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THE EFFECTS OF BURNUP ON FUEL FAILURE

POWER BURST TESTS ON FUEL RODS WITH 13,000 AND 32,000 MWd/MTU BURNUP

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THE EFFECTS OF BURNUP ON FUEL FAILURE

Power Burst Tests on Fuel Rods with
13,000 and 32,000 MWd/MTU Burnup

R. W. Miller

AEROJET NUCLEAR COMPANY

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ABSTRACT

This report presents results from preliminary tests designed to investigate the behavior of preirradiated fuel rods under reactivity initiated accident (RIA) conditions. The tests were conducted in 1970 as part of the SPERT/Capsule Driver Core (CDC) program. The report was intended to be published in a series of Idaho Nuclear Corporation Interim Technical Reports (IN-ITRs); however, the CDC program was terminated before the report could be released. In September 1975, the Nuclear Regulatory Commission concluded that the data contained in the report could be a valuable reference in planning future water reactor safety program tests and requested its release.

SUMMARY

This report discusses salient results of an experimental program established to determine the effects of burnup on the behavior of nuclear fuels during transient overpower accidents. The program initially specified tests on fuel rods with burnups ranging up to 45,000 MWd/MTU. Four tests in the program, two at about 13,000 and two at about 32,000 MWd/MTU, are discussed in this report. The remainder of the tests will not be performed due to termination of the program. The results of these tests indicated that burnup caused both a change in the mode of failure from passive meltdown (as found with unirradiated fuel) to cladding rupture, and a reduction in the energy necessary to induce failure. These results tend to support similar conclusions reached after earlier tests^[1] on fuel rods with very low burnups.

In one test of a fuel rod with 32,000 MWd/MTU, rupture occurred after the rod had received only 85 cal/g-UO₂. Failure of the rod was characterized by three separate longitudinal cracks, which together extended the full active length of the rod, and one ruptured blister.

It is concluded (from the tests reported here and in previous reports of this program) that evidence has been found in these few tests of a significant reduction in failure threshold arising from the ordinary burnup process in UO₂ fuel rods. The mechanisms responsible for this phenomenon were not established by the tests but are consistent with several known physical and metallurgical changes arising from burnup including fuel swelling and cladding embrittlement which in turn give rise to strong fuel-cladding interactions during the test power transient.

The low energy levels at which fuel rod failures were found, viz, 147 and 85 cal/g, were also considered important. Although it is recognized that these tests were initiated under ambient temperature and pressure conditions considerably different from power reactor conditions, these differences are not expected to change the observed failure behavior markedly.

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THE EFFECTS OF BURNUP ON FUEL FAILURE

I. INTRODUCTION

This report presents the results of a group of tests of irradiated BWR-type fuel rods subjected to power bursts simulating reactivity-initiated accidents. Details of the program were described in a companion document^[1] previously issued, as were the method and equipment, and therefore those details are not repeated here. Some results of these tests have been published previously^[24].

The present testing effort on irradiated fuels is part of the Subassembly Testing Program^[2] which was designed to obtain safety-related information about reactor accidents characterized by overpower, such as the reactivity-initiated accident. Thresholds, consequences, and modes of fuel rod failure were the specific objectives of the tests which usually involved a single fuel rod immersed in water in a flux trap of the Spert IV Capsule Driver Core (CDC). The information obtained from these tests will be ultimately incorporated in theoretical models of reactor accidents.

Due to the high cost and long time involved in preirradiation of fuel rods, most of the tests in the Subassembly Testing Program have used fresh fuel^[3,18]. The present small effort to test the effects of burnup on fuel rod responses was initially planned to include twelve fuel rods irradiated in the P-7 loop in Engineering Test Reactor (ETR) to burnups between 10,000 and 45,000 MWd/MTU representative of current design discharge burnups. (Also see appendix.) Difficulty encountered in the preirradiation of a first group of fuel rods led to premature discharge from the reactor. Six of these fuel rods^[1] were subsequently included in the program although they had very low burnups.

A full complement of twelve fuel rods was irradiated to the prescribed terminal burnups, but only the four rods reported here have been tested. The remaining eight fuel rods are in storage and will not be tested due to termination of the program.

Fuel rods used for these tests were designed as a scaled-down version of standard BWR-5 type fuel rods. The design is shown in Figure 1. Except for dimensions, enrichment, and the inclusion of an iron core for differential transformer instrumentation, these rods were fabricated by typical BWR-5 processes and to existing standards by General Electric. They are designated as "GEX" (General Electric Experimental) and further details of the fuel rod design, quality assurance, and assembly processes are found in Reference 1.

It was judged important that the irradiation conditions surrounding the rods be typical of BWR service since several in-service factors including fragment damage, pH, oxygen concentration, and temperature are known to have effects upon the properties of zircaloy-2. Most of these conditions were provided in a loop in the ETR. The irradiations were carried out in the loop with typical BWR thermodynamic and nuclear conditions, except for a slightly lower fast-to-thermal flux ratio (between 0.15 and 0.20). Additional details of the loop are found in the appendix and in Reference 1.

Fig. 1 Schematic of GEX fuel rod showing construction details.

Section II of this report briefly describes the salient details of each individual test including: the irradiation history of each rod; the past irradiation condition of each rod (usually as determined by visual examination and neutron radiography); essential details of the CDC test; and finally the posttest condition of the rod.

Conclusions from each test and from the overall test program along with implications of those conclusions in the field of reactor safety, are found in Section III. Much of the data obtained from the tests (viz, rod growth, fuel stack growth, and internal gas pressure) has not been fully evaluated and important metallurgical analyses have not been performed. When available, this information should be valuable to the study of thermal fuel behavior.

II. EXPERIMENTAL RESULTS

Table I summarizes test conditions for the four tests conducted in this group.

TABLE I

TEST CONDITION SUMMARY

CDC Test No.	Rod Type	Average Burnup (MWd/MTU)	Fast Neutron Fluence (> 1 MeV)	Test Energy Deposition (cal/g-UO ₂)	Burst Half Width (msec)	UO ₂ Temperature Rise[a] (°C)
685	GEX	13,100	1.2×10^{20}	186	27	2,260
684	GEX	12,900	1.1×10^{20}	200	20	2,400
756	GEX	32,700	2.7×10^{20}	176	17	2,400
859	GEX	31,800	2.7×10^{20}	190	16	2,500

[a] Reference GEMP-578 for UO₂ specific heat.

1. TEST 685; GEX ROD; 13,100 MWd/MTU; 186 cal/g-UO₂

1.1 The Fuel Rod

Fuel rod SE-31 received an average burnup of 13,000 MWd/MTU. The rod was under irradiation for 98 days during which its time-averaged linear power was 12.6 kW/ft and its maximum linear power was 17.3 kW/ft. A peak-to-average flux distribution of 1.07 over the

length of the rod indicates that the hot-spot of the rod reached 18.5 kW/ft. All power and burnup values are $\pm 10\%$. Fast neutron (>1 MeV) exposure to the cladding was approximately 1.2×10^{20} nvt.

A neutron radiograph of the rod taken after the preirradiation (and before testing) revealed centerholing throughout the 5.2-inch active length and most predominant at the hottest end. The pellets were cracked in several places but were otherwise intact. Externally, the fuel rod showed slight corrosion and no other detrimental effects from the preirradiation. No swelling or abrasions were found.

Approximately 20 days elapsed after preirradiation was terminated before the test was conducted.

1.2 The CDC Test

The fuel rod was subjected to a 5.75-millisecond-period transient in the CDC which deposited a maximum of 186 cal/g- UO_2 energy in the rod.

Figures 2 and 3 illustrate the power burst and the other recorded data taken during the test.

1.3 Test Results

The fuel rod, shown in Figure 4, survived the test without failing and without visible evidence of swelling or other damage. Slight permanent growth (< 0.020 inch) along the axis of the fuel is indicated. Destructive analysis and neutrography have not been completed.

Figure 2 shows the recorded pressure as measured at the bottom of the capsule. The data exhibit pressure oscillations peaking at ~ 75 psig which are known to result from water oscillations in the capsule.

A leak test (nitrogen-alcohol) was performed on the rod and no evidence of failure was found. From analysis of hydrogen, it was determined that only about 0.05% of the cladding was consumed in metal-water reaction. Mechanical energy converted from thermal energy was too low to be detectable.

In summary, the total response of the rod was favorable with no visible evidence of swelling or leakage being noted.

Fig. 2 Test 685 data on 10 msec/division scale.

Fig. 3 Test 685 data on 100 msec/division scale.

Fig. 4 Three views of fuel rod SE-31 after exposure to test — Test 685. (composite photographs).

2. TEST 684; GEX ROD; 12,900 MWd/MTU; 200 cal/g

2.1 The Fuel Rod

Fuel rod SE-32 received an average burnup of 12,900 MWd/MTU. The rod was under irradiation for 98 days during which its time-averaged linear power was 12.5 kW/ft and its maximum linear power was 17.3 kW/ft. A peak-to-average flux ratio of 1.07 along the length of the rod indicates a hot-spot maximum power of 18.5 kW/ft. All powers and burnup values are $\pm 10\%$. Fast neutron (> 1 MeV) exposure to the cladding was approximately 1.1×10^{20} nvt.

Neutron radiography of the rod indicated that centerholing was present over the entire active length and predominant at the hottest end. Pellet fractures were also evident. Externally, the rod appeared to be in excellent condition with only slight corrosion and no visible swelling or wear.

After preirradiation was complete, a period of 14 days elapsed before the rod was tested.

2.2 The CDC Test

The test consisted of a 5.12-millisecond-period transient in the CDC which deposited a maximum of 200 cal/g- UO_2 energy.

Figures 5 and 6 show the power burst and the other recorded data taken during the test.

2.3 Test Results

The fuel rod, shown in Figure 7, survived the test without failure. Slight diametral swelling, $< 5\%$, was observed to be unevenly distributed over the active length. Slight scorching was also evident.

The recorded data indicate that the dynamic axial growth of the fuel reached about 44 mils or slightly less than 1%. The posttest neutrograph indicates the existence of several small gaps in the fuel column, indicating that the fuel has seized the cladding; otherwise, the spring would have caused the gaps to close.

The recorded pressure data again indicate the occurrence of water column bounce leading to pressure peaks up to about 75 psig. Mechanical energy, however, was too low to be detectable. A metal-water reaction of only 0.14% was measured by hydrogen analysis.

A small quantity of fission products was detected in the capsule indicating either that the fuel rod had failed or that the capsule had been slightly contaminated from previous tests. A nitrogen-alcohol leak test failed to show any indication of a leak in the fuel rod, and it was therefore concluded that the fission products detected were due to capsule contamination.

Fig. 5 Test 684 data on 10 msec/division scale.

Fig. 6 Test 684 data on 100 msec/division scale.

Fig 7 Three views of fuel rod SE-32 after exposure to test — Test 684 (composite photographs).

In summary, the total response of the rod to this test was favorable and no indications of incipient failure could be found.

3. TEST 756; GEX ROD; 32,700 MWd/MTU; 176 cal/g

3.1 The Fuel Rod

Fuel rod SE-30 received an average burnup of 32,700 MWd/MTU. The rod was under irradiation for 216 days during which its time-averaged linear power was 14.3 kW/ft and its maximum linear power was 18.1 kW/ft. If a peak-to-average flux ratio of 1.04 along the length of the rod is taken into account, the hotspot linear power would have reached 18.8 kW/ft. Power levels and burnups are all subject to 10% uncertainty. Fast neutron (> 1 MeV) exposure to the cladding was approximately 2.7×10^{20} nvt.

A neutron radiograph could not be obtained for this fuel rod due to nonavailability of the neutrograph facility during the period between preirradiation and testing. However, the irradiation history of this rod was nearly identical with rod No. SE-33 (Test No. 859), which was neutrographed, and a comparison is probably valid. Rod No. SE-33 displayed slight centerholing over the active length and typically three or four visible fractures per pellet.

After preirradiation was complete, a period of 13 days elapsed before the rod was tested.

Visually, the rod appeared to be in good condition, but exhibited more corrosion than any of the previous rods. The corrosion increased the measured diameter of the rod by about 0.005 inch and occurred over the active length of the cladding only.

3.2 The CDC Test

The test consisted of a 4.42-millisecond-period transient in the CDC, which deposited a maximum of 176 cal/g- UO_2 energy in the fuel. Figures 8, 9, and 10 show the power burst and other recorded data taken during this test.

3.3 Test Results

Although fission products were not observed to escape from the fuel rod, which is shown in Figure 11, failure in the form of a tiny split in the cladding was noted (see Figure 12). The split is about 0.060 inch long and has not (at this writing) been studied directly by metallurgical sectioning to determine depth.

Fig. 8 Test 756 data on 10 msec/division scale.

Fig. 9 Test 756 data on 100 msec/division scale.

Fig. 10 Test 756 data on 1 sec/division scale.

Diametral swelling of the rod had a measured maximum of about 3% over the active cladding. Permanent axial growths of nearly 0.050 inch were observed for both the cladding and the fuel column (see Figure 10).

Although water column bounce is evident from the pressure data, Figures 8 and 9, mechanical energy, converted from thermal energy, was too low to be detected. Pressure pulses were moderate, however, reaching over 150 psig in several cases.

A metal-water reaction was also measured at $< 1\%$ as determined by hydrogen analysis.

In summary, the rod initiated a fracture as a result of this test, but the failure was minor and fission products did not escape.

Fig. 11 Two views of fuel rod SE-30 after exposure to test — Test 756 (composite photographs).

Fig. 12 Section of fuel rod SE-30 showing surface fracture (X8.5) – Test 756.

4. TEST 859; GEX ROD; 31,800 MWd/MTU; 190 cal/g

4.1 The Fuel Rod

Fuel rod SE-33 received an average burnup of 31,800 MWd/MTU. The rod was under irradiation for 216 days during which its average linear power was 13.9 kW/ft and its maximum linear power was 18.1 kW/ft. A hot-spot factor of 1.04 raised the linear power to 18.8 kW/ft over a short section of the rod. All power and burnup figures are $\pm 10\%$. Fast neutron (< 1 MeV) exposure to the cladding was about 2.7×10^{20} nvt.

A neutrograph of the rod taken after the preirradiation indicated slight centerholing over the entire active length and several visible fractures (typically three to four) per pellet.

Appearance of the rod was identical to the preceding rod (SE-30) and indicated corrosion buildup over the active length.

As in all cases, this rod was carefully inspected before preirradiation and again after preirradiation by magnifying periscope in a hot cell prior to testing. No evidence in either inspection was found to indicate a substandard condition of the rod.

4.2 The CDC Test

The fuel rod was placed in a capsule containing room-temperature water under stagnant, atmospheric pressure conditions and subjected to a 3.94-millisecond-period transient in the CDC. The maximum energy deposition during the test was 190 cal/g-UO₂. Figures 13, 14, and 15 show the power burst and other recorded data taken during the test.

4.3 Test Results

The rod failed early in the transient when only about 85 cal/g-UO₂ had been deposited. The time of failure is indicated clearly in Figure 13 by the sudden rise of capsule pressure as well as by disturbance of the signals from the cladding and fuel growth transducers.

The rod is shown in Figures 16, 17, 18, and 19. Four independent failures were found: three fractures, which together extend over most of the active length of the rod, and one ruptured blister.

Fig. 13 Test 859 data on 10 msec/division scale.

Fig. 14 Test 859 data on 100 msec/division scale.

Fig. 15 Test 859 data on 1 sec/division scale.

Fig 16. Fuel rod SE-33 after exposure to 190 cal/g test – Test 850 (composite photograph). Three fractures are visible and extend along most of the active length. (X1)

Fig. 17 Enlarged view of fracture #1 on fuel rod SE-33 (photographs join at arrows) showing detail of fracture edge. Fuel shows inside fracture and corrosion can be seen on cladding — Test 859. (X6)

Fig. 18 Enlarged view of fractures #2 and #3 on fuel rod SE-33, showing material bridge separating the two fractures. End of fracture #1 shows at lower left - Test 859. (X6)

X 7.2

X 6.0

Fig. 19 Two enlarged views of a ruptured blister, failure #4 of fuel rod SE-33 - Test 859.

Failure was accompanied by a multipulse pressure pulse which reached about 70 psig maximum. Sufficient energy was released to cause the water column above the fuel rod to reach a maximum velocity of 5 ft/sec. It was determined that a nuclear-to-mechanical energy conversion of about 0.014% took place. Less than 1% of the active cladding was consumed in a metal-water reaction. Very little fuel was lost through the cracks into the capsule.

Metallurgical examination of the rod was not performed due to termination of the program.

III. CONCLUSIONS

This report presents preliminary results of four power-burst tests on fuel rods with elevated burnups ($\sim 13,000$ to $\sim 32,000$ MWd/MTU). Although additional tests were originally planned (and the fuel rods were subjected to the prescribed burnups), the program has been terminated, and the tests described in this report cannot at this time be corroborated by additional experiments. The reproducibility and variance in test data thus remain uncertainties. It is possible, nevertheless, to reach some important conclusions from the data of these four tests and four tests on GEX fuel rods with low burnup ($< 5,000$ MWd/MTU) previously reported^[1].

The conclusions of Reference 1 were, briefly: (a) that the burnup experience brought about a distinct change in the mode of failure for the rods, from passive meltdown of the cladding to a form of cladding rupture induced by internal pressures; and (b) that the threshold of failure (223 cal/g- UO_2 for fresh fuel rods) was reduced by the burnup experience, as evidenced by a failure found at only 147 cal/g- UO_2 .

A third implication from that study was that greater susceptibility to failure might reasonably be expected as higher burnups are attained.

However, in the group of tests reported here, two tests were conducted on fuel rods in the $13,000$ MWd/MTU burnup range and no failures were noted, although the total energy depositions were 186 and 200 cal/g- UO_2 . The absence of failure in these tests was surprising in view of the much higher burnups involved, and probably indicates statistical variance which may be characteristic of high burnup failure mechanisms.

Finally, two tests were conducted on fuel rods in the $32,000$ MWd/MTU range. Although one of the rods (Test 756) suffered only minor failure during a test at 200 cal/g- UO_2 , the other rod (Test 859) had multiple failures unique to these tests at only 85 cal/g- UO_2 . Thus, the conclusions of the low-burnup study are supported since failure was by fracture (not meltdown), and susceptibility to failure, as evidenced both by the lower energy involved and the multiple failure mode, has increased for reasons which, pending metallurgical study and further testing, can now only be attributed to the burnup process.

Although hidden cladding defects could have existed in rod SE-33, it is not plausible to assume that all four failures were the result of such defects. All of the fuel rods used in the program were fabricated under quality standards as outlined in Reference 1. The cladding material underwent many tests including corrosion tests and ultrasonic tests, and all welds were radiographed and leak-checked. In addition, the fuel rods chosen for preirradiation were carefully inspected visually and by neutron radiography. Thus, although hidden defects could have been present in any of the irradiated rods, the related facts tend to indicate otherwise. In over 35 previous tests of unirradiated fuel of this fuel type, no failures attributable to original defects were found.

Also, it should be pointed out that the failure of rod SE-33 is not attributable to waterlogging. Although failures due to waterlogging do occur at very low energies (40-70 cal/g-UO)^[8,13], fuel dispersal, crack propagation, pressures, and energy conversions associated with waterlogged fuel failures are distinctly absent in the failure of rod SE-33.

Both the nature of the fractures and the pressure pulse measured during the failure of rod SE-33 indicate that overpressure by internal gas probably was not the direct causative agent for the failure. A single failure would have been sufficient to release internal pressure, and such a release should have been accompanied by a much higher pressure pulse than the one seen (waterlogged fuel failures, for example, normally produce much higher pressure pulses^[18]), and a large amount of fuel would have been expelled from the rod. Contrary to this, rod SE-33 retained virtually all of its fuel including fragments adjacent to the cladding fractures.

The three cracks seen in SE-33, Figures 16, 17, and 18, appear to be brittle fracture, although this has not been confirmed by metallurgical examination. There is no visible evidence of necking near the fracture surfaces. Fast neutron dosage to the cladding was about 2.7×10^{20} nvt (>1 Mev) and by Coplin's data^[19] should have effected a 30 to 40% loss of total elongation (depending upon the cladding temperature at the time of the test). Bement's data^[20], with conditions more closely approaching the present work, would indicate nearly a 2/3 loss of total elongation, together with a gain in yield strength of 35,000 psi.

From the information available, it appears that the three fractures exhibited by rod SE-33 were probably caused directly by fuel-cladding interaction, viz, by the strain of thermally expanding fuel against embrittled cladding. During service, UO₂ fuel is known to swell due to fission gases, creep and ratcheting of fragments, and to occupy the annular gap. The power history during burnup for these fuel rods was characterized by frequent, large adjustments and would have encouraged pellet enlargement^[21]. Incipient failure of the cladding due to repetitive circumferential straining over pellet fractures^[22] (also abetted by frequent power adjustments) is another possible agent leading to the type of failure seen here, and clearly must be considered. O'Donnel^[23] found also that plastic instability in irradiated zircaloy occurs at greatly reduced strains and imposes a severe limitation on the allowable swelling of UO₂ pellets before fracture will occur. Thus, the postulate that the fractures of SE-33 (and SE-20) resulted from fuel-cladding interaction is probably correct and should be further supported by metallurgical examination of the fuel rods.

The GEX type of fuel rod has now been tested under a broad range of burnup conditions thereby permitting the apparent effects of burnup to be illustrated as in Figure 20. In this plot, test energy depositions are plotted against burnup — the total energy being plotted whenever failure did not occur, and the energy-at-failure being plotted whenever failure was found. Note that for zero burnup a failure "threshold" was defined (between 223 and 256 cal/g-UO₂) with very little variance. In the low burnup group of tests, although variance is found, the paramount effect is lowering of failure energy, the lowest being 147 cal/g-UO₂. The two tests of 13,000 MWd/MTU clearly disagree with this trend. Finally, at

Fig. 20 Failure data as a function of burnup for GEX fuel rods subjected to power bursts. (Data taken from this report and References 1, 6, and 14.)

32,000 MWd/MTU the trend to low failure energy is again found, with incipient failure at 176 cal/g-UO₂ and extensive clad rupture at only 85 cal/g-UO₂.

Data are inadequate at this point to define a statistically meaningful failure "threshold" for irradiated fuels. The variance seen here in irradiated fuel failure energies would indicate, in fact, that the simple concept of a threshold does not exist and that irradiated rods respond and fail under widely variant individual and local conditions in contrast to the consistent manner and energy densities in which fresh fuel rods fail.

It is concluded from this preliminary study, that evidence has been found of low energy failure mechanisms. Similar failures may occur in water reactors with similar fuel which undergo small power transients above operating power.

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APPENDIX A
THE BURNUP PROCESS

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APPENDIX A

1. THE BURNUP PROCESS

1.1 Method

Fuel rods used for this study were irradiated in a pressurized loop facility in the Engineering Test Reactor under thermodynamic conditions closely approximating conventional BWRs.

1.2 The ETR

The Engineering Test Reactor (ETR) located at the Idaho National Engineering Laboratory is an aluminum, plate-type, thermal, water-moderated and -cooled reactor similar to the MTR but capable of achieving higher power (175 MW) and accommodating a greater number of irradiation facilities. The core of the ETR consists of 3- by 3-inch square assemblies of fuel plates each 36 inches in active length arranged in a 10 by 10 square array except for several element locations which are occupied by experimental facilities^[a].

1.3 The P-7 Loop

The 3- by 3-inch P-7 location in the ETR is a reflector position immediately adjacent to the ETR beryllium reflector. This position is occupied by the in-pile tube of the P-7 loop facility which, with its auxiliary equipment in shielded cubicles, is a complete pressurized water cooling system. Except for the in-pile tube, which is zircaloy, the P-7 loop system is stainless steel. The P-7 system includes pumps, ion exchange columns, heat exchanger, pressurizer, clean-up system, and other equipment essential for maintenance and operation. Maximum pressure is 1,600 psig as limited by the in-pile tube, the remainder of the system is rated at 2,500 psig and 600°F. The P-7 system was originally built by Battelle Northwest Laboratories and operated for a study of fuel defects. Additional details of the loop are reported in Reference 1, pages A-44, and A-46.

1.4 Fuel Configuration and Hardware

Based upon the rated (unperturbed) flux (1.33×10^{14} nv) in the P-7 position and the axial and radial gradients, calculations were made to determine an optimum array of fuel rods which could be simultaneously irradiated in the P-7 loop. Desired conditions included the following: pressure at 1,000 psig; cladding surface temperature at 550°F; and linear powers not to exceed 23.7 kW/ft for GEP rods and 20.6 kW/ft for the GEX rods, the calculated powers at which centerline melting is expected.

[a] R. L. Ackaret and A. S. Richardson, *In-Tank Irradiation Facilities at the Test Reactor Area*, IDO-17135 (January 1966).

The optimum fuel configuration (considering both program needs and facility capabilities) consisted of six GEX fuel rods and two GEP fuel rods in a three-level array — 3 GEX rods in the bottom level, 3 GEX rods in the center level, and 2 GEP rods in the top level. An initial set of fuel rod mounting hardware led to vibrational problems and was replaced. Details of the hardware used to irradiate the present group of fuel rods in the P-7 loop are shown in Figures A-1, -2, -3, -4, and -5. A flux suppressor was incorporated in the upper level hardware in order to reduce the axial flux gradient seen by the GEP fuel rods.

1.5 Operating Conditions

Loop and reactor operating conditions during the irradiation are listed in Table A-I.

TABLE A-I

LOOP AND REACTOR OPERATING CONDITIONS

Reactor Power Level, MW	175
Test Section Outlet Pressure, psi	1,000
Bulk Inlet Water Temperature, °F	460
Saturation Temperature, °F	545
Cladding Surface Temperature	550
Bulk Water ΔT , °F	~ 10
Loop Flow Rate, gpm	73
Pressure Drop Across Test Section, psi	59
Net Power, kW	61 $\pm$ 12
Gamma Power (input from reactor), kW	32
Power Loss of Reactor, kW	31
Water pH	10 $\pm$ 0.2
Oxygen Concentration, ppm	< 0.05

1.6 Operating History

All fuel rods were charged into the reactor on May 14, 1969. Fuel rods SE-31 and SE-32 were discharged on September 23, 1969 with an exposure of 77.5 effective days at a reactor power of 175 MW, and fuel rods SE-30 and SE-33 were discharged on February 27, 1970 with an exposure of 182.3 effective days. Since the ETR is a test reactor and subject to the many vagaries of experiments, the power-time profile experienced by these fuel rods is probably much more erratic than that of a power production reactor (power level

adjustments are known to affect fission gas releases, cladding strains, pellet fracturing, and ratcheting). As an indication of the nature of the ETR operation, see IN-ITR-113^[a], pages A-51 and A-62 where daily graphs of ETR power levels are shown for a previous irradiation program. As a further example, it was determined that during the 98 days that fuel rods SE-31 and SE-32 were in the ETR, approximately 350 power adjustments were made, although most were insignificant. More pertinent are the major power adjustments made near maximum power. A count was made of the number of power adjustments (in the same period of time as above, 98 days) which effected a power change of 20% or more, either down from 170 to 140 MW (or lower) or the reverse. A total of 66 adjustments of this type was found.

[a] R. W. Miller, *The Effects of Burnup on Fuel Failure I. Power Burst Tests on Low Burnup UO₂ Fuel Rods*, IN-ITR-113 (July 1970).

Fig. A-1 P-7 Loop basket assembly and details, Mark II.

Fig. A-3 P-7 Loop, GEX fuel rod holding hardware, Mark II.

Fig.A-4 P-7 Loop, cover plates, Mark II hardware.

Fig. A-5 P-7 Lcop. flux monitors, Mark II hardware.

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