.78 ⁻²
Total, β_j^b	8.06 ⁻⁵	7.31 ⁻⁴	6.18 ⁻⁴	1.21 ⁻³	5.56 ⁻⁴	1.81 ⁻⁴	3.37 ⁻³ ^e	---
Effective Decay Constant, λ_j^d (sec ⁻¹)	1.30 ⁻²	3.14 ⁻²	1.36 ⁻¹	3.46 ⁻¹	1.37 ⁻⁰	3.76 ⁻⁰	---	8.88 ⁻² ^f

$$^a \beta_i = \sum_j \beta_{ij}$$

$$^b \beta_j = \sum_i \beta_{ij}$$

$$^c \lambda_i = \beta_i / \sum_j (\beta_{ij} / \lambda_{ij}); \text{ see Table II-7 for } \lambda_{ij}.$$

$$^d \lambda_j = \beta_j / \sum_i (\beta_{ij} / \lambda_{ij}); \text{ see Table II-7 for } \lambda_{ij}.$$

$$^e \beta = \sum_i \beta_i = \sum_j \beta_j$$

$$^f \lambda = \beta / \sum_i (\beta_i / \lambda_i) = \beta / \sum_j (\beta_j / \lambda_j).$$

TABLE II-7. Decay Constants, λ_{ij} (sec⁻¹)

Isotope (i)	Family (j)					
	1	2	3	4	5	6
²³⁵ U	0.01272	0.03174	0.116	0.311	1.40	3.87
²³⁸ U	0.01323	0.03212	0.139	0.359	1.41	4.03
²³⁹ Pu	0.01290	0.03110	0.134	0.332	1.26	3.21
²⁴⁰ Pu	0.01294	0.03131	0.135	0.333	1.36	4.03
²⁴¹ Pu ^a	0.01280	0.02990	0.124	0.352	1.61	3.47

^a²⁴¹Pu data used for ²⁴²Pu.

TABLE II-8. Summary of Calculated Eigenvalues and Kinetics Parameters for Plate and Pin Zone Reference Configurations

Assembly	D's ^a		
		Isotropic	Benoist
Plate Reference		$k_{eff} = 0.98753$	$k_{eff} = 0.98564$
		$\beta_{eff} = 3.4597-3$	$\beta_{eff} = 3.4609-3$
		$Ih/(\delta k/k) = 9.5066+2$	$Ih/(\delta k/k) = 9.5061+2$
		$\delta k = 0.00242$	$\delta k = 0.00109$
Pin-Zone Reference		$k_{eff} = 0.98511$	$k_{eff} = 0.98455$
		$\beta_{eff} = 3.4733-3$	$\beta_{eff} = 3.4736-3$
		$Ih/(\delta k/k) = 9.4736+2$	$Ih/(\delta k/k) = 9.4736+2$
		$\delta k = 0.00056$	$\delta k = 0.00031$
Pin-Zone Modified ^b		---	$k_{eff} = 0.98595$

^a Diffusion coefficient type in 85 drawer central zone. Benoist diffusion coefficients in all other core and blanket regions.

^b Calculational pin zone RZ model with Zone III/radial blanket boundary identical to that of plate reference RZ model.

TABLE II-9. Worth of Pin Zone Replacing Plate Zone:
Experimental Determination

Step	State or Operation	Change in Excess	Excess (Ih)
1	Plate Reference 8/18/76	---	+193.1 $\pm$ 2.2
2	Remove 4 edge drawers	-4*(36.94 $\pm$ 0.28) = -147.76 $\pm$ 1.12	
3	Decay ^{241}Pu for 9 days	-9*(0.12 $\pm$ 0.01) = -1.08 $\pm$ 0.09	
4	Pin Zone Reference Configuration With Plates in the Zone	---	+44.3 $\pm$ 2.5
5	Pin Zone Reference	---	+12.6 $\pm$ 1.2
6	Replace Plates by Pins	12.6 $\pm$ 1.2 -44.3 $\pm$ 2.5 = -31.7 $\pm$ 2.8	

TABLE II-10. Worth of Pin Zone Replacing Plate Zone:
Calculational Determination of Components and Total Worth

Step	State or Operation	Change in Excess	Excess
1	Plate Reference	---	$k_1 = 0.98564$
2	Plate $\rightarrow$ Pin Composition (Composition Change)	$(k_3 - k_1) = +0.00166$ = +157.80 Ih	
3	Plate $\rightarrow$ Pin Cross Sections (Heterogeneity Change)	$(k_4 - k_3) = -0.00264$ -250.96 Ih	
4	Plate $\rightarrow$ Pin Diffusion Coeff. (Streaming Change)	$(k_6 - k_4) = +0.00129$ = +122.63 Ih	
5	Sum of Effects yields Pin Zone in the Plate Reference Outer Core Boundary	$\Delta\rho = (k_3 - k_1)$ $+ (k_4 - k_3)$ $+ (k_6 - k_4)$ = +29.47 Ih	$k_6 = 0.98595$
	C-E	= +29.47 - (-31.66) = 61.13 Ih = 0.0006 Δk	
6	Remove Edge Drawers	$(k_7 - k_6) = -0.0014$ = -132.63 Ih	$k_7 = 0.98455$
	C/E	= 132.63/147.76 = 0.90	

TABLE II-11. Calculated Components of the Pin-for-Plate Replacement Worth

Calculation Number	Outer Boundary	Central Zone			Result	
		Number Densities	σ 's	D's	k	$I_h/\% \Delta k$
1	Plate Reference	plate	plate	Benoist plate	0.98564	950.61
2	" "	plate	plate	Isotropic plate	0.98763	
3	" "	pin	plate	Benoist plate	0.98730	
4	" "	pin	pin	Benoist plate	0.98466	
5	" "	plate	pin	Benoist plate	0.98309	
6	" "	pin	pin	Benoist pin	0.98595	
7	Pin Reference	pin	pin	Benoist pin	0.98455	947.36
8	" "	pin	pin	Isotropic pin	0.98511	

TABLE III-1. Reactivity Worth Sample Description

Sample ID	Major Sample Component	Material State	Sample Geometry	Sample Size, In.			Sample Mass, g	Sample Composition ^a or Purity	Capsule Mass, g	Capsule Description
				O.D.	Length	Wall Thickness				
PU-25	239PU-AL	Metal	Cylinder	0.100	2.173	---	4.480	P239-B	10.758	II
PU-27	239PU-AL	Metal	Cylinder	0.200	2.173	---	17.062	P239-B	11.207	II
MB-10	239PU-AL	Metal	Annulus	0.835	1.156	0.015	9.956	P239-A	13.458	I
PU-240-2D	240PUO ₂	Powder	Annulus	0.604	1.800	0.205	45.135	P240-A	28.821	IV
U-233-3	233U	Metal	Strip	0.830	1.805	0.010	4.158	U233-A	16.513	VI
MB-21	233U	Metal	Annulus	0.835	1.688	0.015	15.778	U235-A	13.729	I
U-3	235U	Metal	Cylinder	0.200	2.173	---	21.015	U235-C	11.112	II
MB-25	238U	Metal	Annulus	0.835	1.688	0.036	38.163	U238-A	13.691	I
A-7	10B	Powder	Annulus	0.400	2.173	0.0094	0.4968	B10-A	20.776	VII
LI-5	6Li	Metal	Cylinder	0.309	1.678	---	0.9736	LI6-A	2.0468	XI
CH2(F)-1	POLYETHYLENE	Foam	Cylinder	0.875	2.656	---	0.843	CH2-A	---	Bare Sample
CH2(F)-6	POLYETHYLENE	Foam	Cylinder	0.975	2.00	---	0.898	CH2-A	---	Bare Sample
POLY-1	POLYETHYLENE	Solid	Cylinder	0.390	2.173	---	4.024	(CH2,CH2)N	10.567	II
H2O-1A	H ₂ O	Liquid	Cylinder	0.440	1.710	---	4.177	99.9999%	6.648	XII
FE-1	FE	Metal	Cylinder	0.389	2.172	---	33.277	99.99%	10.611	II
CR-3	CR	Metal	Cylinder	0.375	2.173	---	26.999	99.996%	10.644	II
MN-1	MN	Powder	Cylinder	0.399	2.173	---	18.010	99.99%	10.343	II
D-1	SST DUMMY	---	---	0.420	2.625	0.010	---	---	10.667	II
MB-19	SST DUMMY	---	---	---	---	---	---	---	13.807	I
MT-RAH-4	RABBIT CAN	---	---	---	---	---	---	---	57.670	X
DUM-2D	INCONEL DUM.	---	---	---	---	---	---	---	28.473	IV
LI-DUM	ALUM. DUMMY	---	---	0.352	1.99	0.020	---	---	2.0545	XI
NSD-56 ^c	NEUT. SOURCE	Solid	Point	---	---	---	0.0000374	C252-A	---	XIII

Capsule Description:

I- Material: 304 SST.^d

Size, inches: O.D., 0.865; length, 2.00; wall and end thickness, 0.015. Ends are recessed 0.094 inches.

II- Material: 304 SST.

Size, inches: O.D., 0.420; length, 2.625; wall thickness, 0.010; end thicknesses, 0.226.

IV- Material: Inconel 600.^e

Size, inches: O.D. outer cylinder, 0.670; O.D., inner cylinder, 0.195; wall thickness, outer cylinder, 0.033; wall thickness, inner cylinder, 0.030; length, 2.00; end thicknesses, 0.090 and 0.110. Capsule has 0.135 inch diameter axial hole through center.

VI- Material: 304 SST.

Size, inches: O.D., 0.420; length, 2.625; wall thickness, 0.010; end thicknesses, 0.310.

VII- Material: 304 SST.

Size, inches: O.D., outer cylinder, 0.420; O.D., inner cylinder, 0.380; wall thickness, outer cylinder, 0.010; wall thickness, inner cylinder, 0.020; length, 2.625; end thicknesses, 0.392.

X- Material: 304 SST.

Size, inches: O.D., 0.938; length, 2.719; wall thickness, 0.031 for 2.00 inches of inside length, 0.094 for the next 0.437 inches of inside length, 0.253 for the last 0.219 inches of inside length; end thicknesses, 0.031.

XI- Material: Aluminum.

Size, inches: O.D., 0.352; length, 1.99; wall and end thickness, 0.020. Ends are recessed 0.12 inches.

XII- Material: 304 SST.

Size, inches: O.D., 0.470; length, 2.00; wall and end thickness, 0.015. Ends are recessed 0.094 inches.

XIII- Material: 304L SST.

Size, inches--capsule portion: O.D., 0.500; length, 1.525; wall and bottom thickness, 0.100; top thickness, 0.375.

Size, inches--threaded portion: O.D., 0.250; length, 0.462. Overall length is 1.987 inches with the threaded portion at the top end of the capsule.

^aSee Table III-2.^bDimension is sample width.^cNSD-56 is a californium neutron source with the point source deposit of Cf encapsulated in an aluminum pellet. The Cf is located about 0.233 inches from the bottom of the capsule.^dTypical analysis of 304 SST: Fe, 70.39 w/o; CR, 18 w/o; NI, 9.71 w/o; MN, 1.46 w/o.^eTypical analysis of Inconel 600: NI, 75.8 w/o; CR, 15.74 w/o; FE, 7.72 w/o; SI, 0.22 w/o; MN, 0.20 w/o; CU, 0.11 w/o.

TABLE III-2. Reactivity Worth Sample Composition

Sample ID	Composition ID	Sample Material	Sample Mass, (g)	Material Composition, w/o	Isotopic Composition, w/o
MB-10	P239-A	PU-AL	9.956	PU - 97.985 AL - 1.208	²³⁹ PU - 98.932 ²⁴⁰ PU - 1.012 ²⁴¹ PU - 0.053 ²⁴² PU - 0.003
PU-25 PU-27	P239-B	PU-AL	4.480 17.062	PU - 98.26 AL - 0.95 NI - 1.00 ^a FE - 0.17 ^a CR - 0.11 ^a	²³⁹ PU - 98.926 ²⁴⁰ PU - 1.023 ²⁴¹ PU - 0.049 ²⁴² PU - 0.002
PU-240-2D	P240-A	PUO ₂	45.135	PU - 86.10 O - 11.97 H - 0.035 N - 0.02	²³⁹ PU - 1.05 ²⁴⁰ PU - 93.73 ²⁴¹ PU - 0.57 ²⁴² PU - 4.65
U-233-J	U233-A	U	4.158	U - 99.8 O - 0.31 ^a FE - 0.15 ^a CR - 0.02 ^a NA - <0.01 ^a	²³³ U - 99.47 ²³⁴ U - 0.183 ²³⁵ U - 0.071 ²³⁶ U - 0.014 ²³⁸ U - 0.266
MB-21	U235-A	U	15.778	U - 100.0	²³⁴ U - 0.665 ²³⁵ U - 93.244 ²³⁶ U - 0.316 ²³⁸ U - 5.775
U-3	U235-C	U	21.015	U - 100.0	²³⁴ U - 0.945 ²³⁵ U - 93.192 ²³⁶ U - 0.259 ²³⁸ U - 5.604
MB-25	U238-A	U	38.163	U - 100.0	²³⁵ U - 0.233 ²³⁸ U - 99.767
NSD-56 ^b	C252-A	CF	0.0000374	CF ^b - -	²⁴⁹ CF 1.40 ^b ²⁵⁰ CF 7.73 ^b ²⁵¹ CF 2.17 ^b ²⁵² CF 88.34 ^b ²⁵³ CF 0.327 ^b ²⁵⁴ CF 0.037 ^b
Li-5	Li6-A	Li	0.9736	Li - 99.870 C - 0.045	⁶ Li 99.208 ⁷ Li 0.792
B-7	B10-A	BORON	0.4968	B - 94.50 O - 1.43 C - 0.96 ^a SI - 0.26 ^a H - 0.09 ^a AL - 0.05 ^a	¹⁰ B - 92.19 ¹¹ B - 7.81
CH2(F)-1 CH2(F)-6	CH2-A	POLYETHYLENE	0.843 0.898	CH2- 99.8 ^c ZN - 0.12 ^a CA - 0.10 ^a	C - 85.50 ^c H - 14.50 ^c

^aFactor of 2 uncertainty.^bNSD-56 is a spontaneous fission (²⁵²Cf) neutron source. The only composition information available is the isotopic composition of californium--date of analysis: 2/11/72.^cThe actual ratio of carbon to hydrogen atoms was determined by analysis.

TABLE III-3. Experimental Small Sample Central Reactivity Worths in GCFR Phase III

Sample ID	Principal Material or Isotope	Sample, Sample Capsule, and SST ^a Worth (lh)	Sample Mass (g)	Sample Capsule and SST ^a Mass (g)	Dummy ID	Dummy Worth Correction Factor ^b	Net Sample Worth (lh)	Specific Sample Worth (lh/kg)
Fiissile & Fertile								
Pu-25	²³⁹ Pu	0.315 ± 0.011	4.480	70.725	D-1	1.0019	0.634 ± 0.014	143 ± 3
Pu-27	²³⁹ Pu	2.095 ± 0.022	17.062	71.130	D-1	1.0076	2.415 ± 0.013	141.8 ± 1.4
MB-10	²³⁹ Pu	1.079 ± 0.012	9.956	71.029	MB-19	0.9966	1.411 ± 0.013	141.7 ± 1.3
Pu-240-2D ^c	²⁴⁰ PuO ₂	0.258 ± 0.007	45.135	67.385	SST		0.773 ± 0.013	17.2 ± 0.3
				28.821	Inconel			
U-233-3	²³³ U	0.442 ± 0.016	4.158	74.057	MB-19	1.0391	0.789 ± 0.017	189 ± 4
U-3	²³⁵ U	1.828 ± 0.022	21.015	71.079	D-1	1.0069	2.148 ± 0.024	102.3 ± 1.1
MB-21	²³⁵ U	1.297 ± 0.013	15.778	71.302	MB-19	0.9996	1.630 ± 0.014	103.3 ± 0.9
MB-25	²³⁸ U	-0.625 ± 0.011	38.163	71.329	MB-19	1.0008	-0.291 ± 0.012	-7.65 ± 0.32
Structurals								
FE-1	Fe	-0.445 ± 0.007	33.277	70.418	D-1	0.9976	-0.128 ± 0.011	-3.85 ± 0.34
CR-3	Cr	-0.428 ± 0.011	26.999	70.551	D-1	0.9994	-0.110 ± 0.014	-4.07 ± 0.53
MM-1	Mn	-0.448 ± 0.007	18.010	70.310	D-1	0.9960	-0.131 ± 0.011	-7.27 ± 0.63
D-1	SST	-0.318 ± 0.009	-	70.590	None	-	-	-4.50 ± 0.13
MB-19	SST	-0.334 ± 0.005	-	71.272	None	-	-	-4.68 ± 0.07
MT	SST	-0.270 ± 0.003	-	57.670	None	-	-	-4.68 ± 0.05
DUM-2D	Inconel	-0.484 ± 0.006	24.473	67.385	MT	1.1685	-0.169 ± 0.009	-6.91 ± 0.35
Scatterers								
CH ₂ (F)-1	CH ₂ (foam)	-0.262 ± 0.007	0.8434	57.638	MT	0.9964	+0.007 ± 0.009	8 ± 10
CH ₂ (F)-6	CH ₂ (foam)	+0.008 ± 0.004	0.914	-	None	-	-	9 ± 4
POLY-1	CH ₂	0.306 ± 0.013	4.024	70.534	D-1	0.9992	0.624 ± 0.016	155 ± 4
H ₂ O-1A	H ₂ O	0.121 ± 0.012	4.177	71.104	MB-19	0.9976	0.453 ± 0.013	108 ± 3
Absorbers								
LI-5	⁶ Li	-1.767 ± 0.019	0.97359	-	LI-DUM	-	-1.462 ± 0.020	-1501 ± 20
B-7	¹⁰ B	-1.335 ± 0.018	0.4968	80.667	D-1	1.1427	-0.972 ± 0.020	-1956 ± 40
					MB-19	1.1318	-0.958 ± 0.019	-1928 ± 38

^aSST refers to the stainless steel capsule holders and stainless steel shims or spacers, if used.^bRatio of sample capsule and SST mass to dummy capsule and SST mass.^cDummy, DUM-2D + capsule holder, is composed of INCONEL and SST, respectively.

TABLE III-4. Experimental Small Sample Radial Reactivity Worth Traverses in GCFR Phase III

Sample ID	Principal Material or Isotope	Radial Position (col)	(cm)	Sample, Sample Capsule, and SST Worth (lh)	Sample Mass (g)	Sample Capsule and SST Mass (g)	Dummy ID	Dummy Worth Adjustment Factor ^b	Net Sample Worth (lh)	Specific Sample Worth (lh/kg)
MB-10	²³⁹ Pu	23	0.00	1.079 ± 0.012	9.956	71.029	MB-19	0.9966	1.411 ± 0.013	141.7 ± 1.3
		24	5.52	1.066 ± 0.012					1.382 ± 0.016	138.8 ± 1.6
		26	16.57	1.016 ± 0.012					1.307 ± 0.014	131.2 ± 1.4
		28	27.62	0.926 ± 0.012					1.169 ± 0.013	117.4 ± 1.3
		30	38.67	0.824 ± 0.009					1.014 ± 0.013	101.7 ± 1.3
		33	55.25	0.681 ± 0.007					0.652 ± 0.009	65.5 ± 0.9
		35	66.29	0.562 ± 0.011					0.395 ± 0.012	39.6 ± 1.2
		38	82.87	0.181 ± 0.008					0.137 ± 0.009	13.8 ± 0.9
MB-21	²³⁵ U	23	0.00	1.297 ± 0.013	15.778	71.302	MB-19	0.9996	1.630 ± 0.014	103.3 ± 0.9
		24	5.52	1.275 ± 0.014					1.592 ± 0.018	100.9 ± 1.1
		26	16.57	1.229 ± 0.013					1.521 ± 0.015	96.4 ± 1.0
		29	33.15	1.054 ± 0.017					1.281 ± 0.019	81.2 ± 1.2
		33	55.25	0.777 ± 0.010					0.748 ± 0.011	47.4 ± 0.7
		35	66.29	0.651 ± 0.007					0.483 ± 0.009	30.6 ± 0.6
		38	82.87	0.264 ± 0.006					0.220 ± 0.008	13.9 ± 0.5
MB-25	²³⁸ U	23	0.00	-0.625 ± 0.011	38.163	71.329	MB-19	1.0008	-0.291 ± 0.012	-7.65 ± 0.32
		26	16.57	-0.566 ± 0.007					-0.274 ± 0.011	-7.17 ± 0.29
		29	33.15	-0.434 ± 0.005					-0.207 ± 0.009	-5.42 ± 0.25
		33	55.25	-0.035 ± 0.009					-0.064 ± 0.010	-1.68 ± 0.27
		35	66.29	+0.159 ± 0.008					-0.009 ± 0.009	-0.24 ± 0.25
		38	82.87	+0.061 ± 0.007					+0.017 ± 0.009	+0.45 ± 0.24
MB-19	SST	23	0.00	-0.334 ± 0.005	---	71.272	None	---	---	-4.68 ± 0.07
		24	5.52	-0.317 ± 0.011					---	-4.45 ± 0.15
		26	16.57	-0.292 ± 0.008					---	-4.10 ± 0.11
		28	27.62	-0.244 ± 0.006					---	-3.42 ± 0.08
		29	33.15	-0.227 ± 0.007					---	-3.18 ± 0.11
		30	38.67	-0.191 ± 0.008					---	-2.68 ± 0.13
		33	55.25	+0.029 ± 0.005					---	+0.41 ± 0.07
		35	66.29	+0.168 ± 0.005					---	+2.36 ± 0.07
		38	82.87	+0.044 ± 0.005					---	+0.62 ± 0.07
B-7	B	23	0.00	-1.335 ± 0.018	0.4968	80.667	MB-19	1.1318	-0.958 ± 0.019	-1928 ± 38
		26	16.57	-1.230 ± 0.014					-0.900 ± 0.017	-1812 ± 34
		29	33.15	-1.016 ± 0.011					-0.759 ± 0.014	-1528 ± 28
		33	55.25	-0.410 ± 0.007					-0.443 ± 0.009	-892 ± 18
		35	66.29	-0.073 ± 0.008					-0.263 ± 0.010	-529 ± 20
		38	82.87	+0.016 ± 0.005					-0.034 ± 0.008	-68 ± 16
CH ₂ (F)-6	CH ₂ (foam)	23	0.00	+0.008 ± 0.004	0.9104	---	None	---	---	9 ± 4
		26	16.57	+0.008 ± 0.003					---	9 ± 3
		29	33.15	+0.013 ± 0.002					---	14 ± 2
		33	55.25	+0.077 ± 0.005					---	85 ± 5
		35	66.29	+0.030 ± 0.004					---	33 ± 4
		38	82.87	-0.048 ± 0.003					---	-53 ± 3

^aSST refers to the stainless steel capsule holders and stainless steel shims or spacers, if used.^bRatio of sample capsule and SST mass to dummy capsule and SST mass.

TABLE III-5. LI-5 (⁶Li) Experimental Small Sample Radial Reactivity Worth Traverse in GCFR Phase III

Radial Position (col)	Radial Position (cm)	LI-5 Sample, Al Sample Capsule, and SST Worth (Ih)	Sample Mass (g)	LI-DUM Al Sample Capsule and SST Worth (Ih)	Dummy Worth Adjustment Factor	Net Sample Worth (Ih)	Specific Sample Worth (Ih/kg)
23	0.00	-1.767 ± 0.019	0.97359	-0.306 ± 0.006	0.9971	-1.462 ± 0.020	-1501 ± 20
24	5.52	-1.760 ± 0.018		-0.310 ± 0.003		-1.451 ± 0.018	-1491 ± 19
26	16.57	-1.651 ± 0.017		-0.280 ± 0.014		-1.372 ± 0.022	-1409 ± 23
28	27.62	-1.495 ± 0.015		-0.243 ± 0.005		-1.253 ± 0.016	-1287 ± 16
30	38.67	-1.238 ± 0.013		-0.184 ± 0.003		-1.055 ± 0.013	-1083 ± 14
33	55.25	-0.629 ± 0.007		+0.040 ± 0.008		-0.669 ± 0.011	-693 ± 11

^aAl capsule mass 2.0468 g; SST shims and capsule holder mass 63.192 g.^bAl capsule mass 2.0545 g; SST shims and capsule holder mass 63.374 g.TABLE III-6. ORNL-NSD-56 (²⁵²Cf) Experimental Small Sample Radial Reactivity Worth Traverse in GCFR Phase III

Sample ID	Radial Position ^a (col) (cm)		Sample Worth (Ih)			Slope ^b (Ih * Power)	Relative Worth	
			FAR Power Level:	5.45 × 10 ⁻⁶	1.00 × 10 ⁻⁵			4.90 × 10 ⁻⁵
ORNL-NSD-56	23	-1.95		2.951 ± 0.030	1.345 ± 0.014	-0.120 ± 0.003	1.8835 × 10 ⁻⁵	1.00
	24	3.58		2.949 ± 0.030	-	-0.111 ± 0.003	1.8764 × 10 ⁻⁵	0.996
	26	14.62		2.913 ± 0.029	-	-0.083 ± 0.003	1.8372 × 10 ⁻⁵	0.975
	28	25.67		2.844 ± 0.028	-	-0.033 ± 0.002	1.7642 × 10 ⁻⁵	0.937
	30	36.72		2.695 ± 0.021	-	+0.039 ± 0.001	1.6287 × 10 ⁻⁵	0.865
	33	53.30		2.481 ± 0.025	-	+0.302 ± 0.006	1.3362 × 10 ⁻⁵	0.709
	35	64.35		2.120 ± 0.023	-	+0.447 ± 0.006	1.0259 × 10 ⁻⁵	0.545

^aPoint ²⁵²Cf source -1.95 cm from center of each column.^bSlope of reactivity versus inverse power level.

TABLE III-7. Calculated and Experimental
Central Small Sample Reactivity Worths for
GCFR Phase III

Sample ID	Principal Material	Sample Worth (1h/kg)		C/E ^b	
		Calculated ^a	Experimental		
<u>Fissile & Fertile</u>					
PU-25	²³⁹ Pu	165.0	(-0.93%)	143 ± 3	1.15 ± 0.02
PU-27	²³⁹ Pu	165.0	(-0.93%)	141.8 ± 1.4	1.16 ± 0.01
MB-10	²³⁹ Pu	164.9	(-0.86%)	141.7 ± 1.3	1.16 ± 0.01
PU-240-2D	²⁴⁰ PuO ₂	20.13	(-0.77%)	17.2 ± 0.3	1.17 ± 0.02
U-233-3	²³³ U	219.9	(-0.86%)	189 ± 4	1.16 ± 0.02
U-3	²³⁵ U	123.7	(-0.85%)	102.3 ± 1.1	1.21 ± 0.01
MB-21	²³⁵ U	123.7	(-0.85%)	103.3 ± 0.9	1.20 ± 0.01
MB-25	²³⁸ U	-8.313	(-1.04%)	-7.65 ± 0.32	1.09 ± 0.05
<u>Structurals</u>					
FE-1	Fe	-5.249	(-1.30%)	-3.85 ± 0.34	1.36 ± 0.12
CR-3	Cr	-6.460	(-1.34%)	-4.07 ± 0.53	1.59 ± 0.21
MN-1	Mn	-12.73	(-1.18%)	-7.27 ± 0.63	1.75 ± 0.15
D-1 ^c	304SST	-5.931	(-1.33%)	-4.50 ± 0.13	1.32 ± 0.04
MB-19 ^c	304SST	-5.931	(-1.33%)	-4.68 ± 0.07	1.27 ± 0.02
MT	304SST	-5.931	(-1.33%)	-4.68 ± 0.05	1.27 ± 0.01
<u>Scatterers</u>					
CH ₂ (F)-6	CH ₂	-69.58	(1.78%)	9 ± 4	-7.7 ± 3.4
POLY-1	CH ₂	-69.24	---	155 ± 4	-0.45 ± 0.01
H ₂ O-1A	H ₂ O	-50.62	---	108 ± 3	-0.47 ± 0.01
<u>Absorbers</u>					
LI-5	⁶ Li	-1720	(0.88%)	-1502 ± 20	1.15 ± 0.02
B-7 ^d	¹⁰ B	-2055	(0.87%)	-1956 ± 40	1.05 ± 0.02

^aThe number in parentheses is the deviation of the axially off-center mesh (Z=4-6 cm) from the central mesh (Z=0-2 cm).

^bThe uncertainty associated with the C/E is derived solely from the uncertainty in the experimental values; $\sigma(C/E) = (C/E) \times \frac{\sigma(E)}{E}$. No sample size correction effects are included.

^cWorth of SST sample and rabbit.

^dExperimental value uses D-1 dummy.

TABLE III-8. Calculated Central Isotopic Reactivity Worths

Isotope/ Element	Calculated Worth (lh/kg)	C/E ^a
H	-316.76	-
³ He	-9657.4	-
⁴ He	-154.57	-
⁶ Li	-1735.3	1.15 ± 0.02
⁷ Li	-41.070	-
⁹ Be	-49.040	-
¹⁰ B	-2281.9	1.05 ± 0.02
¹¹ B	-31.190	-
¹² C	-27.665	-
¹⁴ N	-37.675	-
¹⁶ O	-17.086	-
²³ Na	-9.7077	-
²⁷ Al	-9.1911	-
Si	-8.7434	-
Cr	-6.4597	1.59 ± 0.21
⁵⁵ Mn	-12.730	1.75 ± 0.15
Fe	-5.2485	1.36 ± 0.12
Ni	-8.8468	-
Mo	-17.385	-
¹⁵¹ Eu	-200.97	-
¹⁵³ Eu	-127.76	-
¹⁸¹ Ta	-42.593	-
²³² Th	-16.819	-
²³³ U	221.16	1.16 ± 0.02
²³⁴ U	3.5375	-
²³⁵ U	133.22	1.20 ± 0.01
²³⁶ U	-14.559	-
²³⁸ U	-8.6430	1.09 ± 0.05
²³⁸ Pu	102.29	-
²³⁹ Pu	168.68	1.15 ± 0.01
²⁴⁰ Pu	22.854	1.17 ± 0.02
²⁴¹ Pu	240.14	-
²⁴² Pu	18.081	-
²⁴¹ Am	2.7327	-

^aSample C/E of smallest sample for which the specified isotope or element is the predominant component.

TABLE III-9. Calculated and Experimental Radial Reactivity Worth Traverse Results for MB-10 (^{239}Pu) and MB-21 (^{235}U)

	Sample Position (COL) (CM)	MB-10 (^{239}Pu)				MB-21 (^{235}U)			
		Reactivity Calculated	Worth (lh/Kg) Experimental	C/E	C-E	Reactivity Calculated	Worth (lh/Kg) Experimental	C/E	C-E
CORE ZONE I	23 0.000	164.92	141.7 $\pm$ 1.3	1.16 $\pm$ 0.01	23.2 $\pm$ 1.3	123.70	103.3 $\pm$ 0.9	1.20 $\pm$ 0.01	20.4 $\pm$ 0.9
	24 5.524	163.88	138.8 $\pm$ 1.6	1.18 $\pm$ 0.01	25.1 $\pm$ 1.6	122.89	100.9 $\pm$ 1.1	1.22 $\pm$ 0.01	22.0 $\pm$ 1.1
	25 11.049	160.75	---	---	---	120.49	---	---	---
	26 16.573	155.62	131.2 $\pm$ 1.4	1.19 $\pm$ 0.01	24.4 $\pm$ 1.4	116.52	96.4 $\pm$ 1.0	1.21 $\pm$ 0.01	20.1 $\pm$ 1.0
	27 22.098	148.56	---	---	---	111.07	---	---	---
	28 27.622	139.71	117.4 $\pm$ 1.3	1.19 $\pm$ 0.01	22.3 $\pm$ 1.3	104.21	---	---	---
	29 33.147	129.29	---	---	---	96.11	81.2 $\pm$ 1.2	1.18 $\pm$ 0.02	14.9 $\pm$ 1.2
	30 38.671	117.49	101.7 $\pm$ 1.3	1.16 $\pm$ 0.01	15.8 $\pm$ 1.3	86.92	---	---	---
	31 44.196	104.56	---	---	---	76.80	---	---	---
	(2) 32 49.720	90.48	---	---	---	65.85	---	---	---
II ^a (3)	33 55.245	75.17	65.5 $\pm$ 0.9	1.15 $\pm$ 0.02	9.7 $\pm$ 0.9	54.59	47.4 $\pm$ 0.7	1.15 $\pm$ 0.02	7.2 $\pm$ 0.7
(1)	34 60.769	59.51	---	---	---	43.57	---	---	---
II	35 66.294	44.45	39.6 $\pm$ 1.2	1.12 $\pm$ 0.03	4.8 $\pm$ 1.2	33.53	30.6 $\pm$ 0.6	1.10 $\pm$ 0.02	2.9 $\pm$ 0.6
RADIAL BLANKET	36 71.818	31.58	---	---	---	25.54	---	---	---
	37 77.343	21.59	---	---	---	18.51	---	---	---
	38 82.867	14.60	13.8 $\pm$ 0.9	1.06 $\pm$ 0.07	0.8 $\pm$ 0.9	13.02	13.9 $\pm$ 0.5	0.93 $\pm$ 0.03	-0.9 $\pm$ 0.5
	39 88.392	9.96	---	---	---	9.07	---	---	---
	40 93.916	7.19	---	---	---	6.54	---	---	---

^aThe numbers in parentheses indicate the drawer type of the three drawer unit cell zone II loading.

TABLE III-10. Calculated and Experimental Radial Reactivity Worth Traverse Results for MB-25 (^{238}U) and MB-19 (SST-304)

	Sample Position (COL) (CM)		MB-25 (^{238}U)				MB-19 (SST-304)			
			Reactivity Calculated	Worth (lh/Kg) Experimental	C/E	C-E	Reactivity Calculated	Worth (lh/Kg) Experimental	C/E	C-E
CORE ZONE I	23	0.000	-8.313	-7.65 ± 0.32	1.09 ± 0.04	-0.66 ± 0.32	-5.930	-4.68 ± 0.07	1.27 ± 0.02	-1.25 ± 0.07
	24	5.524	-8.252	---	---	---	-5.883	-4.45 ± 0.15	1.32 ± 0.05	-1.44 ± 0.15
	25	11.049	-8.071	---	---	---	-5.742	---	---	---
	26	16.573	-7.772	-7.17 ± 0.29	1.08 ± 0.04	-0.60 ± 0.29	-5.510	-4.10 ± 0.11	1.34 ± 0.04	-1.41 ± 0.11
	27	22.098	-7.360	---	---	---	-5.192	---	---	---
	28	27.622	-6.841	---	---	---	-4.796	-3.42 ± 0.08	1.40 ± 0.03	-1.37 ± 0.08
	29	33.147	-6.232	-5.42 ± 0.25	1.15 ± 0.05	-0.81 ± 0.25	-4.330	-3.18 ± 0.11	1.36 ± 0.04	-1.15 ± 0.11
	30	38.671	-5.543	---	---	---	-3.812	-2.68 ± 0.13	1.42 ± 0.06	-1.13 ± 0.13
	31	44.196	-4.789	---	---	---	-3.263	---	---	---
	(2)	32	49.720	-3.894	---	---	-2.474	---	---	---
II ^a (3)	33	55.245	-2.833	-1.68 ± 0.27	1.69 ± 0.26	-1.16 ± 0.27	-1.408	0.41 ± 0.07	-3.46 ± 0.60	-1.81 ± 0.07
(1)	34	60.769	-1.822	---	---	---	-0.350	---	---	---
III	35	66.294	-0.720	-0.24 ± 0.25	3.05 ± 3.05	-0.48 ± 0.25	1.024	2.36 ± 0.07	0.43 ± 0.01	-1.33 ± 0.07
RADIAL	36	71.818	-0.004	---	---	---	1.543	---	---	---
	37	77.343	-0.018	---	---	---	0.958	---	---	---
BLANKET	38	82.867	-0.019	0.45 ± 0.24	-0.04 ± 0.02	-0.46 ± 0.24	0.537	0.62 ± 0.07	0.87 ± 0.10	-0.08 ± 0.07
	39	88.352	-0.020	---	---	---	0.278	---	---	---
	40	93.916	-0.024	---	---	---	0.131	---	---	---

^aThe numbers in parentheses indicate the drawer type of the three drawer unit cell zone II loading.

TABLE III-11. Calculated and Experimental Radial Reactivity Worth Traverse Results for B-7 (^{10}B) and LI-5 (^6Li)

	Sample Position (COL) (CM)	B-7 (^{10}B)				LI-5 (^6Li)				
		Reactivity Worth (lh/Kg)		C/E	C-E	Reactivity Worth (lh/Kg)		C/E	C-E	
		Calculated	Experimental			Calculated	Experimental			
CORE ZONE I	23	0.000	-2054.7	-1928. $\pm$ 38.	1.07 $\pm$ 0.02	-126. $\pm$ 38.	-1719.8	-1501. $\pm$ 21.	1.15 $\pm$ 0.02	-219. $\pm$ 21.
	24	5.524	-2041.0	---	---	---	-1708.8	-1491. $\pm$ 18.	1.15 $\pm$ 0.01	-218. $\pm$ 18.
	25	11.049	-2000.1	---	---	---	-1676.2	---	---	---
	26	16.573	-1932.8	-1812. $\pm$ 34.	1.07 $\pm$ 0.02	-121. $\pm$ 34.	-1622.3	-1409. $\pm$ 23.	1.15 $\pm$ 0.02	-213. $\pm$ 23.
	27	22.098	-1840.2	---	---	---	-1548.5	---	---	---
	28	27.622	-1723.9	---	---	---	-1456.1	-1287. $\pm$ 16.	1.13 $\pm$ 0.01	-169. $\pm$ 16.
	29	33.147	-1588.7	-1528. $\pm$ 28.	1.04 $\pm$ 0.02	-61. $\pm$ 28.	-1347.4	---	---	---
	30	38.671	-1437.2	---	---	---	-1224.6	-1083. $\pm$ 13.	1.13 $\pm$ 0.01	-142. $\pm$ 13.
	31	44.196	-1272.9	---	---	---	-1090.4	---	---	---
	(2)	32	49.720	-1093.7	---	---	---	-942.1	---	---
II ^a (3)	33	55.245	-900.0	-892. $\pm$ 18.	1.01 $\pm$ 0.02	-8. $\pm$ 18.	-775.1	-693. $\pm$ 11.	1.12 $\pm$ 0.02	-82. $\pm$ 11.
(1)	34	60.769	-707.8	---	---	---	-603.0	---	---	---
III	35	66.294	-524.3	-529. $\pm$ 20.	0.99 $\pm$ 0.04	5. $\pm$ 20.	-432.8	---	---	---
	36	71.818	-351.1	---	---	---	-271.3	---	---	---
RADIAL	37	77.343	-216.0	---	---	---	-161.8	---	---	---
BLANKET	38	82.867	-128.3	-68. $\pm$ 16.	1.87 $\pm$ 0.44	-60. $\pm$ 16.	-92.0	---	---	---
	39	88.392	-76.4	---	---	---	-52.1	---	---	---
	40	93.916	-48.8	---	---	---	-30.8	---	---	---

^aThe numbers in parentheses indicate the drawer type of the three drawer unit cell zone II loading.

TABLE III-12. Calculated and Experimental Radial Reactivity Worth Traverse Results for CH₂(F)-6 (CH₂-Foam)

		CH ₂ (F)-6 (CH ₂)					
		Sample Position (COL) (CM)		Reactivity Worth (1h/Kg) Calculated Experimental		C/E	C-E
CORE ZONE I	23	0.000	-69.58	8.8 ± 4.4	-7.92 ± 3.96	-78.4 ± 4.4	
	24	5.524	-69.61	---	---	---	
	25	11.049	-69.65	---	---	---	
	26	16.573	-69.53	8.8 ± 3.3	-7.91 ± 2.97	-78.3 ± 3.3	
	27	22.098	-68.92	---	---	---	
	28	27.622	-67.01	---	---	---	
	29	33.147	-61.74	14.3 ± 2.2	-4.32 ± 0.67	-76.0 ± 2.2	
	30	38.671	-50.79	---	---	---	
	31	44.196	-30.00	---	---	---	
	(2)	32	49.720	2.09	---	---	
II ^a	(3)	33	55.245	17.24	84.6 ± 5.5	0.20 ± 0.01	-67.3 ± 5.5
(1)	34	60.769	21.45	---	---	---	
III	35	66.294	3.70	33.0 ± 4.4	0.11 ± 0.01	-29.3 ± 4.4	
	36	71.818	-65.34	---	---	---	
RADIAL	37	77.343	-73.51	---	---	---	
BLANKET	38	82.867	-57.79	-52.7 ± 3.3	1.10 ± 0.07	-5.1 ± 3.3	
	39	88.392	-37.86	---	---	---	
	40	93.916	-21.87	---	---	---	

^aThe numbers in parentheses indicate the drawer type of the three drawer unit cell zone II loading.

TABLE III-13. Comparison of GCFR Phase I and Phase III Central Worth C/E's

Sample I.D.	Isotope	C/E ^a		²³⁹ Pu Normalized C/E ^b		PD Adjusted C/E ^c	
		I	III	I	III	I	III
MB-10	²³⁹ Pu	1.27	1.16	-	-	0.95	1.00
PU-240-2D	²⁴⁰ PuO ₂	1.36	1.17	1.07	1.01	1.02	1.01
U-233-3	²³³ U	1.27	1.16	1.00	1.00	0.95	1.00
MB-21	²³⁵ U	1.32	1.20	1.04	1.03	0.99	1.03
MB-25	²³⁸ U	1.12	1.09	0.88	0.94	0.84	0.94
B-7	¹⁰ B	1.12	1.05	0.88	0.90	0.84	0.90
MB-19	SST	1.66	1.27	1.31	1.09	1.25	1.09

^aFirst-order perturbation theory calculations.

^bSample C/E divided by ²³⁹Pu sample C/E.

^cSample C/E multiplied by perturbation denominator C/E.

TABLE IV-1. Mass and Composition of Fission Counter Sources

Principal Isotope	Mass (μg)	Composition	
		Isotope	Wt. %
^{239}Pu	27.06 ± 0.14	^{239}Pu	98.94
		^{240}Pu	1.01
		^{241}Pu	0.05
^{239}Pu	81.47 ± 0.41^a	^{239}Pu	98.94
		^{240}Pu	1.01
		^{241}Pu	0.05
^{235}U	78.17 ± 0.63	^{234}U	1.02
		^{235}U	98.39
		^{236}U	0.45
		^{238}U	0.14
^{238}U	416.87 ± 3.33	^{235}U	0.01
		^{238}U	99.99

^aUsed as the monitor counter.

TABLE IV-2. Measured and Calculated Central Cavity Spectral Indices in the GCFR Phase III Assembly

Loading Configuration	Ratio	Measured ^a	Calculated ^b	C/E
Pin Loading	f^{25}/f^{49}	1.035 ± 0.013	1.034	0.999
	f^{28}/f^{49}	0.0259 ± 0.0003	0.0259	1.000
Plate Loading	f^{25}/f^{49}	1.040 ± 0.013	1.041	1.001
	f^{28}/f^{49}	0.0249 ± 0.0003	0.0253	1.016

^aRatios computed on a per-atom basis.

^bCalculations do not account for the detector cavity materials which have been shown to affect the experimental results -- particularly of f^{28}/f^{49} .

TABLE IV-3. Gamma-ray Peaks Analyzed to Determine Fission and Capture Rates in Foils

Reaction Rate	γ -ray Energy (keV)	Isotope	γ -ray Intensity	Half-Life (hr)	Detection Efficiency ^a
$^{235}\text{U}(n,f)$	529.9	^{133}I	0.891	21.0	0.038
$^{238}\text{U}(n,f)$					
$^{239}\text{Pu}(n,f)$	657.9	^{97}Nb	0.983	17.0	0.030
	667.7	^{132}I	1.0	80.0	0.029
	743.4	^{97m}Nb	0.939	17.0	0.026
$^{238}\text{U}(n,\gamma)$	277.6	^{239}Np	0.141	56.5	0.080

^aApproximate value which varies slightly for different detectors.

TABLE IV-4. Description of Activation Foils Used for Plate Measurements

Target Isotope	Material and Form	Diameter (in.)	Nominal Thickness (mils)	Appropriate Weight of Target Element, (g)
U	Enriched Uranium ^a	0.500	4.4	0.25
U	Depleted Uranium ^b	0.500	5.5	0.31
Pu	Pu-Al alloy, ^c clad in 5-mil aluminum ^d	0.425	0.4	0.02

^aIsotopic composition of enriched uranium foils:

^{234}U :	1.03 wt%
^{235}U :	93.07
^{236}U :	0.27
^{238}U :	5.63

^bIsotopic composition of depleted uranium foils:

^{235}U :	0.215
^{236}U :	0.005
^{238}U :	99.78

^cIsotopic composition of the plutonium foil alloy which is 98.0 wt% Pu and 1.3 wt% Al:

^{239}Pu :	94.98
^{240}Pu :	4.7
^{241}Pu :	0.303
^{242}Pu :	0.019

^dAluminum cladding is 0.5-in. diameter and 5 mils thick.

TABLE IV-5. In-Cell Reaction Rates, Core Zone I

Drawer	Position	Interface	f^{49} ($\times 10^7$)	f^{25} ($\times 10^7$)	f^{28} ($\times 10^5$)	c^{28} ($\times 10^6$)
S23/23 0-2"	0.0	DR-UO		2.348	5.732	2.844
	0.125	UO-UO		2.321	5.573	2.748
	0.25 ^a	UO-V		2.334	5.711	2.855
	0.875	FE-PU	2.192	2.297	6.264	2.853
	1.0	PU-PU	2.186	2.308	6.563	2.692
	1.125	PU-FE	2.193	2.346	6.497	2.878
	1.75	V-UO		2.312	5.666	2.901
	1.875	UO-UO		2.348	5.658	2.758
	2.0	UO-DR		2.336	5.746	2.860
S15/23 0-2"	0.0	DR-UO		1.856	4.647	2.277
	0.125	UO-UO		1.824	4.645	2.126
	0.25 ^a	UO-V		1.794	4.700	2.278
	0.875	FE-PU	1.769	1.888	5.151	2.270
	1.0	PU-PU	1.738	1.864	5.393	2.121
	1.125	PU-FE	1.776	1.817	5.149	2.253
	1.75	V-UO		1.818	4.636	2.218
	1.875	UO-UO		1.848	4.753	2.184
	2.0	UO-DR		1.829	4.688	2.265
S23/23 22-24"	0.0	DR-UO		1.283	2.486	1.618
	0.125	UO-UO		1.277	2.517	1.519
	0.25 ^a	UO-V		1.280	2.575	1.615
	0.875	FE-PU	1.163	1.266	2.950	1.637
	1.125	PU-FE	1.139	1.277	2.964	1.616
	1.75	V-UO		1.267	2.547	1.612
	1.875	UO-UO		1.263	2.538	1.530
	2.0	UO-DR		1.280	2.451	1.626

^a Mapping foil locations.

^b UO = depleted uranium oxide; DU = depleted uranium; V = void can;
PU = plutonium fuel; FE = iron oxide; DR = drawer side.

TABLE IV-6. In-Cell Reaction Rates, Core Zone II, Row 13

Drawer	Position(in.)	Interface ^b	f ⁴⁹ (× 10 ⁷)	f ²⁵ (× 10 ⁷)	f ²⁸ (× 10 ⁵)	c ²⁸ (× 10 ⁶)
S13/22 0-2"	0.0	DR-UO		1.539	4.404	1.895
	0.125	UO-UO		1.543	4.445	1.815
	0.25	UO-V		1.547	4.546	1.875
	0.625	FE-PU	1.506	1.563	4.948	1.874
	0.875	PU-FE	1.510	1.532	4.664	1.840
	1.5	V-UO		1.558	4.366	1.878
	1.625	UO-UO		1.550	4.385	1.796
	1.75	UO-V		1.538	4.246	1.906
S13/23 0-2"	2.125	FE-PU	1.489	1.557	4.882	1.933
	2.357	PU-FE	1.503	1.561	4.793	1.870
	3.000	V-UO		1.549	4.374	1.885
	3.125	UO-UO		1.533	4.306	1.823
	3.250	UO-V		1.554	4.546	1.884
	3.625 ^a	FE-PU	1.494	1.562	4.960	1.864
	3.875	PU-FE	1.532	1.532	4.886	1.905
S13/24 0-2"	4.500	V-UO		1.556	4.315	1.917
	4.625	UO-UO		1.543	4.315	1.816
	4.750	UO-V		1.535	4.520	1.876
	5.125	FE-PU	1.479	1.570	4.983	1.883
	5.375	PU-FE	1.482	1.585	4.585	1.896

^aMapping foil location.^bUO = depleted uranium oxide; FE = iron oxide; V = void can; PU = plutonium fuel;
DU = depleted uranium; DR = drawer side.TABLE IV-7. In-Cell Reaction Rates, Core Zone II, Row 23
with Radial Corrections

Drawer	Position(in.)	Interface ^b	f ⁴⁹ (× 10 ⁷)	f ²⁵ (× 10 ⁷)	f ²⁸ (× 10 ⁵)	c ²⁸ (× 10 ⁶)
S23/32 0-2"	0.125	FE-PU	1.619	1.649	5.203	2.017
	0.375	PU-FE	1.575	1.669	5.277	1.953
	1.0	V-UO		1.631	4.903	2.003
	1.125	UO-UO		1.666	4.906	1.922
	1.250	UO-V		1.670	4.956	1.986
	1.625 ^a	FE-PU	1.572	1.620	5.296	1.981
	1.875	PU-FE	1.541	1.610	5.120	1.990
S23/33 0-2"	2.500	V-UO		1.645	4.822	2.051
	2.625	UO-UO		1.657	4.726	1.923
	2.75	UO-V		1.620	4.649	1.992
	3.125	FE-PU	1.633	1.654	5.112	1.998
	3.375	PU-FE	1.582	1.628	5.157	1.989
S23/34 0-2"	4.000	DR-UO		1.606	4.677	2.045
	4.125	UO-UO		1.613	4.762	1.953
	4.250	UO-V		1.656	4.722	1.999
	4.625	FE-PU	1.589	1.635	5.144	2.029
	4.875	PU-FE	1.582	1.640	5.017	1.931
	5.500	V-UO		1.652	4.958	2.000
	5.625	UO-UO		1.617	4.867	1.950
	5.750	UO-V		1.608	4.881	2.026

^aMapping foil location; all values radially corrected to this position.^bUO = depleted uranium oxide; FE = iron oxide; V = void can; PU = plutonium fuel;
DU = depleted uranium; DR = drawer side.

TABLE IV-8. In-Cell Reaction Rates, Core Zone III

Drawer	Position	Interface	f^{49} ($\times 10^7$)	f^{25} ($\times 10^7$)	f^{28} ($\times 10^5$)	c^{28} ($\times 10^6$)
S11/23	0.375	FE-PU	1.146	1.242	3.500	1.553
	0.500	PU-PU	1.114	1.235	3.630	1.431
	0.625	PU-FE	1.178	1.220	3.496	1.551
0-2"	1.375 ^a	FE-PU	1.176	1.252	3.744	1.581
	1.500	PU-PU	1.150	1.224	3.703	1.451
	1.625	PU-FE	1.134	1.247	3.610	1.599

^a Mapping foil location.^b FE = iron oxide, PU = plutonium fuel.

TABLE IV-9. In-Cell Reaction Rates, Axial Blanket Region

Drawer	Position(in.)	Interface ^b	f^{25} ($\times 10^7$)	f^{28} ($\times 10^5$)	c^{28} ($\times 10^6$)
S23/23	0.0	DR-UO	1.083	1.486	1.426
24-26"	0.125	UO-UO	1.091	1.525	1.319
	0.25	UO-V	1.082	1.564	1.381
	0.75	V-UO	1.096	1.532	1.370
	0.875	UO-UO	1.106	1.440	1.303
	1.0	UO-UO	1.077	1.421	1.290
	1.125 ^a	UO-DU	1.087	1.412	1.267
	1.25	DU-V	1.070	1.425	1.343
	1.75	V-UO	1.094	1.566	1.361
	1.875	UO-UO	1.075	1.485	1.298
	2.0	UO-DR	1.073	1.520	1.433
S23/23	0.0	DR-UO	0.6151	0.2547	0.8640
34-36"	0.125	UO-UO	0.6242	0.2712	0.7461
	0.25	UO-V	0.6285	0.2488	0.7942
	0.75	V-UO	0.6394	0.2839	0.7977
	0.875	UO-UO	0.6112	0.2626	0.7212
	1.0	UO-UO	0.6118	0.2592	0.7075
	1.125 ^a	UO-DU	0.6347	0.2509	0.6858
	1.25	DU-V	0.6403	0.2929	0.7803
	1.75	V-UO	0.6388	0.2792	0.7897
	1.875	UO-UO	0.6287	0.2547	0.7349
	2.0	UO-DR	0.6226	0.2650	0.8623

^a Mapping foil locations.^b UO = depleted uranium oxide; DU = depleted uranium; V = void can;
DR = drawer side.

TABLE IV-10. In-Cell Reaction Rates, Radial Blanket Region

Drawer	Position(in.)	Interface ^b	f^{25} ($\times 10^6$)	f^{28} ($\times 10^5$)	c^{28} ($\times 10^6$)
S10/23	0.0	DR-UO	1.063	1.795	1.410
	0.125	UO-UO	1.064	1.767	1.298
	0-2"	UO-UO	1.029	1.795	1.279
	0.25	UO-UO	1.044	1.814	1.282
	0.375	UO-UO	1.059	1.798	1.338
	0.50	UO-V	1.086	1.750	1.330
	1.00	V-UO	1.085	1.764	1.269
	1.125	UO-UO	1.074	1.798	1.255
	1.25 ^a	UO-UO	1.078	1.778	1.252
	1.375	UO-UO	1.069	1.777	1.246
	1.50	UO-DU	1.081	1.778	1.397
	1.625	DU-V			
S06/23	0.0	DR-UO	0.6630	0.2708	0.9217
	0.125	UO-UO	0.6704	0.2511	0.7392
	0-2"	UO-UO	0.6570	0.2724	0.7340
	0.25	UO-UO	0.6637	0.2778	0.7270
	0.375	UO-UO	0.6595	0.3019	0.8189
	0.50	UO-V	0.6652	0.2734	0.8176
	1.00	V-UO	0.6715	0.2859	0.7260
	1.125	UO-UO	0.6735	0.2529	0.7158
	1.25 ^a	UO-UO	0.6633	0.2725	0.7085
	1.375	UO-UO	0.6651	0.2800	0.6938
	1.50	UO-DU	0.6755	0.2545	0.9150
	1.625	DU-V			

^aMapping foil locations.^bUO = depleted uranium oxide; DU = depleted uranium; V = void can;
DR = drawer side.

TABLE IV-11. Cell-Average-to-Mapping-Foil Ratios

Unit Cell Location	Region	Cell Average/Mapping Foil ^a			
		f^{49}	f^{25}	f^{28}	c^{28}
S23/23, 0-2"	Core Zone I	0.999 $\pm$ 0.007	1.012 $\pm$ 0.004	0.962 $\pm$ 0.009	0.980 $\pm$ 0.003
S15/23, 0-2"	Core Zone I	0.992 $\pm$ 0.010	0.976 $\pm$ 0.004	0.960 $\pm$ 0.009	0.969 $\pm$ 0.004
S23/23, 22-24"	Core Zone I	0.986 $\pm$ 0.011	1.004 $\pm$ 0.008	0.927 $\pm$ 0.012	0.959 $\pm$ 0.004
S13/23, 0-2"	Core Zone II	0.999 $\pm$ 0.011	0.993 $\pm$ 0.005	0.950 $\pm$ 0.010	0.981 $\pm$ 0.011
S23/32, 0-2"	Core Zone II	1.006 $\pm$ 0.012	1.009 $\pm$ 0.006	0.959 $\pm$ 0.010	0.978 $\pm$ 0.011
S11/23, 0-2"	Core Zone III	0.974 $\pm$ 0.012	0.987 $\pm$ 0.005	0.969 $\pm$ 0.011	0.953 $\pm$ 0.012
S23/23, 24-26"	Ax. Blanket		0.997 $\pm$ 0.003	1.047 $\pm$ 0.016	1.050 $\pm$ 0.004
S23/23, 34-36"	Ax. Blanket		0.986 $\pm$ 0.003	1.054 $\pm$ 0.030	1.102 $\pm$ 0.006
S10/23, 0-2"	Rad. Blanket		0.990 $\pm$ 0.003	0.992 $\pm$ 0.013	1.028 $\pm$ 0.004
S06/23, 0-2"	Rad. Blanket		0.988 $\pm$ 0.003	1.074 $\pm$ 0.030	1.051 $\pm$ 0.005

^aNo stainless steel corrections applied to mapping foil data for c^{28} .

TABLE IV-12. Measured and Calculated Cell-Averaged Per-Atom Reaction Rate Ratios in the GCFR Phase III Assembly

Location	Region	R, Z (cm)	f^{25}/f^{49}			f^{28}/f^{49}			c^{28}/f^{49}		
			Measured	Calculated	C/E	Measured	Calculated	C/E	Measured	Calculated	C/E
S23/23	Core Zone I	0.0, 1.6	1.044 ± 0.016	1.038	0.994	0.02740 ± 0.00044	0.02640	0.963	0.1272 ± 0.0017	0.1434	1.127
S15/23	Core Zone I	44.2, 1.6	1.032 ± 0.017	1.021	0.989	0.02806 ± 0.00047	0.02803	0.999	0.1248 ± 0.0017	0.1394	1.117
S23/23	Core Zone I	0.0, 55.9	1.090 ± 0.017	1.092	1.002	0.02375 ± 0.00040	0.02253	0.949	0.1363 ± 0.0021	0.1533	1.125
S13/22-24	Core Zone II	55.2, 1.6	1.021 ± 0.018	1.016	0.995	0.03140 ± 0.00057	0.03012	0.959	0.1219 ± 0.0020	0.1378	1.130
S23/32-34	Core Zone II	51.3, 1.6	1.017 ± 0.018	1.013	0.996	0.03200 ± 0.00059	0.03021	0.944	0.1221 ± 0.0020	0.1372	1.124
S11/23	Core Zone III	66.3, 1.6	1.060 ± 0.018	1.043	0.984	0.03153 ± 0.00056	0.02804	0.889	0.1309 ± 0.0022	0.1426	1.089
						f^{28}/f^{25}			c^{28}/f^{49}		
						Measured	Calculated	C/E	Measured	Calculated	C/E
S23/23	Axial Blanket	0.0, 62.7				0.01382 ± 0.00025	0.01460	1.057	0.1243 ± 0.0016	0.1356	1.091
S23/23	Axial Blanket	0.0, 86.4				0.00428 ± 0.00011	0.00328	0.766	0.1223 ± 0.0017	0.1185	0.969
S10/23	Radial Blanket	71.8, 1.6				0.01698 ± 0.00030	0.01743	1.026	0.1228 ± 0.0016	0.1335	1.087
S06/23	Radial Blanket	93.9, 1.6				0.00413 ± 0.00010	0.00342	0.827	0.1145 ± 0.0016	0.1148	1.003

TABLE IV-13. Description of Activation Foils for Pin Zone Measurements

Target Isotope	Material and Form	Diameter, in.	Nominal Thickness, mils	Approximate Weight of Target Element, g
U	Enriched Uranium ^a	0.346	4.4	0.12
U	Depleted Uranium ^b	0.346	5.5	0.16
Pu	Pu-Al alloy, ^c clad in 5-mil aluminum ^d	0.140	4.0	0.012
^a Isotopic composition of enriched uranium foils:				²³⁴ U: 1.03 wt%
				²³⁵ U: 93.07
				²³⁶ U: 0.27
				²³⁸ U: 5.63
^b Isotopic composition of depleted uranium foils:				²³⁵ U: 0.215
				²³⁶ U: 0.005
				²³⁸ U: 99.78
^c Isotopic composition of the plutonium foil alloy which is 98.6 wt% Pu and 1.25 wt% Al:				²³⁸ Pu: 0.01
				²³⁹ Pu: 94.91
				²⁴⁰ Pu: 4.60
				²⁴¹ Pu: 0.48

^dAluminum cladding is 0.20-in. diameter and 5-mils thick.

TABLE IV-14. GCFR Phase III Pin Zone Intra-Cell Reaction Rates

Region	Axial Distance (cm)	Cell Location ^a	f^{49} ($\times 10^6$)	f^{25} ($\times 10^6$)	f^{28} ($\times 10^5$)	c^{28} ($\times 10^5$)
Core	7.62	A1	7.166 ± 0.050	---	---	---
Zone I		A2	---	---	1.979 ± 0.020	9.166 ± 0.095
S23/23		A3	---	7.646 ± 0.083	---	---
		B6	7.169 ± 0.050	---	---	---
		B8	---	---	2.002 ± 0.020	9.005 ± 0.095
		C1	---	7.680 ± 0.084	---	---
		C2	7.042 ± 0.049	---	---	---
		C3	---	---	2.018 ± 0.020	8.980 ± 0.094
Axial	68.58	A1		---	0.327 ± 0.004	4.082 ± 0.044
Blanket		A2		3.474 ± 0.038	---	---
S23/23		B6		---	0.334 ± 0.004	4.058 ± 0.043
		B8		3.489 ± 0.038	---	---
		C2		---	0.331 ± 0.004	3.960 ± 0.042
		C3		3.458 ± 0.038	---	---

^aLocations refer to Fig. IV-26.

TABLE IV-15. Cell-Averaged Reaction Rate Ratios in the GCFR Phase III Plate- and Pin-Loaded Assemblies

Ratio ^a	Region ^b	Z(cm) ^c (pin/plate)	Pin Loaded Zone			Plate Loaded Zone		
			Measured	Calculated	C/E	Measured	Calculated	C/E
f^{25}/f^{49}	Core	7.6/ 1.6	1.056 ± 0.014	1.034	0.979 ± 0.013	1.044 ± 0.016	1.038	0.994 ± 0.015
f^{28}/f^{49}	Core	7.6/ 1.6	0.02791 ± 0.00034	0.02627	0.941 ± 0.012	0.02740 ± 0.00044	0.02640	0.963 ± 0.015
c^{28}/f^{49}	Core	7.6/ 1.6	0.1267 ± 0.0016	0.1445	1.141 ± 0.014	0.1272 ± 0.0017	0.1434	1.127 ± 0.015
f^{28}/f^{25}	Axial Blanket	68.6/62.7	0.00966 ± 0.00016	0.00956	0.989 ± 0.016	0.01382 ± 0.00025	0.01460	1.057 ± 0.019
c^{28}/f^{25}	Axial Blanket	68.6/62.7	0.1176 ± 0.0018	0.1380	1.173 ± 0.018	0.1243 ± 0.0016	0.1356	1.091 ± 0.014

^aRatios are given on a per-atom basis.^bAll measurements were made in S-23/23.^cAxial distances from the assembly midplane.

TABLE IV-16. Normalized Experimental Radial Reaction
Rate Distributions in the GCFR Phase III
Plate-Loaded Assembly

Row/ Column	Radius (cm)	f ⁴⁹	f ²⁵	f ²⁸	c ²⁸
S23/23	0.00	1005.2	1002.9	1001.7	986.3
S22/23	5.52	989.5	1007.5	987.7	996.2
S21/23	11.05	990.1	1005.7	995.7	990.2
S20/23	16.57	968.8	978.0	949.3	963.1
S19/23	22.10	957.6	949.0	952.3	946.8
S18/23	27.62	938.8	930.3	925.2	914.3
S17/23	33.15	869.4	857.0	908.1	875.0
S16/23	38.67	828.6	833.0	867.2	826.5
S15/23	44.20	811.2	794.9	861.9	788.0
S14/23	49.72	749.8	725.8	821.2	724.0
S13/23	55.25	683.9	667.8	769.5	657.0
S12/23	60.77	614.2	605.2	679.2	588.5
S11/23	66.29	518.6	530.6	596.9	526.3
S10/23	71.82		476.8	303.0	462.4
S 9/23	77.34		417.8	186.5	421.5
S 8/23	82.87		367.0	107.7	358.8
S 7/23	88.39		329.4	69.44	311.8
S 6/23	93.92		300.5	45.21	269.7

TABLE IV-17. Normalized Experimental Axial Reaction
Rate Distributions in the GCFR Phase III
Plate-Loaded Assembly

Axial Distance (cm)	f ⁴⁹	f ²⁵	f ²⁸	c ²⁸
1.59		1003.9	961.7	1002.5
3.81	995.0			
7.62		982.1	983.2	987.1
11.43	972.4			
15.24		958.2	966.3	953.4
19.05	907.1			
22.86		923.8	911.9	901.8
26.67	884.9			
30.48		840.1	836.4	838.6
34.29	805.6			
38.10		774.0	714.3	787.8
41.91	728.5			
45.72		686.5	647.2	666.8
49.53	627.2			
53.34		584.2	501.0	582.0
57.15	511.6			
60.96		484.3	331.2	509.0
68.58		417.4	148.1	413.6
76.20		330.4	85.66	347.7
83.82		299.2	50.61	287.9
90.17		279.0	35.90	257.1

TABLE IV-18. Normalized Calculated Radial Reaction
Rate Distributions in the GCFR Phase III
Plate-Loaded Assembly

Radius (cm)	f ⁴⁹	f ²⁵	f ²⁸	c ²⁸
1.38	1000.0	1000.0	1000.0	1000.0
4.14	998.4	998.4	998.5	998.3
6.91	995.3	995.0	995.6	994.9
9.67	990.5	990.1	991.3	989.8
12.43	984.2	983.4	985.6	983.0
15.19	976.3	975.1	978.4	974.4
17.96	966.8	965.1	970.0	964.1
20.72	955.8	953.5	960.2	952.0
23.48	943.1	940.1	949.3	938.2
26.24	928.8	924.8	937.2	922.3
29.00	913.0	908.1	924.2	905.0
31.77	895.7	889.7	910.4	885.8
34.53	876.8	869.6	896.2	864.8
37.29	856.4	847.7	881.6	842.0
40.05	834.4	824.1	867.3	817.4
42.82	810.9	798.7	853.6	790.7
45.58	785.8	771.5	841.4	762.0
48.34	754.1	740.3	828.7	729.5
51.10	724.1	709.0	818.0	697.3
53.86	691.8	676.7	788.4	664.8
56.63	657.3	643.5	751.0	632.1
59.39	621.0	609.5	706.5	599.3
62.15	583.2	575.2	655.3	566.6
64.91	540.4	538.0	600.2	531.1
67.68	500.0	506.6	507.0	503.3
70.44		487.7	368.2	471.5
73.20		459.4	283.0	444.4
75.96		430.8	217.6	415.6
78.72		403.0	167.3	386.2
81.49		377.2	128.4	357.8
84.25		353.3	99.05	330.0
87.01		332.6	76.58	304.1
89.77		316.4	59.34	280.9
92.54		306.2	46.12	261.2
95.30		304.1	35.94	246.3

TABLE IV-19. Normalized Calculated Axial Reaction
Rate Distributions in the GCFR Phase III
Plate-Loaded Assembly

Axial Distance (cm)	f ⁴⁹	f ²⁵	f ²⁸	c ²⁸
1.00	1000.0	1000.0	1000.0	1000.0
3.00	998.6	998.6	998.6	998.6
5.00	995.7	995.7	995.6	995.8
7.00	991.4	991.5	991.3	991.5
9.00	985.6	985.8	985.5	985.9
11.00	973.5	978.8	978.3	978.9
13.00	969.9	970.4	969.7	970.6
15.00	960.0	960.6	959.6	960.8
17.00	948.7	949.5	948.2	949.8
19.00	936.1	937.2	935.3	937.5
21.00	922.1	923.5	921.1	924.0
23.00	906.9	908.6	905.5	909.2
25.00	890.4	892.5	888.5	893.3
27.00	872.7	875.3	870.2	876.3
29.00	853.9	857.0	850.6	858.2
31.00	833.9	837.6	829.6	839.1
33.00	812.8	817.3	807.2	819.1
35.00	790.7	796.0	783.6	798.2
37.00	767.7	773.9	758.5	776.6
39.00	743.7	751.1	732.1	754.3
41.05	718.4	727.3	703.5	731.0
43.16	691.4	702.0	672.5	706.3
45.26	663.8	676.1	639.6	681.2
47.36	635.4	650.0	604.9	655.8
49.47	606.6	623.5	568.1	630.3
51.57	577.5	597.3	528.9	604.9
53.68	548.2	571.4	487.0	579.9
55.78	519.1	546.2	442.1	555.6
57.88	490.3	522.2	393.6	532.3
59.99	462.2	499.8	340.8	510.4
62.04		484.0	277.2	475.6
64.04		464.8	235.0	455.6
66.04		445.6	199.4	435.3
68.04		426.5	169.2	415.0
70.04		407.9	143.6	394.8
72.06		390.3	121.3	375.1
74.11		372.8	102.7	355.3
76.16		356.4	87.09	336.2
78.21		341.4	73.88	318.0
80.26		327.9	62.74	301.0
82.30		316.4	53.33	285.2
84.35		307.1	45.38	270.8
86.40		300.6	38.65	258.2
88.45		297.5	32.94	247.6
90.50		298.4	28.09	239.4

TABLE IV-20. Experimental ^{239}Pu Axial Fission Rate Distributions in the GCFR Phase III Plate and Pin Loadings

Axial Distance ^a (cm)	^{239}Pu Fission Rate	
	Pin Zone	Plate Loading
60.96	479.3	
57.15		511.6
53.34	582.4	
49.53		627.2
45.72	674.2	
41.91		728.5
38.10	780.0	
34.29		805.6
30.48	855.4	
26.67		884.9
22.86	916.6	
19.05		907.1
15.24	977.6	
11.43		972.4
7.62	993.2	
3.81		995.0
0.00	968.8	
-0.00	996.5	
-7.62	990.7	
-15.24	970.4	
-22.86	873.8	
-30.48	859.1	
-38.10	775.6	
-45.72	678.4	
-53.34	578.0	
-60.96	454.7	

^a Axial distance from midplane, values <0 are in the movable half.

TABLE IV-21. Calculated ^{239}Pu Axial Fission Rate Distribution in the GCFR Phase III Pin Zone

Axial Distance (cm)	^{239}Pu Fission Rate
1.00	1000.00
3.00	998.55
5.00	995.65
7.00	991.32
9.00	985.55
11.00	978.36
13.00	969.76
15.00	959.78
17.00	948.42
19.00	935.72
21.00	921.70
23.00	889.83
25.00	889.83
27.00	872.05
29.00	853.10
31.00	833.03
33.00	811.89
35.00	789.74
37.00	766.64
39.00	742.69
41.05	717.49
43.16	690.65
45.26	663.12
47.36	635.06
49.47	606.67
51.57	578.18
53.68	549.90
55.78	522.23
57.88	495.72
59.99	471.19

TABLE V-1. Central Cavity Fission Rate Ratios in the GCFR Phase III Assembly

Ratio	Measured (E) ^a	Calculated (C) ^a	C/E
$^{23}\text{f}/^{49}\text{f}$	1.521 ± 0.025	1.518	0.997 ± 0.016 ^b
$^{25}\text{f}/^{49}\text{f}$	1.040 ± 0.013	1.041	1.001 ± 0.013
$^{28}\text{f}/^{49}\text{f}$	0.0249 ± 0.0003	0.0253	1.016 ± 0.012
$^{40}\text{f}/^{49}\text{f}$	0.2204 ± 0.0017	0.2251	1.0214 ± 0.0081 ^b

^aRatios on a per-atom basis.

^bThese C/E values are taken from the GCFR Phase II measurements (Ref. 2). The corresponding "measured" values were obtained by dividing the C/E ratio into the calculated value. No direct measurements of $^{23}\text{f}/^{49}\text{f}$ and $^{40}\text{f}/^{49}\text{f}$ were made in the GCFR Phase III assembly.

TABLE V-2. Absolute Reaction Rate Measurements in the GCFR Phase III Assembly

Matrix	Position (cm)	R ₀ /R for $^6\text{Li}(n,\alpha)$	R _{α0} (^6Li) 10 ⁹ events/sec-g	R ₀ /R for $^{239}\text{Pu}(n,f)$	R _{f0} (^{239}Pu) 10 ⁷ events/sec-g
S23/23	0.000	1.0586	1.509 ± 0.012 ^a	1.0010	6.212 ± 0.054
S23/24	5.524	1.0586	1.498 ± 0.012	1.0010	6.187 ± 0.054
S23/26	16.574	1.0586	1.464 ± 0.012	1.0010	6.014 ± 0.052
S23/28	27.622	1.0585	1.397 ± 0.012	1.0011	5.739 ± 0.050
S23/30	38.672	1.0583	1.289 ± 0.011	1.0012	5.334 ± 0.046
S23/32	49.720	1.0582	1.1051 ± 0.0091	1.0014	4.654 ± 0.041
S23/33	55.245	1.0582	1.0008 ± 0.0083 ^a	1.0015	4.220 ± 0.037
S23/34	60.770	1.0588	0.8949 ± 0.0074	1.0014	3.787 ± 0.033
S23/35	66.294			1.0005	3.399 ± 0.030

^aInterpolated value based on C/E measurements of the $^6\text{Li}(n,\alpha)/^{239}\text{Pu}(n,f)$ reaction rate ratio. See Table V-13.

TABLE V-3. Description of the GCFR Phase III Reactivity Samples

Sample Ident	Geometry	Dimension, In.			Sample Mass (g)	Capsule Mass (g)	Capsule Material	Composition Ident ^a	Principal Isotope
		Length	O.D.	Wall					
Li-5	Cylinder	1.678	0.309	-	0.9736	2.0468	Al	LI6-A	⁶ Li
U-233-3	Strip	1.805	0.830	0.010	4.1576	16.5131	SS	U233-A	²³³ U
U-3	Cylinder	2.173	0.200	-	21.0147	11.1122	SS	U235-C	²³⁵ U
MB-21	Annulus	1.688	0.835	0.015	15.7780	13.7293	SS	U235-A	²³⁵ U
MB-25	Annulus	1.688	0.835	0.036	38.1631	13.6910	SS	U238-A	²³⁸ U
Pu-25	Cylinder	2.173	0.100	-	4.4799	10.7579	SS	P239-B	²³⁹ Pu
Pu-27	Cylinder	2.173	0.200	-	17.0618	11.2068	SS	P239-B	²³⁹ Pu
MB-10	Annulus	1.156	0.835	0.015	9.956	13.458	SS	P239-A	²³⁹ Pu
Pu-240-2D	Annulus	1.800	0.604	0.205	45.135	28.821	Inconel	P240-A	²⁴⁰ Pu

^aSee Table V-4.

TABLE V-4. Composition (w/o) of Reactivity Samples

Composition I.D.:	LI6-A	U233-A	U235-C	U235-A	U238-A	P239-B	P239-A	P240-A
	LI-5	U-233-3	U-3	MB-21	MB-25	Pu-25,27	MB-10	Pu-240-2D
<u>Major Elements</u>								
Li	99.870							
C	0.045							
O								11.97
Al						9.95	1.208	
U		99.8	~100.0	~100.0	~100.0			
Pu						98.26	97.985	86.10
<u>Isotopic Composition</u>								
⁶ Li	98.21							
⁷ Li	0.79							
²³³ U		99.47						
²³⁴ U		0.183	0.9452	0.6651				
²³⁵ U		0.071	93.1920	93.2438	0.2328			
²³⁶ U		0.014	0.2585	0.3162				
²³⁸ U		0.266	5.6043	5.7750	99.7672			
²³⁹ Pu						98.926	98.932	1.05
²⁴⁰ Pu						1.023	1.012	93.73
²⁴¹ Pu						0.049	0.053	0.57
²⁴² Pu						0.002	0.003	4.65

TABLE V-5. Small Sample Reactivity Measurements in the GCFR Phase III Assembly

Sample	Matrix Location	Radial Position (cm)	Principal Isotope i	$\rho(E)$ (lh/kg)	ρ_0/ρ	$i\rho_0/\rho_0$	$i\rho_0(E)$ (lh/kg)
LI-5	S23/23	0.000	^6Li	-1500.77 ± 6.13	1.06552	1.00911	-1613.66 ± 6.59
"	S23/24	5.524	"	-1490.77 ± 1.59	1.06551	1.00911	-1602.90 ± 1.71
"	S23/26	16.574	"	-1409.02 ± 9.18	1.06545	1.00911	-1514.92 ± 9.87
"	S23/28	27.622	"	-1286.68 ± 3.63	1.06647	1.00911	-1384.71 ± 3.90
"	S23/30	38.672	"	-1083.14 ± 3.15	1.06624	1.00912	-1165.42 ± 3.39
"	S23/23	55.245	"	-692.66 ± 5.22	1.06774	1.00918	-746.37 ± 5.63
U-233-3	S23/23	0.000	^{233}U	189.46 ± 2.00	1.00467	1.00701	191.68 ± 2.03
U-3	S23/23	0.000	^{235}U	102.34 ± 0.30	1.01926	1.07759	112.41 ± 0.33
MB-21	S23/23	0.000	"	103.30 ± 0.21	1.01536	1.07724	112.99 ± 0.23
"	S23/24	5.524	"	100.92 ± 0.46	1.01535	1.07723	110.39 ± 0.50
"	S23/26	16.574	"	96.44 ± 0.25	1.01522	1.07719	105.46 ± 0.28
MB-25	S23/23	0.000	^{238}U	-7.651 ± 0.164	1.00601	1.03783	-7.988 ± 0.171
"	S23/23	16.574	"	-7.167 ± 0.114	1.00591	1.03809	-7.484 ± 0.119
Pu-25	S23/23	0.000	^{239}Pu	143.10 ± 1.33	0.99544	1.02719	146.32 ± 1.36
Pu-27	S23/23	0.000	"	141.76 ± 0.37	0.97762	1.02719	142.36 ± 0.37
MB-10	S23/23	0.000	"	141.66 ± 0.41	1.00122	1.03012	146.11 ± 0.43
"	S23/24	5.524	"	138.52 ± 0.71	1.00121	1.03012	143.17 ± 0.73
"	S23/26	16.574	"	131.22 ± 0.53	1.00112	1.03009	135.32 ± 0.55
"	S23/28	27.622	"	117.42 ± 0.56	1.00088	1.03003	121.06 ± 0.58
"	S23/30	38.672	"	101.73 ± 0.86	1.00030	1.02991	104.80 ± 0.88
"	S23/33	55.245	"	65.50 ± 0.32	1.00684	1.02930	67.88 ± 0.33
"	S23/35	66.294	"	39.61 ± 0.63	1.01976	1.02819	41.53 ± 0.66
Pu-240-2D	S23/23	0.000	^{240}Pu	17.17 ± 0.11	1.00259	1.15448	19.87 ± 0.12

NOTE: The uncertainties in this table are statistical uncertainties only. They do not include uncertainties (~1%) in the autorod calibration nor in the sample size correction factor, ρ_0/ρ , and thus are not identical to those listed in the tables of Section III.

TABLE V-6. Apparent Worth of ^{252}Cf Spontaneous Fission Neutrons in the GCFR Phase III Assembly

Sample	Matrix Location	Radial Position, (cm) ^a	$\rho'(E)$ _(Ih) ^b	ρ_0'/ρ'	$\rho_0'(E)$ _(Ih)	S(7/21/76) ^c (n/sec)	$\bar{\phi}_{f_0}^* (\text{Cf}) \times 10^{-5}$
ORNL-NSD-56	S23/23	-1.948	0.11673 ± 0.00035	1.01815	0.11885 ± 0.00036	$(9.335 \pm 0.061)10^7$	2.2387
"	S23/24	3.576	0.11636 ± 0.00035	1.01815	0.11848 ± 0.00036	"	2.2382
"	S23/26	14.625	0.11395 ± 0.00034	1.01815	0.11602 ± 0.00035	"	2.1924
"	S23/28	25.674	0.10942 ± 0.00033	1.01814	0.11141 ± 0.00033	"	2.0913
"	S23/30	36.723	0.10105 ± 0.00030	1.01813	0.10288 ± 0.00031	"	1.9349
"	S23/33	53.297	0.08275 ± 0.00025	1.02148	0.08453 ± 0.00025	"	1.5887
"	S23/35	64.346	0.06349 ± 0.00019	1.02769	0.06524 ± 0.00020	"	1.2271

^aMeasurements were made with the point source displaced 1.948 cm from the center of the matrix position in the negative X direction.

^b $\rho'(E)$ has been evaluated at the power level used for the ^6Li and ^{239}Pu reaction rates given in Table V-2. Errors are statistical only.

^cThe source strength corresponds to the time of the ρ' measurements.

TABLE V-7. Calculated Quantities (ENDF/B-IV) for the
GCFR Phase III Assembly

Isotope	Matrix Location	Radial Position (cm)	$\bar{\phi}_f^* \times 10^{-5}$	$\bar{\phi}_a^* \times 10^{-5}$	$(1 + \bar{\alpha})$	$\bar{v}$	RCF	FCF $\times 10^4$	ACF
^6Li	S23/23	0.000		1.7650			0.9642		1.00043
"	S23/24	5.524		1.7611			0.9642		1.00043
"	S23/26	16.574		1.7191			0.9646		1.00043
"	S23/28	27.622		1.6362			0.9654		1.00043
"	S23/30	38.672		1.5159			0.9672		1.00045
"	S23/33	55.245		1.2490			0.9774		1.00050
^{233}U	S23/23	0.000	2.2058	1.7730	1.0934	2.4835	1.0090	-4.0866	
^{235}U	S23/23	0.000	2.2093	1.7671	1.2838	2.4506	1.0147	-5.2649	
"	S23/24	5.524	2.2041	1.7631	1.2838	2.4506	1.0146	-5.2671	
"	S23/26	16.574	2.1493	1.7210	1.2833	2.4507	1.0143	-5.2871	
^{238}U	S23/23	0.000	2.2139	1.7940	6.8134	2.7718	0.6807	-475.50	
"	S23/26	16.574	2.1537	1.7475	6.7830	2.7717	0.6838	-475.56	
^{239}Pu	S23/23	0.000	2.2247	1.8081	1.2551	2.9373	1.0108	-2.3373	
"	S23/24	5.524	2.2195	1.8040	1.2550	2.9373	1.0107	-2.3381	
"	S23/26	16.574	2.1642	1.7608	1.2540	2.9375	1.0105	-2.3442	
"	S23/28	27.622	2.0540	1.6756	1.2513	2.9380	1.0099	-2.3640	
"	S23/30	38.672	1.8900	1.5525	1.2465	2.9395	1.0088	-2.4217	
"	S23/33	55.245	1.5244	1.2806	1.2338	2.9447	1.0015	-2.6940	
"	S23/35	66.294	1.1481	0.9465	1.2478	2.9411	0.9796	-2.5760	
^{240}Pu	S23/23	0.000	2.2185	1.8942	2.1777	3.0725	1.0858	-4.9619	

NOTE: The quantities in this table are defined by Eqs. V-1 to V-4 and refer to an infinitely dilute sample.

TABLE V-8. Un-normalized Perturbation
Denominator for the GCFR Phase III
Assembly

Matrix Location	$D(252Cf) \times 10^{-14}$	$D(6Li) \times 10^{-14}$
S23/23	1.758 ± 0.013	1.712 ± 0.016
S23/24	1.764 ± 0.013	1.708 ± 0.014
S23/26	1.764 ± 0.013	1.723 ± 0.018
S23/28	1.752 ± 0.013	1.710 ± 0.015
S23/30	1.756 ± 0.013	1.734 ± 0.015
S23/33	1.755 ± 0.013	1.714 ± 0.019
S23/35	1.756 ± 0.013	
$\bar{D}$:	1.758 ± 0.012	1.717 ± 0.012
$\bar{D}(252Cf)/\bar{D}(6Li) = 1.024 \pm 0.010$		

TABLE V-9. Normalized Perturbation Denominator
in the GCFR Phase III Assembly

Quantity	Value
$\bar{D}(252Cf)$	$(1.758 \pm 0.021^A)10^{14}$
$\bar{D}(6Li)$	$(1.717 \pm 0.021^A)10^{14}$
$S^*(0)$	2.22331×10^5
$S(0)$	$(7.916 \pm 0.086)10^7$
$1h/\delta k/k$	9.5683×10^4
$NF = S^*(0) S(0)/1h/(\delta k/k)$	$(1.839 \pm 0.020)10^8$
$D_n(252Cf) = \bar{D}(252Cf)/NF$	$(9.558 \pm 0.156)10^5$
$D_n(6Li) = \bar{D}(6Li)/NF$	$(9.335 \pm 0.152)10^5$
$D_n(C)$	8.1900×10^5
$C/E(252Cf)$	0.857 ± 0.014
$C/E(6Li)$	0.877 ± 0.014

^AError includes a 1.0% uncertainty in the
autorod calibration.

TABLE V-10. Thin Sample $(1 + \bar{\alpha})$ Values in the GCFR Phase III Assembly

Reactivity Sample	Isotope	Matrix Location	Radial Position (cm)	$(1 + \bar{\alpha})$ Calculated (C)	$(1 + \bar{\alpha})$ Measured (E)	C/E
U-233-3	^{233}U	S23/23	0.000	1.093	1.086 ± 0.051	1.007 ± 0.047
U-3	^{235}U	S23/23	0.000	1.284	1.306 ± 0.037	0.983 ± 0.028
MB-21	"	"	0.000	1.284	1.297 ± 0.037	0.990 ± 0.028
"	"	S23/24	5.524	1.284	1.326 ± 0.038	0.968 ± 0.027
"	"	S23/26	16.574	1.283	1.312 ± 0.037	0.978 ± 0.028
MB-25	^{238}U	S23/23	0.000	6.813	6.737 ± 0.107	1.011 ± 0.016
"	"	S23/26	16.574	6.783	6.727 ± 0.096	1.008 ± 0.014
Pu-27	^{239}Pu	S23/23	0.000	1.255	1.330 ± 0.038	0.943 ± 0.027
Pu-25	"	"	0.000	1.255	1.269 ± 0.044	0.987 ± 0.034
MB-10	"	"	0.000	1.255	1.272 ± 0.039	0.986 ± 0.030
"	"	S23/24	5.524	1.255	1.304 ± 0.040	0.963 ± 0.029
"	"	S23/26	16.574	1.254	1.309 ± 0.039	0.958 ± 0.029
"	"	S23/28	27.622	1.251	1.335 ± 0.039	0.937 ± 0.028
"	"	S23/30	38.672	1.246	1.303 ± 0.042	0.957 ± 0.031
"	"	S23/33	55.245	1.234	1.264 ± 0.038	0.976 ± 0.030
"	"	S23/35	66.294	1.248	1.313 ± 0.051	0.950 ± 0.037
PU-240-2D	^{240}Pu	S23/23	0.000	2.178	2.080 ± 0.078	1.047 ± 0.039

TABLE V-11. Errors in $(1 + \bar{\alpha})$ from Uncertainties in the Measured Quantities at the Central Location of the GCFR Phase III Assembly

Isotope	$(1 + \bar{\alpha})$ Measured	$\delta\bar{D}(^6\text{Li})$	$\delta\bar{D}(^{252}\text{Cf})$	$\delta\rho$	δR_f	$\delta\bar{v}$	Total Error (1σ)
^{233}U	1.086 ± 0.051	0.0078	0.0200	0.0204	0.0359	0.0211	0.0511
^{235}U	1.297 ± 0.037	0.0093	0.0198	0.0035	0.0258	0.0150	0.0372
^{238}U	6.737 ± 0.107	0.0477	0.0221	0.0716	0.0496	0.0334	0.1071
^{239}Pu	1.272 ± 0.039	0.0091	0.0234	0.0066	0.0196	0.0212	0.0388
^{240}Pu	2.080 ± 0.078	0.0148	0.0233	0.0088	0.0167	0.0703	0.0778

TABLE V-12. Error Sensitivities in $(1 + \bar{\alpha})$ Measurements at the Central Location of the GCFR Phase III Assembly

A 1.0% Increase In:	Causes This Percent Increase in $(1 + \bar{\alpha})$				
	^{233}U	^{235}U	^{238}U	^{239}Pu	^{240}Pu
$\bar{D}(^6\text{Li})/\bar{\phi}_a^*$	1.000	1.000	0.993	1.000	1.000
$\bar{v}\bar{\phi}_f^*/\bar{D}(^{252}\text{Cf})$	2.779	2.306	0.496	2.774	1.689
$\rho\text{RCF}/R_f$	-1.780	-1.306	0.497	-1.774	-0.689
$D(^6\text{Li}) = -\frac{R_a(^6\text{Li})\bar{\phi}_a^*(^6\text{Li})}{\rho(^6\text{Li})\text{RCF}(^6\text{Li})}$	1.000	1.000	0.993	1.000	1.000
$D(^{252}\text{Cf}) = \frac{S(\text{Cf})\bar{\phi}_f^*(\text{Cf})}{\rho^*(\text{Cf})}$	-2.779	-2.306	-0.496	-2.774	-1.689

TABLE V-13. Some C/E Ratios for the GCFR Phase III Assembly

Matrix Location	Core Zone	$R_{\alpha_0}(\text{Li-6})/R_{f_0}(\text{Pu-239})$	Pu Reactivity Sample	$\rho_0(\text{Li-6})/\rho_0(\text{Pu-239})$	$\frac{\rho_0^f(\text{Cf})}{{}^4_9\rho_0} \times \frac{{}^4_9R_{f_0}}{S(\text{Cf})}$
S23/23	I		Pu-27	0.9302 ± 0.0045^a	0.955 ± 0.011^a
S23/23	I		Pu-25	0.9561 ± 0.0097	0.982 ± 0.014
S23/23	I		MB-10	0.9547 ± 0.0048	0.980 ± 0.011
S23/24	I	1.004 ± 0.012	MB-10	0.9418 ± 0.0049	0.969 ± 0.012
S23/26	I	0.998 ± 0.012	MB-10	0.9416 ± 0.0072	0.967 ± 0.012
S23/28	I	0.996 ± 0.012	MB-10	0.9213 ± 0.0051^a	0.948 ± 0.012^a
S23/30	I	0.999 ± 0.012	ME-10	0.9479 ± 0.0084	0.961 ± 0.014
S23/32	II	1.000 ± 0.012			
S23/33	II		MB-10	0.9497 ± 0.0085	0.972 ± 0.012
S23/34	II	1.006 ± 0.012			
$\overline{\text{C/E}}$:		1.000 ± 0.012		0.9486 ± 0.0062	0.972 ± 0.012
$\overline{\text{C/E}}$ (GCFR Phase II):		0.986 ± 0.013		0.9145 ± 0.0043	0.993 ± 0.014

^aData point omitted in the evaluation of $\overline{\text{C/E}}$.

TABLE V-14. Central Point Conversion Ratio Measurement in the GCFR Phase III Assembly

Quantity	Measured (E)	Calculated (C)	C/E
$^{49}\text{N} \times 10^{-21} \text{ (cm}^{-3}\text{)}$	0.8842		
$^{40}\text{N} \times 10^{-21} \text{ (cm}^{-3}\text{)}$	0.1171		
$^{41}\text{N} \times 10^{-21} \text{ (cm}^{-3}\text{)}$	0.0130		
$^{28}\text{N} \times 10^{-21} \text{ (cm}^{-3}\text{)}$	5.8098		
$^{25}\text{N} \times 10^{-21} \text{ (cm}^{-3}\text{)}$	0.0126		
$(1 + ^{49}\alpha)$ cell avg.	1.254 ± 0.038	1.2389	0.988 ± 0.030
$(1 + ^{40}\alpha)$ " "	1.962 ± 0.073	2.0538	1.047 ± 0.039
$(1 + ^{41}\alpha)$ " "	1.306 ± 0.119	1.1781	0.902 ± 0.082^a
$(1 + ^{25}\alpha)$ " "	1.300 ± 0.037	1.2822	0.986 ± 0.028
$(1 + ^{28}\alpha)$ " "	6.366 ± 0.101	6.4382	1.011 ± 0.016
$^{28}\text{C}/^{49}\text{f}$ " "	0.1265 ± 0.0018	0.1434	1.133 ± 0.016
$^{40}\text{f}/^{49}\text{f}$ " "	0.2351 ± 0.0019	0.2402	1.0218 ± 0.0081^a
$^{41}\text{f}/^{49}\text{f}$ " "	1.306 ± 0.019	1.3452	1.030 ± 0.015^a
$^{25}\text{f}/^{49}\text{f}$ " "	1.053 ± 0.015	1.0386	0.986 ± 0.014
$^{28}\text{f}/^{49}\text{f}$ " "	0.0271 ± 0.0004	0.02637	0.973 ± 0.014
$C = \frac{^{28}\text{N } ^{28}\text{C}/^{49}\text{f}}{^{49}\text{N}(1 + ^{49}\alpha)}$	0.663 ± 0.022	0.7606	1.147 ± 0.038
$C' = \frac{^{28}\text{N } ^{28}\alpha \text{ } ^{28}\text{f}/^{49}\text{f}}{^{49}\text{N}(1 + ^{49}\alpha)}$	0.762 ± 0.030	0.7606	0.998 ± 0.039
$[N]^b$	1.0360 ± 0.0028	1.0356	0.9996 ± 0.0027
$[N']^b$	1.0314 ± 0.0025	1.0356	1.0041 ± 0.0024
$[D]^c$	1.0355 ± 0.0021	1.0341	0.9986 ± 0.0020
$CR_p = C \text{ N/D}$	0.663 ± 0.022	0.7620	1.149 ± 0.039
$CR'_p = C' \text{ N'/D}$	0.759 ± 0.030	0.7620	1.004 ± 0.039

^a Not measured in the GCFR Phase III assembly. C/E values taken from the GCFR Phase II measurement.

^b

$$[N] \equiv 1 + \frac{^{40}\text{N } ^{40}\alpha \text{ } ^{40}\text{f}/^{49}\text{f}}{^{28}\text{N } ^{28}\text{C}/^{49}\text{f}}$$

$$[N'] \equiv 1 + \frac{^{40}\text{N } ^{40}\alpha \text{ } ^{40}\text{f}/^{49}\text{f}}{^{28}\text{N } ^{28}\alpha \text{ } ^{28}\text{f}/^{49}\text{f}}$$

^c

$$[D] \equiv 1 + \frac{^{41}\text{N}(1 + ^{41}\alpha) \text{ } ^{41}\text{f}/^{49}\text{f}}{^{49}\text{N}(1 + ^{49}\alpha)} + \frac{^{25}\text{N}(1 + ^{25}\alpha) \text{ } ^{25}\text{f}/^{49}\text{f}}{^{49}\text{N}(1 + ^{49}\alpha)}$$

TABLE VI-1. Worth of Steam Zone Relative to Steam-free Reference

Axial Half-Height of Steam Zone	Plate Environment		Pin Environment	
	Mass of CH ₂ (g)	Worth of Steam Zone (Ih)	Mass of CH ₂ (g)	Worth of Steam Zone (Ih)
12 in.	632	69.8 ± 1.9	687	107.5 ± 2.7
24 in.	1265	109.3 ± 2.2	1378	176.8 ± 2.3
36 in.	1901	84.4 ± 2.0	2075	146.4 ± 2.2

TABLE VI-2. Steam Worth for Each 12-in. Axial Increment of the Steam Zone

Steam Loading	Plate Environment (Ih/kg)	Pin Environment (Ih/kg)	Pin/Plate
0 - 12 in. Axial Loading	110 ± 3	156 ± 4	1.42
12 in. - 24 in. Axial Loading	62 ± 4	100 ± 5	1.60
24 in. - 36 in. Axial Loading	-39 ± 4	-44 ± 5	1.11
Total Worth, 0 - 36 in. Axial Loading	44 ± 1	71 ± 1	1.59

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