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HRB-21 Irradiation Phase Test Report

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Metals and Ceramics Division

HRB-21 IRRADIATION PHASE TEST REPORT

G. L. Bell, G. L. Copeland, J. T. Parks, and L. C. Emerson

[redacted]

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ABBREVIATIONS AND ACRONYMS

DOE	U.S. Department of Energy
EFPD	Effective Full-Power Days
EOC	End-of-Cycle (outage)
FIMA	Fissions Per Initial Metal Atom
HFIR	High Flux Isotope Reactor
HRB-21	Test Identification
IFEL	Irradiated Fuels Examination Laboratory
LEU	Low-Enriched Uranium
MHTGR	Modular High-Temperature Gas-Cooled Reactor
RB	Removable Beryllium
R/B	Release Rate-to-Birth Rate Ratio
TC	Thermocouple
3-D	Three-Dimensional
RERC	Reactor Experiment Review Committee

HRB-21 IRRADIATION PHASE TEST REPORT*

G. L. Bell, G. L. Copeland, J. T. Parks, and L. C. Emerson

ABSTRACT

Irradiation capsule HRB-21 is a test capsule containing samples of candidate low-enriched-uranium (LEU) fuel for the Modular High-Temperature Gas-Cooled Reactor (MHTGR). Its function is to provide fuel performance data at normal MHTGR operating temperatures in an accelerated irradiation environment.[1] The accelerated irradiation test was performed in the High Flux Isotope Reactor (HFIR) removable beryllium (RB) position, RB-3B. The irradiation period began with cycle 298 on June 20, 1991, and concluded at the end of cycle 302 on November 21, 1991, for a total of 105 equivalent full-power days. This report presents the data collected during the irradiation test. Included are test thermocouple and gas flow data, the inferred test fuel temperatures, measured gaseous fission product activity in the purge gas, and associated release rate-to-birth rate (R/B) results. Also included are key reactor parameters monitored as part of the test data validation process.

*Research sponsored by the Office of Advanced Reactor Programs, Division of HTGRs, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

SECTION 1

INTRODUCTION

1.1 BACKGROUND

The HRB-21 capsule was installed on June 15, 1991, in the High Flux Isotope Reactor (HFIR) RB-3B position, during the end-of-cycle (EOC) 297 outage. The test was originally scheduled to be irradiated for six cycles, but due to loss of ability to maintain test temperatures within the allowable limit (coupled with a higher-than-expected fission gas release rate), the irradiation was terminated after the fifth cycle, cycle 302, which ended on November 21, 1991. The total irradiation time at power was 104.7 effective full-power days (EFPDs).

The reactor was operated at a nominal power of 85 MW(t) throughout the irradiation period, except at the beginning of cycle 302. As will be shown in the data, the reactor power was temporarily reduced to about 80 MW(t) for about 30 h at the beginning of cycle 302 to resolve a thermocouple alarm setpoint problem on the HRB-21 test. This report presents test thermocouple and gas flow data, inferred average fuel compact temperatures, measured gaseous fission product release rates, and associated release-rate to birth-rate (R/B) calculations. Key reactor parameters are also presented as a means of characterizing reactor operation.

SECTION 2

CAPSULE OPERATION IN THE HFIR

The capsule was operated in the HFIR in accordance with the operating guideline, which included a staged ascent to reactor power to minimize particle failures due to rapid increases in the power generated per particle.[2] Table 2-1 presents the dates bounding the HRB-21 irradiation. The startup time is taken to be the time at which the reactor reaches full-power operation [85 MW(t)]. Reactor shutdown is attained by rapidly inserting the control shims (reactor scram). The sweep gas at startup was 100% helium for all cycles. The sweep gas between cycles was 100% helium.

Table 2-1.

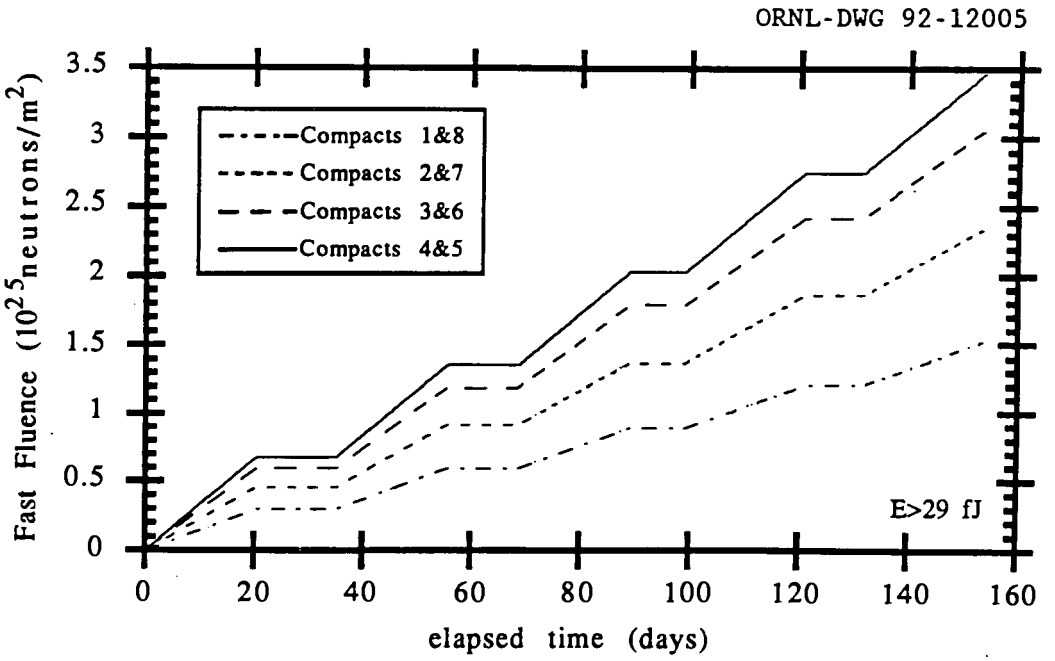
HRB-21 IRRADIATION DATES, WITH TIME ELAPSED SINCE FIRST HFIR FULL-POWER EXPOSURE, CYCLE TIME AT FULL POWER AND TOTAL TIME AT FULL POWER.

HFIR cycle	Cycle start/end	Cumulative calendar time (d)	Cycle length (d)	Cumulative time at power (d)
298	6/20/91 18:15	0	20.526	20.526
	7/11/91 06:53	20.526		
299	7/25/91 22:10	35.163	20.448	40.974
	8/15/91 08:55	55.611		
300	8/28/91 11:48	68.731	20.247	61.222
	9/17/91 17:44	88.978		
301	9/27/91 21:18	99.127	21.845	83.067
	10/19/91 17:35	120.972		
302	10/30/91 12:00	131.781	21.596	104.663
	11/21/91 02:18	153.377		

The HRB-21 capsule was operated to meet the goal of controlling the volume-averaged fuel temperature at 975°C without exceeding a local maximum fuel temperature of 1250°C. Capsule temperatures were adjusted as required by changing the composition of the sweep gas flowing in the annular regions between the fuel compacts and the graphite fuel holders and between the graphite fuel holders and the primary containment. Helium and neon were the

sweep gases utilized to control the temperature. Greater fractions of helium, which has the higher thermal conductivity by a factor of three, decrease thermal resistance in the gap resulting in lower capsule temperatures.

The burnup and fluence goals for the test[1] were to achieve a fast fluence ($E \geq 29$ fJ) of $\leq 5 \times 10^{25}$ neutrons/m^2 and a peak fissile burnup of $\leq$26% fissions per initial metal atom (FIMA). As shown in Fig. 2-1, shortening the irradiation time to five cycles rather than six achieved fluence and burnup levels of 70 and 87% of the desired peaks based on the best predictions currently available.[3,4] The increasing temperatures, which caused the test to be shortened, may have been partly due to increased fertile material fissions because of the much longer average time between cycles than had been anticipated during the thermal design. The postirradiation thermal neutron fluence and burnup analyses will provide pertinent data for these important parameters.



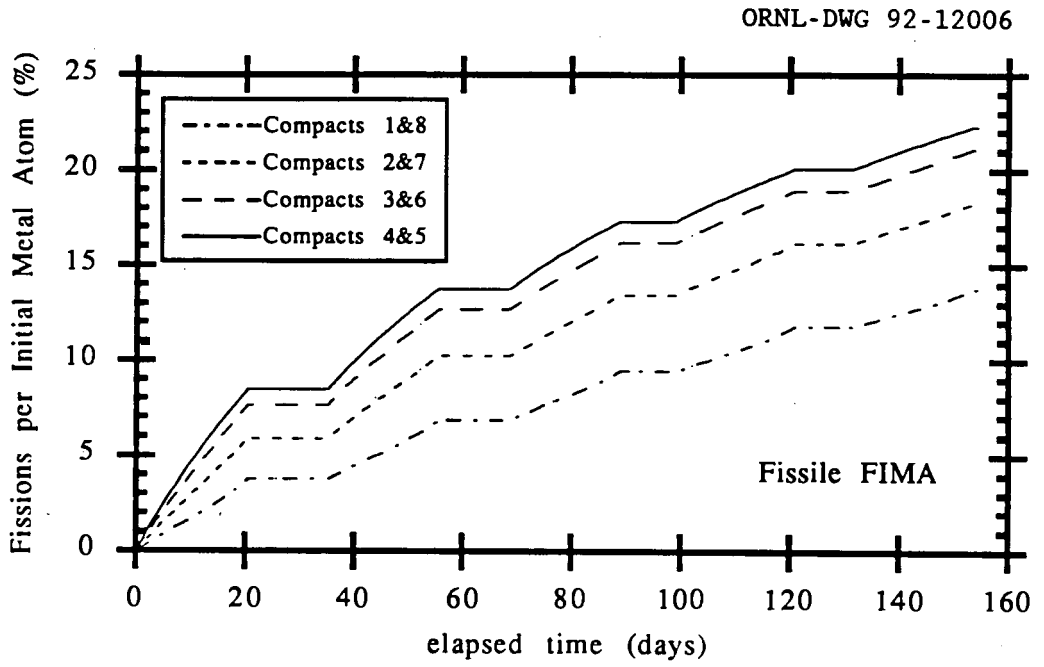


Figure 2-1.

CAPSULE HRB-21 FUEL BURNUP AND FAST FLUENCE.

SECTION 3

CALCULATION OF VOLUME-AVERAGED FUEL COMPACT TEMPERATURE

The thermocouples were located at the axial midplane in each graphite body at the locations shown in Fig. 3-1 (three out of four of the positions in each body are occupied since 24 thermocouples are available). The axial arrangement of the thermocouples in the fuel regions is shown in Fig. 3-2. Since there were no thermocouples in contact with the fuel compacts, the fuel compact temperatures were calculated based on the temperatures measured by the thermocouples located in the graphite bodies. It is important to note that the fuel temperatures quoted herein are best estimates extracted from thermocouple measurements of the graphite fuel holder temperature. The calculated volumetric fuel temperature is a function of several variables, including the thermocouple (TC) temperatures, the thermal conductivity of the fuel compact, the thermal conductivity of the graphite, the gas gap between the fuel and the graphite, the gas gap between the graphite and the primary containment wall, and the helium-filled gap between the primary and secondary containments.

In the course of the irradiation, the properties of the fuel and graphite change as a function of fast fluence and temperature. The variation of the thermal conductivity of the graphite and fuel compacts, and the gas gaps as a function of fast fluence and temperature, were included as part of the thermal analysis to calculate the best possible estimate of the volume-averaged fuel temperature and the maximum local fuel temperature. The agreement between the model and physical reality is, of course, dependent on the "goodness" of the model, the accuracy of the design equations used to calculate physical parameters such as gas gaps and thermal conductivities, and the accuracy of the neutronics description of the irradiation facility. The quality of the calculation itself is assured via verification of the computer codes by proper review and documentation, and validation of the model by benchmarking against properly qualified empirical data.

The three-dimensional (3-D) numerical model (Fig. 3-3) of a 60° section of the capsule was generated for thermal analysis by the HEATING 7.0 computer code.[5] In this model, each geometric region was assigned a thermal conductivity (constant or temperature dependent), a power generation rate

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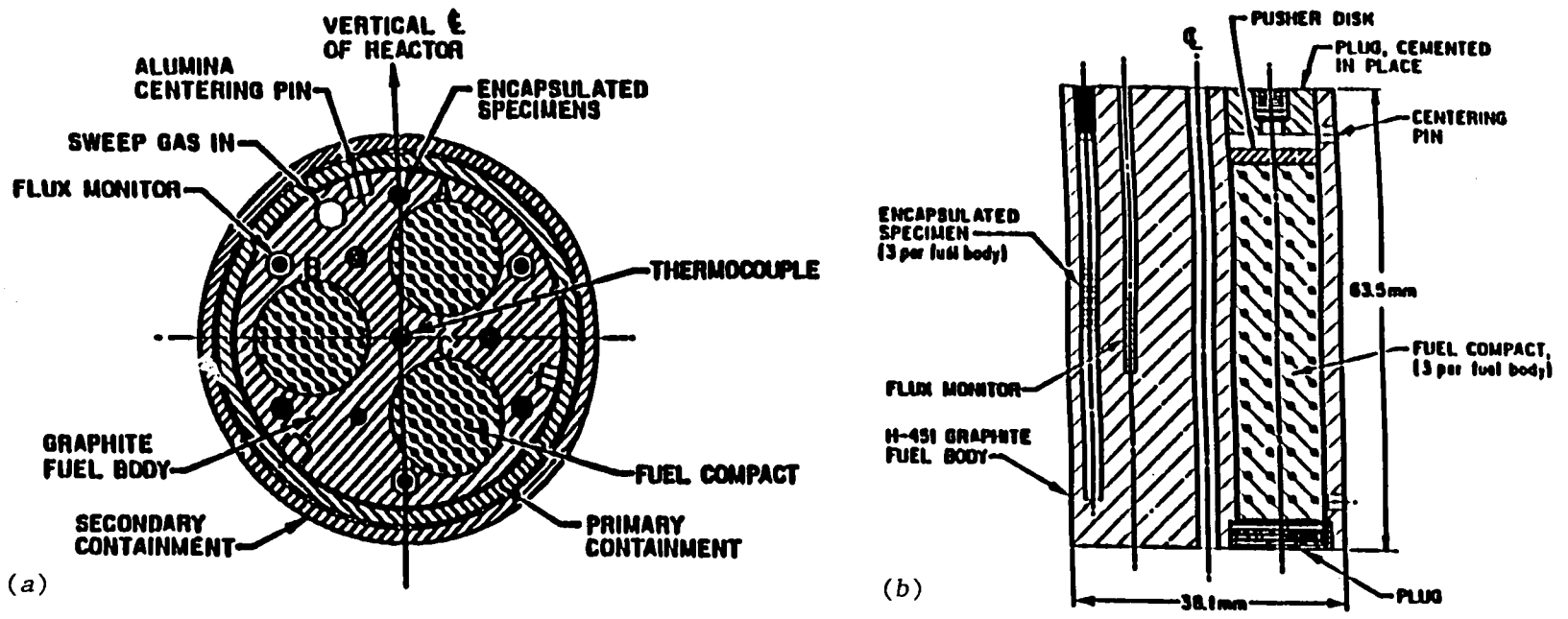

Figure 3-1.

SCHEMATIC CROSS SECTIONS OF CAPSULE HRB-21 SHOWING ARRANGEMENT OF FUEL COMPACTS, ENCAPSULATED PIGGYBACK SPECIMENS, FLUX MONITORS, AND THERMOCOUPLES: (*a*) HORIZONTAL AND (*b*) VERTICAL.

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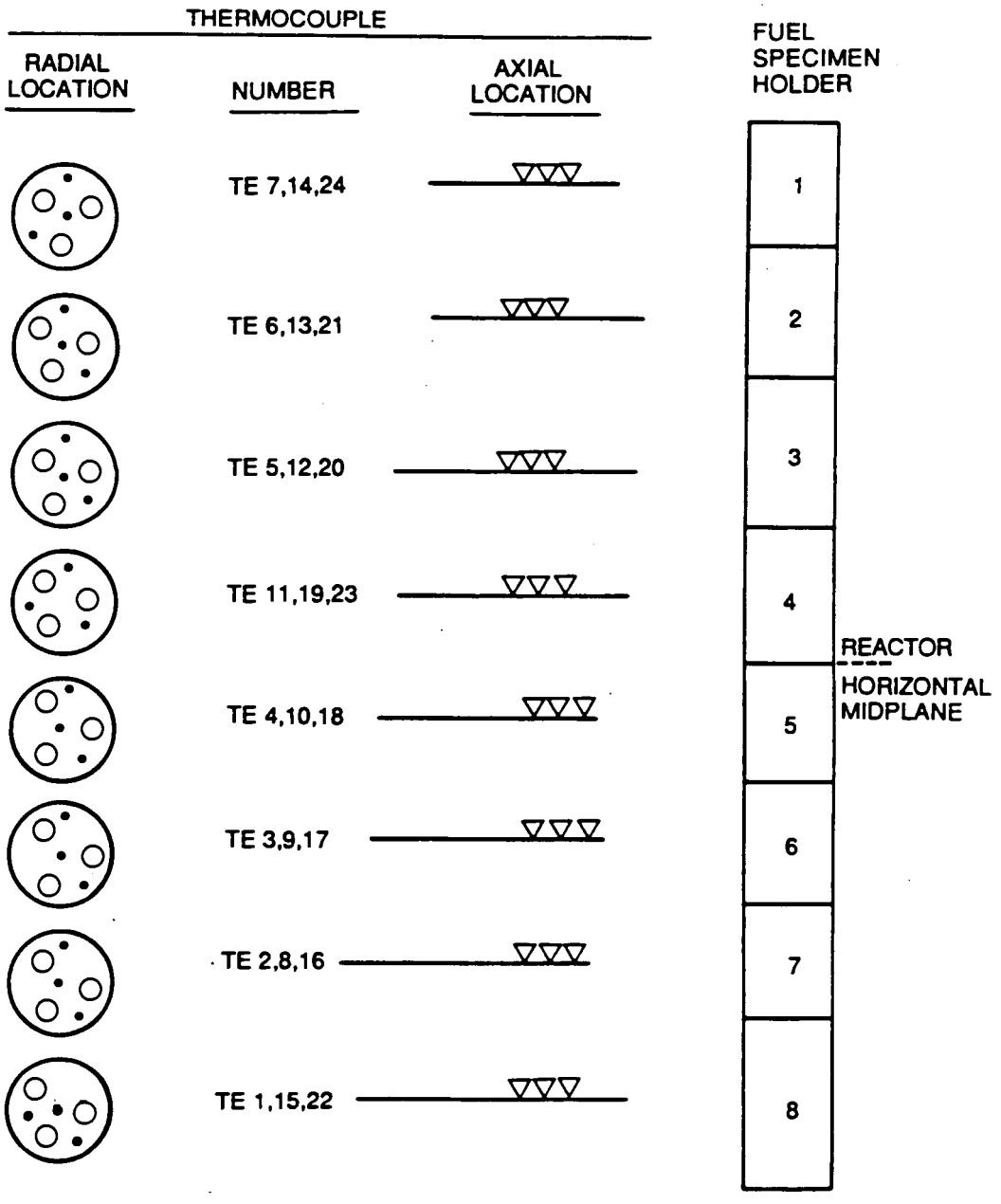

Figure 3-2.

THERMOCOUPLE ARRANGEMENT IN IRRADIATION CAPSULE HRB-21.

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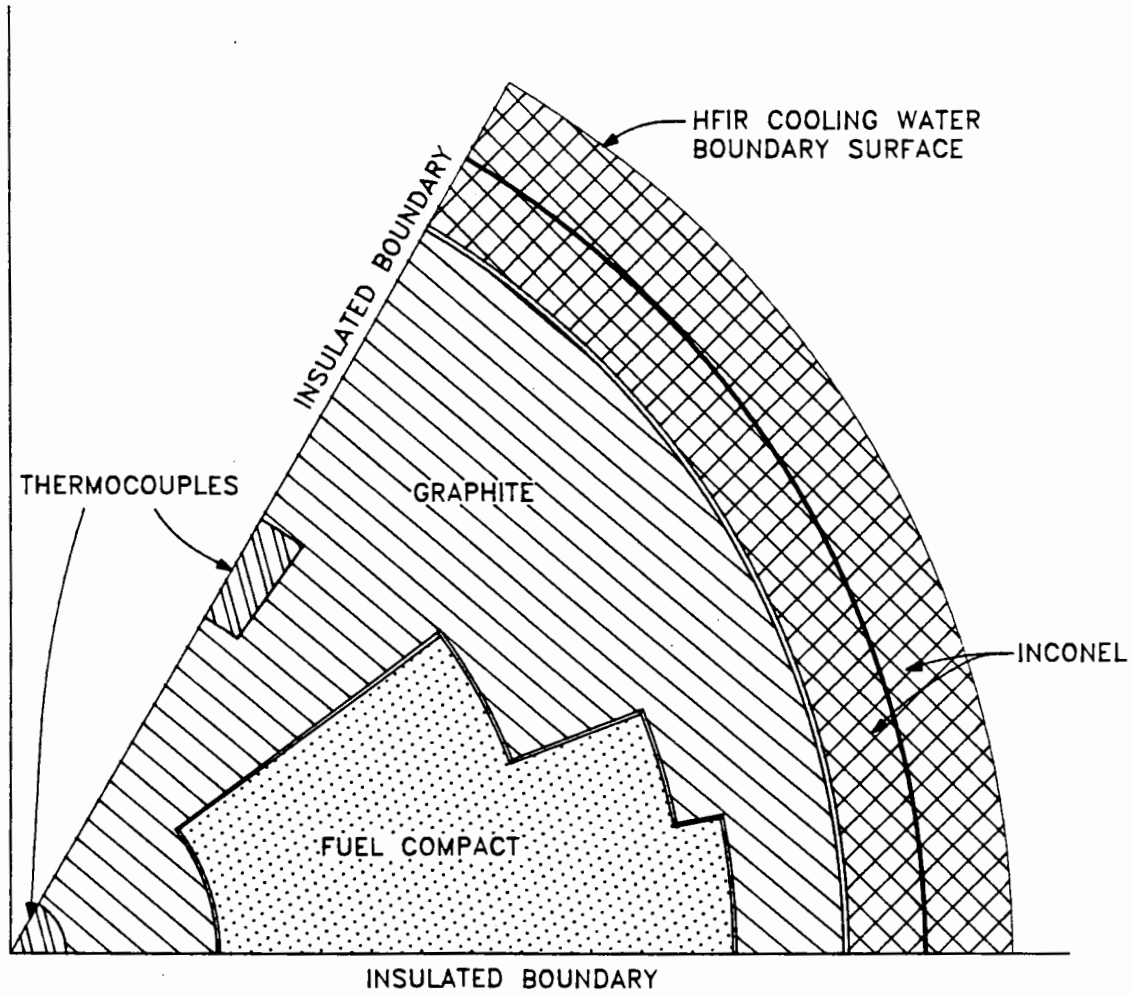

Figure 3-3.

CROSS-SECTION MOCK-UP OF IRRADIATION CAPSULE HRB-21 FOR THERMAL DESIGN CALCULATIONAL PURPOSES: HORIZONTAL CROSS SECTION, R-θ VIEW.

(power density), and specific boundary conditions (radiative emissivity, surface heat flux, etc.) to form a mathematical model of the heat transport problem posed by the capsule. In this model, the thermocouples were included as regions with a nuclear heating rate determined by the average density of the thermocouple array tube. The piggyback samples and the inlet gas passages were assumed to be filled with H451 graphite. The gap between the fuel and the graphite was assumed to be filled with the sweep gas. It was assumed that the fuel compact was perfectly centered in the hole, and that the graphite fuel body was perfectly centered within the containment tube. Results of the HEATING 7.0 execution (nodal temperature map) were post-processed to provide:

1. <T> = volume-averaged fuel temperature,
2. TC = average thermocouple temperature,
3. radial temperature profiles through the compact horizontal midplanes, and
4. axial profiles through the compacts which pass through the maximum temperature node.

To facilitate day-to-day control of the fuel temperature, a program was developed to map measured thermocouple temperatures into calculated average fuel temperatures. Due to the large amounts of time required to execute the HEATING 7.0 model of the HRB-21 capsule, a program was written to quantify the dependence of <T> on the various input parameters.

To develop parametric dependences, a series of HEATING 7.0 runs were executed in which the input parameters were scanned over the range of their expected values. The parameters of interest are:

P_v = heat-generation rate of the compact (W/cm^3) from fission and nuclear heating (gamma heat),
K_g = thermal conductivity of H-451 graphite ($W/cm \cdot K$),
K_f = thermal conductivity of the fuel compact ($W/cm \cdot K$),
f_g = radial gas gap between the fuel compact and the graphite (cm),
g_inc = radial gas gap between the graphite and the primary wall (cm), and
%He = percentage of helium in the helium/neon sweep gas.

A standard HEATING input model was prepared from the design model. A base parameter set (P_{vo}, K_{go}, K_{fo}, f_g_o, g_inc_o, $\%He_o$) was included in the standard input case. A set of computer runs was then carried out where one parameter was varied over its expected range, while all other parameters were held constant. Scaling equations derived from these parametric scans were incorporated into the program Txave.f (where x denotes the set of three compacts in a given axial location) to generate an estimate of <T> when the program is provided with inputs TC, reactor thermal power, and time. K_g, K_f, f_g, and g_inc are calculated by subroutines using design equations.[6-8] The flow chart shown in Fig. 3-4 outlines the logic path. A program listing is provided in Appendix A. The methodology used in the development of this program can be examined in ref. 8. A summary and explanations of the inputs required for Txave.f to generate the nominal <T> are shown below.

3.1 MEASURED AND CALCULATED INPUT PARAMETERS

1. TCob = average of the outboard thermocouple readings from a given holder at time t. For fuel holder 4, TCob is the average of the temperatures indicated by thermocouples 11, 19, and 23.
2. TCcl = the centerline thermocouple reading from a given holder at time t. For fuel holder 5, TCcl is the temperature indicated by thermocouple 4.
3. t = time elapsed since first exposure to HFIR full-power operation (used to calculate fast fluence).
4. HFIR thermal power output at time t (used to calculate fast fluence). The fast flux is calculated from design equations at the axial location of the horizontal midplane of the fuel compact.[3] The flux equations were developed for 100-MW(t) HFIR operation. The flux used in the calculation of the fluence is the 100-MW(t) flux multiplied by the current thermal power level/100 MW(t). The time is measured from the beginning of the irradiation where t_0 = time when the test first experienced HFIR 85MW(t) operation.

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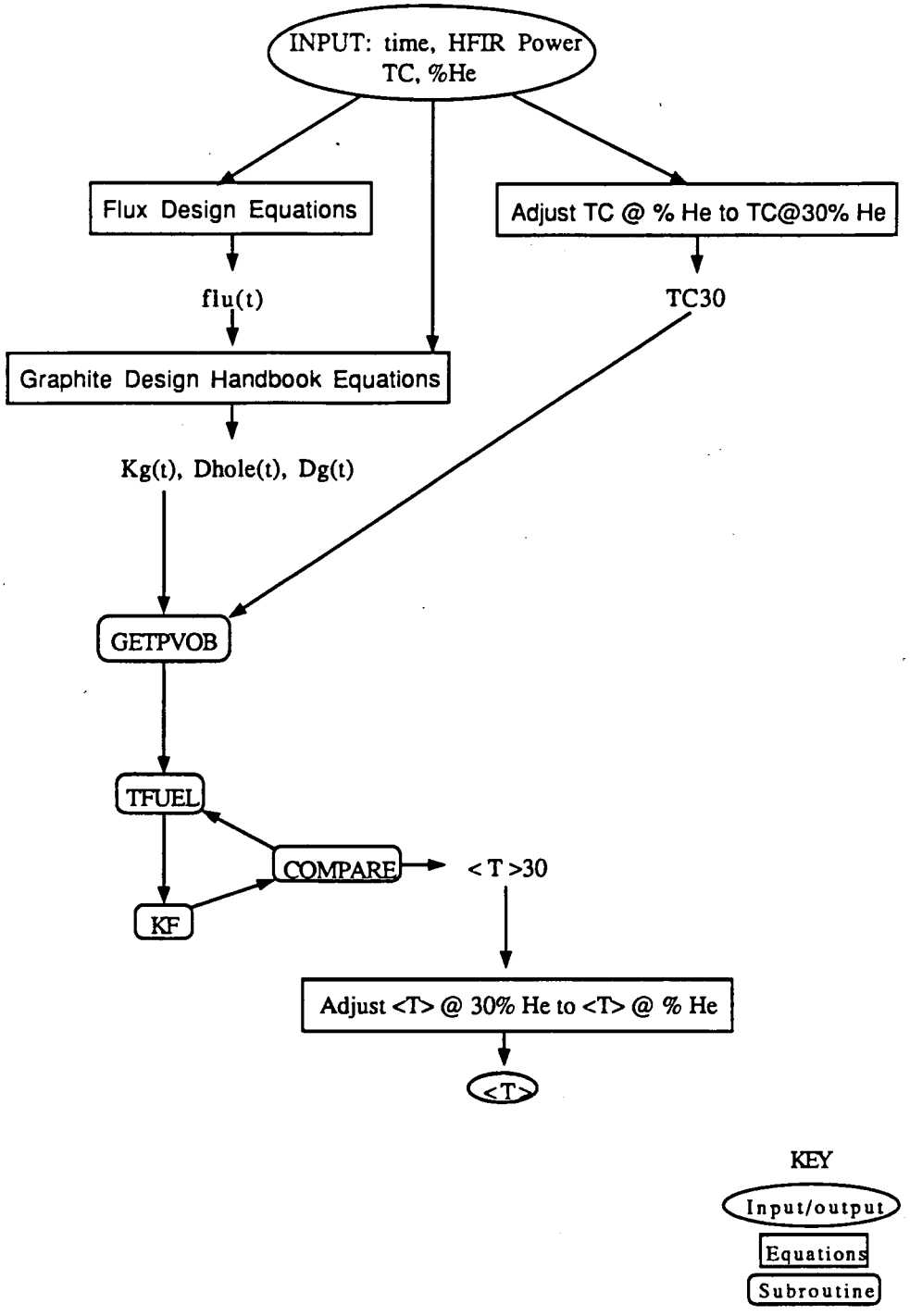

Figure 3-4.

LOGIC PATH OF COMPUTER PROGRAM USED TO ESTIMATE THE VOLUME-AVERAGED FUEL COMPACT TEMPERATURE FROM MEASURED THERMOCOUPLE TEMPERATURES.

3.2 PARAMETERS CALCULATED FROM DESIGN EQUATIONS

These parameters are used in the calculation of the volumetric fuel temperature and are calculated as functions of temperature and fast fluence.

1. K_g, the diameter of the graphite fuel holder, and the diameter of the fuel hole in the holder are calculated from design equations found in the HTGR Graphite Design Handbook.[6] They are functions of the graphite fuel body temperature (TC) and the fast fluence.
2. K_f and the diameter of the fuel compact are calculated from design equations found in the Fuel Design Data Manual (Issue F, 1987) supplied by General Atomics.[7] They are functions of fuel temperature and fast fluence.
3. f_g is calculated from the diameter of the fuel hole and the diameter of the fuel compact and is thus a function of fluence and temperature.
4. g_inc is calculated from the diameter of the primary containment wall and the diameter of the graphite fuel holder. The primary containment diameter is assumed to be held constant at 300°C. This needs to be corrected for the fission power density changing as a function of time. The diameter of the graphite in the zone of interest is calculated starting from the 25°C fabrication diameter and is a function of TCob and fast fluence.

All of these parameters are functions of temperature and fluence and are implicitly time dependent. The only time these parameters are constant is when the reactor power level is below 0.2 MW(t). For those times, the fuel temperature is assumed to be at the average TC temperature.

SECTION 4

CALCULATION OF THE LOCAL MAXIMUM FUEL TEMPERATURE

The maximum fuel temperature, Tmax, is calculated using the linear least-squares fit shown in Fig. 4-1. This scatter plot includes results from all model executions used in the derivation of the scaling equations discussed above. Note that the ratio Tmax/<T> is, in general, a function of K_f and P_v. In this treatment, the K_f and P_v parametric scan results are included in the family of points in Fig. 4-1 and are thus included in the least-squares linear fit. Scatter plots for all cases executed for which Tmax ≥ 1200°C show Tmax ≤ 1.17 <T>. Figure 4-2 is an example of a scatter plot for fuel zone 4. Since the power and fuel loadings in the experiment are symmetrical about the axial centerline, the test consists of four fuel zones for calculational purposes. Zone 1 consists of fuel holders 1 and 8, zone 2 is fuel holders 2 and 7, zone 3 is fuel holders 3 and 6, and zone 4 is holders 4 and 5.

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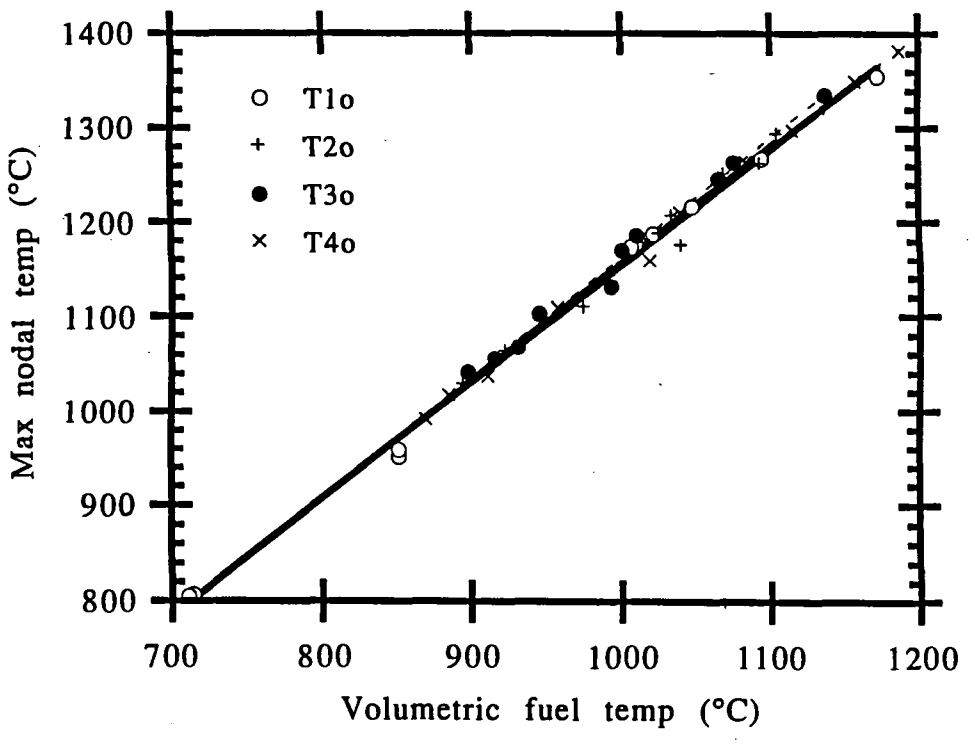

Figure 4-1.

MAXIMUM LOCAL FUEL TEMPERATURE AS A FUNCTION OF THE VOLUMETRIC FUEL TEMPERATURE.

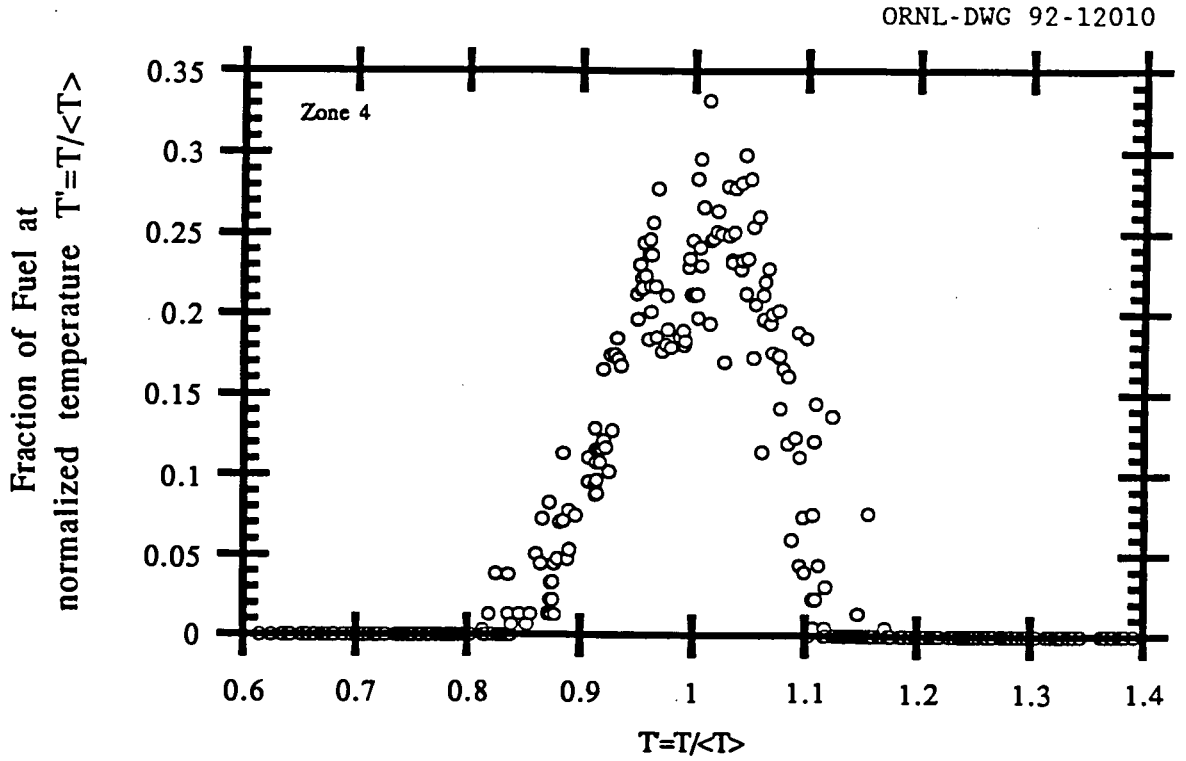

Figure 4-2.

FRACTION OF FUEL AT NORMALIZED TEMPERATURE FOR CASES IN WHICH Tmax ≥ 1200°C FOR FUEL ZONE 4.

SECTION 5

RESULTS OF TEMPERATURE CALCULATIONS

Using the technique for calculating the volume average fuel compact temperature described above, the time evolution of the fuel temperature and the measured thermocouple temperatures are shown in Fig. 5-1. Figure 5-2 shows the average fuel temperature and local maximum fuel temperature for each zone. Typical capsule temperatures during reactor shutdowns were about 45°C. Note that these volume-averaged fuel temperatures are preliminary. Once the postirradiation dimensional measurements are complete and the flux monitors are analyzed, the data will be incorporated into a revised calculation of the volumetric average fuel temperature.

Two of the 24 thermocouples failed during the test. Thermocouple TC-101, a centerline thermocouple in region 8, failed after 102 d of service. Thermocouple TC-105, a centerline thermocouple in region 5, failed after 142 d of service. At random intervals, isolated thermocouple data were flagged by the data acquisition software as bad data, but the total amount of bad data accumulated was negligible. At no time did loss of thermocouple data threaten the continuity of the experiment.

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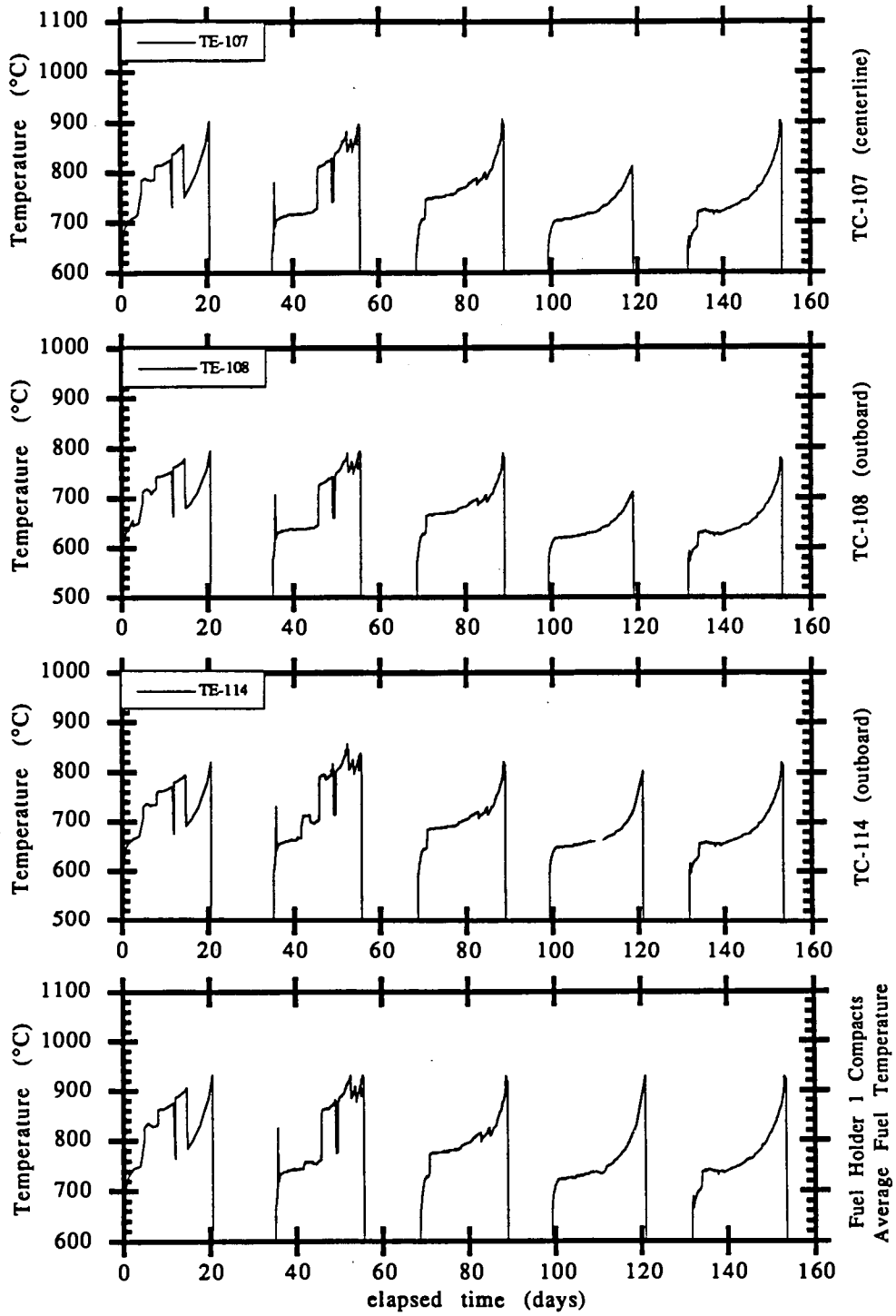

Figure 5-1.

MEASURED THERMOCOUPLE TEMPERATURES AND CALCULATED VOLUMETRIC FUEL TEMPERATURES FOR EACH FUEL HOLDER.

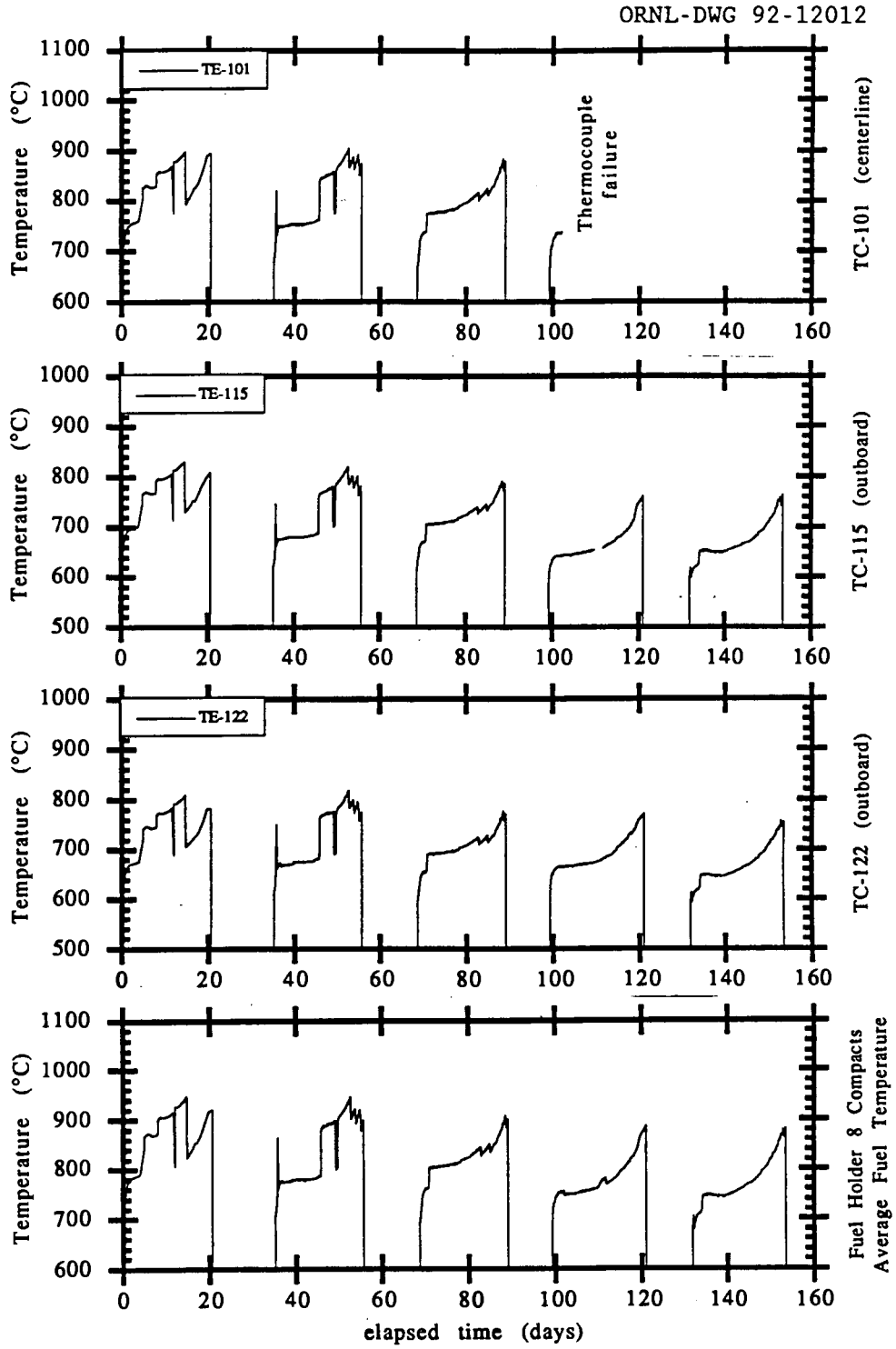

Figure 5-1. CONTINUED.

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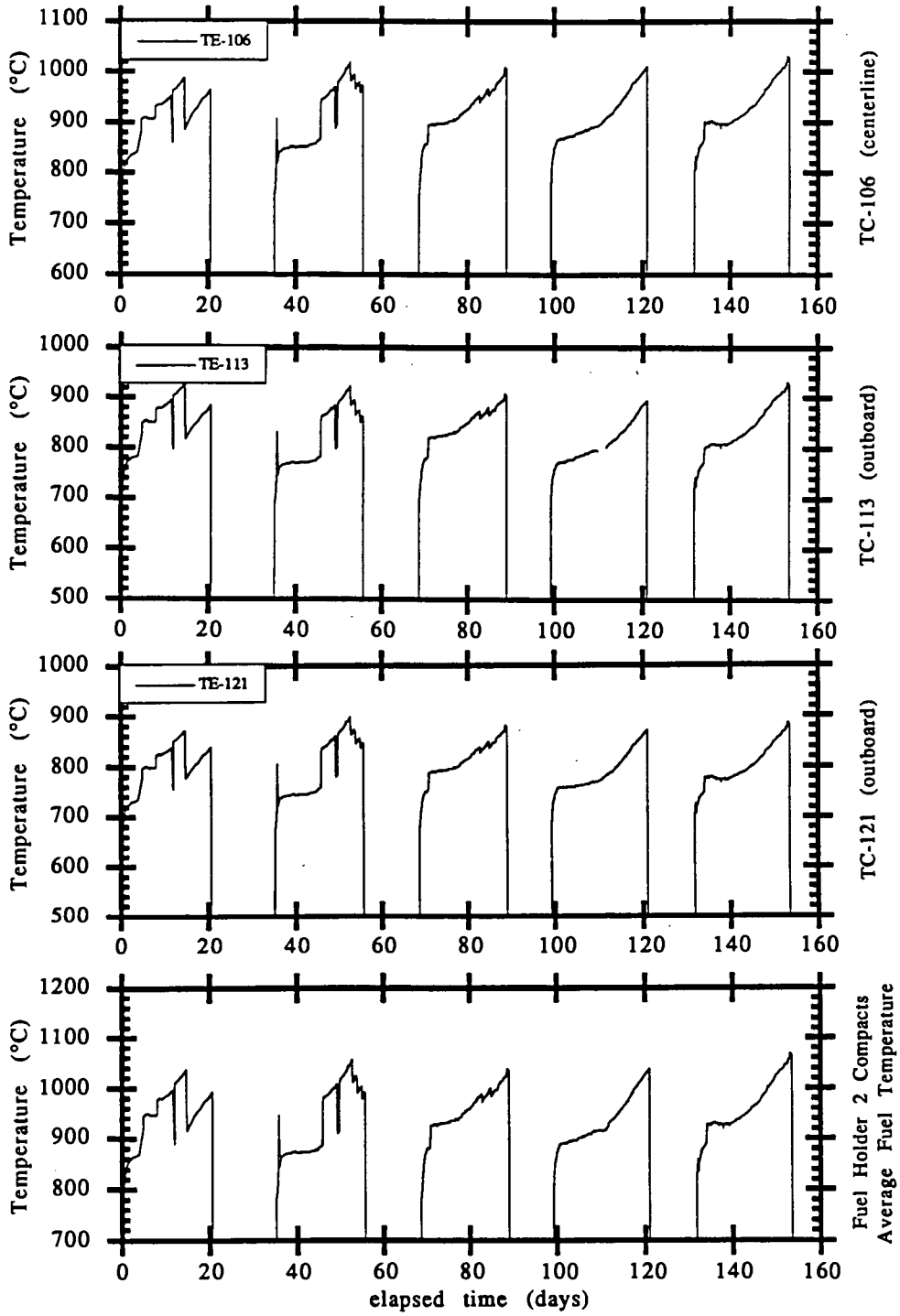

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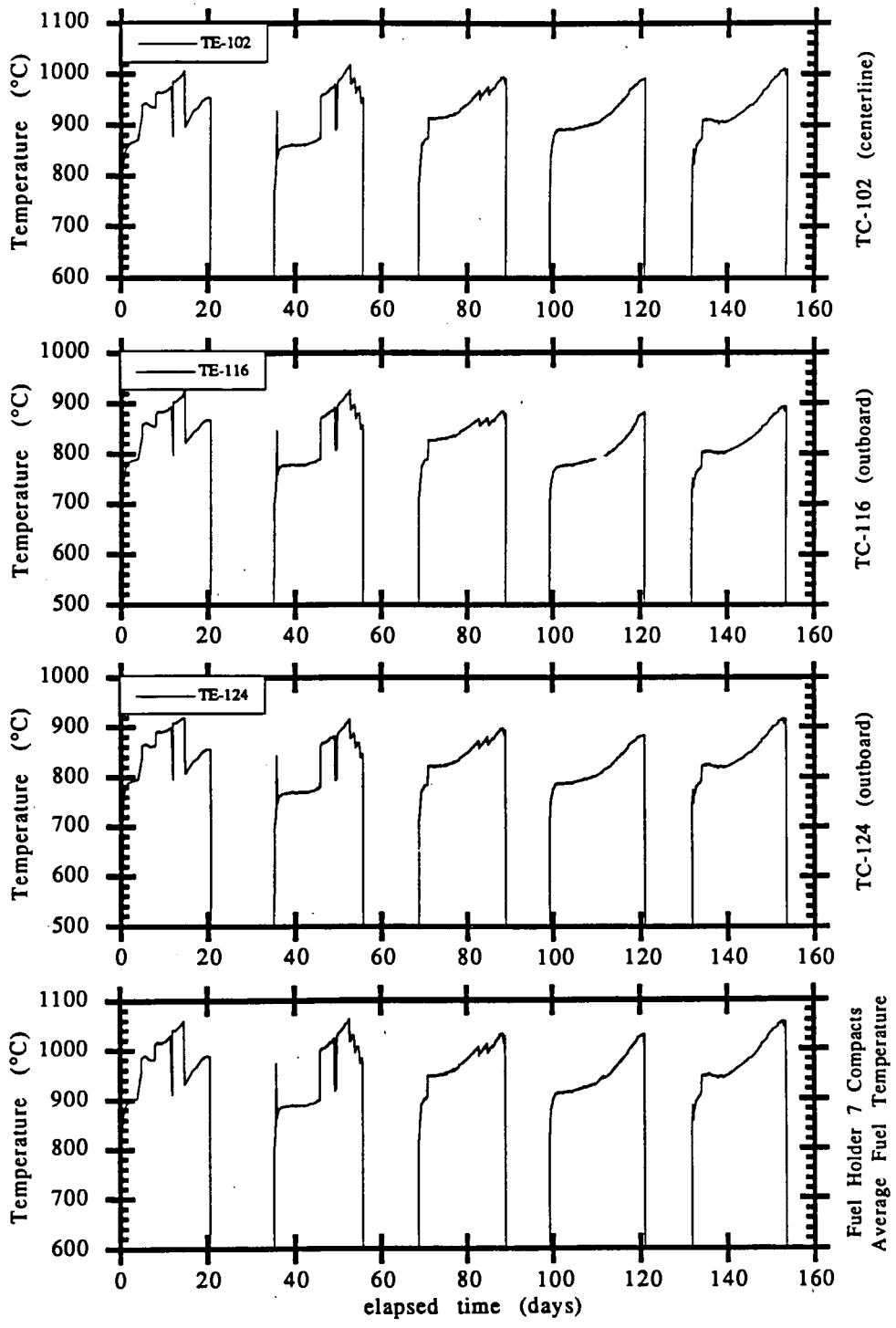
ORNL-DWG 92-12014



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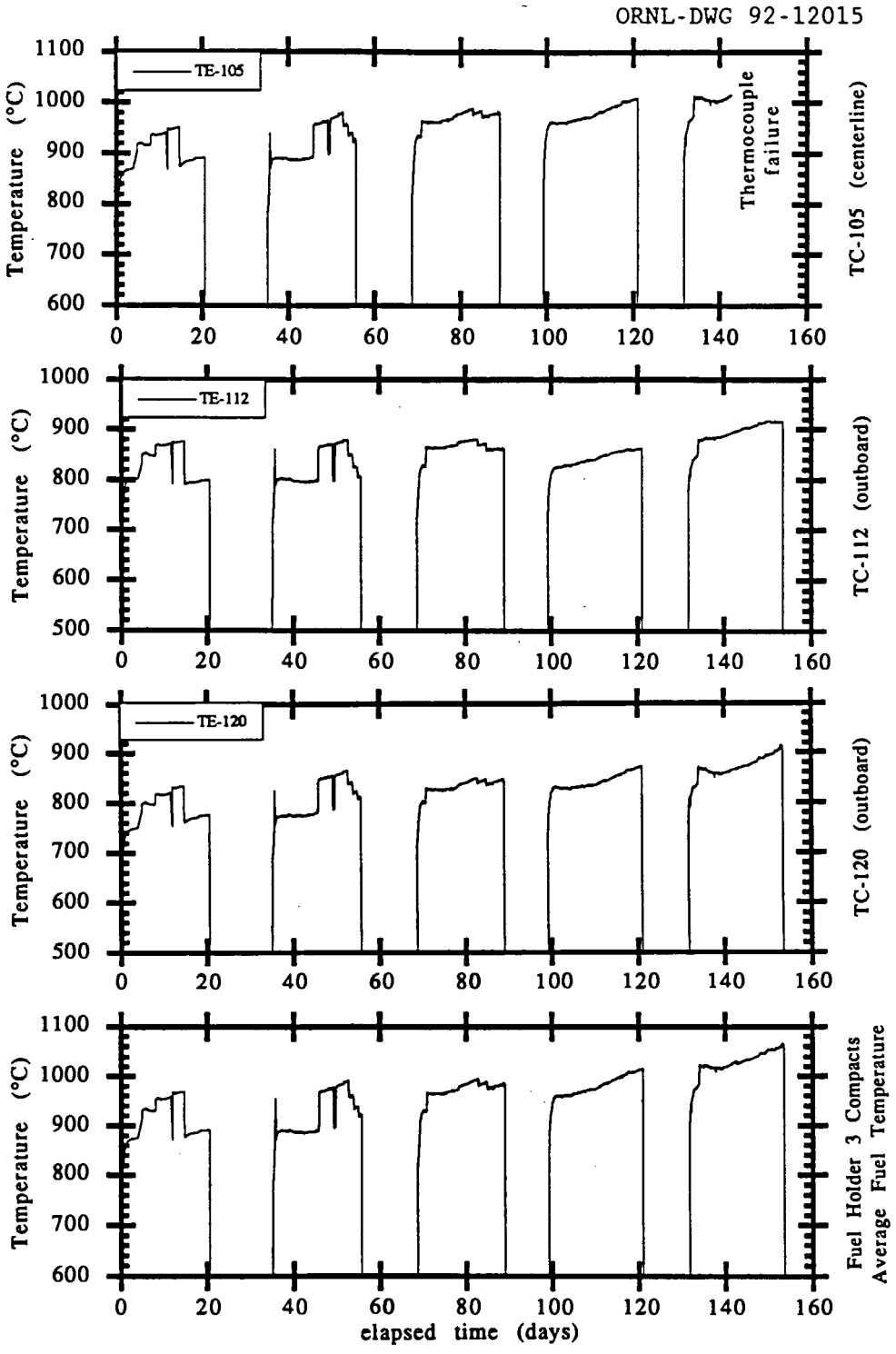

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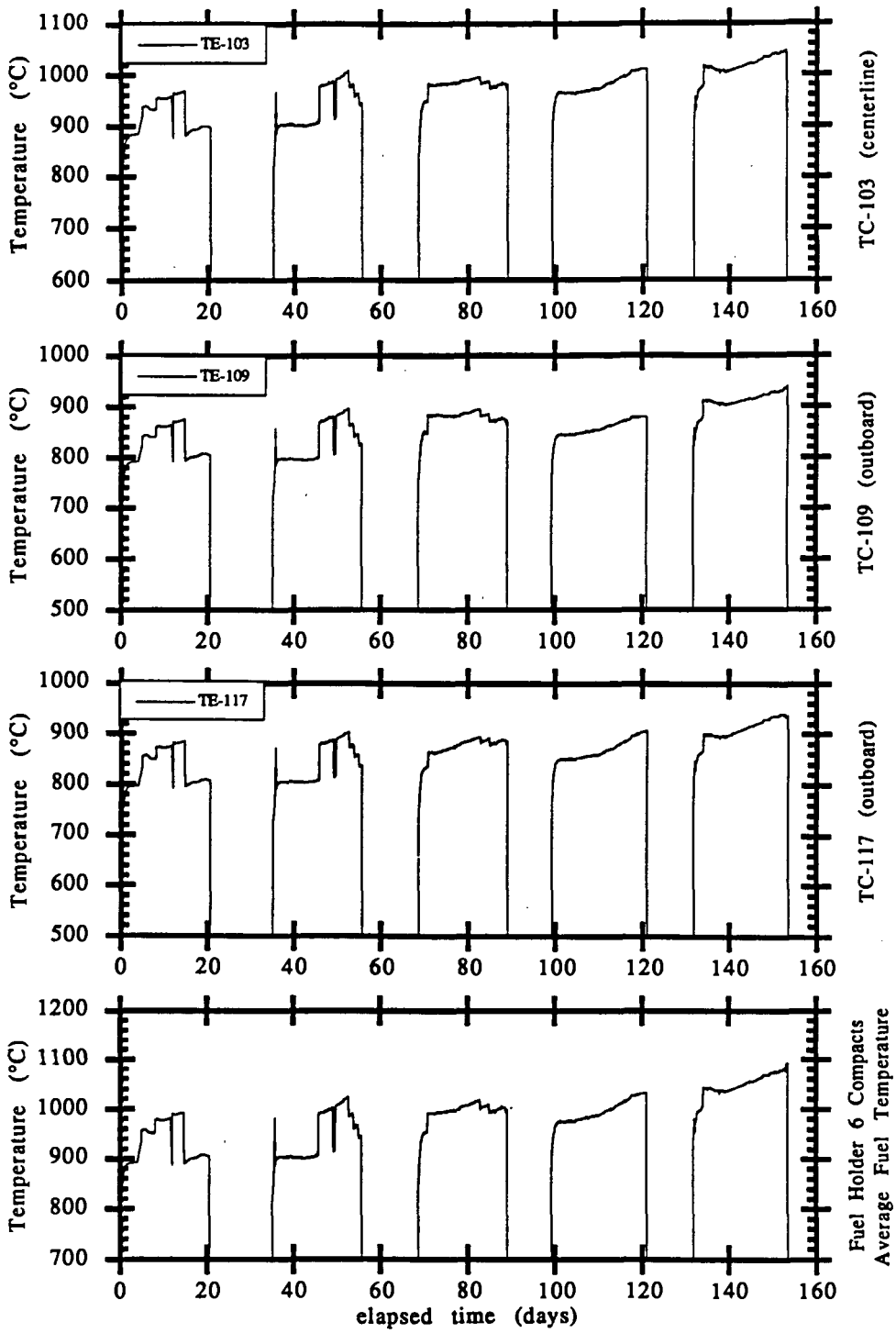
ORNL-DWG 92-12016



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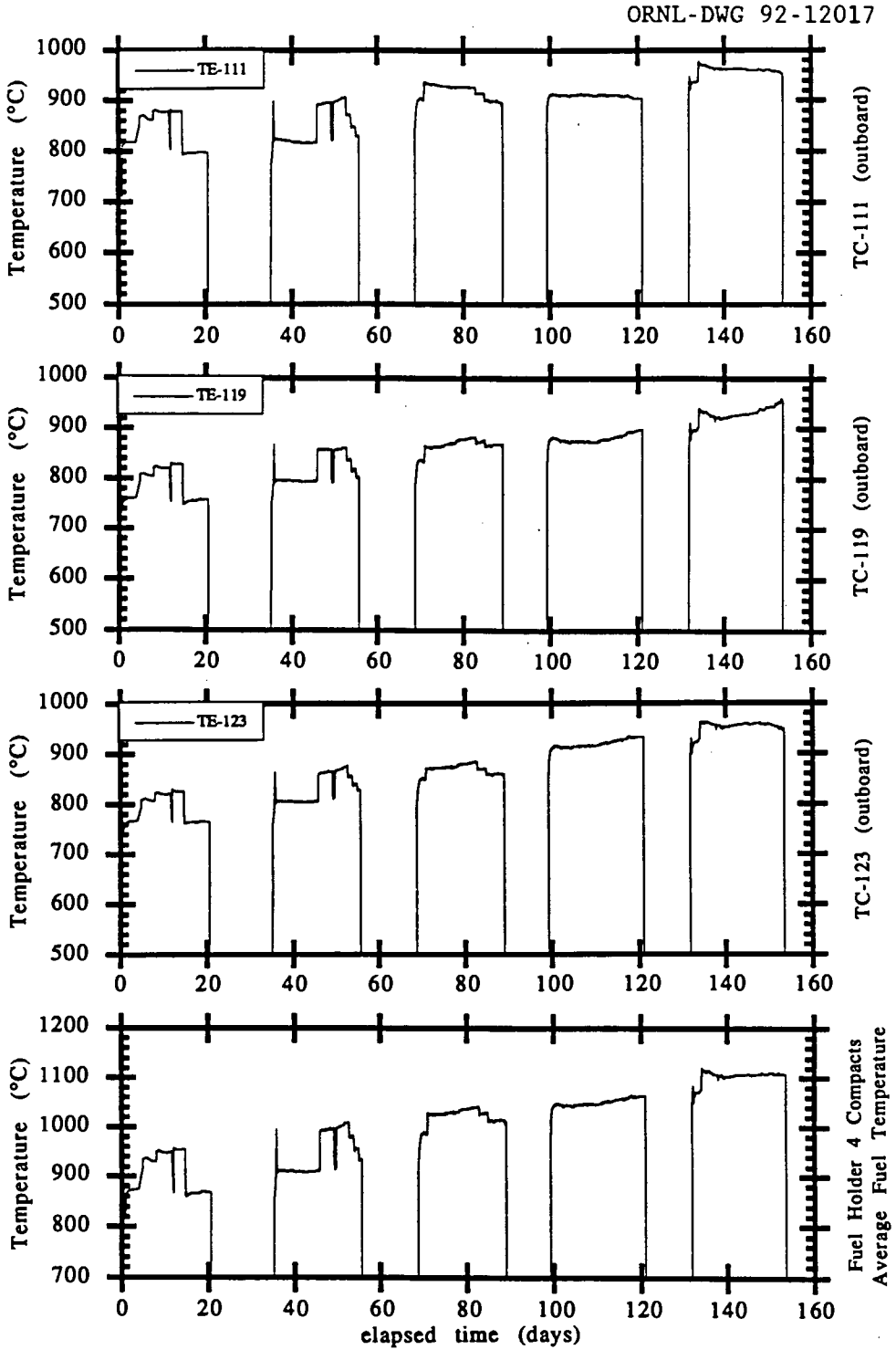

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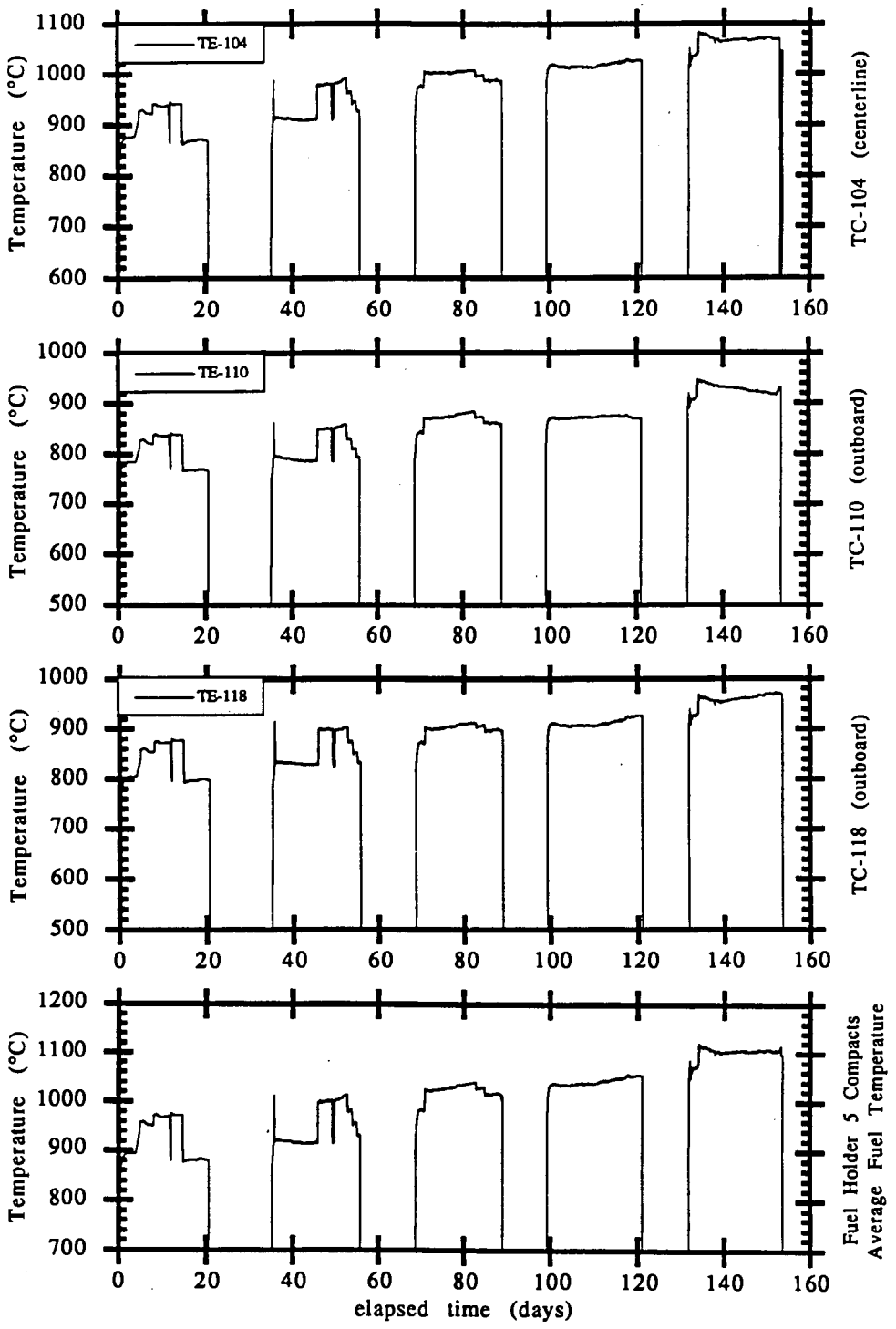
ORNL-DWG 92-12018



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ORNL-DWG 92-12019

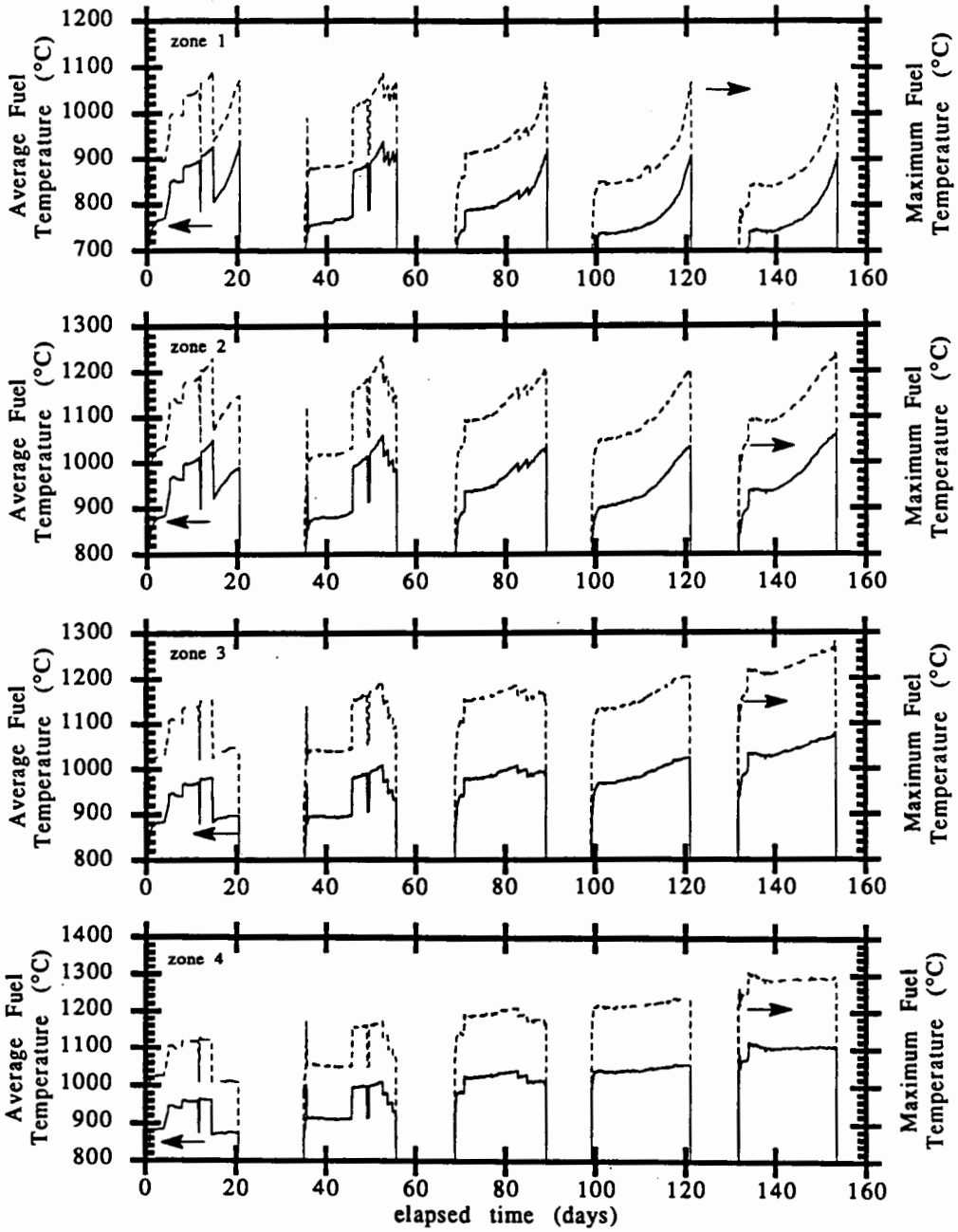


Figure 5-2.

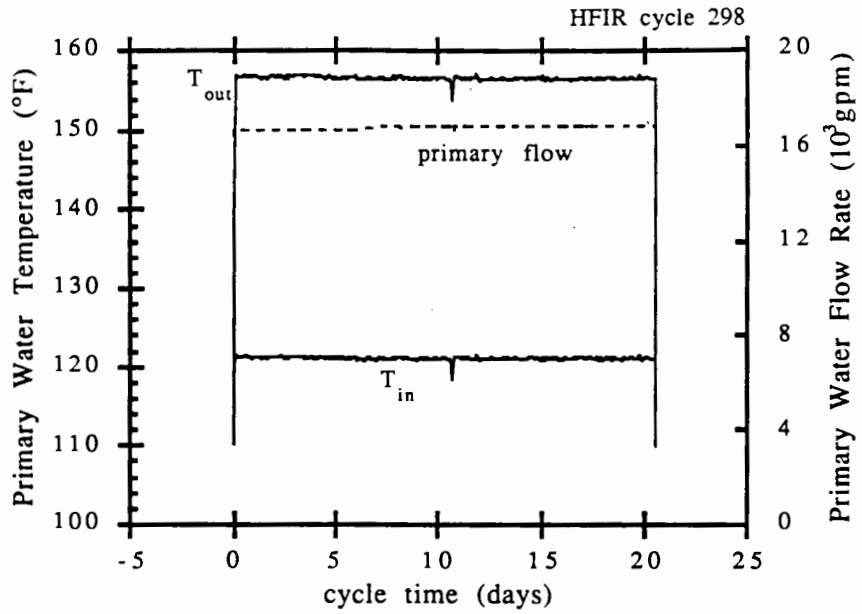
AVERAGE FUEL COMPACT TEMPERATURE AND THE LOCAL MAXIMUM FUEL TEMPERATURE FOR EACH OF THE FOUR FUEL-LOADING ZONES AS A FUNCTION OF ELAPSED TIME.

SECTION 6

REACTOR OPERATION

Figures 6-1 through 6-4 provide reactor plant data for HFIR cycles 299 through 302. Shown are the reactor vessel primary inlet and outlet cooling water temperature and the primary cooling water flow rate (Fig. 6-1), the inlet primary water pressure and pressure drop between the primary inlet and outlet (Fig. 6-2), the position of the control plates (Fig. 6-3), and a neutron flux chamber signal (Fig. 6-4). The data for cycle 298 were not available on magnetic media, and these data were reconstructed from hard copy for experimental data validation. Thus, the cycle 298 data are constructed from discrete points at 1-h intervals rather than continuous data as is the case for the remaining cycles. The correlation between control rod withdrawal and temperature of the capsule ends (Fig. 5-1, regions 1 and 8) is readily observed. Detailed review of these reactor data has validated the thermocouple data from the test. The plotted data exhibit no unusual or inexplicable characteristics.

ORNL-DWG 92-12020



ORNL-DWG 92-12021

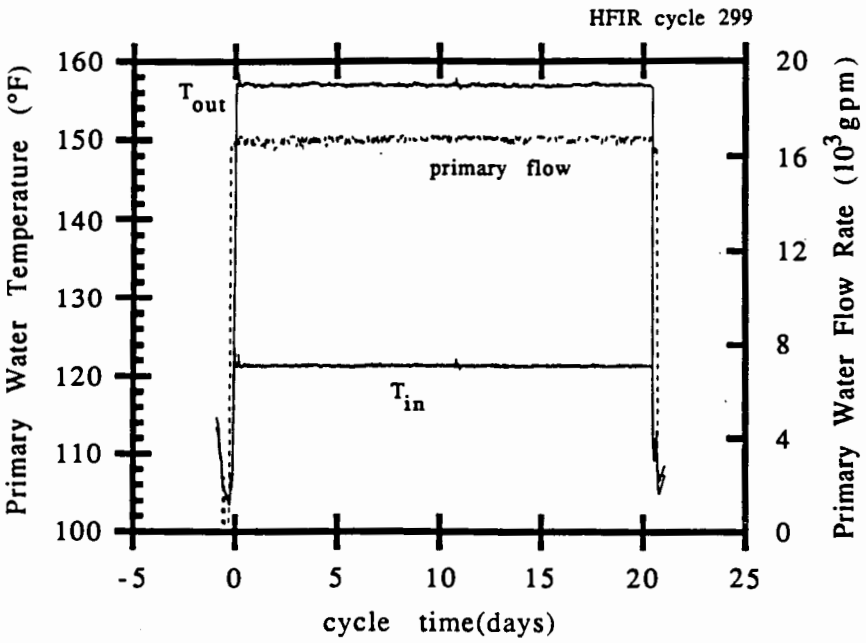
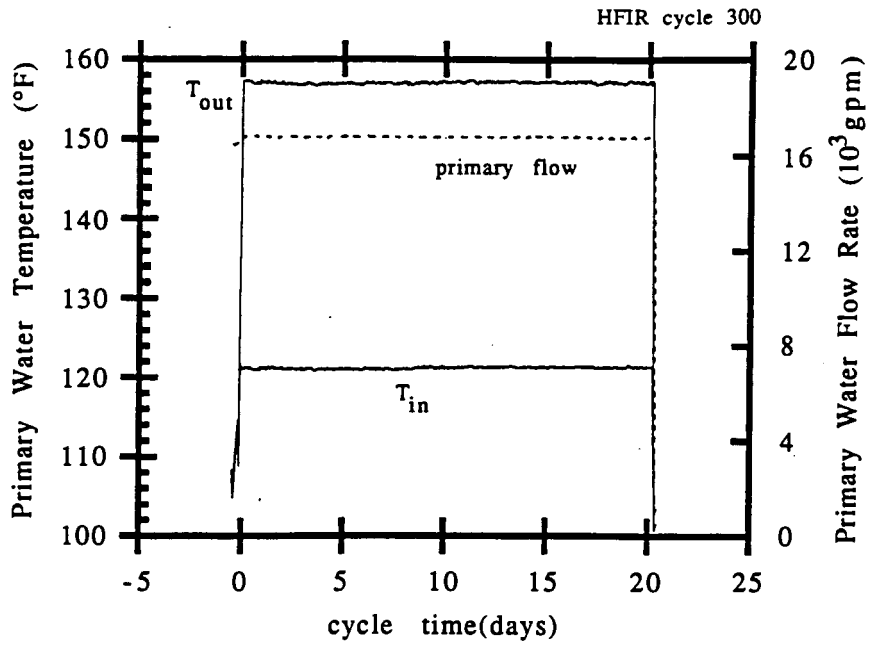


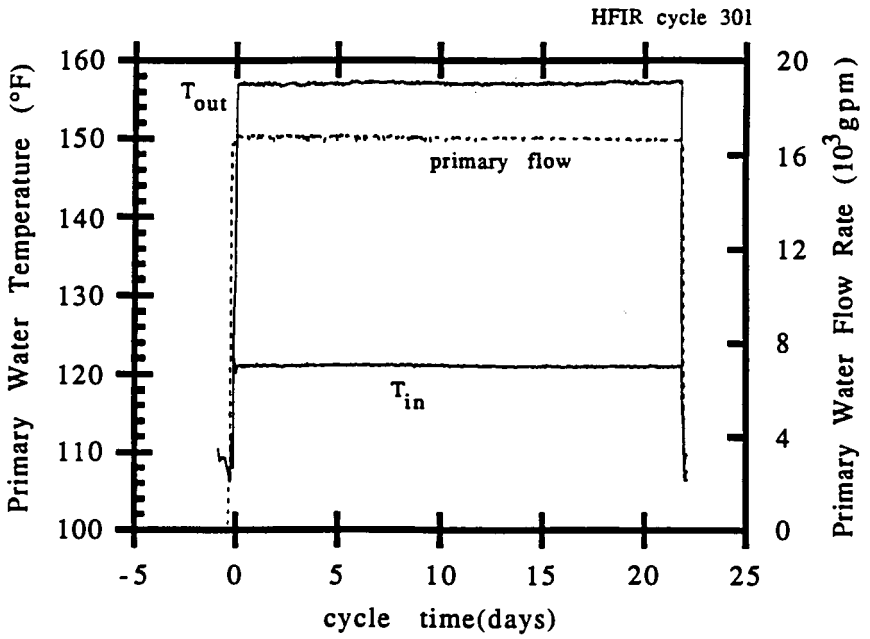
Figure 6-1.

INLET AND OUTLET PRIMARY CIRCUIT COOLING WATER TEMPERATURES AND PRIMARY WATER FLOW RATE FOR CYCLES 298 THROUGH 302.

ORNL-DWG 92-12022



ORNL-DWG 92-12023



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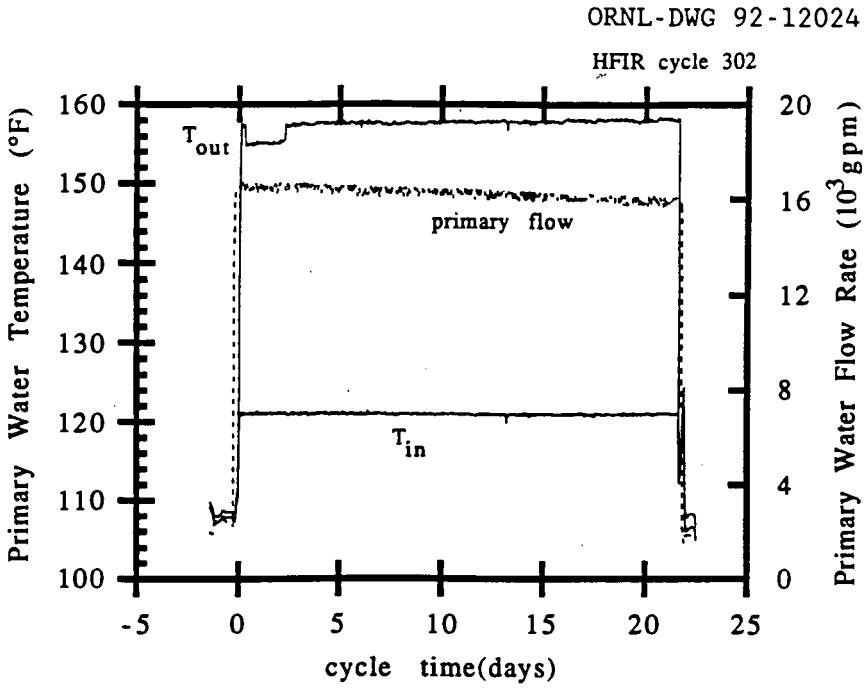

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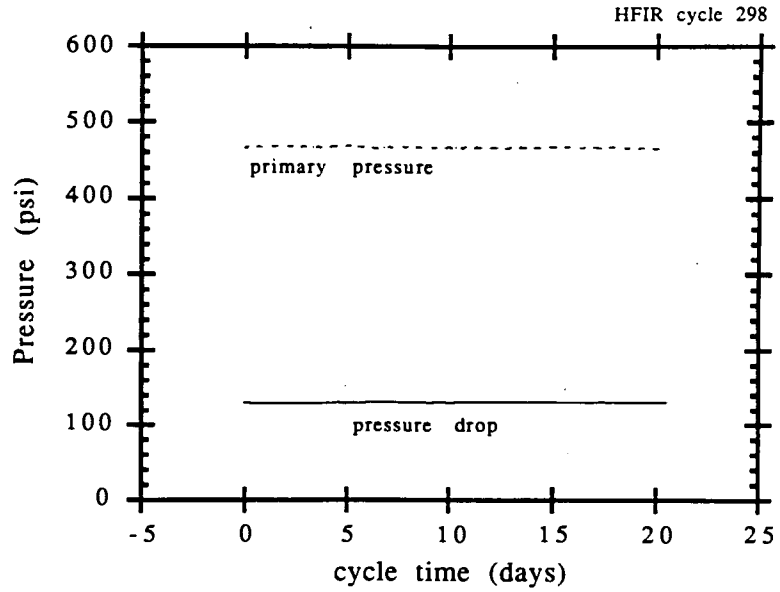
ORNL-DWG 92-12025



ORNL-DWG 92-12026

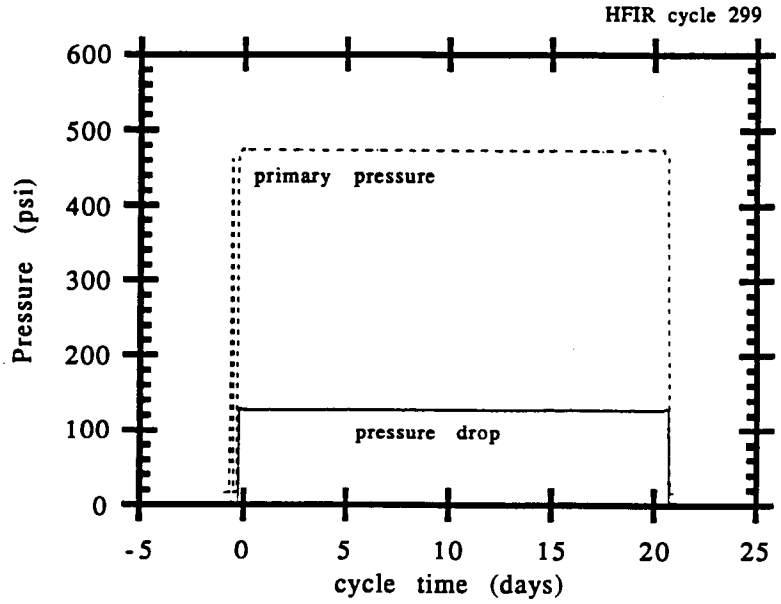
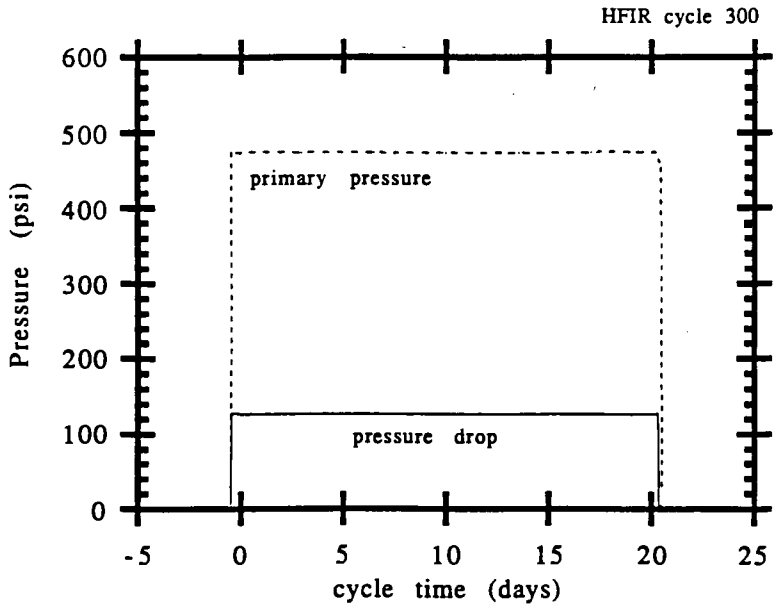


Figure 6-2.

PRIMARY INLET PRESSURE AND THE PRESSURE DROP BETWEEN THE PRIMARY INLET AND OUTLET FOR CYCLES 298 THROUGH 302.

ORNL-DWG 92-12027



ORNL-DWG 92-12028

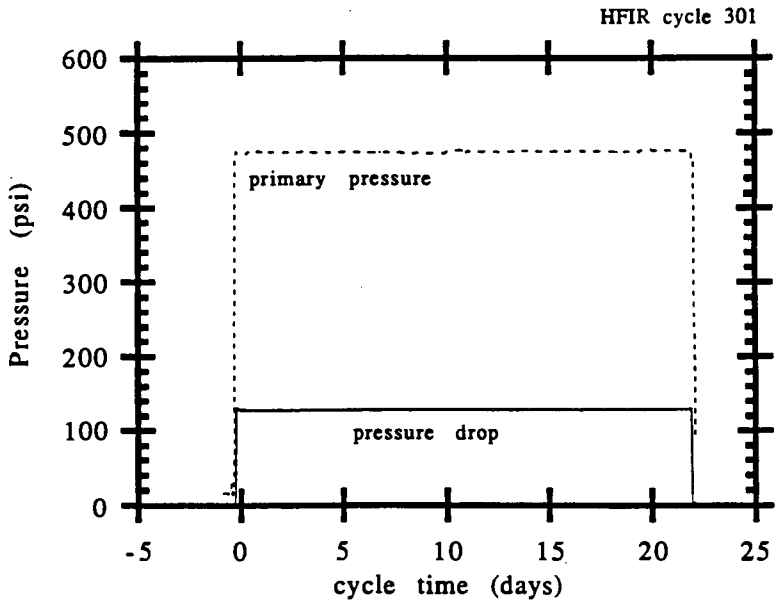


Figure 6-2. CONTINUED.

ORNL-DWG 92-12029

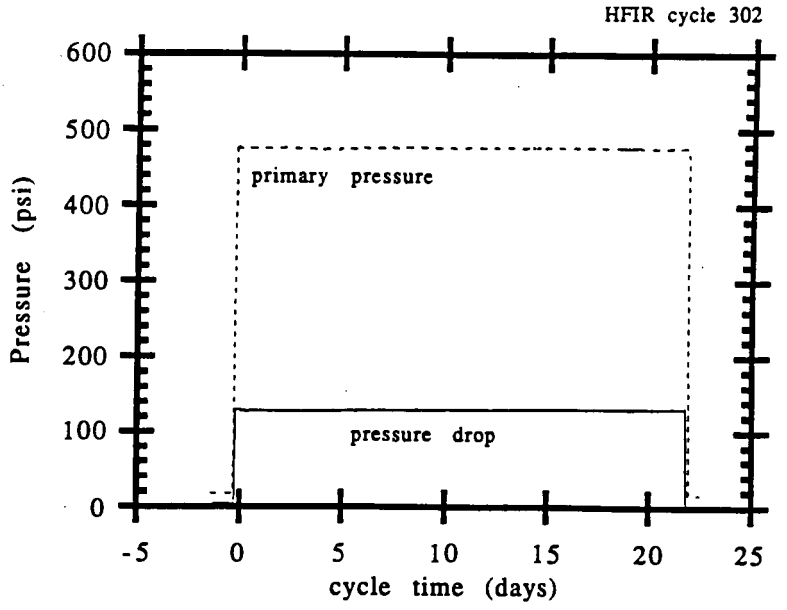
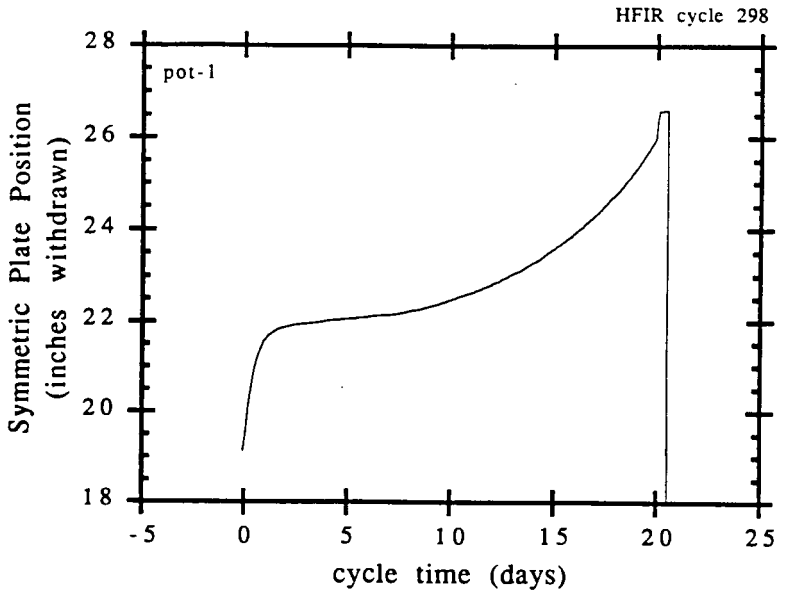


Figure 6-2. CONTINUED.

ORNL-DWG 92-12030



ORNL-DWG 92-12031

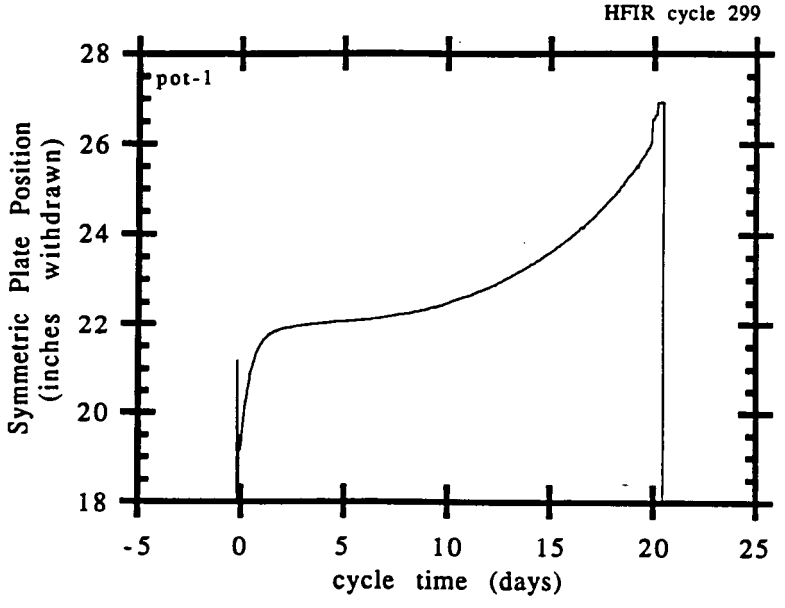
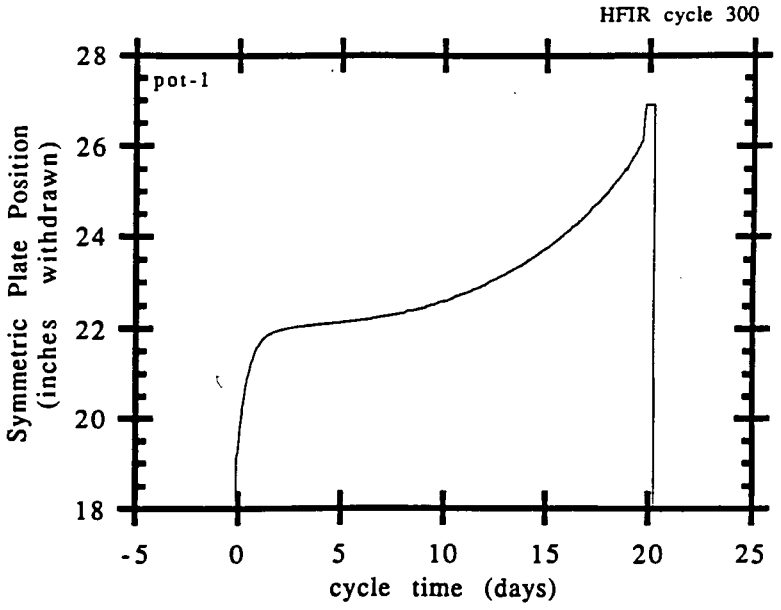


Figure 6-3.

POSITION OF THE CONTROL PLATES SHOWN AS INCHES WITHDRAWN FOR CYCLES 298 THROUGH 302.

ORNL-DWG 92-12032



ORNL-DWG 92-12033

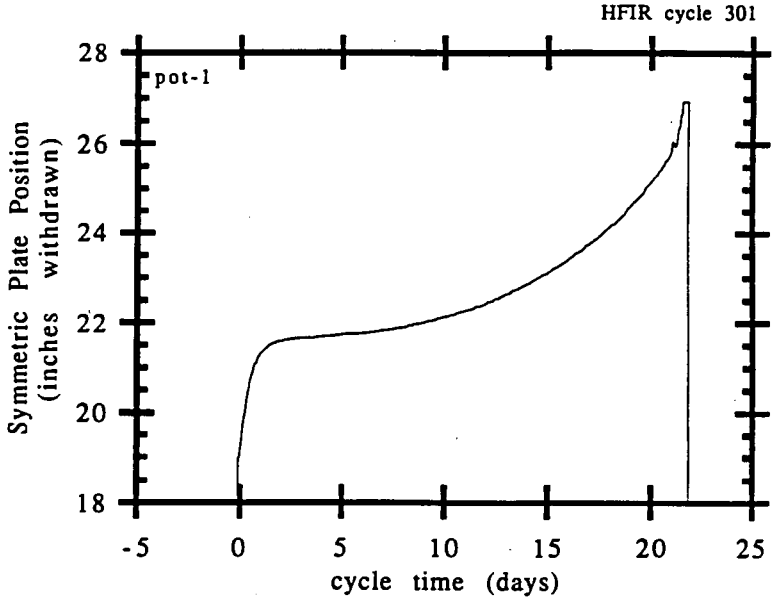


Figure 6-3. CONTINUED.

ORNL-DWG 92-12034

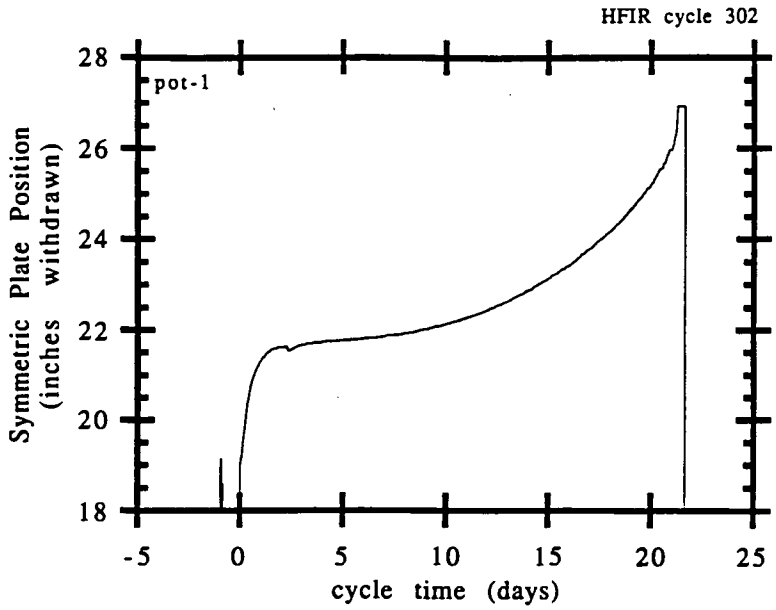
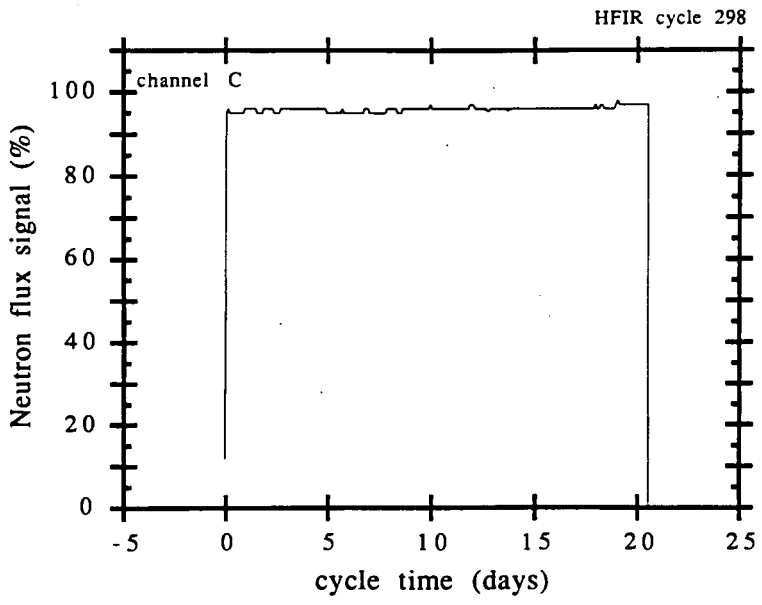


Figure 6-3. CONTINUED.

ORNL-DWG 92-12035



ORNL-DWG 92-15997

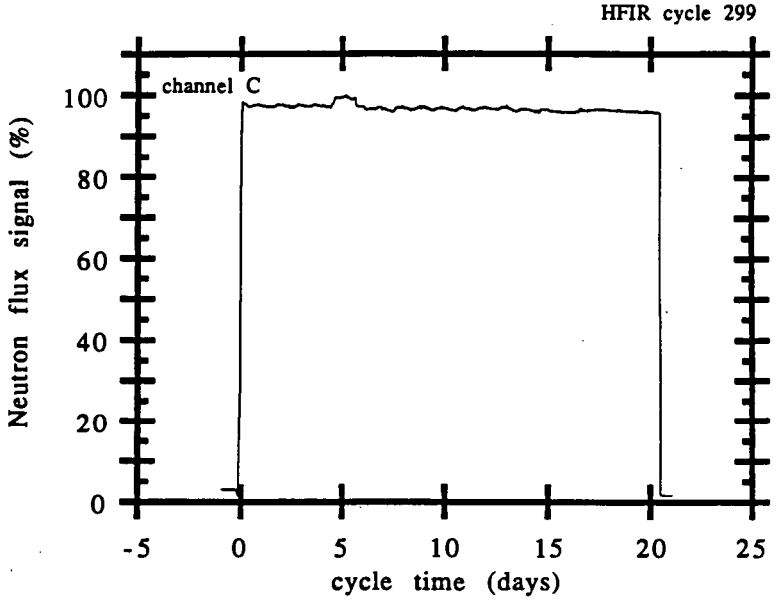
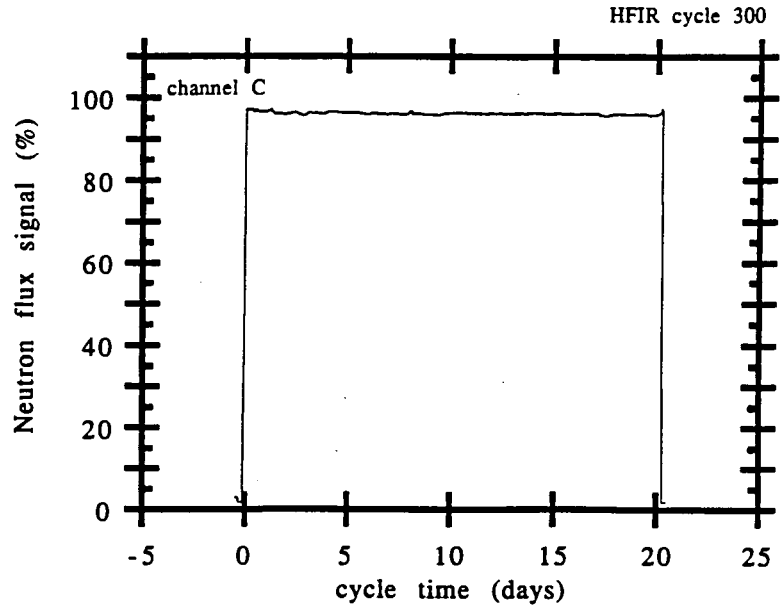


Figure 6-4.

NEUTRON FLUX CHAMBER SIGNAL FOR
CYCLES 298 THROUGH 302.

ORNL-DWG 92-15998



ORNL-DWG 92-15999

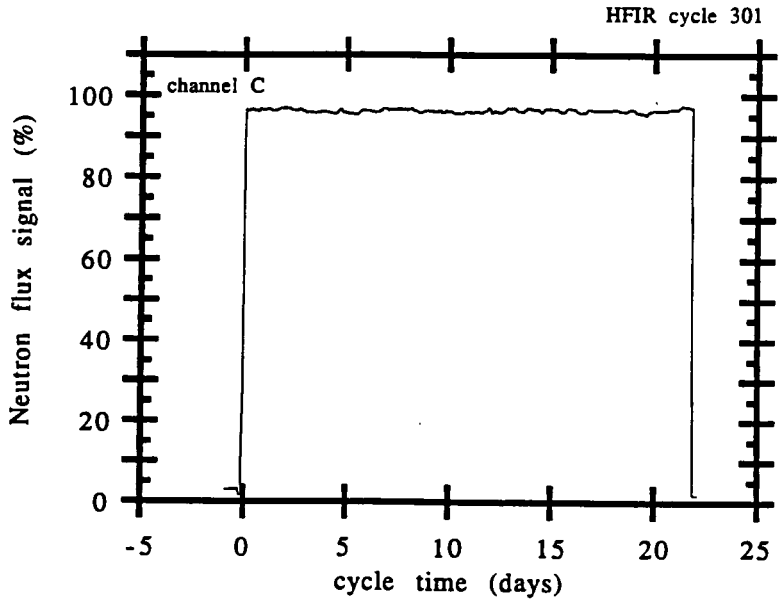


Figure 6-4. CONTINUED.

ORNL-DWG 92-16000

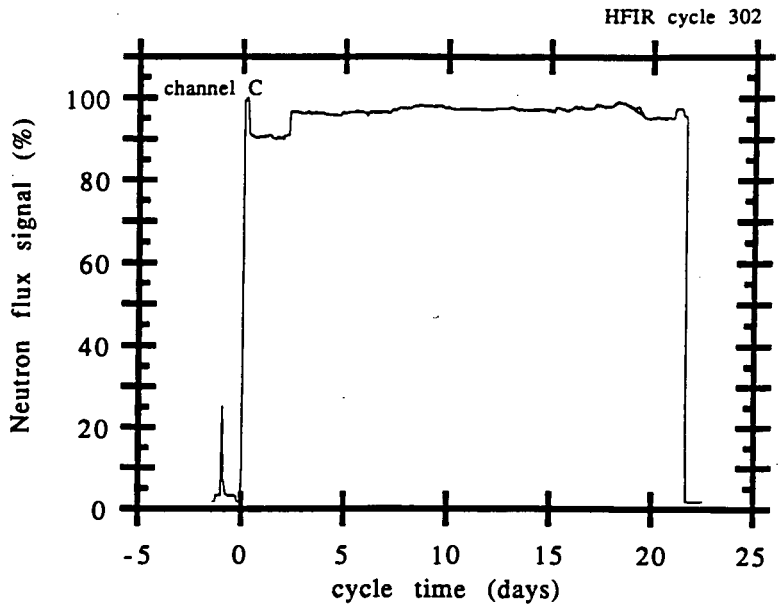


Figure 6-4. CONTINUED.

SECTION 7

DISCUSSION OF CAPSULE OPERATION

Figure 7-1 presents an overview of the capsule operation showing the capsule average volumetric fuel temperature and the sweep gas composition as a function of elapsed time. Figure 7-2 provides the indicated helium and neon flow rates. Figure 7-3 again illustrates the temperature chronology and is labeled to point out some events of interest. The capsule was first brought to operating temperature on June 21, 1991, by the addition of neon to the sweep gas. The sharp down spikes at points (A) in Fig. 7-3 were induced by a change in the sweep gas to 100% He. The periodic operation for a short time at 100% He provides valuable data under well characterized sweep

ORNL-DWG 92-16001

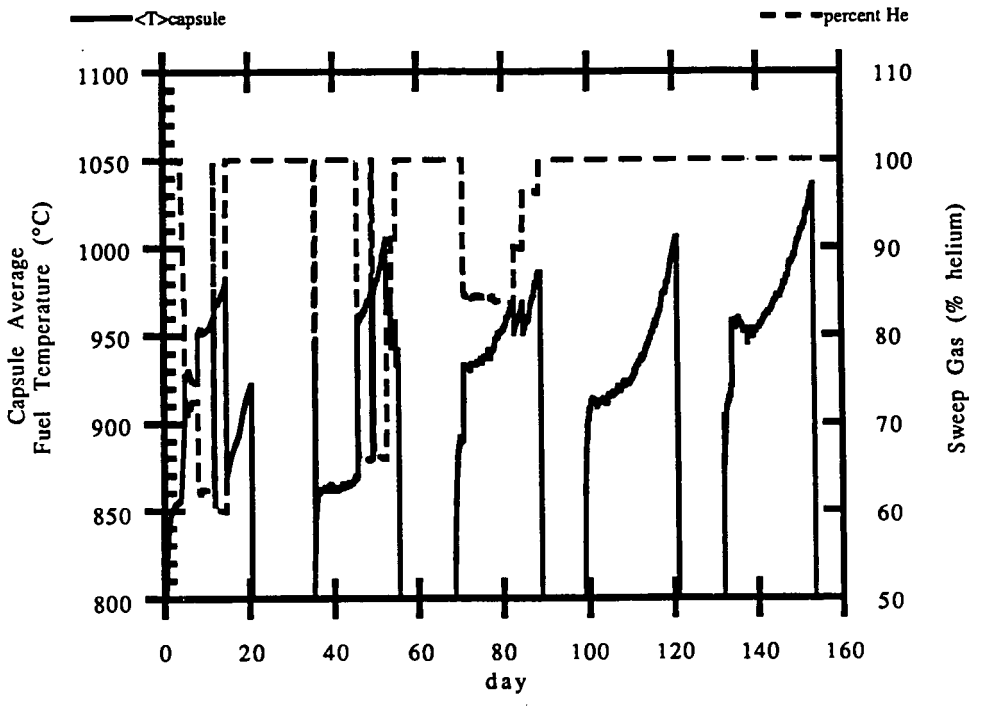
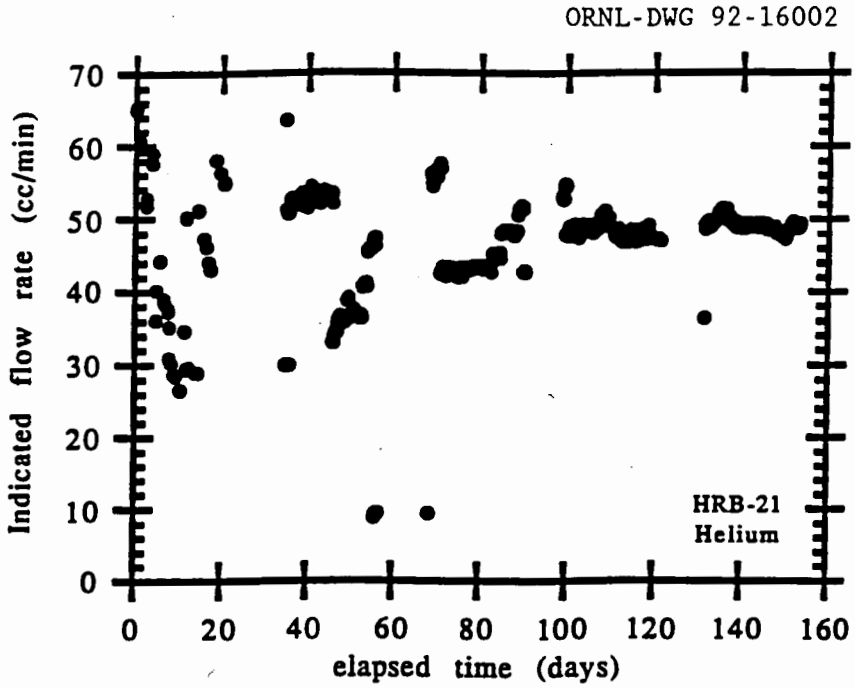


Figure 7-1.

OVERVIEW OF THE CAPSULE OPERATION SHOWING THE TIME EVOLUTION OF THE CAPSULE AVERAGE FUEL TEMPERATURE AND THE PERCENT HELIUM IN THE CAPSULE SWEEP GAS.



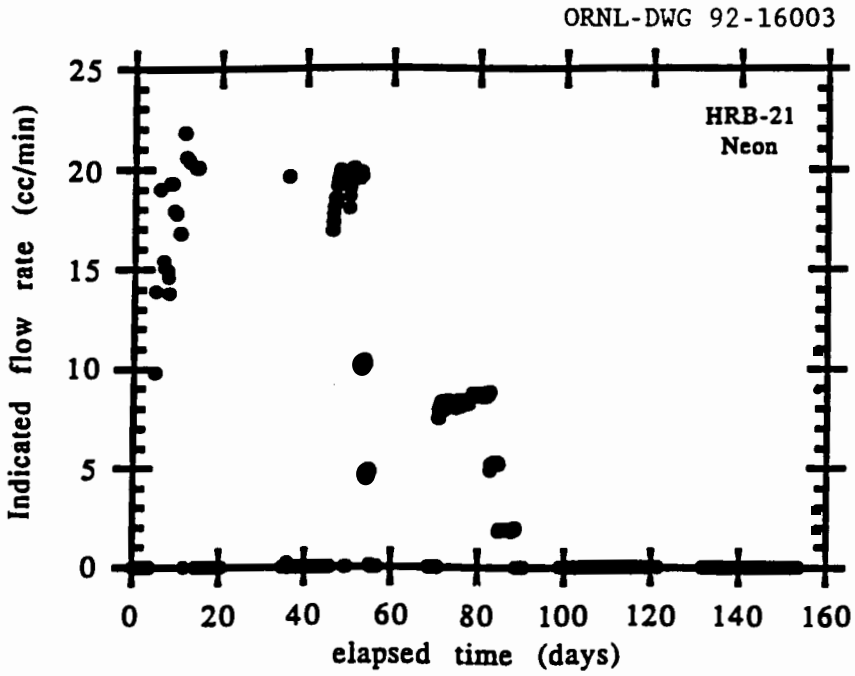


Figure 7-2.

INDICATED HELIUM AND NEON FLOW RATES AS A FUNCTION OF ELAPSED TIME.

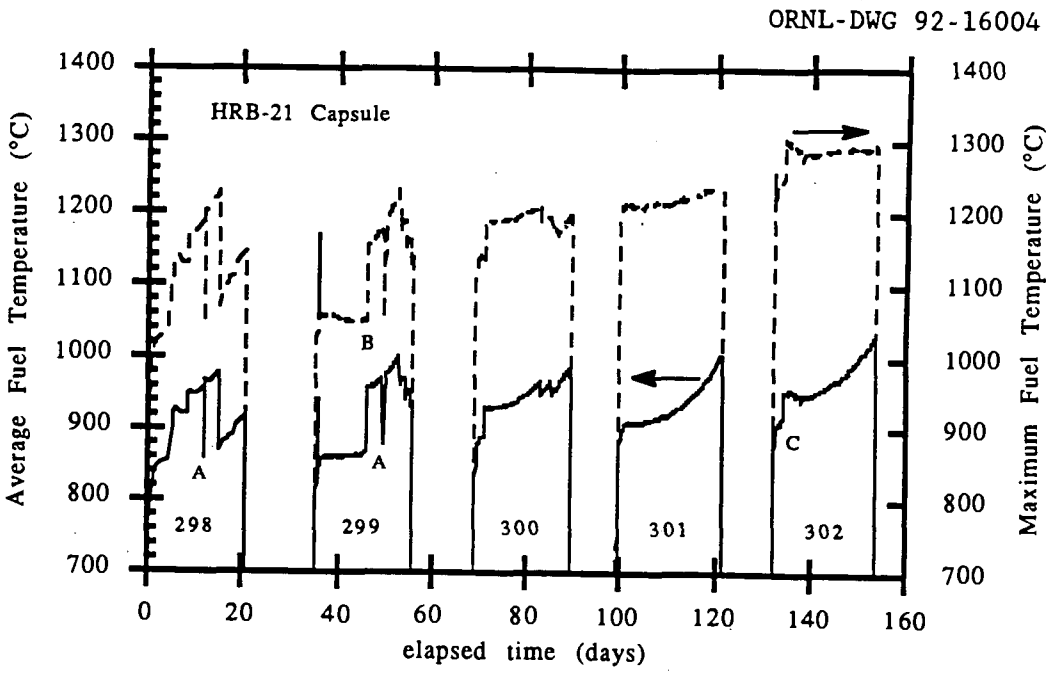


Figure 7-3.

CAPSULE AVERAGE FUEL TEMPERATURE WITH POINTS OF INTEREST LABELED FOR DISCUSSION. THE CYCLE NUMBERS ARE LISTED JUST ABOVE THE ABSCISSA.

gas conditions and contributes to reducing uncertainties in the thermal analysis. Near the end of the first cycle, the sweep gas was changed to 100% helium because there was some uncertainty in the rate of the anticipated temperature increase near the ends of the capsule as the control plate withdrawal rate increases. No pulses in the activity of the sweep gas were observed during the first cycle of operation.

At the beginning of the second cycle (299), after the test was brought up to operating temperature by an increase in the neon concentration (about 12 h after the reactor reached full power), the ionization chamber recorded sharp pulses in sweep gas activity characteristic of particle failure (see discussion below). Since no particle failures were expected at this time in this fuel, a programmatic decision was made to lower the capsule temperature while the experimental facility was examined to ensure that experimental anomalies were not causing the unexpected radioactivity pulses. The capsule temperature was reduced by changing the sweep gas back to 100% He (14:05 h,

July 26, 1991). At this point, all systems that could contribute to experimental anomalies were checked. The experimental facility was found to be functioning correctly (temperature monitoring, sweep gas integrity, He and Ne purity, etc.). The gas cylinders in use at this time were removed from the manifold and analyzed. The results are in Table 7-1 as "re-analysis," which shows both gases to be of high purity. The vendor analyses received

Table 7-1.

ANALYSES OF He AND Ne GAS CYLINDERS FROM HFIR CYCLE 299 STARTUP COMPARED TO PRE-TEST VALUES.

Constituent	Helium cylinder		Neon cylinder	
	Pre-test (ppm)	Re-analysis (ppm)	Pre-test (ppm)	Re-analysis (ppm)
O_2	0.76	≤1	1.5	≤1
CO (N_2)	-	≤5	-	≤10
CO_2	-	≤1	≤1	≤1
H_2O	0.08	≤10	≤1	≤10
H_2	-	≤1	-	≤1
CH_4	-	≤1	≤0.5	≤1

with the gases originally are also shown in Table 7-1 as "pre-test." With the concurrence of program management, neon was added to the sweep gas at 13:20 h on August 5, 1991, to raise the capsule temperature to the design operating range.

Cycle 300 progressed nominally, with the temperature of the capsule regulated as necessary to maintain the target temperature. During this cycle, it became clear that a point in time would soon be reached where the local maximum fuel temperature could exceed 1250°C. This unexpected increase in capsule temperature may be due to the breeding in of ^{233}U at a level greater than that anticipated due to the long shutdown periods between operation. In the thermal and neutronic analyses upon which the capsule design is based, the down time between cycles was taken to be 1 d based on previous HFIR experience. The actual average downtime was about 12.2 d while the half life of ^{233}Pa (^{233}U precursor) is 27.4 d. Therefore, the ^{233}U

concentration at the beginning of each cycle was higher than planned for. Postirradiation analysis of the fuel should provide conclusive evidence as to why this temperature increase occurred. It was decided to continue operation of the capsule pending further review.

The sweep gas was 100% He for cycles 301 and 302. At the beginning of cycle 302, the reactor power was lowered to 80 MW(t) to clear a high-temperature alarm (point C, Fig. 7-3). After the Reactor Experiment Review Committee (RERC) review and authorization from the Department of Energy (DOE) to operate with TC temperatures up to 1100°C, 85-MW(t) operation was resumed. At the end of cycle 302, the HRB-21 capsule was removed from the reactor and placed in the experiment storage facility in the reactor pool.

SECTION 8

DISCUSSION OF FUEL PERFORMANCE

There are two measures of fuel performance while the experiment is undergoing testing. Both monitor the ability of the fuel to retain its gaseous fission products, and both relate to the presence of radioactive fission products in the sweep gas. The first measure is the monitoring of the radiation level of the sweep gas after it exits the capsule. The second method involves obtaining a grab sample of the sweep gas, determining its fission gas content, and computing an R/B ratio for the specific fission product isotopes in the fuel.

8.1 SWEEP GAS RADIATION LEVEL MONITORING

The radiation level of the sweep gas exiting the capsule is continuously monitored by two independent ionization chambers with chart recorders. The failure of a fuel particle in this type fuel test has been shown to yield a sharp, distinctive pulse on the chart recordings.[9] The behavior of the ionization chamber chart during the addition of neon to raise the temperature at the start of the second cycle is shown in Fig. 8-1. The distinctive shape of the pulses is obscured somewhat by the effects of adding neon and raising the temperature. The general radiation level of the sweep gas increases when neon is added due to the presence of ^{23}Ne, which is an activation product of ^{22}Ne. More classic examples of particle failure pulses are shown in Fig. 8-2 in which the temperature is stable and the sweep gas is 100% helium. The pulse is characterized by a very rapid increase in radiation level of only 2 to 3 min duration at half height, followed by a slower return to a level somewhat higher than the original. Figure 8-3 is a characteristic pulse, while the sweep gas is a mixture of helium and neon—the chart line is more erratic when neon is present. The chart pulses representing particle failures continued for the duration of the test. Figure 8-4 shows a plot of the cumulative number of pulses as a function of time superimposed on a plot of the R/B for ^{85m}Kr (see below). This count is not final since some spikes are not as well defined and subject to some interpretation. This tentative count indicates a total of about 130 particle failures. As a note of caution

YP16105

Figure 8-1(*a*).

PHOTOGRAPH OF STRIP-CHART RECORDING OF IONIZATION CHAMBER RESPONSE DURING BEGINNING OF SECOND IRRADIATION CYCLE - CAPSULE HRB-21. THE SWEEP GAS He CONCENTRATION WAS CHANGED FROM 100 TO ABOUT 61% BETWEEN 10:04 AND 10:29, 7/26/91.

ORNL-DWG 92-16005

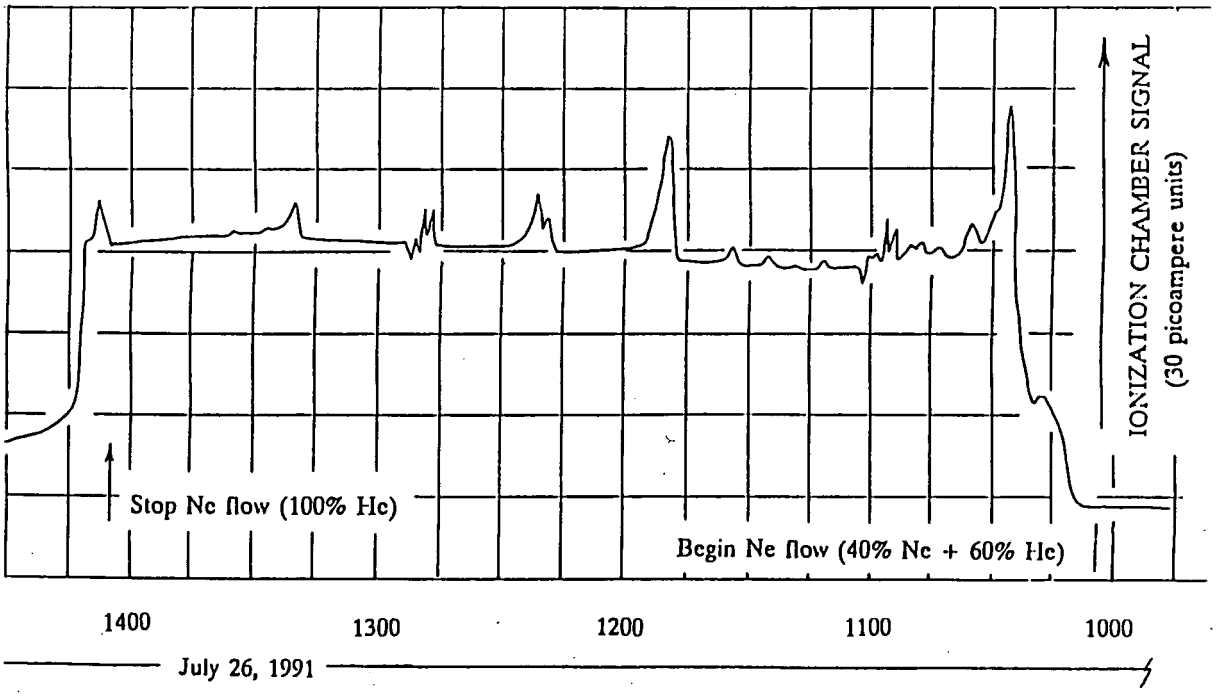


Figure 8-1(*b*).

IONIZATION CHAMBER RESPONSE DURING BEGINNING OF SECOND IRRADIATION CYCLE - CAPSULE HRB-21. IN THIS DRAWING, THE EFFECT OF AMMETER SCALE CHANGES SEEN IN 8-1(*a*) HAS BEEN COMPENSATED FOR.

YP16104

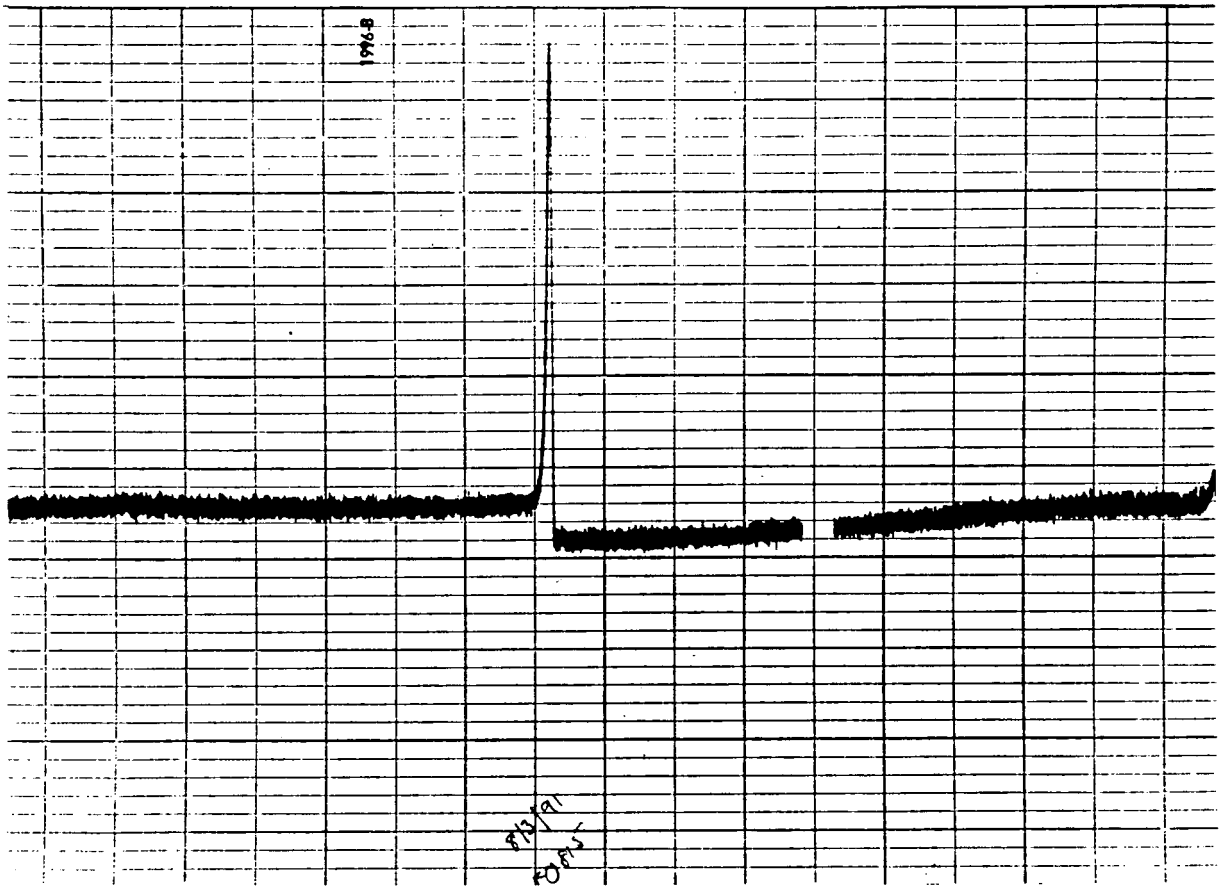


Figure 8-2.

THIS PHOTOGRAPH OF A "CLASSIC" EXAMPLE OF PARTICLE FAILURE PULSE IS FROM A STRIP CHART RECORDING THE OUTPUT CURRENT FROM THE IONIZATION CHAMBER DURING THE SECOND IRRADIATION CYCLE - CAPSULE HRB-21 - ON PURE HELIUM. ON 8/3/91 AT 08:15 hr THE TEST WAS 8.42 d INTO CYCLE 299. ELAPSED TIME = 43.583 d. FULL-POWER DAYS = 28.947.

Figure 8-3.

PHOTOGRAPH OF STRIP-CHART RECORDING OF IONIZATION CHAMBER RESPONSE DURING THE SECOND IRRADIATION CYCLE - CAPSULE HRB-21. THE SWEEP GAS He CONCENTRATION WAS ABOUT 65% HELIUM. ON 8/8/91 AT 01:53 hr THE TEST WAS 13.155 d INTO CYCLE 299. ELAPSED TIME = 48.318 d. FULL-POWER DAYS = 33.681.

ORNL-DWG 92-16006

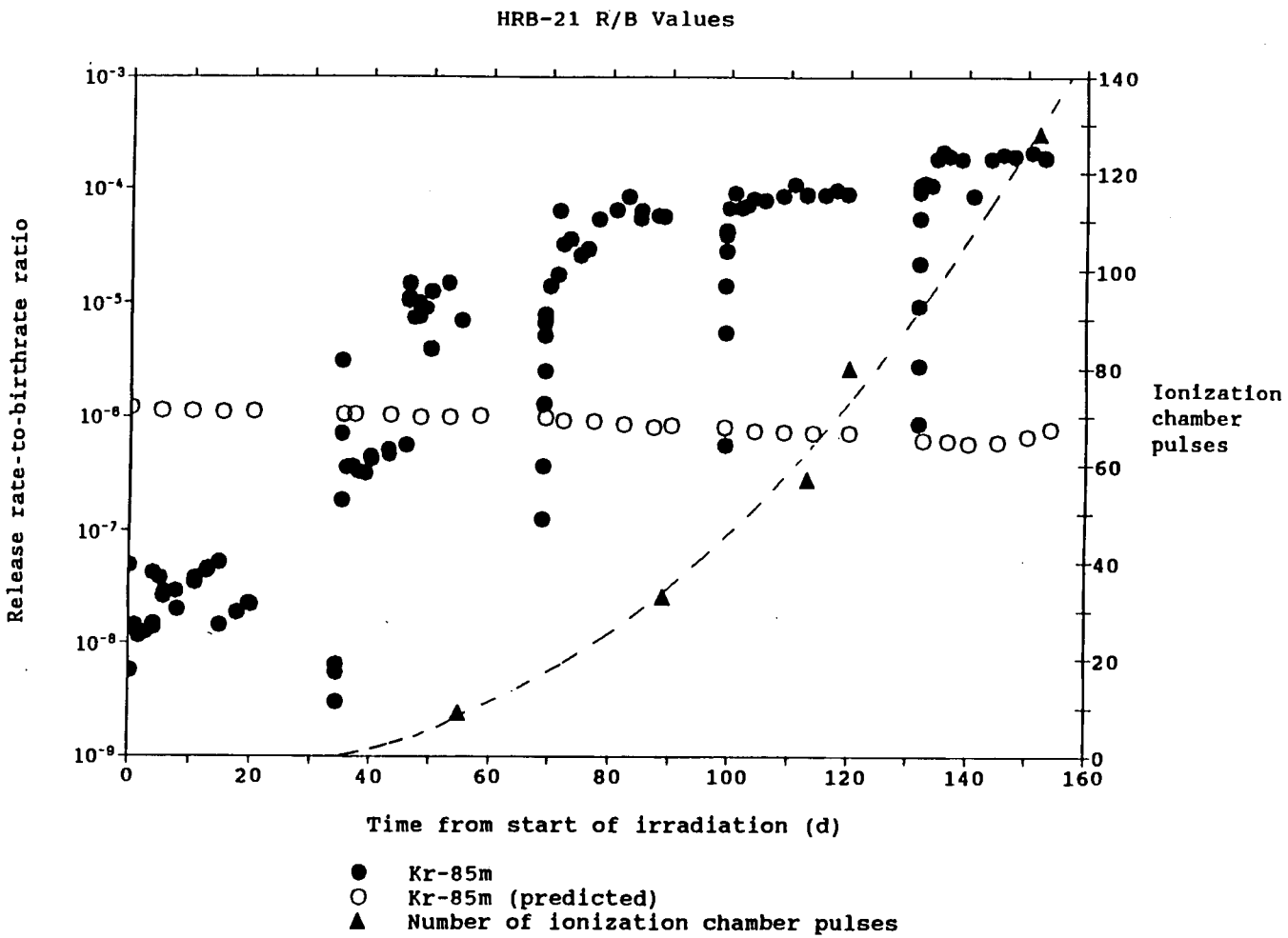


Figure 8-4.

CUMULATIVE COUNT OF IONIZATION CHAMBER PULSES (FAILED PARTICLES) AND ^{85m}Kr R/B FOR HRB-21 CAPSULE.

on interpretation of these results, this test also contained some "piggyback specimens," which included 192 as-fabricated defective (bufferless) particles sealed in Nb-1Zr containers. The failure of these defective particles, combined with the failure of the sealed container, could contribute to the particle failure count. This possibility will be investigated in the postirradiation examination.

8.2 R/B RATIOS

Measurements of the fission gas release rates were carried out using the grab sample technique for sampling the sweep gas.[10] The gas samples were collected in serum bottles at the HFIR.[11] They were then transported to the Irradiated Fuels Examination Laboratory (IFEL) where they were analyzed for fission gas inventory using a high-efficiency germanium detector gamma spectroscopy system.[12] Birth rates were calculated using the initial fuel loadings and one group of neutron flux and cross-section data as input to the CACA-2 computer program.[4] The release rate data for these five cycles are presented in Table 8-1. The calculated R/B ratios for the five irradiation cycles are presented in Table 8-2. R/B plots for Xe-133, Xe-138, Kr-85m, and Kr-88, along with the capsule average fuel temperature, are shown in Figs. 8-5 and 8-6.

The reactor startup sequence was modified for this test to minimize particle failures due to rapid increases in power generated per particle. Hold times of 10 to 15 min were instituted at reactor power levels of 10, 30, 50, 70, and 90% of full power. The sweep gas was sampled for R/B measurements at each of the hold points, and two samples were taken when full power was achieved. Following each startup, two samples per day were taken for the first 5 d of operation. Then, for the remainder of each cycle, two samples per day were taken 3 d per week.

The R/B ratios started out very low supporting the low heavy-metal contamination reported for the fuel as well as the low measured preirradiation[13] values and predictions[14] for the test. For example, the R/B for one isotope of interest, ^{85m}Kr;

10^{-8} to 10^{-7}	preirradiation
10^{-7} or 10^{-6}	predicted (two models)
10^{-8} increasing to 10^{-4}	during test

Table 8-1.

MEASURED RELEASE RATES FOR KRYPTON AND XENON ISOTOPES FOR THE HRB-21 CAPSULE .

Sweep Gas Concentration (uCi/ml) Cycle 298

Sample	Kr-85m	Kr-87	Kr-88	Kr-89	Xe-133	Xe-135m	Xe-135	Xe-138
HRB21-1	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.513E-04
HRB21-2	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.867E-04
HRB21-3	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	8.366E-04
HRB21-4	0.000E+00	0.000E+00	1.487E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.343E-03
HRB21-5	5.875E-04	3.591E-04	1.663E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.858E-03
HRB21-6	0.000E+00	1.804E-05	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
HRB21-7	6.810E-05	5.368E-04	3.743E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.806E-03
HRB21-8	1.880E-04	7.654E-04	7.613E-04	0.000E+00	0.000E+00	3.041E-04	0.000E+00	2.864E-03
HRB21-9	1.721E-04	9.037E-04	7.270E-04	0.000E+00	0.000E+00	3.812E-04	1.039E-04	1.740E-03
HRB21-10	1.467E-04	7.712E-04	7.638E-04	0.000E+00	0.000E+00	5.487E-04	8.503E-05	2.079E-03
HRB21-11	1.632E-04	8.617E-04	5.592E-04	0.000E+00	0.000E+00	2.923E-04	7.054E-05	1.969E-03
HRB21-12	1.795E-04	9.546E-04	6.668E-04	0.000E+00	0.000E+00	1.547E-04	8.327E-05	1.506E-03
HRB21-13	1.827E-04	9.014E-04	8.139E-04	0.000E+00	0.000E+00	2.672E-04	8.365E-05	1.981E-03
HRB21-14	1.843E-04	8.424E-04	6.506E-04	0.000E+00	0.000E+00	2.116E-04	1.211E-04	1.857E-03
HRB21-15	1.730E-04	8.093E-04	7.664E-04	0.000E+00	0.000E+00	3.467E-04	6.080E-05	1.858E-03
HRB21-16	6.032E-04	1.919E-03	1.970E-03	0.000E+00	4.662E-05	0.000E+00	9.609E-05	3.373E-03
HRB21-17	5.428E-04	1.868E-03	1.889E-03	0.000E+00	5.626E-05	5.378E-04	7.024E-05	2.796E-03
HRB21-18	2.752E-04	1.564E-03	1.247E-03	0.000E+00	1.749E-05	3.924E-04	5.083E-05	1.879E-03
HRB21-19	3.185E-04	1.568E-03	1.205E-03	0.000E+00	2.776E-05	5.706E-04	7.362E-05	2.568E-03
HRB21-20*	3.418E-04	1.074E-03	1.192E-03	0.000E+00	3.312E-05	0.000E+00	9.205E-05	0.000E+00
HRB21-21	3.729E-04	1.453E-03	1.367E-03	0.000E+00	3.944E-05	7.471E-04	7.970E-05	2.887E-03
HRB21-22	2.645E-04	1.315E-03	1.007E-03	0.000E+00	2.725E-05	2.534E-04	1.058E-04	1.737E-03
HRB21-23	5.345E-04	2.142E-03	1.929E-03	0.000E+00	4.708E-05	8.293E-04	1.189E-04	2.749E-03
HRB21-24	5.919E-04	2.485E-03	2.165E-03	0.000E+00	4.542E-05	6.729E-04	1.153E-04	3.509E-03
HRB21-25	5.777E-04	2.374E-03	2.228E-03	0.000E+00	4.107E-05	7.229E-04	1.216E-04	2.593E-03
HRB21-26	6.111E-04	2.422E-03	2.210E-03	0.000E+00	5.821E-05	4.436E-04	1.277E-04	2.794E-03
HRB21-27	7.053E-04	3.155E-03	2.815E-03	0.000E+00	7.385E-05	6.366E-04	1.642E-04	3.742E-03
HRB21-28	1.847E-04	8.397E-04	4.679E-04	0.000E+00	1.817E-05	7.019E-04	1.249E-04	2.032E-04
HRB21-29	3.011E-04	1.572E-03	1.409E-03	3.110E-03	2.765E-05	5.044E-04	1.147E-04	2.048E-03
HRB21-30	3.222E-04	1.235E-03	1.090E-03	0.000E+00	2.615E-05	4.243E-04	8.919E-05	1.919E-03
HRB21-31	2.868E-04	1.235E-03	1.061E-03	0.000E+00	2.332E-05	5.451E-04	9.199E-05	1.796E-03
HRB21-32	2.871E-04	1.230E-03	1.072E-03	0.000E+00	2.397E-05	4.252E-04	9.254E-05	2.339E-03

* Sample taken through hold-up volume

Table 8-1. CONTINUED.

Sweep Gas Concentration (μCi/ml) Cycle 299

Sample	Kr-85m	Kr-87	Kr-88	Kr--89	Xe-133	Xe-135m	Xe-135	Xe-138
HRB21_33	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	9.744E-05
HRB21_34	0.000E+00	2.680E-05	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.936E-04
HRB21-35	0.000E+00	5.546E-05	3.650E-05	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.265E-04
HRB21_36	0.000E+00	7.421E-05	9.687E-05	0.000E+00	0.000E+00	4.045E-05	0.000E+00	5.047E-04
HRB21_37	3.986E-05	2.713E-04	1.500E-04	0.000E+00	0.000E+00	1.268E-04	0.000E+00	1.096E-03
HRB21_38	7.204E-05	3.981E-04	3.190E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.350E-03
HRB21_39	8.499E-05	4.927E-04	3.293E-04	0.000E+00	0.000E+00	1.369E-04	2.018E-05	1.297E-03
HRB21_40	4.304E-02	8.207E-02	1.242E-01	0.000E+00	1.285E-01	6.085E-02	1.499E-02	1.081E-01
HRB21_41	9.741E-03	2.722E-02	3.073E-02	0.000E+00	8.485E-03	1.069E-01	2.814E-02	3.271E-02
HRB21_42	2.349E-03	9.477E-03	8.370E-03	0.000E+00	1.980E-03	1.145E-01	3.163E-02	1.695E-02
HRB21_43	4.854E-03	1.988E-02	1.779E-02	6.403E-02	1.333E-03	2.556E-02	6.720E-03	2.986E-02
HRB21_44	4.510E-03	1.862E-02	1.646E-02	5.999E-02	1.042E-03	1.241E-02	3.066E-03	2.944E-02
HRB21_45	3.946E-03	1.581E-02	1.426E-02	5.749E-02	8.657E-04	8.805E-03	2.308E-03	2.613E-02
HRB21_46	3.891E-03	1.561E-02	1.417E-02	6.432E-02	8.628E-04	8.936E-03	2.209E-03	2.510E-02
HRB21_47	5.264E-03	2.137E-02	1.887E-02	9.505E-02	1.387E-03	1.230E-02	3.001E-03	3.609E-02
HRB21_48	5.122E-03	2.106E-02	1.856E-02	8.386E-02	1.321E-03	1.250E-02	3.031E-03	3.393E-02
HRB21_49	5.939E-03	2.420E-02	2.138E-02	9.260E-02	1.660E-03	1.472E-02	3.601E-03	3.960E-02
HRB21_50	5.610E-03	2.200E-02	1.985E-02	7.403E-02	2.022E-03	1.373E-02	3.342E-03	3.774E-02
HRB21_51	6.501E-03	2.639E-02	2.335E-02	1.239E-01	2.502E-03	1.693E-02	3.992E-03	4.389E-02
HRB21_52	1.313E-01	2.626E-01	3.566E-01	5.191E-01	9.823E-01	1.520E-01	3.433E-02	3.482E-01
HRB21_53	1.386E-01	2.666E-01	3.662E-01	4.496E-01	9.421E-01	6.754E-01	1.607E-01	3.524E-01
HRB21_54	1.857E-01	3.104E-01	4.614E-01	5.378E-01	1.153E+00	8.926E-01	2.516E-01	3.798E-01
HRB21_55	9.012E-02	2.755E-01	2.805E-01	9.073E-01	2.490E-01	1.635E+00	4.046E-01	6.817E-01
HRB21_56	1.163E-01	3.696E-01	3.622E-01	1.768E+00	2.262E-01	1.305E+00	3.103E-01	1.422E+00
HRB21_57	8.884E-02	3.380E-01	3.011E-01	1.705E+00	1.561E-01	1.246E+00	2.949E-01	1.491E+00
HRB21_58*								
HRB21_59**	1.055E-01	2.928E-01	3.259E-01	0.000E+00	2.576E-01	4.095E-01	3.039E-01	4.655E-01
HRB21_60**	1.070E-01	3.021E-01	3.348E-01	0.000E+00	2.580E-01	3.929E-01	2.781E-01	4.895E-01
HRB21_61**	6.673E-02	1.851E-01	2.149E-01	0.000E+00	1.188E-01	1.438E-01	2.283E-01	1.789E-01
HRB21_62**	1.537E-01	3.982E-01	4.820E-01	0.000E+00	5.995E-01	2.859E-01	1.797E-01	5.827E-01
HRB21_63**	1.863E-01	6.273E-01	6.418E-01	0.000E+00	4.853E-01	6.199E-01	3.943E-01	1.394E+00
HRB21_64**	1.004E-01	3.582E-01	3.647E-01	0.000E+00	9.538E-02	2.793E-01	1.761E-01	7.771E-01

* Sample not analyzed

** Sample taken through "Hold-up" tank

Table 8-1. CONTINUED.

Sweep Gas Concentration (uCi/ml) Cycle 300

Sample	Kr-85m	Kr-87	Kr-88	Kr-89	Xe-133	Xe-135m	Xe-135	Xe-138
HRB21_65	1.238E-03	7.683E-03	5.034E-03	5.044E-02	1.379E-02	3.338E-03	4.451E-04	5.821E-02
HRB21_66	3.310E-03	2.371E-02	1.497E-02	1.601E-01	6.495E-02	8.623E-03	1.057E-03	1.765E-01
HRB21-67	1.155E-02	7.855E-02	5.040E-02	3.786E-01	1.378E-01	2.613E-02	3.090E-03	4.965E-01
HRB21_68	2.259E-02	1.504E-01	9.873E-02	8.461E-01	1.012E-01	4.974E-02	5.099E-03	9.143E-01
HRB21_69	4.608E-02	2.989E-01	2.031E-01	0.000E+00	1.349E-01	1.000E-01	9.649E-03	1.805E+00
HRB21_70	5.988E-02	3.723E-01	2.630E-01	0.000E+00	7.786E-02	1.357E-01	1.523E-02	2.260E+00
HRB21_71*	6.286E-02	3.078E-01	2.659E-01	0.000E+00	3.812E-02	5.830E-02	2.239E-02	6.912E-01
HRB21_72*	7.161E-02	3.188E-01	2.936E-01	0.000E+00	2.338E-02	6.608E-02	3.275E-02	6.544E-01
HRB21_73	1.212E-01	4.787E-01	4.241E-01	0.000E+00	7.132E-02	8.767E-01	1.833E-01	2.302E+00
HRB21_74	1.487E-01	6.343E-01	5.345E-01	5.037E+00	9.718E-02	1.530E+00	2.953E-01	3.353E+00
HRB21_75	6.169E-01	1.627E+00	1.753E+00	7.593E+00	1.228E+00	2.712E+00	5.288E-01	6.180E+00
HRB21_76	3.000E-01	1.291E+00	1.062E+00	8.297E+00	2.243E-01	3.391E+00	6.752E-01	6.937E+00
HRB21_77	3.367E-01	1.453E+00	1.204E+00	1.006E+00	3.080E-01	3.624E+00	7.142E-01	8.054E+00
HRB21_78	2.401E-01	1.105E+00	9.009E-01	9.212E+00	1.845E-01	2.001E+00	3.759E-01	5.688E+00
HRB21_79	2.691E-01	1.160E+00	9.741E-01	9.124E+00	3.838E-01	1.890E+00	3.725E-01	5.331E+00
HRB21_80	4.827E-01	1.536E+00	1.457E+00	1.032E+01	2.348E+00	2.415E+00	4.642E-01	5.575E+00
HRB21_81	5.843E-01	1.867E+00	1.768E+00	1.051E+01	3.369E+00	3.290E+00	6.440E-01	7.422E+00
HRB21_82	7.793E-01	3.290E+00	2.743E+00	2.136E+01	1.277E+00	6.523E+00	1.236E+00	1.420E+01
HRB21_83	5.401E-01	2.186E+00	1.856E+00	9.992E+00	8.595E-01	3.209E+00	6.538E-01	7.586E+00
HRB21_84	6.438E-01	2.667E+00	2.228E+00	1.317E+01	9.171E-01	4.010E+00	7.886E-01	9.828E+00
HRB21_85	6.071E-01	2.582E+00	2.110E+00	1.311E+01	1.053E+00	4.060E+00	7.567E-01	9.194E+00
HRB21_86	6.084E-01	2.653E+00	2.195E+00	1.487E+01	9.159E-01	3.758E+00	6.702E-01	9.523E+00

* Sample taken thru' hold-up volume

Table 8-1. CONTINUED.

Sweep Gas Concentration (uCi/ml) Cycle 301

Sample	Kr-85m	Kr-87	Kr-88	Kr-89	Xe-133	Xe-135m	Xe-135	Xe-138
HRB21_87	5.438E-03	4.107E-02	2.267E-02	2.711E-02	3.275E-01	2.058E-02	2.309E-03	3.135E-01
HRB21_88*								
HRB21_89	5.382E-02	3.476E-01	2.228E-01	1.657E+00	1.083E+00	1.410E-01	1.530E-02	2.086E+00
HRB21_90	1.383E-01	8.097E-01	5.439E-01	4.121E+00	1.206E+00	2.920E-01	3.077E-02	4.168E+00
HRB21_91	2.748E-01	1.694E+00	1.152E+00	8.350E+00	1.458E+00	5.461E-01	4.897E-02	7.316E+00
HRB21_92	3.842E-01	2.265E+00	1.583E+00	1.026E+01	8.543E-01	7.677E-01	7.903E-02	9.864E+00
HRB21_93	4.109E-01	2.325E+00	1.635E+00	1.186E+01	3.556E-01	1.055E+00	1.322E-01	9.469E+00
HRB21_94	4.022E-01	2.167E+00	1.602E+00	1.010E+01	2.654E-01	1.109E+00	1.705E-01	8.520E+00
HRB21_95	7.134E-01	3.119E+00	2.573E+00	1.412E+01	3.643E-01	3.185E+00	5.996E-01	1.181E+01
HRB21_96	9.465E-01	4.101E+00	3.314E+00	2.462E+01	5.434E-01	6.568E+00	1.239E+00	1.632E+01
HRB21_97	6.889E-01	2.859E+00	2.433E+00	1.284E+01	4.753E-01	4.450E+00	9.309E-01	1.061E+01
HRB21_98	7.282E-01	3.083E+00	2.574E+00	1.449E+01	6.406E-01	4.544E+00	9.304E-01	1.144E+01
HRB21_99	8.120E-01	3.486E+00	2.886E+00	1.842E+01	7.367E-01	5.541E+00	1.033E+00	1.387E+01
HRB21_100	7.766E-01	3.464E+00	2.764E+00		6.327E-01	5.502E+00	1.004E+00	1.469E+01
HRB21_101	8.101E-01	3.633E+00	2.898E+00	1.936E+01	6.759E-01	4.991E+00	9.653E-01	1.343E+01
HRB21_102	1.059E+00	4.797E+00	3.814E+00	2.676E+01	8.055E-01	6.369E+00	1.184E+00	1.798E+01
HRB21_103	9.164E-01	4.101E+00	3.317E+00	2.928E+01	9.473E-01	5.081E+00	9.405E-01	1.460E+01
HRB21_104	9.390E-01	4.373E+00	3.418E+00	2.657E+01	6.698E-01	5.448E+00	9.998E-01	1.520E+01
HRB21_105	9.911E-01	4.465E+00	3.553E+00	2.602E+01	8.294E-01	5.517E+00	1.058E+00	1.519E+01
HRB21_106	1.097E+00	4.737E+00	3.891E+00	2.645E+01	1.037E+00	5.964E+00	1.144E+00	1.588E+01
HRB21_107	1.085E+00	4.585E+00	3.744E+00	2.527E+01	1.853E+00	5.519E+00	1.055E+00	1.533E+01

* Corrupted Data

** Counting delay – data lost

Table 8-1. CONTINUED.

Sweep Gas Concentration (uCi/ml) Cycle 302

Sample	Kr-85m	Kr-87	Kr-88	Kr-89	Xe-133	Xe-135m	Xe-135	Xe-138
HRB21-108	9.575E-03	6.606E-02	3.816E-02	0.000E+00	1.109E-01	4.223E-02	3.754E-03	5.434E-01
HRB21-109	3.148E-02	2.409E-01	1.487E-01	1.870E+00	1.264E+00	1.326E-01	1.347E-02	2.021E+00
HRB21-110	1.039E-01	7.188E-01	4.467E-01	6.383E+00	1.446E+00	3.925E-01	2.648E-02	5.267E+00
HRB21-111	2.443E-01	1.593E+00	1.032E+00	1.033E+01	1.092E+00	7.160E-01	5.931E-02	9.131E+00
HRB21-112	6.124E-01	3.775E+00	2.528E+00	2.287E+01	2.041E+00	1.531E+00	1.289E-01	1.878E+01
HRB21-113	1.036E+00	6.147E+00	4.213E+00	3.698E+01	2.148E+00	2.534E+00	2.367E-01	2.791E+01
HRB21-114	1.149E+00	6.277E+00	4.560E+00	3.808E+01	7.886E-01	3.230E+00	4.292E-01	2.490E+01
HRB21-115	1.217E+00	6.321E+00	4.662E+00	3.606E+01	7.072E-01	3.779E+00	5.554E-01	2.342E+01
HRB21-116	1.239E+00	5.573E+00	4.470E+00	*	3.809E-01	6.297E+00	1.150E+00	2.007E+01
HRB21-117	1.160E+00	5.286E+00	4.153E+00	2.777E+01	4.472E-01	6.741E+00	1.267E+00	1.821E+01
HRB21-118	1.938E+00	8.715E+00	6.950E+00	4.552E+01	1.331E+00	1.278E+01	2.474E+00	2.760E+01
HRB21-119	2.167E+00	9.857E+00	7.677E+00	5.425E+01	1.533E+00	1.397E+01	2.683E+00	3.103E+01
HRB21-120	2.038E+00	9.496E+00	7.291E+00	5.030E+01	1.375E+00	1.377E+01	2.651E+00	3.085E+01
HRB21-121	1.886E+00	8.901E+00	6.778E+00	5.564E+01	1.184E+00	1.185E+01	2.155E+00	2.972E+01
HRB21-122	9.067E-01	4.136E+00	3.238E+00	2.130E+01	5.981E-01	4.970E+00	9.561E-01	1.338E+01
HRB21-123	1.975E+00	9.340E+00	7.137E+00	5.524E+01	1.358E+00	1.147E+01	2.054E+00	3.208E+01
HRB21-124	2.199E+00	1.041E+01	7.895E+00	6.192E+01	1.528E+00	1.274E+01	2.259E+00	3.592E+01
HRB21-125	2.203E+00	1.032E+01	7.929E+00	6.014E+01	1.749E+00	1.177E+01	2.190E+00	3.372E+01
HRB21-126	2.581E+00	1.171E+01	9.114E+00	5.861E+01	2.507E+00	1.458E+01	2.750E+00	3.958E+01
HRB21-127	2.395E+00	1.089E+01	8.491E+00	6.272E+01	2.181E+00	1.352E+01	2.598E+00	3.707E+01
HRB21-128	2.340E+00	1.082E+01	8.320E+00	6.383E+01	1.690E+00	1.410E+01	2.549E+00	3.827E+01

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* Data lost due to counting delay

Table 8-2 .

R/B VALUES FOR SELECTED ISOTOPES FOR THE HRB-21 CAPSULE.

Cycle 298

Sample I.D.	Date	Time	T frm Begin	Fl R cc/m	Release Rate / Birth Rate							
					Kr-85m	Kr-87	Kr-88	Kr-89	Xe-133	Xe-135m	Xe-135	Xe-138
HRB21_1	20-Jun-91	16:58	0.00	69.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.47E-10
HRB21_2	20-Jun-91	17:19	0.01	65.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.65E-10
HRB21_3	20-Jun-91	17:41	0.03	65.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.73E-10
HRB21_4	20-Jun-91	17:57	0.04	65.2	0.00E+00	0.00E+00	2.90E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.24E-09
HRB21_5	20-Jun-91	18:13	0.05	65.0	4.88E-08	4.36E-09	3.24E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.70E-09
HRB21_6	20-Jun-91	19.03	0.09	64.5	0.00E+00	2.17E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HRB21_7	20-Jun-91	22:06	0.21	65.4	5.70E-09	6.56E-09	7.33E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.67E-09
HRB21_8	21-Jun-91	15:37	0.94	60.5	1.45E-08	8.65E-09	1.38E-08	0.00E+00	0.00E+00	1.74E-09	0.00E+00	2.49E-09
HRB21_9	21-Jun-91	16:44	0.99	60.0	1.35E-08	1.02E-08	1.33E-08	0.00E+00	0.00E+00	2.16E-09	3.28E-09	1.50E-09
HRB21_10	22-Jun-91	08:21	1.64	60.5	1.16E-08	8.80E-09	1.41E-08	0.00E+00	0.00E+00	3.14E-09	2.71E-09	1.81E-09
HRB21_11	22-Jun-91	08:57	1.75	58.5	1.25E-08	9.51E-09	9.99E-09	0.00E+00	0.00E+00	1.62E-09	2.17E-09	1.66E-09
HRB21_12	23-Jun-91	08:12	2.63	52.5	1.26E-08	1.00E-08	1.09E-08	0.00E+00	0.00E+00	7.82E-10	2.34E-09	1.16E-09
HRB21_13	23-Jun-91	08:37	2.65	51.5	1.25E-08	9.27E-09	1.31E-08	0.00E+00	0.00E+00	1.32E-09	2.31E-09	1.50E-09
HRB21_14	24-Jun-91	16:31	3.98	58.0	1.48E-08	9.95E-09	1.23E-08	0.00E+00	0.00E+00	1.22E-09	3.91E-09	1.65E-09
HRB21_15	24-Jun-91	17:05	4.00	57.5	1.38E-08	9.48E-09	1.43E-08	0.00E+00	0.00E+00	1.98E-09	1.95E-09	1.64E-09
HRB21_16	25-Jun-91	17:15	4.01	50.0	4.18E-08	1.95E-08	3.20E-08	0.00E+00	1.76E-08	0.00E+00	2.67E-09	2.58E-09
HRB21_17	25-Jun-91	17:50	5.04	49.5	3.79E-08	1.91E-08	3.10E-08	0.00E+00	2.13E-08	2.69E-09	1.96E-09	2.15E-09
HRB21_18	26-Jun-91	08:52	5.66	66.2	2.57E-08	2.14E-08	2.74E-08	0.00E+00	8.87E-09	2.62E-09	1.90E-09	1.94E-09
HRB21_19	26-Jun-91	13:43	5.86	63.8	2.87E-08	2.07E-08	2.55E-08	0.00E+00	1.36E-08	3.67E-09	2.65E-09	2.55E-09
HRB21_20*	27-Jun-91	16:07	6.96	54.4	0.00E+00	1.23E-08	2.18E-08	0.00E+00	1.42E-08	0.00E+00	2.91E-09	0.00E+00
HRB21_21	28-Jun-91	08:36	7.65	53.3	2.89E-08	1.66E-08	2.49E-08	0.00E+00	1.66E-08	4.08E-09	2.47E-09	2.48E-09
HRB21_22	28-Jun-91	12:53	7.83	52.7	2.03E-08	1.48E-08	1.81E-08	0.00E+00	1.13E-08	1.37E-09	3.24E-09	1.47E-09
HRB21_23	01-Jul-91	08:48	10.66	43.2	3.48E-08	2.05E-08	2.96E-08	0.00E+00	1.66E-08	3.78E-09	3.08E-09	1.99E-09
HRB21_24	01-Jul-91	13:13	10.84	42.7	3.81E-08	2.35E-08	3.28E-08	0.00E+00	1.58E-08	3.03E-09	2.95E-09	2.51E-09
HRB21_25	03-Jul-91	08:36	12.65	50.2	4.40E-08	2.67E-08	4.00E-08	0.00E+00	8.79E-08	1.67E-09	6.95E-09	2.98E-09
HRB21_26	03-Jul-91	14:45	12.91	49.7	4.61E-08	2.69E-08	3.93E-08	0.00E+00	1.23E-07	1.01E-09	7.23E-09	3.18E-09
HRB21_27	05-Jul-91	09:28	14.69	49.5	5.25E-08	3.46E-08	4.95E-08	0.00E+00	1.54E-07	1.43E-09	9.19E-09	4.23E-09
HRB21_28	05-Jul-91	10:28	14.73	52.0	1.44E-08	9.67E-09	8.64E-09	0.00E+00	3.99E-08	1.66E-09	7.34E-09	2.41E-10
HRB21_29	08-Jul-91	08:57	17.67	43.6	1.88E-08	1.45E-08	2.08E-08	6.69E-10	4.86E-08	9.52E-10	5.40E-09	1.96E-09
HRB21_30	08-Jul-91	13:22	17.85	41.1	1.90E-08	1.07E-08	1.52E-08	0.00E+00	4.33E-08	7.55E-10	3.96E-09	1.73E-09
HRB21_31	10-Jul-91	08:23	19.64	57.5	2.28E-08	1.45E-08	2.00E-08	0.00E+00	5.20E-08	1.31E-09	5.51E-09	2.19E-09
HRB21_32	10-Jul-91	16:13	19.97	56.2	2.23E-08	1.41E-08	1.97E-08	0.00E+00	5.22E-08	9.98E-10	5.42E-09	2.79E-09

* Sample taken through hold-up volume

Table 8-2. CONTINUED.

Cycle 299

Sample I.D.	Date	Time	T frm Begin	Fl R cc/m	Release Rate / Birth Rate							
					Kr-85m	Kr-87	Kr-88	Kr-89	Xe-133	Xe-135m	Xe-135	Xe-138
HRB21_33	25-Jul-91	20:57	34.16	54.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.28E-11
HRB21_34	25-Jul-91	21:17	34.18	52.0	0.00E+00	3.04E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.77E-10
HRB21-35	25-Jul-91	21:36	34.19	52.2	0.00E+00	6.31E-10	6.71E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.93E-10
HRB21_36	25-Jul-91	21:55	34.20	52.6	0.00E+00	8.50E-10	1.80E-09	0.00E+00	0.00E+00	2.02E-10	0.00E+00	4.68E-10
HRB21_37	25-Jul-91	22:09	34.21	52.1	3.01E-09	3.08E-09	2.75E-09	0.00E+00	0.00E+00	6.28E-10	0.00E+00	1.01E-09
HRB21_38	25-Jul-91	22:41	34.24	52.1	5.45E-09	4.52E-09	5.86E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.24E-09
HRB21_39	25-Jul-91	23:20	34.26	52.2	6.44E-09	5.60E-09	6.06E-09	0.00E+00	0.00E+00	6.79E-10	6.53E-10	1.19E-09
HRB21_40	26-Jul-91	11:00	34.75	50.1	3.13E-06	8.96E-07	2.19E-06	0.00E+00	5.49E-05	2.90E-07	4.66E-07	9.55E-08
HRB21_41	26-Jul-91	12:53	34.83	50.1	7.08E-07	2.97E-07	5.42E-07	0.00E+00	3.62E-06	5.09E-07	8.75E-07	2.89E-08
HRB21_42	26-Jul-91	14:38	34.90	53.9	1.84E-07	1.11E-07	1.59E-07	0.00E+00	9.09E-07	5.87E-07	1.06E-06	1.61E-08
HRB21_43	27-Jul-91	08:43	35.65	50.1	3.58E-07	2.20E-07	3.19E-07	1.76E-08	5.80E-07	1.24E-07	2.13E-07	2.69E-08
HRB21_44	28-Jul-91	08:19	36.64	53.8	3.62E-07	2.24E-07	3.22E-07	1.80E-08	4.96E-07	6.55E-08	1.06E-07	2.90E-08
HRB21_45	29-Jul-91	08:42	37.65	55.2	3.28E-07	1.97E-07	2.90E-07	1.79E-08	4.28E-07	4.82E-08	8.29E-08	2.68E-08
HRB21_46	30-Jul-91	11:57	38.79	53.3	3.16E-07	1.90E-07	2.80E-07	1.96E-08	4.17E-07	4.77E-08	7.77E-08	2.52E-08
HRB21_47	31-Jul-91	09:32	39.69	55.1	4.46E-07	2.73E-07	3.90E-07	3.02E-08	7.00E-07	6.84E-08	1.10E-07	3.79E-08
HRB21_48	31-Jul-91	12:32	39.81	54.2	4.26E-07	2.64E-07	3.78E-07	2.62E-08	6.56E-07	6.84E-08	1.09E-07	3.50E-08
HRB21_49	02-Aug-91	08:35	42.65	55.0	5.11E-07	3.13E-07	4.51E-07	3.02E-08	8.60E-07	8.31E-08	1.35E-07	4.28E-08
HRB21_50	02-Aug-91	10:38	42.73	53.4	4.69E-07	2.77E-07	4.06E-07	2.35E-08	1.02E-06	7.52E-08	1.22E-07	3.96E-08
HRB21_51	05-Aug-91	08:54	45.66	54.4	5.53E-07	3.38E-07	4.87E-07	4.03E-08	1.29E-06	9.39E-08	1.49E-07	4.74E-08
HRB21_52	05-Aug-91	15:01	45.92	50.9	1.04E-05	3.15E-06	6.96E-06	1.58E-07	4.73E-04	7.89E-07	1.20E-06	3.52E-07
HRB21_53	05-Aug-91	16:53	46.00	51.2	1.10E-05	3.20E-06	7.13E-06	1.37E-07	4.53E-04	3.50E-06	5.59E-06	3.56E-07
HRB21_54	05-Aug-91	18:10	46.13	51.3	1.48E-05	3.73E-06	9.00E-06	1.64E-07	5.56E-04	4.63E-06	8.77E-06	3.85E-07
HRB21_55	06-Aug-91	15:20	46.93	52.7	7.36E-06	3.40E-06	5.62E-06	2.84E-07	1.23E-04	8.71E-06	1.45E-05	7.09E-07
HRB21_56	07-Aug-91	08:49	47.66	57.1	1.02E-05	4.86E-06	7.76E-06	5.93E-07	1.20E-04	7.43E-06	1.19E-05	1.59E-06
HRB21_57	07-Aug-91	12:41	47.82	55.8	7.58E-06	4.34E-06	6.31E-06	5.59E-07	8.09E-05	6.93E-06	1.11E-05	1.63E-06
HRB21_58*					0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HRB21_59**	07-Aug-91	15:13	47.93	55.7	8.99E-06	3.75E-06	6.81E-06	0.00E+00	1.33E-04	2.27E-06	1.14E-05	5.07E-07
HRB21_60**	08-Aug-91	11:11	48.76	55.6	8.95E-06	3.80E-06	6.90E-06	0.00E+00	1.31E-04	2.14E-06	1.02E-05	5.25E-07
HRB21_61**	09-Aug-91	09:02	49.67	40.0	3.94E-06	1.65E-06	3.12E-06	0.00E+00	4.27E-05	5.52E-07	5.93E-06	1.36E-07
HRB21_62**	09-Aug-91	11:45	49.78	55.5	1.26E-05	4.92E-06	9.72E-06	0.00E+00	2.99E-04	1.52E-06	6.48E-06	6.13E-07
HRB21_63**	12-Aug-91	08:47	52.66	57.8	1.49E-05	7.54E-06	1.26E-05	0.00E+00	2.36E-04	3.20E-06	1.38E-05	1.43E-06
HRB21_64**	14-Aug-91	15:53	54.95	51.9	6.92E-06	3.75E-06	6.21E-06	0.00E+00	4.03E-05	1.25E-06	5.37E-06	6.96E-07

* Sample not analyzed

** Sample taken through "Hold-up" tank

Table 8-2. CONTINUED.

Cycle 300

Sample I.D.	Date	Time	T frm Begin	Fl R cc/m	Release Rate / Birth Rate							
					Kr-85m	Kr-87	Kr-88	Kr-89	Xe-133	Xe-135m	Xe-135	Xe-138
HRB21_65	28-Aug-91	10:21	68.72	72.4	1.24E-07	1.16E-07	1.23E-07	2.03E-08	9.02E-06	2.19E-08	2.09E-08	8.28E-08
HRB21_66	28-Aug-91	10:43	68.74	79.9	3.65E-07	3.94E-07	4.03E-07	7.12E-08	4.69E-05	6.26E-08	5.48E-08	2.77E-07
HRB21-67	28-Aug-91	11:03	68.75	80.9	1.29E-06	1.32E-06	1.37E-06	1.71E-07	1.01E-04	1.92E-07	1.62E-07	7.89E-07
HRB21_68	28-Aug-91	11:23	68.77	80.5	2.51E-06	2.52E-06	2.68E-06	3.79E-07	7.36E-05	3.64E-07	2.67E-07	1.45E-06
HRB21_69	28-Aug-91	11:40	68.78	80.5	5.12E-06	5.01E-06	5.51E-06	0.00E+00	9.81E-05	7.31E-07	5.04E-07	2.85E-06
HRB21_70	28-Aug-91	12:10	68.80	80.9	6.68E-06	6.27E-06	7.17E-06	0.00E+00	5.69E-05	9.97E-07	8.00E-07	3.59E-06
HRB21_71*	28-Aug-91	13:38	68.86	79.9	6.93E-06	5.12E-06	7.16E-06	0.00E+00	2.75E-05	4.23E-07	1.16E-06	1.08E-06
HRB21_72*	28-Aug-91	14:58	68.92	79.8	7.88E-06	5.29E-06	7.90E-06	0.00E+00	1.69E-05	4.79E-07	1.70E-06	1.03E-06
HRB21_73	29-Aug-91	09:18	69.68	83.1	1.40E-05	8.36E-06	1.20E-05	0.00E+00	5.45E-05	6.71E-06	1.00E-05	3.82E-06
HRB21_74	30-Aug-91	10:23	70.95	83.7	1.75E-05	1.13E-05	1.54E-05	2.41E-06	7.59E-05	1.20E-05	1.65E-05	5.69E-06
HRB21_75	30-Aug-91	14:36	71.13	72.4	6.34E-05	2.53E-06	4.41E-05	3.18E-06	8.39E-04	1.85E-05	2.59E-05	9.20E-06
HRB21_76	31-Aug-91	07:18	71.83	75.1	3.20E-05	2.08E-06	2.77E-05	3.60E-06	1.59E-04	2.40E-05	3.43E-05	1.07E-05
HRB21_77	01-Sep-91	08:55	72.89	73.7	3.56E-05	2.32E-05	3.12E-05	4.33E-07	2.17E-04	2.54E-05	3.59E-05	1.23E-05
HRB21_78	03-Sep-91	09:10	74.67	74.9	2.61E-05	1.82E-05	2.40E-05	4.08E-06	1.34E-04	1.45E-05	1.95E-05	9.00E-06
HRB21_79	04-Sep-91	13:20	75.85	74.5	2.92E-05	1.92E-05	2.60E-05	4.05E-06	2.79E-04	1.36E-05	1.94E-05	8.46E-06
HRB21_80	06-Sep-91	08:38	77.65	75.6	5.35E-05	2.59E-05	3.97E-05	4.70E-06	1.75E-03	1.78E-05	2.47E-05	9.08E-06
HRB21_81	09-Sep-91	08:51	80.66	76.6	6.47E-05	3.14E-05	4.82E-05	4.80E-06	2.51E-03	2.41E-05	3.43E-05	1.21E-05
HRB21_82	11-Sep-91	08:27	82.64	76.3	8.36E-05	5.36E-05	7.25E-05	9.45E-06	9.22E-04	4.62E-05	6.38E-05	2.25E-05
HRB21_83	13-Sep-91	09:55	84.70	73.7	5.39E-05	3.30E-05	4.56E-05	4.11E-06	5.76E-04	2.11E-05	3.13E-05	1.12E-05
HRB21_84	13-Sep-91	12:33	84.81	72.8	6.34E-05	3.98E-05	5.41E-05	5.35E-06	6.07E-04	2.60E-05	3.73E-05	1.43E-05
HRB21_85	16-Sep-91	08:49	87.66	74.1	5.71E-05	3.68E-05	4.89E-05	5.10E-06	6.65E-04	2.51E-05	3.41E-05	1.28E-05
HRB21_86	17-Sep-91	08:37	88.65	73.4	5.62E-05	3.73E-05	5.02E-05	5.70E-06	5.69E-04	2.28E-05	2.97E-05	1.30E-05

* Sample taken thru' hold-up volume

Table 8-2. CONTINUED.

Cycle 301

Sample I.D.	Date	Time	T frm Begin	Fl R cc/m	Release Rate / Birth Rate							
					Kr-85m	Kr-87	Kr-88	Kr-89	Xe-133	Xe-135m	Xe-135	Xe-138
HRB21_87	27-Sep-91	19:10	99.09	77.4	5.54E-07	6.41E-07	5.87E-07	1.19E-08	2.36E-04	1.40E-07	1.18E-07	5.07E-07
HRB21_88*	27-Sep-91	19:34	99.11	78.1								
HRB21_89	27-Sep-91	20:30	99.15	77.4	5.48E-06	5.43E-06	5.77E-06	7.26E-07	7.82E-04	9.60E-07	7.85E-07	3.37E-06
HRB21_90	27-Sep-91	20:54	99.16	77.6	1.41E-05	1.27E-05	1.41E-05	1.81E-06	8.73E-04	1.99E-06	1.58E-06	6.76E-06
HRB21_91	27-Sep-91	21:15	99.18	77.5	2.80E-05	2.65E-05	2.98E-05	3.66E-06	1.05E-03	3.72E-06	2.51E-06	1.18E-05
HRB21_92	27-Sep-91	21:35	99.19	77.4	3.91E-05	3.54E-05	4.10E-05	4.49E-06	6.17E-04	5.23E-06	4.05E-06	1.60E-05
HRB21_93	27-Sep-91	22:51	99.24	77.8	4.21E-05	3.65E-05	4.25E-05	5.22E-06	2.58E-04	7.22E-06	6.82E-06	1.54E-05
HRB21_94	28-Sep-91	00:06	99.30	77.4	4.10E-05	3.38E-05	4.15E-05	4.42E-06	1.92E-04	7.55E-06	8.74E-06	1.38E-05
HRB21_95	28-Sep-91	09:56	99.71	70.6	6.63E-05	4.44E-05	6.07E-05	5.64E-06	2.40E-04	1.98E-05	2.81E-05	1.74E-05
HRB21_96	29-Sep-91	08:28	100.64	71.9	9.04E-05	6.01E-05	8.05E-05	1.01E-05	3.70E-04	4.21E-05	6.00E-04	2.49E-05
HRB21_97	30-Sep-91	08:48	101.66	72.5	6.70E-05	4.26E-05	6.03E-05	5.39E-06	3.31E-04	2.91E-05	4.60E-05	1.65E-05
HRB21_98	1-Oct-91	08:03	102.63	71.5	7.05E-05	4.58E-05	6.34E-05	6.04E-06	4.44E-04	2.96E-05	4.57E-05	1.78E-05
HRB21_99	2-Oct-91	08:31	103.65	72.9	8.09E-05	5.31E-05	7.30E-05	7.91E-06	5.25E-04	3.71E-05	5.23E-05	2.22E-05
HRB21_100	4-Oct-91	08:23	105.64	72.9	7.81E-05	5.33E-05	7.07E-05	**	4.57E-04	3.73E-05	5.15E-05	2.38E-05
HRB21_101	7-Oct-91	09:36	108.69	75.8	8.55E-05	5.87E-05	7.80E-05	8.86E-06	5.14E-04	3.54E-05	5.20E-05	2.29E-05
HRB21_102	9-Oct-91	08:29	110.65	73.9	1.08E-04	7.52E-05	9.93E-05	1.19E-05	5.94E-04	4.37E-06	6.18E-05	2.98E-05
HRB21_103	11-Oct-91	08:33	112.65	70.5	8.74E-05	6.01E-05	8.08E-05	1.22E-05	6.52E-04	3.26E-05	4.58E-05	2.26E-05
HRB21_104	11-Oct-91	10:41	112.74	69.9	8.88E-05	6.35E-05	8.26E-05	1.09E-05	4.57E-04	3.46E-05	4.83E-05	2.34E-05
HRB21_105	14-Oct-91	10:40	115.74	69.5	8.82E-05	6.11E-05	8.08E-05	1.01E-05	5.32E-04	3.30E-05	4.81E-05	2.19E-05
HRB21_106	16-Oct-91	08:29	117.65	71.5	9.70E-05	6.42E-05	8.76E-05	1.02E-05	6.54E-04	3.53E-05	5.12E-05	2.25E-05
HRB21_107	18-Oct-91	08:28	119.64	69.9	8.99E-05	5.83E-05	7.91E-05	9.09E-06	1.09E-03	3.04E-05	4.42E-05	2.04E-05

* Corrupted Data

** Counting delay – data lost

Table 8-2. CONTINUED.

Cycle 302

Sample I.D.	Date	Time	T frm Begin	Fl R cc/m	Release Rate / Birth Rate							
					Kr-85m	Kr-87	Kr-88	Kr-89	Xe-133	Xe-135m	Xe-135	Xe-138
HRB21-108	30-Oct-91	10:25	131.73	72.2	8.55E-07	9.04E-07	8.58E-07	0.00E+00	7.45E-05	2.56E-07	1.78E-07	8.38E-07
HRB21-109	30-Oct-91	10:41	131.74	71.5	2.78E-06	3.27E-06	3.31E-06	7.35E-07	8.41E-04	7.97E-07	6.32E-07	3.09E-06
HRB21-110	30-Oct-91	11:07	131.75	72.1	9.27E-06	9.83E-06	1.00E-05	2.53E-06	9.70E-04	2.38E-06	1.25E-06	8.11E-06
HRB21-111	30-Oct-91	11:29	131.77	71.8	2.17E-05	2.17E-05	2.31E-05	4.08E-06	7.30E-04	4.32E-06	2.80E-06	1.40E-05
HRB21-112	30-Oct-91	11:54	131.79	71.8	5.44E-05	5.14E-05	5.65E-05	9.02E-06	1.36E-03	9.24E-06	6.08E-06	2.88E-05
HRB21-113	30-Oct-91	12:20	131.81	71.9	9.21E-05	8.38E-05	9.43E-05	1.46E-05	1.44E-03	1.53E-05	1.12E-05	4.29E-05
HRB21-114	30-Oct-91	13:55	131.87	71.4	1.01E-04	8.50E-05	1.01E-04	1.49E-05	5.24E-04	1.94E-05	2.01E-05	3.80E-05
HRB21-115	30-Oct-91	15:37	131.94	71.2	1.07E-04	8.53E-05	1.03E-04	1.41E-05	4.69E-04	2.26E-05	2.60E-05	3.56E-05
HRB21-116	31-Oct-91	08:42	132.65	72.5	1.12E-04	7.77E-05	1.02E-04	*	2.61E-04	3.89E-05	5.55E-05	3.14E-05
HRB21-117	1-Nov-91	09:08	133.67	73.1	1.07E-04	7.50E-05	9.65E-05	1.14E-05	3.12E-04	4.24E-05	6.25E-05	2.92E-05
HRB21-118	2-Nov-91	08:13	134.63	74.6	1.84E-04	1.27E-04	1.66E-04	1.92E-05	9.57E-04	8.30E-05	1.26E-04	4.55E-05
HRB21-119	3-Nov-91	09:07	135.67	75.9	2.11E-04	1.47E-04	1.88E-04	2.35E-05	1.13E-03	9.30E-05	1.40E-04	5.25E-05
HRB21-120	4-Nov-91	09:20	136.68	73.6	1.94E-04	1.38E-04	1.74E-04	2.12E-05	9.92E-04	8.95E-05	1.35E-04	5.10E-05
HRB21-121	6-Nov-91	09:22	138.68	73.4	1.81E-04	1.31E-04	1.63E-04	2.38E-05	8.61E-04	7.76E-05	1.11E-04	4.95E-05
HRB21-122	8-Nov-91	11:32	140.77	71.6	8.55E-05	5.98E-05	7.67E-05	8.90E-06	4.26E-04	3.19E-05	4.81E-05	2.19E-05
HRB21-123	11-Nov-91	11:42	143.78	71.4	1.82E-04	1.33E-04	1.66E-04	2.28E-05	9.53E-04	7.23E-05	1.02E-04	5.17E-05
HRB21-124	13-Nov-91	11:35	145.77	71.4	1.99E-04	1.44E-04	1.79E-04	2.49E-05	1.04E-03	7.82E-05	1.09E-04	5.62E-05
HRB21-125	15-Nov-91	10:13	147.72	71.8	1.94E-04	1.39E-04	1.75E-04	2.35E-05	1.15E-03	6.99E-05	1.02E-04	5.10E-05
HRB21-126	18-Nov-91	10:14	150.72	70.2	2.10E-04	1.46E-04	1.86E-04	2.11E-05	1.52E-03	7.99E-05	1.18E-04	5.50E-05
HRB21-127	20-Nov-91	11:00	152.75	71.1	1.89E-04	1.31E-04	1.68E-04	2.19E-05	1.28E-03	7.17E-05	1.07E-04	4.96E-05
HRB21-128	20-Nov-91	15:40	152.94	71.4	1.86E-04	1.31E-04	1.65E-04	2.24E-05	9.93E-04	7.51E-05	1.06E-04	5.14E-05

finis

* Data lost due to counting delay

ORNL-DWG 92-16007

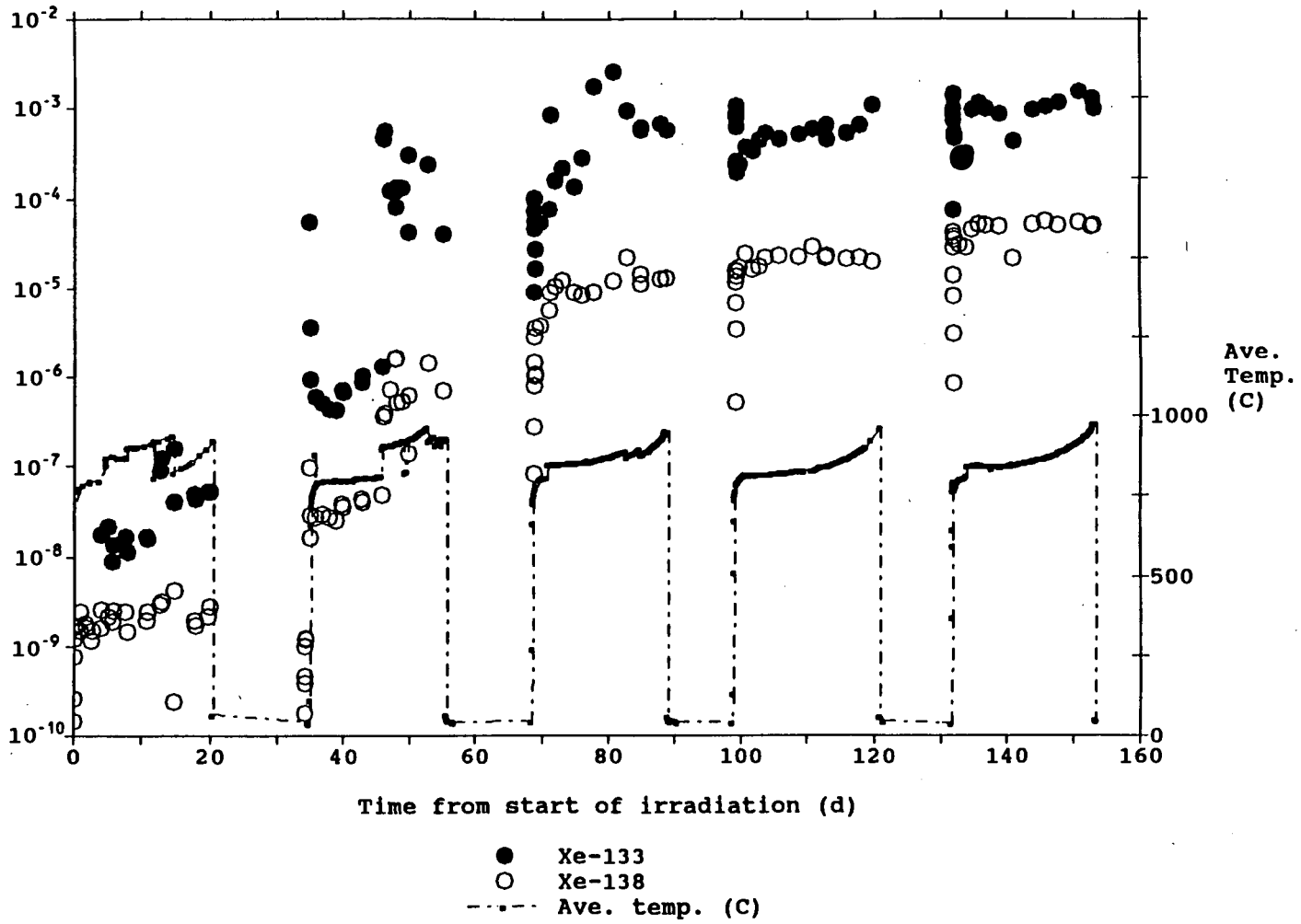

Figure 8-5.

R/B VALUES FOR Xe-133 AND Xe-138 AND THE CAPSULE AVERAGE FUEL TEMPERATURE AS A FUNCTION OF TIME FROM THE START OF THE IRRADIATION.

ORNL-DWG 92-16008

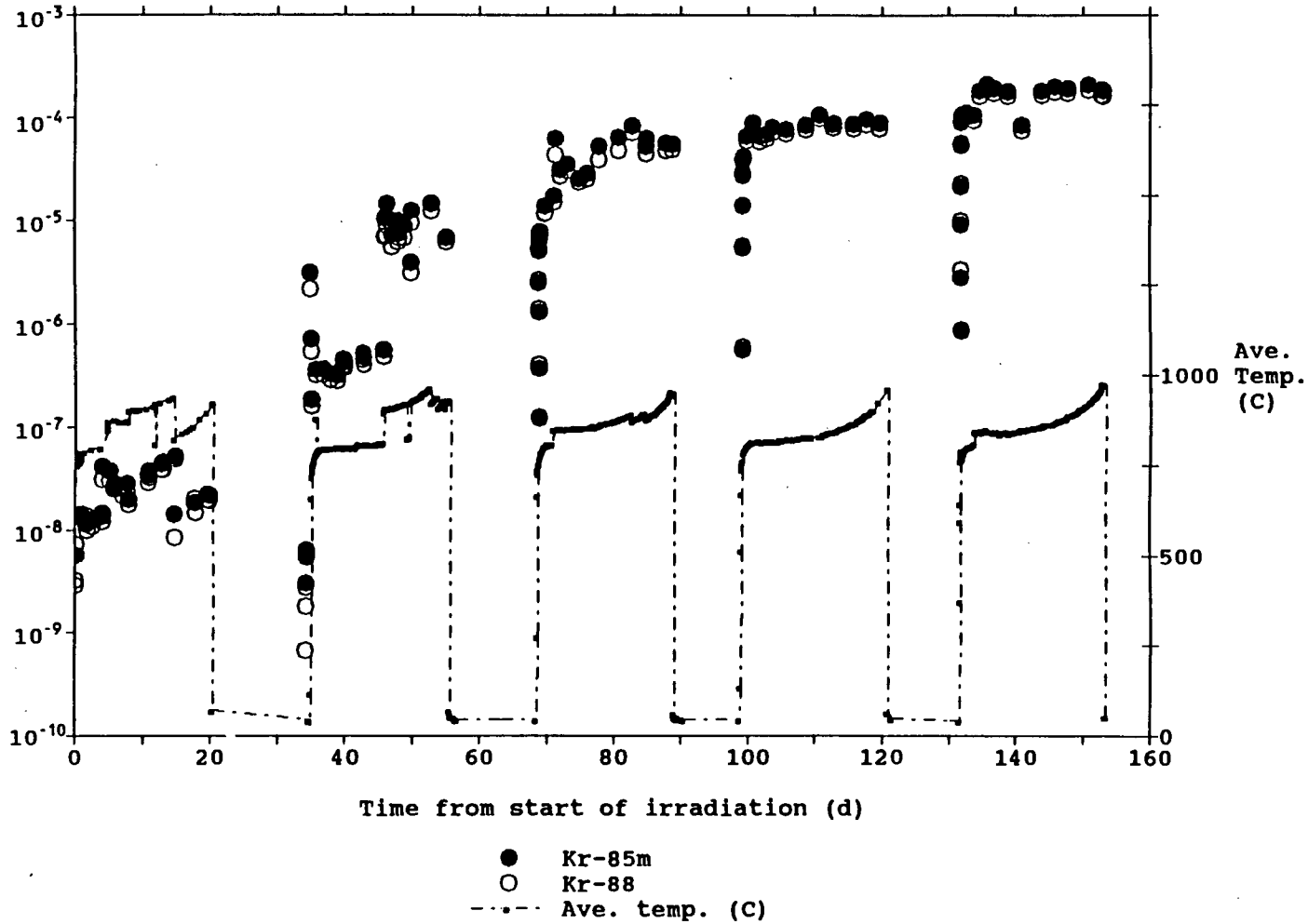

Figure 8-6.

R/B VALUES FOR ^{85m}Kr AND ^{88}Kr AND THE CAPSULE AVERAGE FUEL TEMPERATURE AS A FUNCTION OF TIME FROM THE START OF THE IRRADIATION.

The R/B ratios remained low during the first cycle but rose rapidly at the beginning of cycle 299 and then increased steadily during the remaining irradiation consistent with the indications of particle failures as shown in Fig. 8-4.

SECTION 9

CONCLUSIONS

The HRB-21 experiment operated successfully in the HFIR reactor for five cycles. The mean average volumetric temperature for the fuel appears to have been very close to the desired 975°C. The calculated maximum fuel compact temperature exceeded the specified 1250°C limit in compacts in zones 3 and 4 during the fifth cycle (cycle 302). It was anticipated that greater maximum temperatures could be reached during the planned sixth cycle; therefore, the capsule was removed after the fifth cycle. Even so, fluence and burnup levels of 70 and 87% of the desired peaks were achieved. The temperature, sweep gas radiation level, and R/B sampling systems functioned properly throughout the test.

SECTION 10

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SECTION 11

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APPENDIX A

MAPPING THERMOCOUPLE DATA TO FUEL COMPACT TEMPERATURE

[Note: This program estimates the volumetric average fuel temperature based on the thermocouple readings (in the graphite) and the accumulated fast fluence effects in the graphite and the fuel compacts.]

```
c       t1ave.f
c       This program reads termocouple data from the HRB21 irradiation
c       test from the file TCTEMP1.DAT.
c
c       From the TC temperatures the dimensions of the graphite and the
c       conductivity of the graphite are calculated.  Using scaling
c       equations the fission power density is then estimated.
c
c       Using the power density, the graphite-inconel gap, the
c       fuel graphite gap and the conductivity of the fuel, the
c       fuel temperature is estimated.
c       Gary L. Bell, June, 1991.

        dimension tcond(2000),dayin(2000),fluxmag(2000),
     .tcondf(2000),f_g(2000),rhole(2000),hegas(2000)
        real k1,k2,k10,k20,kappa,lambdat
        common/block1/fluence(2000),rffab,tmpcl(2000),npts,rgraph(2000),
     .iday(2000),ichange,h451k(2000),tmpob(2000),fueltemp(2000)
        open(50,status='old',form='formatted',file='tctemp1.dat')
        open(90,status='old',form='formatted',file='kh451table.dat')
        open(92,status='new',form='formatted',file='t1aveout.dat')
        open(93,status='new',form='formatted',file='grafdata1.dat')
        open(94,status='new',form='formatted',file='scrndata1.dat')
        open(95,status='new',form='formatted',file='errormsg1.dat')
        open(57,status='new',form='formatted',file='fueldata1.dat')
        open(51,status='new',form='formatted',file='diag1.dat')
        read(50,752)
752     format(/)
c-----------------------------------------------------------------
c       write out some file headers.
c-----------------------------------------------------------------
        write(92,920)
920     format('t1aveout.dat (output from T1ave.f)',/)
        write(57,727)
727     format('fueldata1.dat (output from T1ave.f',/,
     .'day  temp(C)    fluence   Kfuel(W/cmK)    rfuel(cm) ',/)


        write(94,819)
819   format(/,
     .8x,'day',6x,'TCcl',7x,'TCob',9x,'%He',6x,'Pv(W/cc)',3x,'<T1>')

c*****************************************************************
c       SECTION I OF MAIN.
c*****************************************************************
        errnum=0.0
c-----------------------------------------------------------------
c       This first section reads the thermocouple temperatures
c       for the centerline and outboard temperatures of the grapghite.
c       The outboard thermocouple is assumed to most accurately map
c       the bulk H451 graphite temperature as thus the outboard
c       TC temperature is used, along with the fast fluence, to
c       calculate the thermal conductivity of the graphite and
c       the radius of the graphite so as to obtain an estimate
c       of the graphite-inconel gas gap.
c-----------------------------------------------------------------
c       Some required values.
c-----------------------------------------------------------------
c       As fabricated diminsions for compact and holder hole in H451.
        rhfab=0.49675/2.0       !H451 compact holder hole radius (in), 25 C.
```

```
      dg=1.4976        !#1 fuel holder fabrication diameter (in), 25C.
      rffab=0.488189/2.0       !#1 fuel compact radius (in) @25C.

      dlim=2.0                 !limit of % diff for kf-f_g iteration.
      ichange=47
      dchange=float(ichange)
c     print *,'Enter z location of fuel (cm)'
c     read *,za1
      za1=22.606
c-----------------------------------------------------------------
c     Stuff for neutron induced H451 radial change calculation.
c-----------------------------------------------------------------
      hc1=1.158111
      hc2=-0.8374059e-2
      hc3=0.1728673e-4
      hc4=-0.1288228e-7
      hc5=0.2846460e-11
      hc6=0.3958980
      hc7=-0.3689394e-2
      hc8=0.1287180e-4
      hc9=-0.2043258e-7
      hc10=0.1438031e-10
      hc11=0.1306940e-1
      hc12=-.1877240e-3
      hc13=0.1022022e-5
      hc14=-0.2709323e-8
      hc15=0.3665231e-11
      hc16=-0.3621619e-14
      hc17=-0.2369797e-14
      hc18=0.5766467e-18
c-----------------------------------------------------------------
c     Read in day, power level, temperature data from file containing
c     the termocouple temperatures.
c-----------------------------------------------------------------
      m=0
422   read(50,433,end=99)tme,xmag,tccltemp,tcobtemp,gas
433   format(f8.3,f8.3,f8.2,f8.2,f8.2)
      write(*,433)tme,xmag,tccltemp,tcobtemp,gas
      m=m+1
      fluxmag(m)=xmag/100.0
      dayin(m)=tme
      iday(m)=int(tme)
      tmpcl(m)=tccltemp                !thermocouple temp, Celsius
      tmpob(m)=tcobtemp                !thermocouple temp, Celsius
      hegas(m)=gas
      go to 422
99    kd=m    !npts=number of time, etc data points.

      npts=kd
      write(*,639)npts
639   format(/////,
     .'*******************************************************',/,
     .'     NUMBER OF DATA POINTS IN TCTEMP.DAT=',i3,/,
     .'*******************************************************',/)
c-----------------------------------------------------------------
c     load up fluence array
c     coefficients for fast neutron flux (neutrons/m*m*s)
c-----------------------------------------------------------------
      ff0=1.55139e18
      ff1=0.357201e18
```

```
      ff2=3.22098e16
      ff3=-4.89680e15
      ff4=1.06604e14
      ff5=6.60525e11
      za=10.0-za1/2.54        !coefficients require z from midplane.

      fluxofz0=ff0 + ff1*za + ff2*za**2 + ff3*za**3
     .+ ff4*za**4 + ff5*za**5
      fluxprnt=0.85*fluxofz0

      write(92,921)za1,fluxprnt
921   format('For 85 MW HFIR power ',/,
     .'flux @',f8.4,' =',e12.5,' (N/m^2s, RB)')

      write(92,923)
923   format(1x,/,1x,
     .'day  <T>(C)  flu(N/m^2)',4x,'Kg    Kf   g_inc(in)',3x,
     .'f_g(in)  Pv(W/cc)   %He')
c-----------------------------------------------------------------
c     Load up flux array.  Include zero flux days between cycles.
c-----------------------------------------------------------------
      flu1=0.0
c     Calculate fluence using fluxmag and dayin
c for dayin 1:
      fluence(1)=fluxmag(1)*dayin(1)*24.0*3600.0*fluxofz0/1.0e25
      do 10 i=2,kd
      day=dayin(i)
      deltatime=dayin(i)-dayin(i-1)
c     flux to fluence in units of 1.0e25 Neutrons/m^2.
      fluxofz=fluxmag(i)*fluxofz0
      dflu=deltatime*24.0*3600.0*fluxofz/1.0e25
      write(*,717)fluxmag(i)
717   format('fluxmag=',f9.3,/)
      fluence(i)=fluence(i-1)+dflu
10    continue
c-----------------------------------------------------------------
c     Calculate day 0 at temperature dimension of fuel holder hole.
c-----------------------------------------------------------------
      t0=tmpc1(1)     !use TCc1 because it is closer to hole.
      drorgraf=(5.75714e-4*t0 - 0.0732905)/100.0      !from fit to
      rhole0=rhfab*(1.0 + drorgraf)           !h451 design handbook.
      rhole(1)=rhole0
c-----------------------------------------------------------------
c     Calculate day 0 at temperature radius of fuel holder.
c-----------------------------------------------------------------
      drorgraf=(5.75714e-4*tmpob(1) - 0.0732905)/100.0
      dgx=1.0 + drorgraf
      rgraph(1)=(2.54*dg/2.0)*dgx     !store hole radius in array.
      rd=rgraph(1)
      rgcm=2.54*dg/2.0
      write(*,341)tmpob(1),dgx,rgcm
341   format('"parameter test"',/,
     . 'TCob=',f12.2,/,
     .'1+dror=',f12.5,/,
     .'Rgo=',f12.2,/)
c-----------------------------------------------------------------
c     Calculate H451 dimensional changes.
c     Use TCob for dimension of holder radius and
c     use TCc1 for dimension of fuel compact hole.
c-----------------------------------------------------------------
```

```
      do 20 j=2,npts
      gamma=fluence(j)
      g2=gamma**2.0
      g3=gamma**3.0
c---------------------------------
c     Calculate radius of holder.
c---------------------------------
      tc=tmpob(j)     !graphite temperature from TCob.
      t1=(hc1+hc2*tc+hc3*tc**2+hc4*tc**3+hc5*tc**4)*gamma
      t2=(hc6+hc7*tc+hc8*tc**2+hc9*tc**3+hc10*tc**4)*g2
      t3=hc16*g2*tc**5
      t4a=(hc11+hc12*tc+hc13*tc**2+hc14*tc**3+hc15*tc**4)
      t4b=hc17*tc**5 + hc18*tc**6
      t4=t4a+t4b
      dror=t1 + t2 + t3 + t4*g3       !thermal strain (%).
      rhldr=rd*(1.0+dror/100.0)       !holder radius.
      rgraph(j)=rhldr                 !store hole radius is array.
c---------------------------------
cTest lines
      write(77,293)dayin(j),fluence(j),tc,dror
293   format(4f10.4)
c---------------------------------
c     Now do it for compact hole.
c---------------------------------
      tc=0.5*(tmpcl(j)+tmpob(j)) !ave graph temp from TCcl&TCob.
c3/18/92
      if(tmpcl(j).eq.0.0)then
      tc=0.5*(1.0+1.1)*tmpob(j)
      end if
c3/18/92

c      tc=tmpcl(j)    !graphite temperature from TCcl.
      t1=(hc1+hc2*tc+hc3*tc**2+hc4*tc**3+hc5*tc**4)*gamma
      t2=(hc6+hc7*tc+hc8*tc**2+hc9*tc**3+hc10*tc**4)*g2
      t3=hc16*g2*tc**5
      t4a=(hc11+hc12*tc+hc13*tc**2+hc14*tc**3+hc15*tc**4)
      t4b=hc17*tc**5 + hc18*tc**6
      t4=t4a+t4b
      dror=t1 + t2 + t3 + t4*g3       !thermal strain (%).
      rhole(j)=rhole0*(1.0+dror/100.0)        !fuel hole radius.
20    continue
c-------------------------------------------------------------------
c     Now use the fluence array and the temperature array
c     to calculate the thermal conductivity of the H-451 graphite.
c-------------------------------------------------------------------
      zdum=0.0        !dummy pass argument.
      call kh451(zdum)        !calculate Kh451.
c     calculate unirradiated thermal conductivity of graphite.
      h451k(1)=1.2984 - 9.91e-4*tmpob(1) +2.993e-7*(tmpob(1)**2)

      do 45 n=1,npts
      write(93,894)dayin(n),tmpob(n),fluence(n),h451k(n),rhole(n),
     .rgraph(n)
894   format(f8.3,f8.2,e12.2,f6.4,f8.4,f8.4)
45    continue
```

```
c*********************************************************************
c       SECTION II OF MAIN.
c*********************************************************************

c---------------------------------------------------------------------
c       Now we have the thermal conductivity of the H-451 and
c       the graphite-inconel gap as calculated quantities
c       based on the outboard thermocouple reading.  Now estimate
c       the fission power density based on the centerline and
c       outboard TC data.
c---------------------------------------------------------------------
c       HAVING READ THERMOCOUPLE DATA FILE:
c
c       (1) Calculate the adjustment to the thermocouple data as a
c       function of helium in the sweep gas.  This provides
c       He/Ne=70/30 values.  He/Ne=70/30 was the gas mix used
c       in the parameter scans used to generate the dependence
c       of TC and fuel temperature on Kf, Kg, f_g, g_inc and Pv.

c       (2) Calculate the power density in the fuel consistent with
c       the inboard TC temperature and the centerline TC temperature,
c       calculate the average of the two and calculate the percent
c       difference.

c       (3) Using this power density, calculate the fuel temperature
c       consistent with Kg, Kf, f_g, g_inc.  These four quantities
c       are functions of the temperature and fluence history.
c       For Kf and f_g, start with a guess.  Use these guesses along
c       the 'known' Kg, g_inc, and Pv to calculate <T>.
c       Then pass this <T> back to the fuel subroutine and see
c       if the initial guess is consistent with the temperature
c       calculated based on the initial guess.  If yes, goto next pt.
c       If not, take the average Kf and f_g and iterate again.
c
c       (4) Adjust the fuel temperature as a function of helium
c       in the sweep gas.  This get us back to the helium
c       concentration at which the TC data was taken.
c---------------------------------------------------------------------
c---------------------------------------------------------------------

        do 50 n=1,kd
        write(*,622)dayin(n)
622     format(///,'START DAY  ' ,f8.2,/)

        ttccl=tmpcl(n)
        ttcob=tmpob(n)
        xkg=h451k(n)
        gas=hegas(n)
        hotincid=1.51672*2.54   !300(C) hot inconel ID (cm).
c       hotincid=1.525*2.54     !300(C) hot inconel ID (cm).
        hotincir=hotincid/2.0   !hot inconel inner radius (cm).
        xgi=1000.0*(hotincir-rgraph(n))/2.54   !change units cm to mil.

        write(*,820)ttccl,xkg,xgi,hotincir,rgraph(n)
820     format('Parameter check: TCcl=',f9.4,/,
     .'Kh451=',f9.4,/,
     .'g_inc gap=',f9.4,/,
     .'hotincr(in)=',f9.4,/,
     .'rgraph(n)(in)=',f9.4,/)
```

```
c-----------------------------------------------------------------------
c       Adjust TC temperatures for gas mix.
c       i.e. get equivalent 70/30 temperature, to feed to TFUEL to
c       get estimate of fuel temperature.
c-----------------------------------------------------------------------
c Centerline
        gcl0=1.4332668  !Coefficients for TCcl gas adjust.
        gcl1=-0.0119144
        gcl2=1.14304e-4
        gcl3=-4.572789e-7

        gasfactcl=gcl0 + gcl1*gas +gcl2*gas**2 + gcl3*gas**3
        ttccl=ttccl/gasfactcl

c Outboard
        gob0=1.4715783  !Coefficients for TCob gas adjust.
        gob1=-0.013038
        gob2=1.2593165e-4
        gob3=-5.051349e-7

        gasfactob=gob0 + gob1*gas + gob2*gas**2 + gob3*gas**3
        ttcob=ttcob/gasfactob


        write(51,722)dayin(n),gas,ttccl,ttcob,gasfactcl,gasfactob
722     format(//,
     .'=================================================================',/,
     .'=================================================================',/,
     .'DAY=',f8.2,' gas =',f7.2,' % Helium',/,
     .'TCcl=',f8.2,' (C)',/,
     .'TCob=',f8.2,' (C)',/,
     .'********* gasfactcl=',f10.5,/,
     .'********* gasfactob=',f10.5,/))

c-----------------------------------------------------------------------
c       use subroutines to get estimates of fission power density
c       based on thermocouple temperatures
c-----------------------------------------------------------------------
c3/18/91
        if(ttccl.eq.0.0)go to 550       !3/18/92
c3/18/91

        call getpvcl(xkg,xgi,ttccl,xpvcl) !get Pv from TCcl.

550        call getpvob(xkg,xgi,ttcob,xpvob) !get Pv from TCob.

c3/18/91
        if(ttccl.eq.0.0)xpvcl=xpvob     !3/18/92
c3/18/91

        avepwr=0.5*(xpvob+xpvcl)          !use average Pv.

        pdiff=100.0*abs(xpvob-xpvcl)/avepwr  !calculate % difference.
c-----------------------------------------------------------------------
c8/8/91
        if(avepwr.lt.0.0)avepwr=0.0
c8/8/91
c-----------------------------------------------------------------------
c       Check for large differences in the fission power
c       density estimated by TCcl and TCob.  For now make
```

```
c       a note in the error file.
c-----------------------------------------------------------------
836     if(pdiff.ge.10.0)then
        errnum=errnum+1.0
        write(*,737)ttccl,xpvcl,ttcob,xpvob,pdiff
737     format(///,
     .'TCcl(C)=',f10.2,'  giving Pv=',f10.2,/,
     .'TCbo(C)=',f10.2,'  giving Pv=',f10.2,/,
     .'for a % difference=',f8.1,/)
c     .'Do you want to change anything?',/,
c     .'YES=1,  NO=0',/)
c       read(*,738)ichoose
c738    format(i3)
c         if(ichoose.ne.0.and.ichoose.ne.1)then
c         write(*,749)
c749      format(//,'READ THE DIRECTIONS and TRY AGAIN!!!')
c         go to 836
c         endif
        write(95,759)errnum,dayin(n),ttccl,xpvcl,ttcob,xpvob,pdiff
759     format(/,
     .'-------------------------------------------------------',/,
     .'ERROR # ',f8.1,/,
     .'day=',f8.2,/,
     .'TCcl(C)=',f10.2,'  giving Pv=',f10.2,/,
     .'TCbo(C)=',f10.2,'  giving Pv=',f10.2,/,
     .'for a % difference=',f8.1,/,
     .'-------------------------------------------------------',/)
        endif
c-----------------------------------------------------------------



        write(*,292)xpvcl,xpvob,avepwr,pdiff
292     format(//,'Pv from cl=',f9.3,/,
     . 'Pv from ob=',f9.3,/,
     . 'Average=',f9.3,'+/-',f7.1,' %',/)


        write(51,510)xkg,xgi,ttccl,xpvcl,ttcob,xpvob,avepwr,pdiff
510     format(//,'TEST OUTPUT FROM t1ave.f',/,
     .'from getpvcl&getpvob subroutines',/,
     .'Kg=',f9.4,/,'g_inc=',f7.2,/,
     .'ttccl=',f8.2,'   Pvcl=',f8.2,/,
     .'ttcob=',f8.2,'   Pvob=',f8.2,/,
     .'Average=',f9.3,'+/-',f7.1,' %',/)

c-----------------------------------------------------------------
c       Now we have TC, Kh451,g_inc and Pv.  To get fuel temp
c       we still need f_g and Kfuel for call to TFUEL.
c-----------------------------------------------------------------
        if(n.eq.1)then
        xkf=0.16        !starting estimate of Kf (W/cmK).
        xfg=4.0         !starting estimate of f_g gap (mils).
        tcondf(1)=xkf
        f_g(1)=xfg
        else
        xkf=tcondf(n-1) !use previous Kf values for iteration.
        xfg=f_g(n-1)    !use previous f_g for iteration
```

```
        endif
c-----------------------------------------------------------------------
c       Get first estimate of 70/30 fuel temperature.
c-----------------------------------------------------------------------
c8/8/91.
c       If reactor power is zero then let fuel temp equal
c       average of thermocouple temperatures.
        if(fluxmag(n).lt.0.2)then
        t4est=0.5*(ttccl+ttcob)
        fluxtemp=t4est
        go to 760
        endif
c8/8/91.
c-----------------------------------------------------------------------

        call tfuel(avepwr,xgi,xfg,xkf,xkg,t4est)

c  Adjust <T> to present gas mix.
        gf0=1.4850385
        gf1=-0.013004
        gf2=1.202567e-4
        gf3=-4.712046e-7
        gasfactf=gf0 + gf1*gas + gf2*gas**2 + gf3*gas**3

        write(51,723)gasfactf,t4est
723     format(/,'*******gasfactf=',f10.5,/,'pret4=',f8.2,/)
        t4est=t4est*gasfactf
        t4est0=t4est
c-----------------------------------------------------------------------
c  Now we have 1st estimate of the fuel temperature at the
c       present gas mix.
c  Pass this fuel temperature along to the subroutine kf to calculate
c       a thermal conductivity of the fuel as well as a radius of
c       the fuel compact.  Then compare the new xkf and xfg to see
c       if they are consistent (within 10%) of the values used to
c       calculate the fuel temperature in the first iteration.
c-----------------------------------------------------------------------
        nday=n  !n is the loop counter and specifies array elements.
760     call kf(xkf1,rfuel,nday,t4est)

c calculate f_g consistent with 1st estimate of <T> and TCob.
        xfg1=(rhole(n)-rfuel)*1000.0    !f_g gap in mils.
c-----------------------------------------------------------------------
c       Compare the values used with the subroutine values.
c-----------------------------------------------------------------------
        xkfave=0.5*(xkf+xkf1)
        xfgave=0.5*(xfg+xfg1)
        akfdiff=100.0*abs(xkf-xkf1)/xkfave      !%difference.
        afgdiff=100.0*abs(xfg-xfg1)/xfgave      !%difference.
        write(*,331)nday,t4est,xkf,xkf1,akfdiff,xfg,xfg1,afgdiff
331     format(/,'**********',/,
     .'Day of iteration=',i4,/,
     .'Fuel temp (C)=',f9.2,/,
     .'fuel cond: OLD=',f9.4,' NEW=',f9.4,' %diff=',f8.2,/,
     .'fuel-graphite gap:OLD=',f9.4,' NEW=',f9.4,' %diff=',f8.2,/,
     .'Now go to TFUEL with average Kf and f_g to improve estimate',/,
     .'**********',///)
c-----------------------------------------------------------------------
c       make another call to TFUEL using latest values
c       of f_g and Kf.
```

```
c-----------------------------------------------------------------
740     call tfuel(avepwr,xgi,xfg1,xkf1,xkg,t4est1)
        t4est1=t4est1*gasfactf
c-----------------------------------------------------------------
c8/8/91.
c       If reactor power is zero then let fuel temp equal
c       average of thermocouple temperatures.
        if(fluxmag(n).lt.0.2)t4est1=fluxtemp
c8/8/91.
c-----------------------------------------------------------------
c-----------------------------------------------------------------
c       Compare 1st <T> estimate with this new <T> estimate.
c-----------------------------------------------------------------

        call compare(t4est1,t4est0,dlim,decision)

        if(decision.eq.1.0)then         !within limits(</= dlim).
        tcondf(n)=xkf1  !store Kf
        f_g(n)=xfg1     !store f_g
        go to 739
        endif


        if(decision.eq.0.0)then         !not in limit (>dlim).
        xkf1=xkfave     !use average of old and new value.
        xfg1=xfgave     !use average of old and new value.
c-----------------------------------------------------------------
c       let t4est0=average of two estimates and define old est using
c       new estimate value.  Then call Kf with this new <T> to get
c       new estimates for Kf and f_g.
c-----------------------------------------------------------------
        testave=0.5*(t4est0+t4est1)
        t4est00=t4est0
        t4est0=t4est1
        t4est1=testave
        endif

        write(*,444)
444     format('^^^^^ trying to adjust kf and f_g to converge^^^^^')

        go to 740       !call TFUEL to get new estimate of <T>.

c-----------------------------------------------------------------
c  Control comes here when kf, f_g, <T> consistency is reached.
c-----------------------------------------------------------------
739     fueltemp(n)=t4est1      !got good agreement so store <T>
        f_g(n)=xfg1
        tcondf(n)=xkf1


        write(45,571)dayin(n)
571     format('-----------------------------',/,
     .'end of day ',f8.2,/,
     .'-----------------------------',/)
        write(51,512)avepwr,xgi,f_g(n),tcondf(n),xkg,t4est
512     format('from tfuel subroutine',/,'Pv=',f8.2,/,
     .'g_inc=',f9.4,/,
     .'f_g=',f9.4,/,
     .'Kf=',f9.4,/,
```

```
     .'Kg=',f9.4,/,
     .'<T1> estimate=',f9.4,/,
     .'==============================================================',/)
        write(94,870)dayin(n),tmpcl(n),tmpob(n),gas,avepwr,fueltemp(n)
        write(*,870)dayin(n),tmpcl(n),tmpob(n),gas,avepwr,fueltemp(n)
870     format(6(2x,f9.1))
        write(92,562)dayin(n),fueltemp(n),fluence(n),xkg,tcondf(n),
     .xgi,f_g(n),avepwr,hegas(n)
c562    format(f8.3,f8.2,e12.4,2f6.4,4f10.2)
562      format(f7.3,f9.2,e11.3,2f8.4,2f8.2,f10.2,f8.2)
50      continue

        if(errnum.gt.0.0)then
        write(*,933)errnum
933     format(//,'SEE file ERRORMSG1.dat for',f5.1,' ERRORS')
        else
        write(*,934)
934     format(//,'RAN WITH NO ERRORS')
        endif

        stop
        end

c-----------------------------------------------------------------------
c       END OF MAIN
c-----------------------------------------------------------------------
c-----------------------------------------------------------------------



c-----------------------------------------------------------------------
c       SUBROUTINE kh451
c-----------------------------------------------------------------------
        subroutine kh451(zdum)

c       This subprogram calculates the thermal condutivity of
c       H-451 graphite based on equations found in the HTGR
c       Graphite Design Handbook, DOE-HTGR-88111/Rev.0.
        dimension hk(140)
        real ku,kb,kd
        common/block1/fluence(2000),rffab,tmpcl(2000),npts,rgraph(2000),
     .iday(2000),ichange,h451k(2000),tmpob(2000),fueltemp(2000)
        common/block2/tc(35),ku(35),kb(35),kd(35)
c-----------------------------------------------------------------------
        rt=25.0 !room temperature in celsius.
        alfa=5.707
        beta=6.165e6
c-----------------------------------------------------------------------
c       Read tabular data
c-----------------------------------------------------------------------
        do 20 m=1,35
        read(90,100)tdum,aku,akb,akd
100     format(4e12.4)
        tc(m)=tdum-273.0        !tc in degrees Celsius.
        ku(m)=aku       !units are (W/mK)
        kb(m)=akb
        kd(m)=akd
20      continue
```

```
      uk=0.0
      bk=0.0
      dk=0.0
c-----------------------------------------------------
c     Get Kd(RT)
c-----------------------------------------------------
      call linterp(rt,uk,bk,dk)
      kdrt=dk
c-----------------------------------------------------
c     Get Ko(RT), k unirradiated at room temperature.
c-----------------------------------------------------
      call kzero(rt,aki)
      hk(1)=aki
c-------------------------------------------------------------------
c     Calculate thermal conductivity of H-451 graphite as a
c     function of temperature and fast fluence.  Use the
c     temperature recorded by the outboard thermocouple
c     as the H-451 representative temperature in the calculation
c     of the graphite-inconel gas gap.
c-------------------------------------------------------------------
      do 30 i=2,npts
      t1=tmpob(i)     !use TCob as bulk temperature.
      t1k=t1+273.0
      flu=fluence(i)
      flum=fluence(i-1)
      if(t1.ge.300.0.and.t1.le.600.0)biga=0.2687

      if(t1.ge.600.0.and.t1.le.1400.0)then
      biga=-0.5676
      c=2.2726
      d=1.222e-3
      endif

      if(t1.le.600.0)bigb=0.0
      if(t1.gt.600.0.and.t1.lt.1400.0)bigb=9.58e-4

      tau=biga + bigb*t1k
      rksati=exp(c+d*t1k)

      expterm=exp( (flum-flu)/tau)
      hk(i)=rksati + (hk(i-1) - rksati)*expterm

      call linterp(t1,uk,bk,dk)
      dterm=(kdrt/alfa)*( 1.0/hk(i) - 1.0/hk(1) )

      term1=1.0/uk
      term2=beta/bk
      term3=dterm/dk

      tcon=1.0/(alfa*(term1+term2+term3))     !Kh451 (W/mk)
      tconcm=tcon/100.0       !change to W/cmK).
      h451k(i)=tconcm         !store in array to pass on.
      g_incgap=(1.5494-rgraph(i))/2.54        !g_inc gap (inches)
30    continue        !end of fluence loop
      return
      end
```

```
c-----------------------------------------------------------------------
c       SUBROUTINE linterp.
c-----------------------------------------------------------------------
        subroutine linterp(t1,uk,bk,dk)
        real ku,kb,kd
        common/block2/tc(35),ku(35),kb(35),kd(35)
        do 10 i=1,34
        if(t1.le.tc(1))then
        uk=ku(1)
        bk=kb(1)
        dk=kd(1)
        endif
        if(t1.ge.tc(35))then
        uk=ku(35)
        bk=kb(35)
        dk=kd(35)
        endif
        if(t1.ge.tc(i).and.t1.le.tc(i+1))kk=i
10      continue
        tlow=tc(kk)
        thi=tc(kk+1)
        difftc=abs(thi-tlow)
        tfract=(t1-tlow)/difftc

        alowku=ku(kk)
        hiku=ku(kk+1)
        diffku=(hiku-alowku)
        uk=ku(kk)+tfract*diffku

        alowkb=kb(kk)
        hikb=kb(kk+1)
        diffkb=(hikb-alowkb)
        bk=kb(kk)+tfract*(diffkb)

        alowkd=kd(kk)
        hikd=kd(kk+1)
        diffkd=(hikd-alowkd)
        dk=kd(kk)+tfract*diffkd
        return
        end


c-----------------------------------------------------------------------
c       SUBROUTINE kzero.
c-----------------------------------------------------------------------
        subroutine kzero(t1,ak0)
        call linterp(t1,aku,akb,akd)
        alfa=5.707
        beta=6.165e6
        denom=alfa*( (1.0/aku)+(beta/akb) )
        ak0=1.0/denom
        return
        end
```

```
c-----------------------------------------------------------------
c       SUBROUTINE tfuel.
c-----------------------------------------------------------------
        subroutine tfuel(xpv,xgi,xfg,xkf,xkg,t4est)
c       This subprogram calculates the volumetric temperature of
c       HRB21 compact #4 as a function of
c       1)fission power density.
c       2)graphite_inconel gap
c       3)fuel_graphite gap
c       4)thermal conductivity of fuel
c       5)thermal conductivity of H-451 graphite
        real kf,kh,x(6),t4(6)
        fp=xpv          !fission power density (W/cc).
        fggap=xfg       !fuel-graphite gap (mils).
        ginc=xgi        !graphite-inconel gap (mils).
        kf=xkf          !thermal conductivity of fuel (W/cmK).
        kh=xkg          !thermal concuctivity of H451 (W/cmK).
c-----------------------------------------------------------------
c       Calculate volumetric temperature for given fission power
c       density and g_inc gap.
c-----------------------------------------------------------------
        ael=6.0         !number of elements or equations.
        x(1)=8.0
        x(2)=9.0
        x(3)=11.0
        x(4)=13.0
        x(5)=15.0
        x(6)=17.0

        a1=392.83
        a2=399.87
        a3=446.39
        a4=480.43
        a5=513.24
        a6=515.46

        b1=3.605165
        b2=3.808461
        b3=3.888343
        b4=4.04484
        b5=4.17854
        b6=4.56829

        t4(1)=a1 + b1*fp
        t4(2)=a2 + b2*fp
        t4(3)=a3 + b3*fp
        t4(4)=a4 + b4*fp
        t4(5)=a5 + b5*fp
        t4(6)=a6 + b6*fp

        sxy=x(1)*t4(1) + x(2)*t4(2) + x(3)*t4(3) + x(4)*t4(4) +
     .  x(5)*t4(5) + x(6)*t4(6)
        sx=x(1) + x(2) + x(3) + x(4) + x(5) + x(6)
        sy=t4(1) + t4(2) + t4(3) + t4(4) + t4(5) + t4(6)
        sx2=x(1)**2 + x(2)**2 + x(3)**2 + x(4)**2 + x(5)**2 +
     .  x(6)**2
        ybar=sy/ael
        xbar=sx/ael
        bb1=(ael*sxy - sx*sy)/(ael*sx2 - sx**2)
        bb0=ybar - bb1*xbar
```

```
      t4a=bb0 + bb1*ginc
      t4a=t4a/0.9640885
c-----------------------------------------------------------------
c     Adjust for fuel_graphite gap.
      fg0=0.9006715
      fg1=0.023044
      fg2=-6.35e-4
      factf_g=fg0 + fg1*fggap +fg2*fggap**2
      t4b=t4a*factf_g
c-----------------------------------------------------------------
c     Adjust for thermal conductivity of fuel.
      x1=kf/0.10899
      c0=1.100584
      c1=-0.1467289
      c2=0.046045
      factkf=c0 +c1*x1 + c2*x1**2
      t4c=t4b*factkf
c-----------------------------------------------------------------
c     Adjust for thermal conductivity of H-451 graphite.
      x2=kh/0.4184
      d0=1.2030881
      d1=-0.349232
      d2=0.1806336
      d3=-0.034295

      factkh=d0 + d1*x2 + d2*x2**2 +d3*x2**3
      t4d=t4c*factkh
      t4est=t4d       !return this value to main.
c-----------------------------------------------------------------
      write(45,200)fp,ginc,t4a
200   format(//,'fission power density=',f8.2,/,
     . 'g_inc gap=',f5.2,' mils',/,
     . '<T1>(70/30)before following adjustmests =',f8.2)
      write(45,201)fggap,factf_g
201   format('f_g gap=',f5.2,' mils',/,
     . 'f_g factor=',f12.5)
      write(45,202)kf,factkf
202   format('kfuel=',f12.5,/,
     . 'kf factor=',f12.4)
      write(45,203)kh,factkh,t4d
203   format('k H-451=',f12.5,/,
     . 'kh factor=',f12.4,/,
     . 'temp returned to main=',f8.2,/)
      write(*,204)t4d
204   format(/,
     .'Predicted fuel temp from TFUEL before gas adjust=',f8.2)
      return
      end



c-----------------------------------------------------------------
c     SUBROUTINE getpvcl
c-----------------------------------------------------------------
      subroutine getpvcl(xkg,xgi,ttccl,xpvcl)
c     Calculate an estimate of the fission power density
c     from the dependence of thermocouple temperature on
c     power density for the centerline thermocouple.
c     density and g_inc gap.
```

```
c       xkg=h451 thermal conductivity (W/cmK)
c       xgi=graphite-inconel gap (mils)
c       ttccl=temperature from centerline thermocouple.
c       xpvcl=fission power density (W/cc) based on TCcl
c       @kg=0.4184
        dimension x(6),y(6)
        z=xkg/0.4184
        clkg0=1.386585
        clkg1=-0.652703
        clkg2=0.32763
        clkg3=-0.0612314
        factor=clkg0 +clkg1*z + clkg2*z**2 +clkg3*z**3

        ael=6.0          !number of elements or equations.
        a1=-108.249
        a2=-105.231
        a3=-113.582
        a4=-117.229
        a5=-121.044
        a6=-112.699

        b1=0.27975
        b2=0.265548
        b3=0.257761
        b4=0.246985
        b5=0.238525
        b6=0.219463

        x(1)=8.0
        x(2)=9.0
        x(3)=11.0
        x(4)=13.0
        x(5)=15.0
        x(6)=17.0

        y(1)=a1 + b1*ttccl/factor
        y(2)=a2 + b2*ttccl/factor
        y(3)=a3 + b3*ttccl/factor
        y(4)=a4 + b4*ttccl/factor
        y(5)=a5 + b5*ttccl/factor
        y(6)=a6 + b6*ttccl/factor

c       Least squares fit to (x,y)pairs to get Pv=f(g_inc)
        sxy=x(1)*y(1)+x(2)*y(2)+x(3)*y(3)+x(4)*y(4)+x(5)*y(5)+
     .x(6)*y(6)
        sx=x(1) + x(2) + x(3) + x(4) + x(5) + x(6)
        sy=y(1) + y(2) + y(3) + y(4) + y(5) + y(6)
        sx2=x(1)**2 + x(2)**2 + x(3)**2 + x(4)**2 + x(5)**2 +
     .x(6)**2
        ybar=sy/ael
        xbar=sx/ael
        bb1=(ael*sxy - sx*sy)/(ael*sx2 - sx**2)
        bb0=ybar - bb1*xbar
        xpvcl=bb0 + bb1*xgi

        write(51,525)(k,x(k),y(k),k=1,5)
525     format('from getpvcl--k=',i3,' x=',f7.2,' y=',f9.4)
        write(51,511)z,factor,bb1,bb0,xbar,ybar
511     format(/,'z=',f9.4,/,'Kf factor=',f9.5,/,
     .'bb1=',f12.4,'  bb0=',f12.4,/,
```

```
     .'xbar=',f8.2,' ybar=',f8.2,//)
        return
        end


c-----------------------------------------------------------------
c       SUBROUTINE getpvob
c-----------------------------------------------------------------
        subroutine getpvob(xkg,xgi,ttcob,xpvob)
c       Calculate an estimate of the fission power density
c       from the dependence of thermocouple temperature on
c       power density for the outboard thermocouple.
c       density and g_inc gap.
c       xkg=h451 thermal conductivity (W/cmK)
c       xgi=graphite-inconel gap (mils)
c       ttccl=temperature from outboard thermocouple.
c       xpvcl=fission power density (W/cc) based on TCcl
c       @kg=0.4184
        dimension x(6),y(6)
        z=xkg/0.4184

        obkg0=1.2689257
        obkg1=-0.458588
        obkg2=0.23400896
        obkg3=-0.044107
        factor=obkg0 + obkg1*z +obkg2*z**2 + obkg3*z**3

        ael=6           !number of elements or equations.
        x(1)=8.0
        x(2)=9.0
        x(3)=11.0
        x(4)=13.0
        x(5)=15.0
        x(6)=17.0

        a1=-121.277
        a2=-117.065
        a3=-125.991
        a4=-129.493
        a5=-133.255
        a6=-122.987

        b1=0.3259201
        b2=0.306758
        b3=0.2959225
        b4=0.2816201
        b5=0.2704825
        b6=0.246365

        y(1)=a1 + b1*ttcob/factor
        y(2)=a2 + b2*ttcob/factor
        y(3)=a3 + b3*ttcob/factor
        y(4)=a4 + b4*ttcob/factor
        y(5)=a5 + b5*ttcob/factor
        y(6)=a6 + b6*ttcob/factor

c       Least squares fit to (x,y)pairs to get Pv=f(g_inc)
        sxy=x(1)*y(1)+x(2)*y(2)+x(3)*y(3)+x(4)*y(4)+x(5)*y(5) +
     .x(6)*y(6)
```

```
      sx=x(1) + x(2) + x(3) + x(4) + x(5) + x(6)
      sy=y(1) + y(2) + y(3) + y(4) + y(5) + y(6)
      sx2=x(1)**2 + x(2)**2 + x(3)**2 + x(4)**2 + x(5)**2 +
     . x(6)**2

      ybar=sy/ael
      xbar=sx/ael
      bb1=(ael*sxy - sx*sy)/(ael*sx2 - sx**2)
      bb0=ybar - bb1*xbar
      xpvob=bb0 + bb1*xgi

      write(51,525)(k,x(k),y(k),k=1,5)
525   format('from getpvob--k=',i3,' x=',f7.2,' y=',f9.4)
      write(51,511)z,factor,bb1,bb0,xbar,ybar
511   format(/,'z=',f9.4,/,'Kf factor=',f9.5,/,
     .'bb1=',f12.4,'  bb0=',f12.4,/,
     .'xbar=',f8.2,' ybar=',f8.2)
      return
      end

c-----------------------------------------------------------------
c     Subroutine kf
c-----------------------------------------------------------------
      subroutine kf(xkf1,rfuel,nday,t4est)

c     nday=irradiation day for which fuel temp is being determined.
c     xkf1=thermal concuctivity of fuel to be passed back to
c     main.
c     rfuel=fuel compact radius to be passed back to main, used
c     to calculate fuel-graphite gap (xfg).

c     This subroutine will used the time evolution of
c     the fuel temperature and the fast fluence to calculate
c     the 'latest' fuel thermal conductivity.  Toward this end
c     the common block1 will pass the fluence and the fuel temp
c     arrays along with the fabrication radius of the fuel
c     compact.
c
c     This subroutine calculates the thermal conductivity of
c     the HTGR fuel as a function of the neutron fluence for
c     neutron energies > 29 fJ (181.25 keV) and fuel temperature.
c
c     It also calculates dimensional changes in the fuel compact
c     as a function of temperature and fluence.
c     Gary L. Bell, May 22, 1991.
      dimension tcond(2000),tmpk(2000),dayin(2000)
      real k1,k2,k10,k20,kappa,lambdat
      common/block1/fluence(2000),rffab,tmpc1(2000),npts,rgraph(2000),
     .iday(2000),ichange,h451k(2000),tmpob(2000),fueltemp(2000)

c-------------------------------------------------------------------
c     Stuff for fuel thermal conductivity calculation.
c     Properities of each compact.
c-------------------------------------------------------------------
      cw=0.067          !Coke weight fraction.
      sv=0.0735          !Shim volume fraction.
c-------------------------------------------------------------------
c     constants needed in calculation.
c-------------------------------------------------------------------
      w=6.0
```

```
      tau=0.5
      c1=-7.008326e-01
      c2= 1.091361e01
      c3=-9.103535e00
      c4= 5.334483e-03
      c5= 1.728523e01
      c6=-8.7609808e-3
      c7=-1.636312e01
      c8= 5.671053e00
      c9= 6.104872e01
      c10=2.361024e-2
      c11=-7.228171e-2

      alfa1=c1+c2*sv+c3*cw
      beta1=c5+c7*sv+c8*cw+c9*sv*sv
      alfa2=c4
      beta2=c6+c10*sv+c11*sv*sv
c-----------------------------------------------------------------------
c     Generate fuel temp array in kelvin.
c-----------------------------------------------------------------------
      temp=t4est
      fueltemp(nday)=temp
      do 43 m=1,nday
      tmpk(m)=fueltemp(m)+273.0    !Kelvin
43    continue
c-----------------------------------------------------------------------
c     calculate zero fluence fuel conductivity and compact radius.
c-----------------------------------------------------------------------
      if(nday.eq.1)then
      gamma=0.0
      k1=alfa1+beta1*exp(-1.0*tau*gamma)
      k2=alfa2+beta2*exp(-1.0*tau*gamma)
      lambdat=k1 + k2*tmpk(1)  !Kf (W/mK) day 0
      xkf1=lambdat/100.0   !change units to W/cmK.
      tcond(1)=lambdat
      t0=fueltemp(1)
      afuel=4.85e-6   !unirradiated coefficient of thermal expansion.
      rfuel=rffab*(1.0+afuel*(t0-25.0))   !day 0fuel radius at temp.
      rfday0=rfuel
      write(57,882)nday,fueltemp(1),fluence(1),xkf1,rfuel
      goto 30
      endif
c-----------------------------------------------------------------------
c     Stuff for volumetric change calculation.
c-----------------------------------------------------------------
      a1=-3.930e-01
      a2=-1.769e00
      a3=3.334e-01
      a4=-1.500e-02
      bb1=1.351e00
      b2=1.109e01
      b3=-2.263e00
      b4=1.221e-01
      d1=-5.556e-05
      d2=-8.678e-03
      d3=1.678e-03
      d4=-8.889e-05
c-----------------------------------------------------------------
c     Now use the fluence array and the temperature array
c     to calculate the thermal conductivity of the fuel and
```

```
c       the fuel compact radius.
c-----------------------------------------------------------------
        DO 20 j=2,nday
        gamma=fluence(j)
        gammap=fluence(j-1)
        deltagam=gamma-gammap
        k1=alfa1+beta1*exp(-1.0*tau*gamma)
        k2=alfa2+beta2*exp(-1.0*tau*gamma)

        k10=alfa1+beta1*exp(-1.0*tau*gammap)
        k20=alfa2+beta2*exp(-1.0*tau*gammap)

        kappa=k1 - (1.0/k20)*(k10*k2)
        lambdat=k1 + k2*tmpk(j)
        term1=kappa+(k2/k20)*tcond(j-1) - lambdat
        tcond1=lambdat + term1*exp(-1.0*w* deltagam)  !W/mK.
        tcond(j)=tcond1
        xkf1=tcond1/100.0   !change to (W/cm K).
c-----------------------------------------------------------------
c       Now calculate change in fuel volume.
c-----------------------------------------------------------------
        svt=sv*tmpk(j)
        dv1=a1+bb1*sv+d1*svt
        dv2=a2+b2*sv+d2*svt
        dv3=a3+b3*sv+d3*svt
        dv4=a4+b4*sv+d4*svt
        dvov=dv1 + dv2*gamma +
     .  dv3*(gamma**2) + dv4*(gamma**3)
c-----------------------------------------------------------------
c       Now Calculate change in fuel radius.
c-----------------------------------------------------------------
        deps=0.115*gamma
        dror=(1.0/3.0)*( dvov - deps)
        rfuel=rfday0*(1.0+dror/100.0)   !fuel radius at temp.
        write(57,882)j,fueltemp(j),fluence(j),xkf1,rfuel
882     format(i3,f12.2,e14.4,f12.5,f12.5)
20      continue        !end of fluence loop
30      continue
        return
        end



c-----------------------------------------------------------------
c       SUBROUTINE compare
c-----------------------------------------------------------------
        subroutine compare(t4est1,t4est0,dlim,decision)
        anum=abs(t4est1-t4est0)
        denom=0.5*(t4est1+t4est0)
        diff=100.0*anum/denom
        if(diff.le.dlim)decision=1.0
        if(diff.gt.dlim)decision=0.0
        write(*,671)t4est0,t4est1,diff
671     format(/,
     .'From compare-- T est old=',f8.2,/,
     .'T est new=',f8.2,/,
     .'diff (%)=',f8.2,/)
        return
        end
```

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