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MASTER

GENERAL ATOMIC

DIVISION OF **GENERAL DYNAMICS**

AEC RESEARCH AND
DEVELOPMENT REPORT

GA-6406

40-MW(E) PROTOTYPE HIGH-TEMPERATURE
GAS-COOLED REACTOR
POSTCONSTRUCTION RESEARCH AND DEVELOPMENT PROGRAM

QUARTERLY PROGRESS REPORT
FOR THE PERIOD ENDING
APRIL 30, 1965

Prepared under
Contract AT(04-3)-314
for the
San Francisco Operations Office
U.S. Atomic Energy Commission

May 31, 1965

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POSTCONSTRUCTION RESEARCH AND DEVELOPMENT PROGRAM

QUARTERLY REPORT SERIES

GA-5700—Summary Progress Report for the Period Ending July 31, 1964

GA-5924—August, 1964, through October, 1964

GA-6134—November, 1964, through January, 1965

I. INTRODUCTION

This report is the fourth in the series of quarterly progress reports describing work performed by General Atomic Division of General Dynamics Corporation on the Postconstruction Research and Development Program for the 40-Mw(e) HTGR power plant. This report describes the analyses that have been performed during the period, particularly those analyses centering around the zero-power phase of reactor operation. The reactor core with dummy graphite elements was accessible during the period, and results of neutron measurements made within the core are given. These results are part of those reported for test procedure AO-1. An up-to-date revision of test procedures to be performed during the zero-power phase of measurements is also included.

II. ZERO-POWER TESTS

INITIAL LOADING TO CRITICALITY (BP-1)

The possibility of placing the in-core detectors in the radial reflector, rather than in the core as described in GA-5924, has been investigated. The location of the detectors in the reflector would eliminate the need for moving both the detectors and the detector cables during loading to critical. The detector response in the reflector with a 60-curie Po-Bc source at the core center was calculated both with the GAPLSN transport theory code and the GAZE diffusion theory code. The approximate inverse multiplication (the ratio of the count rate with no fuel to the count rate with fuel) as predicted from calculations with the detectors in the radial reflector is given in Fig. 1. The "ideal" inverse multiplication (1-k) curve is also shown in this figure. Since the detectors are in a nearly constant spectrum region and the detectors are many mean-free paths from the source, the predicted inverse multiplication curve is much closer to the "ideal" curve than it is with detectors in the core (see Fig. 4 of GA-5924). The predicted count rate in the reflector with no fuel and one central 30-curie source is approximately 20 counts per second, which is sufficient to obtain good counting statistics within a reasonable period of time. Measurements in the dummy core have verified this predicted count rate.

An analysis has been performed to determine the reactivity associated with the known or anticipated uncertainties in the core that would alter the number of fuel elements required for initial criticality. The uncertainties included were cross sections and loadings of Th^{232} and U^{235} , graphite loading, and impurity concentrations. These anticipated uncertainties would indicate a reactivity uncertainty of $\pm 0.02 \Delta\rho$.

ISOTHERMAL TEMPERATURE COEFFICIENT (CP-1)

The reactivity change associated with heating the core and reflector uniformly to about 600°F (590°K) will be measured in Test CP-1. The effective multiplication for the fully loaded core has been calculated at different temperatures. It was assumed that 15 control rods (i. e., 6 in Ring 1, 6 in Ring 2, and 3 in Ring 3) are present in the core. The k-versus-temperature curve for different calculational models is shown in Fig. 2.

Fig. 1--Calculated curves of inverse multiplication and $1-k$ as functions of number of fuel elements loaded (detectors in radial reflector)

Fig. 2--Calculated curves of k -effective versus temperature for different energy group structures

The GGC-II code was used to generate temperature-dependent broad-group cross sections for three different group structures (see Table 1). At each of the five temperatures considered, the effective multiplication was determined with the multigroup diffusion code GAZE-2. The k values shown in Fig. 2 were normalized to 1.0 at 300°K. There is quite good agreement between the 5- and 10-group calculations. The 4-group structure gives a negative temperature coefficient of smaller absolute magnitude. This effect is not as marked in the unrodded condition. A careful analysis of the results indicates that the use of a single thermal group and the treatment of the reflector cross sections is responsible for the discrepancies.

Table 1
ENERGY GROUP STRUCTURES

Groups		Lower Energy Boundaries (ev)		
		10 Group	5 Group	4 Group
Fast	1	86500	86500	86500
	2	101	2.38	13.7
	3	13.7		2.38
	4	2.38		
Thermal	1	0.55	0.20	0.00
	2	0.20	0.04	
	3	0.09	0.00	
	4	0.04		
	5	0.015		
	6	0.00		

The presence of 15 control rods in the core increases the magnitude of the negative temperature coefficient ($1/k$) (dk/dt) by about 10% at 600°K (from $-6.2 \times 10^{-5} \Delta\rho/^\circ\text{C}$), whereas at room temperature there is much less change ($-7.5 \times 10^{-5} \Delta\rho/^\circ\text{C}$ to $-7.8 \times 10^{-5} \Delta\rho/^\circ\text{C}$). During the actual measurement of the temperature coefficient (CP-1), the number of control rods in the core will increase by approximately three with temperature. However, this should not affect the results, because the over-all effect on the temperature coefficient of the three additional control rods is less than $0.2 \times 10^{-5} \Delta\rho/^\circ\text{C}$.

CONTROL ROD CELL INVESTIGATIONS

In the prediction of the power distributions and rod worths in the Peach Bottom reactor, the control rods have been treated by using current-to-flux boundary conditions on rectangular nondiffusion regions

in the two-dimensional GAMBLE-IV diffusion code. The boundary conditions were obtained from the results of a cell calculation using the GAPLSN transport code. This GAPLSN rod cell calculation was performed for a cylindrical cell equal in volume to 1/36 of the Peach Bottom active core.

A series of GAZE one-dimensional and GAMBLE two-dimensional rod cells have been analyzed to determine the adequacy of this treatment of control rods, in particular:

1. The effect of the mesh point spacing used around the rod in diffusion cells.
2. The effect of the location where the boundary condition is applied (i. e., at the rod surface or at the outer radius of the guide tube).

Both unrodded and rodded cells were analyzed to determine how the predicted control swing was affected by variations in the parameters mentioned above. In all cases the GAPLSN predicted control swing was considered as the reference "correct" rod worth.

A diagram of the reference GAPLSN rod cell is shown in Fig. 3 for a control rod in which boron is 10 wt-% of the boron-carbon matrix. This rod is typical of those in the centermost ring in Peach Bottom. The GAZE cells were identical to the GAPLSN cell, except that the rod was accounted for by a boundary condition.

The GAMBLE cell used in the analysis is shown in Fig. 4. The GAMBLE is in X-Y geometry, and all regions making up the cell are rectangular. The solid lines represent the gross spacing cell configuration that was used in the prediction of the power distribution and rod worths in Peach Bottom.

The average mesh spacing near the rod in the gross spacing case is about 4.2 cm. In the fine spacing case, the spacing around the rod was about 0.5 cm. The GAZE cell was also analyzed with gross and fine spacing.

The calculated unrodded and rodded k_{eff} values for each of the rod cells analyzed are summarized in Table 2. Also given are the $\Delta\rho$ (unrodded to rodded) for each case and the percent error between the diffusion code $\Delta\rho$ and the "correct" reference GAPLSN $\Delta\rho$.

The GAMBLE two-dimensional rod worths are almost identical to the reference value for both the gross and the fine mesh spacing when the boundary condition is applied at the outer radius of the guide tube. The

REGION	OUTSIDE RADIUS (CM)	CELL VOLUME FRACTION
VOID	1.6637	0.00516
ROD	2.9337	0.01089
VOID	3.1750	0.00274
SLEEVE	4.4500	0.01813
CORE	23.159	0.96308

TEMP = 300°K
 10 NEUTRON GROUPS
 $P_1 - S_4$ SOLUTION
 69 MESH POINTS

SAME ROD CELL USED IN GAZE 1-D DIFFUSION CALCULATION

Fig. 3--Reference rod cell

Fig. 4--Two-dimensional rod cells

GAZE cell results are also very good, with the same fine mesh as used in the GAPLSN case, but the control swing is overpredicted by 14% when the gross (4.2 cm) mesh interval is used. It is also interesting to note that in both the one- and two-dimensional diffusion calculations the rod worth is overpredicted when the boundary condition is applied at the rod poison surface. A cell was also run with GAZE in which the rod was treated by disadvantage factors. This is Case 8 in Table 2, and it is seen that the predicted control swing is quite close to the correct value.

The power distributions with the control rod inserted in each of the cells are compared in Fig. 5. The GAPLSN power distribution was matched very well in those cases where the control swing matched. A mismatch approximately proportional to the error in the predicted control swing was found for the other cases.

It can be concluded that the method of analysis being used in the Peach Bottom core analysis (i. e., gross spacing around the rod in 2-dimensional GAMBLE IV calculations with current-to-flux boundary conditions at the guide tube) should yield an accurate prediction of both the control rod worth and resulting power distributions.

Table 2
PREDICTED CELL EIGENVALUES AND ROD WORTHS

Case No.	Code	Rodded	Mesh Spacing	Boundary ^a Condition	k_{eff}	$\Delta\rho_{rod}$	Percent Error $100 \left(\frac{\Delta\rho - \Delta\rho_{ref}}{\Delta\rho_{ref}} \right)$
1	GAPLSN 1-D	No	Fine		1.32939		
2	GAPLSN 1-D	Yes	Fine		1.05746	0.1934	0.0
3	GAZE 1-D	No	Gross		1.32565		
4	GAZE 1-D	No	Fine		1.32610		
5	GAZE 1-D	Yes	Fine	1	1.05249	0.1960	+1.3
6	GAZE 1-D	Yes	Gross	1	1.02520	0.2210	+14.3
7	GAZE 1-D	Yes	Fine	2	1.04368	0.2041	+5.5
8	GAZE 2-D ^b	Yes	Fine		1.05699	0.1918	-0.82
9	GAMBLE 2-D	No	Gross		1.32157		
10	GAMBLE 2-D	Yes	Gross	1	1.05194	0.1939	+0.26
11	GAMBLE 2-D	Yes	Gross	2	1.03290	0.2115	+9.4
12	GAMBLE 2-D	Yes	Fine	1	1.05476	0.1914	-1.0

^a1 Rodded boundary condition at outer radius of guide tube.

2 Rodded boundary condition at outer radius of rod poison.

^b Rod disadvantage factors used.

Fig. 5--Rodded cell power with fine and gross mesh

III. INDIVIDUAL TEST PROCEDURES

During the period, the detailed listing of the individual test procedures given in Appendix A of GA-5700 has been reviewed and an updated list of Phases A through C prepared. This list is given in Appendix A of this report. In this updated list some tests have been deleted because they produced data of marginal value or repeated routine operational tests. Other groups of tests have been combined under one test or procedure title. Additional updating of this list of tests will, of course, be required as the program proceeds.

IV. MEASUREMENTS, MATERIALS, AND INSTRUMENTATION

Access to the dummy core with air in the vessel was available for approximately two weeks during this period. This permitted the start of the loading of poisoned dummy elements and the checkout in the core with a neutron source of a large part of the equipment and in-core instrumentation that is to be used during the zero-power part of the Post-construction Research and Development Program. The results reported here are part of test AO-1.

During this period of core entry there was no fuel handling equipment on the nozzles and the core contained dry air. A dehumidifier was used to recirculate and keep the air in the core dry. All systems that could dump helium into the primary system were blocked. Core entry was achieved by means of a ladder in the access nozzle. The dummy core was covered with 2-in.-thick polyfoam and plastic wrapped plywood boards. All items going into the core were lowered through one of the nozzles by means of nylon rope. The Po-Be Source (approximately 25 curies) was placed in a specially made 6-ft-long aluminum wand.

The following tests and operations have been carried out in the dummy core:

1. Poisoned Dummy Installation. The removal of a graphite dummy element and the insertion of a poisoned dummy (containing a rod of boron-stainless steel) at 126 positions in the core was started. As of the end of April approximately 94 poisoned dummies have been placed in the core. This transfer was made by using the new fuel grapple (hand operated) on the jib crane through an open nozzle. The jib crane was modified to give it enough travel to reach to the top of the core.

2. Detector Checkout with Source in Core. All of the BF_3 detector probes (5/16 in. diameter and 6 or 12 ft long) have been checked out in the core using a Po-Be source. A Po-Be source was placed in the core at the midplane near the radial center of the core and the detector to be checked was placed about 8 in. away from the source in the tricuspid region between three elements. A voltage plateau (see Fig. 6) was obtained for each detector as well as a pulse height distribution (see Fig. 7) to determine amplifier and discriminator settings. All the detectors performed satisfactorily. This also provided a check of the electronics pre-amplifiers, amplifiers, discriminators, scalers, count rate circuits recorders, and multichannel analyzer and the first test of the installed cabling.

Fig. 6--Voltage plateau obtained with 12-ft-BF₃ detector

Fig 7--Pulse height distance obtained with BF₃ detector

A measurement was made to determine the count rate at the edge of the dummy core relative to that near the center with a source at the center. The sources to be used during fuel loading are expected to produce greater than 50 curies, or about twice that used in these experiments. Twenty-five poisoned dummy elements were in the core during these measurements as shown in Fig. 8.

With the source near the center, the count rate on a BF_3 detector (nominal sensitivity 0.1 CPS/nv) approximately 8 in. from the source was 2×10^3 cps, and at the core-reflector interface the count rate was 40 cps with many poisoned dummies intervening (see Fig. 8). The fact that this poison is not yet uniformly distributed (only about 1/5 complete) means these results are not easily interpretable, but do indicate a satisfactory count rate in the dummy core with a source at the center.

Several stability runs were made on the BF_3 detectors by measuring the count rate periodically over a period of 8 to 10 hr during the night; the stability was excellent. During the day there are still some transients on the line, primarily owing to construction activities.

The plant source range detectors and associated instrumentation were checked by placing the Po-Be source in an empty fuel location in the outer fuel row near the instrument well containing Channel II and III detectors. The source was 0.78×10^8 n/sec, and the count rate on Channel II and Channel III was approximately 10 cps with no water in the instrument well. Running the cadmium shield down over the detector reduced the count rate to approximately 0.5 cps, which is the nominal background with no source present.

3. Pulsed-neutron Source Check and Die-away Measurements on Dummy Core. The pulsed-neutron source has been checked out by using it to pulse the dummy core and determine the die-away with and without control rods inserted. At this stage, the dummy core contained 54 poisoned dummy elements distributed as shown in Fig. 9.

The pulsed-source head (a cylinder 4 in. in diameter by 27 in. long) was wrapped with 1-in.-thick polyfoam enclosed in a plastic bag and positioned horizontally on the top of the dummy core near the radial center. The interconnecting cables were run through an open nozzle to the pulsed source control unit on the refueling floor.

One of the BF_3 detector probes (5/16 in. diameter by 6 ft long) was positioned in a tricuspid coolant channel with the sensitive region approximately 2 ft above the midplane of the core and near the radial center. The Po-Be source that had been used for checking the operation of the BF_3 detectors was removed from the core. In this configuration the detector

Fig. 8--Fuel element positions with twenty-five poisoned dummy elements in the core

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- POISON DUMMIES, 54
- GRAPHITE DUMMIES, 748
- CONTROL RODS
- ⊠ EMERGENCY SHUTDOWN RODS

Fig. 9--Fuel element positions with fifty-four poisoned dummy elements during pulsed-neutron source check and die-away measurements

background with no source was approximately 10 counts/min for all pulse heights.

After some adjustment of parameters to obtain the correct operating pressure in the sealed accelerator tube (having been inactive approximately 4 months), the unit operated satisfactorily over a period of about 8 hr with many on-off cycles, and at pulse rates up to about 5 pulses per second.

The die-away of thermal neutrons in the dummy core was then measured using the in-core BF_3 detector and the pulsed-neutron logic mode of the TMC multichannel analyzer. The analyzer is started by a trigger signal from the pulsed-neutron control unit. A pulse repetition rate of around 2 to 3 pulses per second was used for most of the die-away measurements.

Figures 10, 11, and 12 show the results of measurements with and without control rods in the core. These data were obtained using only about 2000 neutron pulses each, and the statistical accuracy is not as good as would be used in a measurement in the fueled core. The partial distribution of poisoned dummy elements, which are concentrated in one half of the core, makes these results not useful for quantitative determinations, but does indicate that the equipment is functioning and will presumably be satisfactory for the measurements in the fueled core.

4. Steady-state Electronic Source Checkout. The steady-state electronic source has been satisfactorily checked out in the dummy core. This source, which is 2-1/2 in. in diameter by 12 in. long, was mounted in a 3.5-in.-diam aluminum tube and was put in the dummy core replacing a dummy element. A BF_3 detector was placed about 8 in. away in a tri-cuspid coolant channel. The counting rate on the BF_3 detector with the electronic source was compared with the counting rate with the Po-Be source (approximately 25 curies) at the same distance, and a yield for the electronic source determined to be near the design value of 10^8 neutrons per second. The source was operated satisfactorily for approximately 2 hr with several on-off cycles. The control console for this source sits on the refueling floor near the nozzle through which the electrical cables pass.

Fig. 10--Pulsed-neutron die-away: all rods inserted, 2001 pulses

Fig. 11--Pulsed-neutron die-away: hydraulically-operated rods in, emergency rods out, 1690 pulses

Fig. 12--Pulsed-neutron die-away: all rods out (except one outer rod), 1785 pulses

Appendix A

POSTCONSTRUCTION TESTINGPHASE A - Preloading

- (AO-1) Installation and checkout of core loading equipment

PHASE B - Cold Core Loading

- (BO-3) Flow tests (purge rate, core pressure drop, etc.)
 (BP-1) Initial loading to criticality
 (BP-4) Shutdown margin measurement - pulsed source
 (BP-5) Loading adjustment
 (BP-7) Excess reactivity measurement - distributed poison
 (BP-8) Power distribution measurement - unrodded
 (BP-9) Bank control rod worth measurement - pulsed source
 (BP-10) Power distribution measurements with control rods
 (BP-11) Differential control rod worth measurements
 (BP-12) Flux tilt measurements
 (BP-13) Outer bank control rod worth measurements - pulsed source
 (PB-14) Complete rod calibration
 (BP-15) Reactivity worth measurements
 (BP-16) Rod scram transient test
 (BP-17) Helium pressure coefficient
 (BP-18) Helium flow coefficient
 (BP-19) Noise analysis

PHASE C - Low-power Hot Testing (Circulator Heat with Helium in Primary Loop)

- (CE-1) Datum test of failed fuel element locator
 (CM-1) Loop chemistry and purification system confirmation test
 (CO-1) Flow tests, cold to hot (purge rate core pressure drop, helium pressure effects)
 (CP-1) Isothermal temperature coefficient
 (CP-2) Control rod calibration

Appendix B

PROJECT PERSONNEL

This postconstruction research and development program on the 40-Mw(e) prototype HTGR is being carried out by the following project personnel.

Anderson, E. E.
Bingham, B. A.
Brown, J. R.
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Fischer, P. U.
Goss, G. C.
Green, R. W.
Hopkins, G. R.
Lane, R. K.
Merrill, M. H.
Mowry, W. R.
Stewart, H. B.
Van Howe, K. R.
Wallace, W. P.
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