4-5 PREOPERATIONAL TEST EXPERIENCE WITH THE ARMY PULSE RADIATION FACILITY REACTOR

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ABSTRACT

This paper summarizes data obtained in preoperational tests of the Army Pulse Radiation Facility Reactor. During these tests a pulse with a yield of 6.09×10^{17} fissions was obtained, which is three times larger than the anticipated maximum operational yield. The center third of the safety block was melted. The centrally located fuel rings were distorted, and cracks have appeared between the holes and the inner diameter. The bolts were stretched and slightly bent but not broken. The pulse rod, regulating rod, and mass adjustment rod were slightly bent. Most of the U–10 wt% Mo fuel parts no longer meet the original specifications and must be replaced for pulse operation. There was little or no damage to rod drive, supports, etc., no overexposure to radiation of the operations personnel, and no detectable external or airborne radioactive hazards. A number of changes in design, instrumentation, and procedure are being made to place the reactor into full operation at levels of approximately 2×10^{17} fissions/pulse and 10 kw steady state.

This paper describes a preliminary analysis of preoperational tests performed on the Army Pulse Radiation Facility Reactor (APRFR) at the Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland. These tests started with core assembly on July 17, 1968, and ended with pulse 68-30, which produced a yield of 6.09×10^{17} fissions. The yield of this pulse was considerably larger than expected, and as a result the reactor core was damaged. There was no other damage to other parts of the reactor, no detectable external or airborne radiation hazards, and no overexposure of personnel to greater than normal occupational radiation levels.

The primary cause of this inadvertent high yield appears at present to be that the reactivity of the pulse rod passed through a maximum before reaching its seated position. An initiation occurred near this position so that a larger value of reactivity was effective rather than the expected and measured value at the seated position.

Under the section on reactor assembly and prepulse tests, prepulse calibration data are summarized and the assembly tested at APRFR is compared with the assembly tested at the Critical Experiment Facility (CEF) at Oak Ridge National Laboratory (ORNL). In this paper the initial pulse operation, including the maximum yield pulse and the postulated cause for the maximum pulse, are discussed, and a summary of reactor damage is given. The steps required to confirm the postulated cause of the maximum pulse and the steps required for resumption of APRFR operation are discussed under Conclusions. These steps are (1) replacement of damaged core parts; (2) performance of pulse-rod, regulating-rod, and mass-adjustment-rod calibrations at steady-state conditions to obtain data required to determine if the postulated cause can account quantitatively for all features of the excursion; and (3) changes in design, instrumentation, and operating procedures to permit operation of the APRFR with requisite safety at full-performance levels.

REACTOR ASSEMBLY AND PREPULSE TESTS

Initial Configuration

Reactor assembly for the preoperational tests was begun at APRF (Army Pulse Radiation Facility) in July 1968 following receipt of requisite safety approvals. Personnel involved included APRF staff and two specialists from ORNL.

Fuel rings were selected according to size and mass to achieve a critical core configuration with the thermocouple-instrumented fuel ring as close as possible to the center of the total core height. This is desirable since these thermocouples are used to monitor core temperatures which are maximum near the center of the core. Nine fuel bolts were each matched with an Inconel nut and lubricated with Molykote 505 to help assure free movement. The pulse rod, mass adjustment rod, regulating rod, and safety block were assembled. A number of nonfuel components are involved in the reactor assembly. These are listed in Table 1. The assembly is shown schematically in Fig. 1. Table 2 lists the approach-to-critical steps. The reactor first went critical at 1442 on July 24, 1968.

Following configuration E′ on July 24, 1968, core F was assembled with a measured core height of 20.09 cm. This configuration provided adequate control range on the regulating rod and mass adjustment rod and was the basic core used in all experiments during this part of the APRFR preoperational tests. Detailed information on core F fuel components is given in Table 3.

Table 1

NONFUEL COMPONENTS USED FOR APRFR CORE ASSEMBLY

Item	Number required
Core-support ring	1
Safety tube	1
Glory hole liner	1
Cooling shroud	1
Safety cage	1
Control-rod liners	3
Safety-block air deflector	1
Core bolt spacers, 19 mm (3/4 in.)	15
Core bolt spacers, 6.35 mm (1/4 in.)	9
Core bolt nuts	6
Safety-tube locking adaptors	3
Thermocouple inserts	4
Safety-block set screw	1
Regulating-rod adaptor	1
Mass-adjustment-rod adaptor	1
Pulse-rod adaptor	1
Several small pins and set screws	

Table 2

APPROACH-TO-CRITICAL CONFIGURATIONS OF APRFR

Core designation	Fuel alloy mass, kg	Core height, cm	Date	Time assembled
A	81.013	12.578	July 17	1500
B	100.797	15.771	July 19	1100
C	112.633	17.574	July 22	1500
D	118.410	18.463	July 23	1300
E	123.105	19.508	July 24	1000
E′	(Same as E plus safety shield and cooling shroud)			

Prepulse Calibrations

A number of differential regulating-rod and mass-adjustment-rod calibrations were performed. The maximum differential worth of the regulating rod was 5.22¢/cm (13.27¢/in.) and of the mass adjustment rod was 12.0¢/cm (30.5¢/in.). The pulse-rod worth was determined from delayed-critical measurements with pulse rod in and out. The reactivity worth of various components is summarized in Table 4. Differences between the APRFR and CEF data as listed in Table 4 are to be expected because of the slightly different core configuration at CEF, as discussed in the following:

Table 3

APRFR CORE F FUEL COMPONENTS

Components and serial numbers	Weight, kg	Height, cm	Total weight, kg
Fuel rings (9):			
7882-20-0115	5.760	1.272 (top of core)	
7881-99-0009	2.288	0.526	
7882-40-0109	8.637	1.933	
7881-21-0001	11.954	2.667	
7881-19-0003	10.416	2.229	
7882-18-0070	14.516	3.404	
7882-38-0062	8.465	1.895	
7881-17-0004	14.561	3.254	
7881-16-0007	12.272	2.753	
Subtotal	88.869	20.033	88.869
Bolts (9):			
7882-17-0064	1.845		
7882-17-0065	1.841		
7882-17-0067	1.849		
7882-17-0069	1.845		
7882-17-0072	1.845		
7882-17-0073	1.849		
7882-17-0074	1.850		
7882-17-0075	1.842		
7882-17-0076	1.844		
Subtotal	16.610		16.610
Rods:			
Pulse rod			
7882-17-0061	1.467		
Mass adjustment rod			
7881-26-0051	1.964		
Regulating rod			
7881-27-0052	0.753		
Safety block			
7882-22-0085	15.730		
Subtotal	19.914		19.914
		Subtotal	125.393
		Minus pulse rod	1.467
		TOTAL WEIGHT	123.926

Table 4

REACTIVITY WORTH OF REACTOR COMPONENTS

Component	Total worth, ¢	CEF measurement,[1] ¢
Regulating rod	75.5	72
Mass adjustment rod	172.4	168
Pulse rod	127.7	*
Glory hole liner	24.5	No data available
Safety tube†	22.5	55
Thermocouple inserts (4)	5.0	*
Cooling shroud and safety cage	154	148
Displacement-gauge mounting plate	Not present	49
Nitrogen can	2.0	*

*These are new components, and hence no CEF data are available.

†The safety tube was mounted farther away from the core because of the core nuts; hence, its worth was less at APRFR than at CEF.

Differences Between APRFR and CEF Assemblies

The various differences between the assemblies tested at CEF and APRFR can be divided into three broad categories.

DIFFERENCES IN AUXILIARY COMPONENTS. The basic purpose of the tests[1,2] at CEF was to determine the pulse capabilities of the assembly and to check out the controls and instrumentation. Thus the CEF tests were more in the nature of a physics experiment and calibration, plus check-out of instrumentation. The maximum pulse yield obtained at CEF was 3.7×10^{17} fissions, and the data indicated the reactor could be operated with a maximum yield of about 2.1×10^{17} fissions/pulse.

At APRFR the aim of the preoperational tests was to obtain an operational reactor in such a configuration that would be a useful facility for its mission, namely, the safe routine performance of high-yield pulses for radiation effects and other user-oriented experiments. The standard CEF pulse assembly was bare except for experimental equipment nearby; the standard APRFR assembly included cooling shroud, safety cage, safety tube, and glory hole liner as shown in Fig. 1.

At CEF core-displacement gauges and a mounting plate were used during pulse operation. These gauges were used to obtain core-displacement data by Sandia and White Sands Missile Range personnel.[3] At APRF these components were not used.

CHANGES IN REACTOR DESIGN RESULTING FROM CEF EXPERIENCE. One of the purposes of the CEF tests was to identify possible design improvements. A number of changes were thus made at ORNL. These are:

Core Bolting. In the CEF assembly the nine core bolts bolted into the bottom fuel plate. In the APRFR assembly the nine core bolts went through all fuel plates and were secured by Inconel nuts as shown in Fig. 1. This change was made as a result of core-disassembly difficulty following the tests at CEF.

Safety Block. In the CEF assembly the safety block started essentially at the top of the core. The safety block installed at APRFR had been shortened; it started 0.889 cm below the top of the core. This change was made to provide faster reactor shutdown upon withdrawal of the safety block. By moving the safety block down into the core, initial safety-block withdrawal results in a greater rate of reduction in reactivity than when it starts at the core surface.

Thermocouples. In the APRFR assembly the thermocouple holes and inserts in the center fuel plate were made larger but did not penetrate through the fuel to the central hole in the core, as they did in the CEF assembly, and the thermocouple inserts were strengthened. This change was made to eliminate the stress concentration at the thermocouples in place during design-yield pulse operation. During the tests at CEF, the fuel disks cracked at those locations, and the thermocouple inserts would tend to bounce out of the core during higher yield pulse operation.

Pulse Rod. At CEF four different pulse rods were used at different times:

Pulse rod No.	Outside diameter, cm	Length, cm	Enrichment, %	Dynamic worth, ¢
1	1.920	32.21	93.2	
2	1.920	25.40	93.2	97.5
3	2.007	30.48	97.8	
4	2.007	25.40	97.8	110.5

The high-enrichment rods were used to increase rod worth to produce the desired pulse yields. In general, pulse-rod worths at CEF were found to be lower than required for operation at design yield. For the APRFR core the pulse-rod diameter was therefore increased, but enrichment was kept at 93.2%. The pulse rod used at APRFR was 25.40 cm long, and it had an outside diameter of 2.10 cm. The uranium was 93.15% enriched in ^{235}U.

Core Plating. At CEF some fuel pieces were nickel plated and others aluminum-ion plated. All fuel pieces supplied to APRFR were aluminum-ion plated at ORNL because of the superior experience with aluminum-ion-plated fuel obtained at both CEF[4] and Sandia[5].

DIFFERENCES IN OVERALL REACTOR ENVIRONMENT. The APRFR was operated in a reactor building of light-metal construction and at a distance of 242.6 cm above the floor so that neutron room return was minimized. At CEF the experiments were carried out in a room completely shielded by thick concrete walls; but the core was removed from the walls, so the room-return effect was thought to be small. At both APRF and CEF, instrumentation was present above the core, which is thought to be the dominating room-return component.

Core Atmosphere and Cooling. At CEF the assembly was in air at room temperature, and cooling following a pulse was provided by a fan. At APRF cooling was provided by forced air flow; for higher yield pulses the core was kept in a dry-nitrogen atmosphere during a pulse to control stress-corrosion cracking, as indicated by research sponsored by the Ballistics Research Laboratories (BRL) at the University of Arizona.[6] A dry-nitrogen atmosphere is also used at the Sandia Pulsed Reactor on the basis of similar considerations.[7]

PULSE OPERATION

Initial Pulse Operation

Pulse operation was begun on Aug. 12, 1968. Personnel present included APRF staff as well as ORNL specialists. The characteristics of the reactor configuration used in this initial pulse operation are summarized in Table 5. Pulses 68-1 through 68-7 were of low yield

Table 5

CHARACTERISTICS OF REACTOR CONFIGURATION USED DURING INITIAL PULSE OPERATION

Configuration designation	F
Core height, cm	20.06
Safety-block height, cm	20.47
Pulse-rod length, cm	25.40
Pulse-rod diameter, cm	2.10
Pulse-rod enrichment, %	93.15
Pulse-rod mass, kg	1.467
Total fuel mass on assembly (including all rods), kg	125.393
Height of core center above floor, cm	242.6
Auxiliary components installed:	
Cooling shroud, safety cage, safety tube, glory hole liner, and nitrogen can	

and were used to check out the instrumentation. Pulse 68-7 was the first for which a core-temperature rise was observed. Eight more pulses were obtained in this series, culminating in pulse 68-17 with a yield of 12.6×10^{16} fissions. Another pulse, 68-18, had been scheduled but was not performed. From the data obtained from these pulses, it

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was determined that large negative reactivity adjustments of the order of -15¢ had to be made prior to each pulse to obtain the desired pulse yield.

It is desirable to attain the design yield by making a small reactivity adjustment. It was therefore determined that the pulse rod was too large and that its worth had to be reduced. This reduction in worth was accomplished by increasing the adaptor to reduce the length of the pulse rod in the core when fully seated. The pulse rod was a necessary assembly item; its length was to be determined during these tests. Based on pulse rod in vs. out measurements at delayed critical, the new pulse-rod worth was determined to be 110.3¢. This method of reducing pulse-rod worth is in error for pulse operation with the rod drive situated above the core since the rod will go through a reactivity maximum before reaching its fully seated position. Both configurations assembled for these tests were in error in this regard. The pulse rod went through a small reactivity maximum in the first configuration (core F) and through a larger maximum with the longer adaptor. With this new pulse-rod configuration, a new series of pulses was obtained. Pulse 68-19 was scheduled but not performed owing to delays with instrumentation calibrations. Pulses 68-20 through 68-22 were sub-prompt critical, whereas pulses 68-23 through 68-29 ranged in yield from 1.79×10^{16} fissions to 12.26×10^{16} fissions. The delayed critical prompt-neutron decay constant was about 0.60 μsec^{-1} compared with 0.55 μsec^{-1} at CEF. This pulse history failed to reveal that the pulse rod was going through a reactivity maximum before reaching its fully seated position. Pulse 68-29 was fired on Sept. 5, 1968. Its yield of 12.26×10^{16} fissions was satisfactorily close to the expected 13.3×10^{16} fissions. An assembly in which the pulse rod goes through a reactivity maximum before being fully seated can operate for some time without incident and apparently in a reproducible manner. Eventually a pulse will be initiated when the pulse rod has a reactivity worth that is higher than its value in the seated position, and a larger than expected yield will be obtained.

This situation apparently held for all pulses up to 68-30. The probability that the pulse would be initiated just as the pulse rod passed through its reactivity maximum depends upon a number of factors, including background source level, reactivity insertion rate, and total reactivity being added. In general, the probability that initiation will occur increases as reactivity rates and reactivity increase; therefore, as the APRFR assembly was being taken to its target yield of 2.1×10^{17} fissions, this probability increased sharply. The quantitative relations involved in this problem are currently being determined more closely in connection with a delayed-critical experiment at APRF.

Occurrence of Maximum Yield Pulse

Plans were made on the morning of Sept. 6, 1968, to fire pulse 68-30. A physical inspection of the reactor was made that morning; nothing unusual was noted. A new nitrogen bottle, which feeds the pneumatic supply for the neutron start-up source and pulse rod, was connected. It is also used to provide a nitrogen atmosphere immediately preceding and following a pulse. A heavy rain the evening before had caused some puddles on the reactor building floor but not close to the reactor.

The prepulse calibrations and preparations were being made under the direction of the ORNL reactor specialist and the APRFR reactor supervisor. As usual a delayed critical configuration was established as part of the pulse sequence, and no significant changes were observed since the previous pulse 68-29. A number of other APRFR personnel were in the control room, data-acquisition room, and the technical office of the control building.

According to the established procedures, the reactivity insertion step over the previous one should be about 0.5¢. The insertion was 8.05¢, which was 0.64¢ above the 7.41¢ of pulse 68-29. This increase was acceptable. From the extrapolation of previous pulse data, this increase should have produced a yield of 1.68×10^{17} fissions. The pulse occurred at 1058, and the following events were noted:

1. The pulse instrumentation went off scale: Thermocouple recorder on 1200°F scale, photodiode readout on oscilloscopes and tape.
2. A scaler used to measure the wait time between time zero on preburst timer and pulse signal from photodiode read 0.07415 sec. This is evidence that the pulse was initiated before being fully seated. The time required for the pulse rod to seat is about 0.09 sec.
3. The reactor assembly appeared intact as seen on the TV screens and had shaken only slightly following the pulse. However, a persistent glow was observed near where fuel pieces could be seen, namely, at the thermocouple holes and around the safety-tube holes near the scrammed safety block.
4. The safety block scrammed, and all other rods withdrew normally.
5. All scram circuits functioned.
6. Radiation levels were normal for a high-yield pulse.
7. The pulse rod "in" light did not activate. The safety-block magnet light did not go out even though the safety-block drive had gone down as it should have.

The core had been placed in a nitrogen atmosphere prior to the pulse. This was kept on trickle until 1114, when it was turned off to prevent the possible spread of contamination. The reactor cooling system was also left off to prevent the possible spread of contamination. The 1200°F thermocouple recorder came back on scale 23 min. after the pulse. The in-core thermocouple was apparently not significantly damaged. Radiation levels and the state of the reactor indicated that there was no danger of release of radioactivity and that the reactor was shutdown. First entry into the reactor building was made at 1234 by two members of the reactor operations staff and the health physicist. No water was near the core. The floor beneath the reactor had been covered with white absorbent paper. A sulfur pellet, exposed to determine yield, was retrieved at 1252. The core assembly machine was placed below the safety tube and core to prevent the core from falling to the ground in the event the core bolts were broken. (They were not.) The facility was secured at 1555.

Subsequent inspection showed no loosened or missing components on the reactor structure. The dry-nitrogen-gas supply was investigated; it showed no evidence of having been able to supply moisture.

Preliminary analysis showed that the yield was about 6×10^{17} fissions and that the initial period was about 10 μsec. The melting point of the fuel (1150°C) had been exceeded; thus the safety limit of the APRF technical specifications of 1000°C had been exceeded. The required notifications were made that afternoon by the facility supervisor.

Characteristics of Maximum Yield Pulse

The yield of pulse 68-30 was 6.09×10^{17} fissions as determined from a sulfur pellet. The initial period as taken from a scope trace was 9.1 μsec, giving an alpha of 11×10^4 sec^{-1}. The core reached the alloy melting point of 1150°C. Extrapolation from pulse width at half maximum vs. period data indicated a width of 26.5 μsec. The reactivity required to produce 6.09×10^{17} fissions was extrapolated from the existing yield vs. reactivity data to be about 18¢.

The results of inspection of the pulse rod after pulse 68-30 are shown in Fig. 2. If we assumed that the center of the black portion of the pulse rod was in the center of the core during the pulse, then the 25.40-cm-long rod was 1.70 cm above the top of the 20.09-cm-high core and ended 3.61 cm below the core at the time pulse 68-30 initiated.

The insertion time of the pulse rod was 90 msec. The pulse timer indicated that the pulse initiated 74.15 msec following insertion. The rod was therefore 15.85 msec from seating. The rod was 4.52 cm above its seated position, which is 8.18 cm below the bottom of the core. Therefore the bottom of the rod was 8.18 minus 4.52, or 3.66 cm, below the core, and the top was 1.65 cm above the top of the core. This is consistent with the data deduced in the previous paragraph.

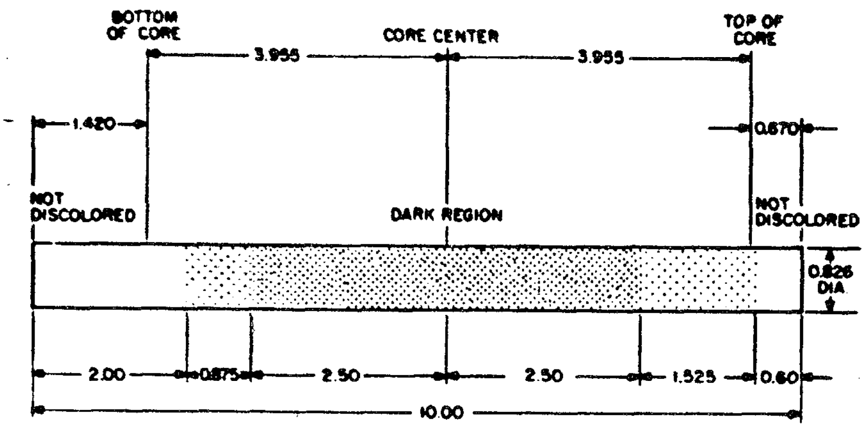

Fig. 2—Sketch of pulse-rod discoloration following pulse 68-30.

Table 6

REMOTE-AREA MONITOR READINGS FOLLOWING PULSE 68-30

Monitor	Dose rate 2 min. after pulse	Dose rate 10 min. after pulse	Dose rate 20 min. after pulse
Air-intake structure	750 mr/hr	80 mr/hr	18 mr/hr
Entrance to control building	70 mr/hr	10 mr/hr	1 mr/hr
Vestibule	None detectable		
Entrance to shielded access tunnel	0.4 mr/hr		
Control room	None detectable		
Instrument trailer room	None detectable		
Entrance to reactor building	None detectable		
Reactor building, near stairs	>100 r/hr	50 r/hr	25 r/hr
Outdoor test site	Not operating		
Reactor handling device	150 r/hr	50 r/hr	Fluctuating

Radiation levels were normal for a pulse of this yield, which is three times the projected maximum operational yield. The following data were obtained by the BRL health physics staff. Table 6 gives the dose rate measured by the 10 APRF remote-area monitors at various times after pulse 68-30. The measured dose rates and the way in which the dose rates decreased with time were normal for a pulse yielding 6×10^{17} fissions.

The APRF is bounded by a warning fence located at a radius of 1500 yd from the reactor. The total dose at this boundary due to pulse 68-30 was calculated to be 0.75 mrem; this is approximately three times greater than the dose expected from a normal pulse yielding 2×10^{17} fissions. The total of 0.75 mrem is the sum of the neutron and gamma dose delivered during the pulse (0.25 mrem) and a gamma dose (approximately 0.5 mrem) delivered after the pulse, due to the residual activity of the reactor core. The Aberdeen Proving Ground boundary nearest the location of the reactor is 0.9 miles to the northwest. The total dose at this point due to pulse 68-30 is calculated to be 0.67 mrem.

In the APRF control building a particulate air monitor draws a continuous sample from the return duct of the control building's fresh-air supply through a fixed particulate filter. This monitor showed no increase in air activity in the control building due to pulse 68-30.

In the APRF reactor building radioactive particulate matter is formed by neutron activation in the reactor building during operations. Continuous sampling of reactor-building air is accomplished via a hose that runs from the reactor building to a particulate air monitor located in the trailer tunnel of the control building. Immediately following pulse 68-30, this monitor indicated a rapid increase in air activity in the reactor room. The rate at which the activity increased and the level it reached were normal for a pulse yielding 6×10^{17} fissions. Approximately 50 min after pulse 68-30, a 24-min sample was cut from the filter of the particulate air monitor. Analysis of this sample indicated an air concentration of 1.4×10^{-7} $\mu c/cm^3$ for beta–gamma activity and 5.9×10^{-13} $\mu c/cm^3$ for alpha activity. A plot was made of activity vs. time which indicated that the beta–gamma activity was decaying with a 36-min half-life and the alpha activity with a 35-min half-life. Further analysis of this air sample indicated that long-lived alpha emitters were not present.

The stack monitor draws a continuous sample from the stack discharge through a particulate filter and charcoal–iodine trap. Analysis of the filter and charcoal indicated the presence of ^{131}I. Analysis of the charcoal indicated an average ^{131}I concentration of 7.8×10^{-10} $\mu c/cm^3$ in the 5-hr postpulse stack discharge, resulting in a release of 200 μc of ^{131}I to the environment.

No increase in air activity was measured at three continuous air monitors located 1.25, 5.9, and 12.2 miles from the APRF. Exposure of all personnel was kept within normal occupational levels. In summary, these preoperational tests of the APRFR, including the maximum yield pulse, have not significantly contributed to the ambient radioactivity levels in the APRF environment.

Effects of the pulse on the physical condition of the core and reactor components are summarized under Summary of Damage to Reactor.

ANALYSIS OF CAUSE OF MAXIMUM YIELD PULSE

Probable Cause of Maximum Yield Pulse

Analyses made to date indicate that the extra reactivity required to produce 6.09×10^{17} fissions was present because of the position of the pulse rod. The maximum reactivity worth of the pulse rod is obtained when this rod is positioned approximately symmetrically in the core. The reactor must be designed and operated such that the pulse rod does not go through a reactivity maximum as a function of time. This criterion was not met in either of the two reactor configurations assembled for these tests.

A postulated qualitative set of differential pulse-rod-worth curves is shown in Fig. 3. Lines A and B are the dynamic worths of the pulse

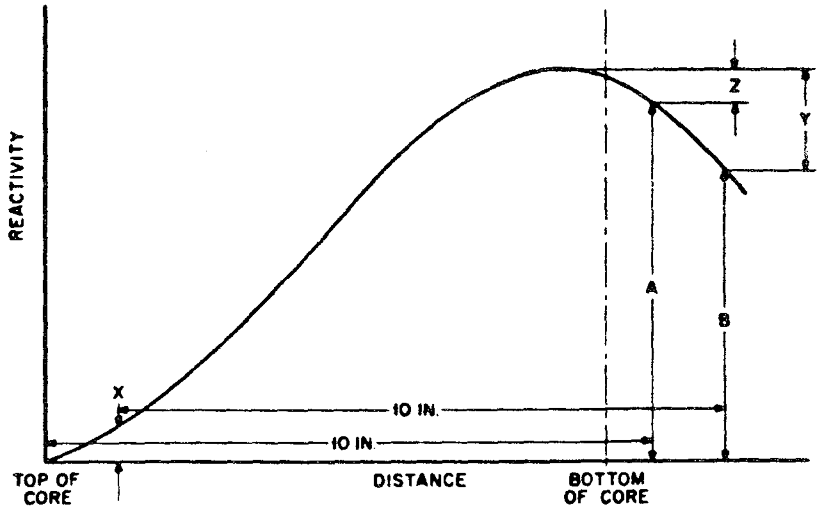

Fig. 3—Postulated differential pulse-rod reactivity curves. (Not to scale)

rod when fully seated for the two reactor configurations. For the first pulse-rod position the rod went through a maximum of z¢. A differential pulse-rod calibration is required for the exact geometry to determine z. An estimate for z is about 2¢ on the basis of CEF data. In this configuration a pulse would have been initiated before the pulse rod fully seated sooner or later, and an extra 2¢ at 2×10^{17} fissions would have resulted in $\sim 3.5 \times 10^{17}$ fissions. Moving the pulse rod down below the top of the core changed the position of the pulse-rod fuel relative to that of the core and reduced the pulse-rod worth by the amount x (2.88-cm steel vs. U–10 wt.% Mo). This caused the pulse rod to go through a larger maximum of magnitude y before being seated. These effects may well account for the extra reactivity required to produce the increase to 6.09×10^{17} fissions from the planned 1.68×10^{17} fissions for pulse 68-30, namely, ~10¢. The above model seems to explain the observed events; however, further measurements and analysis, including a critical experiment, are required to establish more firmly the exact quantitative relations involved in pulse 68-30.

Other Postulated Sources of Unplanned Reactivity Additions

A number of other possible causes for the maximum pulse were analyzed and rejected as not having been able to provide the necessary excess reactivity. The possible causes examined include

1. Dislocation of auxiliary component.
2. Dropping of mass adjustment rod or regulating rod during wait period.
3. Presence of foreign object.
4. Erroneous safety-block seating.
5. Water from nitrogen supply.
6. Error in prepulse control-rod settings.

SUMMARY OF DAMAGE TO REACTOR

The fuel pieces assembled for the reactor configuration existing for pulse 68-30 are listed in Table 3. Following pulse 68-30 the core was partially disassembled and inspected. Further inspection and detailed metallurgical examination of selected pieces are planned. Visual inspection to date has revealed no signs of further cracks or crack propagation owing to stress corrosion or other causes. The damage is summarized in the following paragraphs.

Fuel Rings

The condition of the fuel rings is summarized in Table 7. The three top and bottom rings showed only small damage. The four rings fused together at the inside diameter could probably be separated without much difficulty, but this has not been attempted since these rings are being used in a critical experiment.

Bolts

All bolts showed only very slight dimensional changes and no visible cracks; they came out easily following pulse 68-30 in contrast with the experience at CEF where considerable difficulty was experienced in removing bolts which had bound together in the bottom ring. The condition of the bolts is summarized in Table 8. The present

Table 7

CONDITION OF FUEL RINGS FOLLOWING PULSE 68-30

Fuel-ring serial number	Height, cm	Weight,* kg	Condition
7882-20-0115	1.272†	5.760	No visible cracks, slightly warped; bottom inside diameter slightly charred.
7881-99-0009	0.526	2.288	No visible cracks, charred inside diameter.
7882-40-0109	1.933	8.637	No visible cracks, charred inside diameter.
7881-21-0001	2.667	11.954	Spalling around inside diameter.
7881-19-0003	2.329	10.416	Cracks visible between each bolt and rod hole to the inside diameter of top three plates; no visible cracks on outside; inside of plates charred and fused together.
7882-18-0070	3.404	14.516	
7882-38-0062	1.895	8.465	
7881-17-0004	3.254	14.561	
7881-16-0007	2.753	12.272	No visible cracks, slightly warped; top inside diameter slightly charred.
Total	20.033	88.869	

*Prepulse data.
†Top of core.

Table 8

CONDITION OF FUEL BOLTS FOLLOWING PULSE 68-30

Bolt serial number	Weight,* kg	Necked,† mm	Elongation,† mm
7882-17-0064	1.845	0.2	3.0
7882-17-0065	1.841	0.3	3.7
7882-17-0067	1.849	0.4	3.1
7882-17-0069	1.845	0.2	3.3
7882-17-0072	1.845	0.3	3.0
7882-17-0073	1.849	0.4	3.5
7882-17-0074	1.850	0.5	3.7
7882-17-0075	1.842	0.6	3.1
7882-17-0076	1.844	0.2	3.8
Total	16.610		

*Prepulse measurement.
†Average measurement as compared with drawings.

experience shows the advantage of the present nut-and-bolt design compared with the earlier assembly of screwing the bolts into the bottom ring.

Control Elements

The safety block melted at the hot spot, and it showed gross material deformation. The regulating rod and the mass adjustment rod showed bows of 0.6 and 0.2 mm, respectively; the pulse rod bowed 2.1 mm.

Auxiliary Components

The control-rod liners, the safety-block hanger, and thermocouple inserts will be replaced. It is expected that the safety tube will be modified. It is planned to replace the core-support ring and three core-support rods even though these show no visible damage (these are inexpensive items). All rod drives appear to be undamaged.

CONCLUSIONS

The high-yield pulse of Sept. 6, 1968, having a yield three times larger than authorized, did not result in any detectable external or airborne radiation hazards, nor did it cause any overexposures of any personnel. Damage was essentially limited to fuel pieces, and damage to the reactor in general is small.

The efficient and timely implementation of the facility emergency procedures proved that the procedures were well organized and effective and the operations and health physics personnel well trained. The APRF staff quickly evaluated the situation and did not overreact. No emergency equipment or off-site personnel were called to the scene since none were required. A number of actions are presently in progress to make the APRFR fully operational.

Measurements at Delayed Critical To Establish Reactivity in Core at Time of Pulse 68-30

For confirming the hypothesis that the pulse-rod positioning caused the maximum pulse and for determining more accurately the reactivity in the core for pulse 68-30, a number of calibrations at delayed critical are required.

Differential-rod-worth curves will be obtained on all rods—pulse rod, regulating rod, and mass adjustment rod. The regulating-rod and mass-adjustment rod curves will be used as base-line measurements to compare with existing curves. The pulse-rod curves, using several adaptors, will be used to determine the reactivity maxima. Core F has been reassembled to check physical compatibility of all parts, and this critical experiment can be performed with the present damaged core, provided another safety block is used. The safety block used during the experiments at CEF is available for this purpose. The reactor will, of course, not be pulsed during these measurements at and near delayed critical.

Repair of Core

As discussed in the preceding section, all used fuel pieces will be shipped to ORNL for inspection, remachining, or replacement as required.

Inspection of Reactor System

A complete inspection of the mechanical and electronic reactor system is being made. Studies are under way to investigate position reproducibility of all moving parts and their reactivity effects. Additions and modifications to instrumentation, including reactivity and core-temperature measurement channels, are being considered.

Design and Operation Modifications

The reactor design and operation are being modified so that pulse-rod motion as well as all other rod motions will always result in monotonically increasing reactivity as a function of time. Changes are being considered which would facilitate pulse-rod differential calibrations and improve reproducibility of other components, such as the safety block. The environmental control of the core and its instrumentation is being examined; different auxiliary components, such as cooling shroud, safety cage, safety tube, and nitrogen, will be integrated into one system.

Technical Report

A technical report will be issued following completion of all data analysis including completion of the critical experiment discussed previously.

In summary, operation of the APRFR to date has shown the basic soundness of the overall core design and mechanical systems. The reactor behaved considerably better than might be expected at a performance level well above current routine limits. On the other hand, a number of modifications in design, instrumentation, and operating procedures are clearly necessary. These will be described in detail once they are finalized and implemented.

ACKNOWLE

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REFERENC

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DISCUSSION

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REFERENCES

1. J. T. Mihalczo, Static and Dynamic Measurements with the Army Pulse Radiation Facility Reactor, USAEC Report ORNL-TM-2330, Oak Ridge National Laboratory, June 1969.
2. J. T. Mihalczo, J. J. Lynn, J. E. Watson, R. W. Dickinson, Super-prompt Critical Behavior of a Uranium–Molybdenum Assembly, *Trans. Amer. Nucl. Soc.*, 10: 611 (November 1967).
3. J. A. Reuscher and J. M. Richter, Dynamic Mechanical Measurements on the Army Pulse Reactor, *Trans. Amer. Nucl. Soc.*, *10*: 612 (November 1967).
4. M. I. Lundin, A. P. Litman, and W. J. Leonard, Design and Metallurgical Aspects of the Army Pulse Radiation Facility Reactor, *Trans. Amer. Nucl. Soc.*, 10: 609 (November 1967).
5. P. D. O'Brien, SPR II: Early Operational Experience, USAEC Report SC-DR-67-801, Sandia Corporation, October 1967.
6. S. A. Hoenig and H. Sulsona, A Field Emission Microscope Investigation of the Effects of Ambient Atmosphere on the Stress-Corrosion Cracking of Uranium–Molybdenum Alloys, U. S. Army Technical Ballistics Laboratory, Ballistics Research Laboratory, Aberdeen Proving Ground, Aberdeen, Maryland (Mar. 9, 1968).
7. R. L. Coats and P. D. O'Brien, Pulse Characteristics of Sandia Pulsed Reactor II, *Trans. Amer. Nucl. Soc.*, 11: 219 (June 1968).

DISCUSSION

WILSON: Did you not make any calculations of the worth of the burst rod as a function of position prior to the operation of the reactor?

KAZI: Measurements were made of total-in and total-out reactivity worth at delayed critical.

ZITEK: You indicated that the previous bursts gave 12.3×10^{16} vs. 13.3×10^{16} fissions predicted according to a curve. What was that curve?

KAZI: The curve, for example, of the temperature vs. reactivity, where the temperature is proportional to yield or something like sulfur yield. The main curve we were using was yield vs. reactivity insertion. The previous history did not give any clue that we were going through a reactivity maximum simply because all the pulses initiated a couple of hundred milliseconds after the pulse rod was fully inserted. So this is really a case where the past history to that point gave no indication that we were running through this maximum; the only way that can be picked up is through previous calibrations.