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THE EFFECTS OF CLADDING MATERIAL
AND HEAT TREATMENT ON THE RESPONSE OF
WATERLOGGED UO_2 FUEL RODS TO POWER BURSTS

L. A. Stephan

MASTER

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IDAHO NUCLEAR CORPORATION
NATIONAL REACTOR TESTING STATION
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by

A L. A. Stephan

*Corp
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FOREWORD

This document provides an account of a finite phase of the Spert Subassembly Test Program. The information presented is preliminary in all respects, and may be subsequently refined or revised. Final results will be published either in regular professional journals or in Idaho Nuclear Corporation topical reports.

SUMMARY

Waterlogged fuel rods clad with both Zircaloy-2 and stainless steel have been subjected to transient tests in the Capsule Driver Core (CDC) at Spert. The tests were performed primarily for the purpose of determining the effect of cladding material and cladding heat treatment on the energy deposition required to cause cladding failure, and to obtain further information on the consequences associated with the failure of waterlogged fuel.

The waterlogged fuel rods tested were designated SPXM-B. They were 1/4-inch in diameter, had an active length of 5 inches, and contained 5%-enriched pelletized UO_2 . The cladding material was either Zircaloy-2 (annealed or cold worked) or 304-type stainless steel (annealed or cold worked). The rods were individually subjected to power bursts of either 5.5 or 3.0 msec (total energy depositions of either 225 or 430 cal/g of UO_2) in an ambient water environment.

A total of 10 waterlogged SPXM-B fuel rods were tested. Results indicate a failure threshold in the range of 155 to 165 cal/g of UO_2 for annealed Zr-2 cladding, 85 to 150 cal/g of UO_2 for cold-worked Zr-2 cladding, 330 to 350 cal/g of UO_2 for annealed 304-type stainless steel cladding, and 110 to 115 cal/g of UO_2 for cold-worked 304-type stainless steel cladding. The Zircaloy clad rods were tested at both 5.5 and 3.0 msec periods. The failure threshold of the annealed Zr-2 clad rods was relatively insensitive to period, whereas the shorter period apparently caused the failure threshold of the cold-worked Zr-2 clad rods to decrease significantly. The kinetic energy of the water column, resulting from conversion of thermal to mechanical energy, was considerably higher for all of the 3.0 msec tests than for the 5.5 msec tests.

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1. INTRODUCTION

This report presents the results of a series of transient fuel performance tests conducted in the Capsule Driver Core (CDC) on waterlogged SPXM-B fuel rods as a part of the Subassembly Test Program at Spert. The overall objective of the Subassembly Test Program in the CDC is to provide the AEC and the reactor vendors with useful and necessary experimental information on reactor fuel behavior under transient overpower conditions. Fuel types representative of those used in commercial water reactors are currently being tested to obtain information in the areas of: (1) physical consequences of fuel failure, and (2) thresholds and causality of fuel failure. Details of the overall fuel testing program in the CDC are presented in another report^[1].

The tests described in this report constituted Test Series CDC-109 as described in Reference 1. The primary objective was to determine the effects of cladding material (stainless steel and Zr-2) and cladding heat treatment (cold worked and annealed) on the energy deposition required to cause cladding failure and on the consequences of failure of waterlogged fuel rods.

The waterlogged fuel rods tested, designated SPXM-B, were 1/4-inch in diameter, had an active length of 5 inches and contained 5%-enriched pelletized UO_2 . The cladding material was either Zircaloy-2 (annealed or cold worked) or 304-type stainless steel (annealed or cold worked). All fuel rods in this series were waterlogged by evacuating the fuel rods and then allowing water to enter the evacuated interior. The vacuum technique results in essentially complete waterlogging. Ten waterlogged fuel rods were destructively tested in this series. Six of the fuel rods were clad with Zircaloy-2 and four were clad with 304-type stainless steel.

Section 2 presents a description of the test fuel rods, the environment in which they were tested, the instrumentation and measurements made, and the pre-test preparation of the fuel rods. In Section 3, the results from each test are documented. Section 4 presents the tentative conclusions drawn from the test results.

Results of other tests on waterlogged fuel rods have been previously reported in References 2 and 3. Results of other test series completed in the Subassembly Test Program are presented in References 4, 5, 6, 7, 8, 9, 10 and 11.

2. EXPERIMENTAL METHODS

2.1 Description of Fuel Rods

The fuel rods tested in the experiments described in this report are designated SPXM-B. The letters (SPX) denote that the fuel rods are of the SPX type⁽⁵⁾, the letter (M) denotes that the rods are shorter than the SPX rods, and the letter (B) denotes that the UO_2 fuel pellets are 5%-enriched. These fuel rods were designed specifically for tests in the CDC to obtain basic data typical of the performance of water reactor fuels subjected to transient overpower conditions. The fuel rods tested were 1/4-inch diameter and contained 5%-enriched, pelletized UO_2 fuel. The cladding materials were of four types; Zircaloy-2 (annealed and cold worked) and 304-type stainless steel (annealed and cold worked). The physical and nuclear characteristics of the SPXM-B fuel rods are contained in Table I, and a diagram illustrating the fuel design is shown in Figure 1. The yield stress for 0.2% elongation and the ultimate tensile stress measured for the cladding tubing are contained in Tables II and III. Prior to testing, the fuel rods were not subjected to any significant pre-irradiation.

2.2 Test Environment

2.2.1 The Core and Flux Trap

Figure 2 shows a cross-section plan view of the CDC core. The core is composed of 1/2-inch OD, stainless steel clad, powdered UO_2 fuel rods which are six feet in length. The core is approximately three feet in diameter and surrounds a 3.438-inch stainless steel tube which creates the flux trap region. The core is located in a 25-foot diameter tank, covered with water, and is always at ambient temperature and atmospheric pressure at the initiation of a test.

Additional details about the CDC may be found in Reference 1.

2.2.2 Capsules

For each test, a fuel rod was radially centered in a Type-B capsule, which is a thin-wall stainless steel enclosure with a flanged

SPXM-B FUEL ROD ASSEMBLY

BR-1673

Fig. 1 Schematic of SPXM-B fuel rod showing construction details.

TABLE I
SPXM-B FUEL ROD CHARACTERISTICS

Cladding Material	<u>Zircaloy-2</u>	<u>304 Stainless Steel</u>
Cladding Heat Treatment	Annealed or Cold-Worked	Annealed or Cold-Worked
Enrichment (%)	5	5
Overall Length (in.)	7.662	7.662
Active Length (in.)	5.0	5.0
Outside Diameter (in.)	0.250	0.250
Cladding Thickness (in.)	0.014	0.014
Radial Gas Gap (in.)	0.001	0.001
UO ₂ Density (g/cc)	10.4	10.4
UO ₂ /in. (g/in.)	6.4	6.4
Theoretical Internal Pressure for Tube Yield (psi)	5700 Annealed 9600 Cold-Worked	3600 Annealed 12,700 Cold-worked
Theoretical Internal Pressure for Tube Burst (psi)	9000 Annealed 12000 Cold-Worked	10,000 Annealed 15,000 Cold-worked
Radial Thermal Flux Depression		
$(1 - \frac{\phi_{min}}{\phi_{max}}) 100$ (%)	12.3	11.3
Radial Fission Density (power) Depression		
$(1 - \frac{source\ min}{source\ max}) 100$ (%)	11.7	10.7
Maximum to Average Radial Fission Density		
$(\frac{Source\ Maximum}{Volume\ Average\ Source})$	1.07	1.06
Maximum to Minimum Axial Fission Density	1.04	1.04
Figure-of-Merit ^(a) (fission product analysis)	5.6	5.4

(a) The figure-of-merit is defined as the ratio of the average radial power density at the axial power peak in the test fuel to the maximum power density in the core fuel.

TABLE II

TENSILE PROPERTIES OF SPXM CLADDING TUBING-STAINLESS STEEL

<u>Annealed 304 Stainless Steel</u>		
<u>Test Temperature</u> <u>(°F)</u>	<u>Yield Stress</u> <u>0.2% (psi)</u>	<u>Ultimate Stress</u> <u>(psi)</u>
72	32,000	91,000
300	28,000	68,000
500	25,000	66,000
700	22,000	63,000
900	20,000	60,000
1100	18,000	51,000

<u>Cold-Worked 304 Stainless Steel</u>		
<u>Test Temperature</u> <u>(°F)</u>	<u>Yield Stress</u> <u>0.2% (psi)</u>	<u>Ultimate Stress</u> <u>(psi)</u>
72	113,000	133,000
300	104,000	120,000
500	100,000	116,000
700	96,000	111,000
900	91,000	106,000
1100	75,000	86,000

TABLE III

TENSILE PROPERTIES OF SPXM CLADDING TUBING-ZIRCALOY

<u>Annealed Zircaloy-2</u>		
<u>Test Temperature</u> <u>(°F)</u>	<u>Yield Stress</u> <u>0.2% (psi)</u>	<u>Ultimate Stress</u> <u>(psi)</u>
72	50,000	84,000
300	37,000	61,000
500	23,000	44,000
700	19,000	36,000
900	17,000	30,000
1100	12,000	17,000

<u>Cold-Worked Zircaloy-2</u>		
<u>Test Temperature</u> <u>(°F)</u>	<u>Yield Stress</u> <u>0.2% (psi)</u>	<u>Ultimate Stress</u> <u>(psi)</u>
72	85,000	110,000
300	74,000	97,000
500	62,000	80,000
700	56,000	70,000
900	40,000	47,000
1100	---	---

Fig. 2 Cross-section plan view of the CDC.

head. A drawing of the capsule is shown in Figure 3. The capsules are designed to withstand the dynamic behavior of the fuel rods including explosive reactions, and provide convenient handling for the experiments. Physical characteristics of the Type-B capsules used in this test series are as follows:

Material	304 SS
OD (in.)	3.0
Wall Thickness (in.)	0.065
Inside Cross Section (in. ²)	6.470
Length (in.)	61.4
Volume (w/o hardware [in. ³])	387

The capsule is fitted with a pressure transducer at its bottom end. The head, which is bolted to the upper end, contains a "Conax" fitting which permits penetration of instrument lead wires. The capsule is normally filled with demineralized water to within about 10 inches from the top to allow for steam formation and water column movement. The gases which collect at the top can be withdrawn for analysis via a valve located on the head.

2.2.3 Fuel Rod Mounting Hardware

Figures 4 and 5 illustrate the fuel rod mounting method and the instrumentation used for these tests. The support tube (Figure 4) hangs from the capsule head and is adjusted in length to place the fuel rod at the position of the axial flux peak of the CDC core.

Three connecting rods (Figure 5) attached to the support tube extend down to the pressure transducer housing. The fuel rod is attached rigidly to the pressure transducer at the pressure port end by a turn-buckle type nut. Thus, the fuel rod is supported only at its bottom end; the upper end is free to expand or contract in response to the test. The extension attached to the upper end of the fuel rod slides freely in the cylindrical "cladding growth" LVDT.

2.3 Instrumentation

Instrumentation for the following dynamic variables was included: fuel rod growth, fuel rod internal pressure, capsule pressure, and water column velocity.

Fig. 3 Type-B capsule designed for fueled irradiation experiments in the CDC.

Fig. 4 Capsule and mounting hardware for SPXM-B fuel rods.

Fig. 5 Mounting hardware for SPXM-B fuel rods.

2.3.1 Fuel Rod Growth

Attached to the upper end of the fuel rod was an aluminum extension rod which carried a small slug of silicon-iron-B. The slug acted as a magnetic core for the cladding LVDT (linear variable differential transformer). Extension or contraction of the fuel rod length changed the position of the slug and the coupling between the primary and the secondary windings in the LVDT. A signal proportional to the slug position was recorded. The accuracy of the measurement is about 5% and response time is estimated to be less than 1 msec.

2.3.2 Fuel Rod Internal Pressure

A fast response pressure transducer was attached to the bottom end of the water filled fuel rod by a water filled housing. A hole was drilled axially through the fuel rod end plug forming a pressure port from the inside of the fuel rod to the pressure transducer housing. The pressure generated inside the rod was thus allowed to pass into the housing and act upon the pressure transducer. Response time of the transducer system has been measured at about 3 msec and precision of the transducer signal is in the range of $\pm 10\%$. The measurement may be rendered inaccurate if fuel particles fall through the pressure port onto the pressure transducer diaphragm causing erroneous signals from differential heating of the diaphragm during the test. The measurements may not be representative of the dynamic pressure if the transmission path of the pressure pulse between the pressure generating region of the fuel rod and the pressure transducer is blocked by the expansion of the fuel pellets against the cladding or by an obstruction at the pressure port.

2.3.3 Capsule Pressure

Another fast response pressure transducer was positioned in the bottom of the capsule (Figure 4) to measure dynamic pressure pulses in the capsule water surrounding the fuel rod. Response time of this transducer is $\approx 20 \mu\text{sec}$ with a precision of $\pm 20\%$ in the range up to 20,000 psi. This measurement relates to the problem of determining the level of pressure stresses which reactor vessels may experience in reactivity accidents. From an integral of pressure-time, the measurement also provides a calculation of momentum imparted to the water column.

2.3.4 Capsule Wall Strain

Attached to the capsule wall were strain gauges which measured circumferential and longitudinal strain of the capsule. Similar in purpose to the capsule pressure measurement above, the strain measurement can be interpreted as pressure or used to determine the efficiency of energy conversion from thermal form into strain energy.

2.3.5 Water Slug Velocity

When a fuel rod is heated and boiling occurs, or when the rod fails, releasing gas and producing steam explosions, the slug of water in the capsule above the rod is accelerated. A float which rides on the top of the water column (see Figure 4) carries small magnets which excite a current in a coil wound on the support tube. The coil direction is reversed each half-inch so that a sinusoidal signal is produced as the float rises. The frequency of the signal is thus directly related to water slug velocity. From this measurement and the known mass of water, the kinetic energy of the water column can be determined. This energy relates importantly to accident analysis by indicating the energy available in kinetic form which a reactor vessel must withstand. Water velocity also relates directly to the waterhammer effect possible in BWR's which have a steam dome. Precision of the measurement is about $\pm 15\%$.

2.4 Pre- and Post-Test Measurements and Inspection

2.4.1 Radiography

All fuel rods were neutrographed and inspected prior to testing to determine if flaws existed and to verify proper construction. After the pellets in the fuel rods were fractured by a power burst, the rods were again neutrographed to examine the extent of fragmentation. The fuel rods were neutrographed a third time after waterlogging to determine the extent of internal flooding and the distribution of the water within the rod. Neutrography was done at the Materials Test Reactor, operated by Idaho Nuclear Corporation. The technique was found to be useful for location of water inside fuel rods and a reliable diagnostic tool which was unaffected by radiation from the irradiated fuel.

2.4.2 Weights

All rods were weighed before and after waterlogging to allow for a determination of the amount of water accepted by the fuel rod.

2.4.3 Lengths and Profiles

All rods were initially length measured and passed through a profilometer which provides a profile of the diameter (± 0.0002 -in.) over the active length of the rod. Whenever possible these measurements were repeated after the test.

2.4.4 Photography

After each test the fuel rods, parts, and, occasionally, hardware, were photographed for documentation.

2.5 Energy Deposition Measurement

Measurement of the energy deposition in any test is interpreted as the maximum possible adiabatic enthalpy change of the fuel. However, the following explanations and interpretations should be considered.

Although direct calorimetric measurement techniques are being developed, the primary source of energy release data (reported as calories/gram- UO_2) is from chemical determination of fission-product concentrations. This method proceeds as follows:

a. A clean fuel rod of the type in question is irradiated in the CDC (steady state) until a specific energy of about 200 cal/g UO_2 has been released. Physical and neutronic conditions are identical to initial conditions used in later transient tests with other fuel rods. During this irradiation, a cobalt wire is irradiated and activated at a specific position in the CDC core itself.

b. The rod is chemically analyzed for fission products at ICPP. Data usually return in the form of fission/gram- UO_2 . The cobalt wire activation is measured in terms of counts-per-minute at the flux peak.

c. The fissions/gram- UO_2 data are converted to calories/gram- UO_2 by using the factor of 175 MeV/fission (energy retained within the fuel).

d. The ratio of calories/gram- UO_2 to counts-per-minute provides a calibration for cobalt wires which is constant over the range of interest and which is used in subsequent transient tests.

The following considerations must be recognized:

a. Transient tests are usually in the 3 msec to 7 msec period range and burst half-widths are in the range of 12 to 30 msec. The power burst in itself will release from 100 to 270 MW-sec in this period range, but approximately 20 MW-sec is released after the power burst, independent of the period, during a long sustained power plateau prior to scram. During this time, part of the heat is lost from the fuel to the cladding and therefore does not contribute to the fuel enthalpy change.

b. During a transient with high fuel rod temperatures, boiling void formation, for example, can reduce the flux-trap efficiency. Initial tests of this transient effect have been made using energy releases of up to 200 cal/g. These tests indicate a decrease of 7% for pellet fuel and 4% for powder fuel from the energy deposition expected on the basis of the static calibration. Corrections of these amounts have been applied to all test energy deposition data reported here.

c. Tests which cause failure of the fuel rod and consequent dispersion of the fuel in the capsule greatly alter the neutronic efficiency. No measurements of this effect have been possible and no corrections have been made to the reported data.

2.6 Pre-test Preparation of the Fuel Rods

The initial condition of the cladding, the internal rod hardware, and the fuel were examined by neutrographing the rods prior to any testing. The pellets in the rods were then fractured by subjecting the rods to a power burst resulting in an energy deposition of about 100 cal/g UO_2 within the rods. After the transient to break up the pellets, the pellet rods were neutrographed again to determine the extent of fragmentation. The next step in the pre-test preparation was to waterlog the rods. The procedure for waterlogging was as follows:

a. A vacuum system was connected to the bottom end plug and the internal gas was pumped from the rods through the pressure port designed to measure internal pressure.

b. The vacuum pump was isolated from the rod and water was allowed to enter the evacuated interior.

c. The rods were weighed before and after waterlogging to determine the amount of water deposited in each rod.

d. The rods were neutrographed after waterlogging to determine the extent of waterlogging and the distribution of the water within the rods.

The post-waterlogging neutrographs showed that the void spaces within the rods were completely filled with water.

During the assembly of the fully waterlogged rods into the capsule hardware, the adapter for the pressure transducer measuring internal fuel rod pressure was filled with water. This resulted in a system completely filled with water from the transducer diaphragm to the opposite end of the rod.

The possibility of flux peaking at the ends of the fuel column was not considered during the design of the SPXM-B rods. The flux peaking at the upper end after waterlogging was found to be significant, thus a suppressor was attached to the rods before testing. A length of 10 mil diameter silver wire was wrapped twice around the rod at the top of the fuel stack and taped in place with Mylar tape. This reduced the flux peaking sufficiently to negate any end effects on the response.

3. TEST RESULTS

A total of ten transient tests were performed on waterlogged SPXM-B fuel rods. Two annealed and two cold-worked, 304-type stainless steel clad fuel rods, and three annealed and three cold-worked Zr-2 clad fuel rods were destructively tested. Each fuel rod was subjected to a single high energy power burst. The four stainless steel clad rods and two of the Zr-2 clad rods were each subjected to a 3.0 msec period power burst generating an energy deposition of 380 cal/g of UO_2 for the stainless steel clad rods and 430 cal/g of UO_2 for the Zr-2 clad rods. The remaining four Zr-2 rods were each subjected to a 5.5 msec period power burst generating an energy deposition of 225 cal/g of UO_2 . This section presents a documentation of information obtained from pre-test, dynamic, and post-test measurements for each fuel rod. A summary of the dynamic and post-test measurements is presented in Tables IV and V.

3.1 Test 552 - Annealed Zr-2 Cladding - 3.0 msec Reactor Period

A waterlogged SPXM-B fuel rod having annealed Zircaloy-2 cladding was subjected to a 3.0 msec period power burst which would have resulted in a maximum energy density of 430 cal/g of UO_2 if the rod had not failed. However, the rod failed before the maximum energy density was reached. The rod failed in the form of a 1/2-inch split in the cladding. The rupture occurred about 0.54 msec before peak power at an energy density of 164 cal/g of UO_2 . Figure 6 illustrates axial cladding displacement, fuel rod internal pressure, capsule pressure, reactor power, and fuel rod energy deposition. The time of the rupture is distinguished by a sharp pressure pulse in the capsule, a rapid negative axial cladding displacement and movement of the water column. A second significant pressure pulse was generated in the capsule about 4.8 msec after the first pressure pulse. This pressure pulse was broad and multi-peaked and was initiated at an energy density of 3.5 cal/g of UO_2 . Coincident with this pressure pulse, the water column was accelerated. The fuel rod internal pressure measurement increased and decreased in a smooth manner showing no linkage with the rupture.

The maximum measured fuel rod internal pressure was 1710 psi and the maximum capsule pressure was 140 psi. The maximum water column

TABLE IV

SUMMARY OF TEST RESULTS FOR WATERLOGGED ZIRCALOY-2 CLAD SPXM-B FUEL RODS

Test No.	Reactor Period (msec)	Cladding Type	Energy Deposition of Time of Failure (cal/g UO_2)	Maximum Fuel Rod Internal Pressure (psi)	Maximum Capsule Pressure (psi)	Maximum Water Column Velocity (fps)	Nuclear-to-Mechanical Energy Conversion Ratio (%) ^[a]	Remarks
552	3.0	Annealed Zr-2	165	1710	140	23.2	.18	Rod failed about 0.54 msec before peak power. A 1/2-inch split occurred 1 inch from the bottom of the rod. The cladding was blackened over the active region and was wrinkled indicating melting. All the fuel was expelled from the rod. (Figure 7)
555	5.5	Annealed Zr-2	160	6500	440	7.6	.038	Rod failed 14.7 msec after peak power. A 3/8-in. split occurred 4-1/2 inches from the bottom of the rod. The rod was blackened over the active length. Rod broke in two pieces when removed from hardware. Less than one gram of fuel was expelled from the rod. (Figure 9)
558	5.5	Annealed Zr-2	160	1580	530	9.4	.059	Rod failed 13.6 msec after peak power. A 1/4-in. split occurred 5-1/2 inches from the bottom of the rod. The rod was blackened over the active length. Rod broke in two pieces when removed from the hardware. Less than one gram of fuel was expelled from the rod. (Figure 11)
547	3.0	Cold-Worked Zr-2	85	1830	170	27.5	.25	Rod failed about 4.0 msec before peak power. A 2-in. split occurred 4 inches from the top of the rod. The cladding was blackened over the active region and was wrinkled indicating melting. All the fuel was expelled from the rod. (Figure 13)
556	5.5	Cold-Worked Zr-2	150	11000	530	6.9	.031	Rod failed 13.1 msec after peak power. A 3/8-in. split occurred 4-1/4 inches from the bottom of the rod. The rod was blackened over the active length. Less than one gram of fuel was expelled from the rod. (Figure 15)
559	5.5	Cold-Worked Zr-2	120	1110	406	5.7	.022	Rod failed 5.6 msec after peak power. A 1/4-in. split occurred 6 inches from the bottom of the rod. The rod was blackened over the active length. A portion of the cladding broke from the rod when removed from the hardware. Less than one gram of fuel was expelled from the rod. (Figure 17)

[a] Based on the total nuclear energy at the time of maximum water column velocity.

TABLE V

SUMMARY OF TEST RESULTS FOR WATERLOGGED 304-TYPE STAINLESS STEEL CLAD SPXM-B FUEL RODS - 3.0 MSEC PERIODS

Test No.	Cladding Type	Energy Deposition of Time of Failure (cal/g UO ₂)	Maximum Fuel Rod Internal Pressure (psi)	Maximum Capsule Pressure (psi)	Maximum Water Column Velocity (fps)	Nuclear-to-Mechanical Energy Conversion Ratio (%) ^[a]	Remarks
538	Annealed 304 SS	330	5260	1340	60.3	1.2	Rod failed about 11 msec after peak power. The rod split open over 1½ inches of the length at the top of the rod. All the fuel was expelled from the rod. (Figure 19)
546	Annealed 304 SS	350	3000	1690	58.7	1.1	Rod failed about 10 msec after peak power. The rod split open over 1-1/4 inches of the length at 4 inches from the top. All the fuel was expelled from the rod. (Figure 21)
540	Cold-Worked 304 SS	110	7500	505	24.7	.20	Rod failed in the form of two separate ruptures. The first of about 2.7 msec before and the second at about 2.4 msec after peak power. A 3/4-inch split occurred 1½ inches below the top. Another split (1-inch long) occurred 5 inches from the top. All the fuel was expelled from the rod. (Figure 23)
544	Cold-Worked 304 SS	115	6700	330	23.2	.18	Rod failed about 2.3 msec before peak power. A 3/4-inch split occurred 3 inches from the top. Another split (1-inch long) occurred 6 inches from the top. All the fuel was expelled from the rod. (Figure 25)

[a] Based on the total nuclear energy at the time of maximum water column velocity.

Fig. 6 Reactor power, energy deposition, axial displacement, fuel rod internal pressure, and capsule pressure during Test 552

velocity was 23.2 fps, which corresponds to a nuclear-to-mechanical energy conversion ratio of 0.18%.

A post-test photograph of the fuel rod is shown in Figure 7. The rod had a 1/2-inch split at the bottom end of the active region. The cladding was blackened and wrinkled over the active region. The edges of the split were badly burned. All the fuel was expelled from the rod.

Fig. 7 Waterlogged SPXM-B fuel rod after Test 552.

3.2 Test 555 - Annealed Zr-2 Cladding - 5.5 msec Reactor Period

A waterlogged SPXM-B fuel rod having annealed Zircaloy-2 cladding was subjected to a 5.5 msec period burst, which would have resulted in a maximum energy density of 225 cal/g of UO_2 if the rod had not failed. However, the rod failed before the maximum energy density was reached. The rod failed in the form of a 3/8-inch split in the cladding. The rupture occurred about 14.7 msec after peak power at an energy density of 159 cal/g of UO_2 . Figure 8 illustrates axial cladding displacement, fuel rod internal pressure, capsule pressure, reactor power, and fuel rod energy deposition. The time of the rupture is distinguished by a sharp pressure pulse in the capsule, a rapid negative axial cladding displacement, a sharp decrease in the fuel rod internal pressure and movement of the water column.

The maximum measured fuel rod internal pressure was 6500 psi and the maximum capsule pressure was 440 psi. The maximum water column velocity was 7.6 fps, which corresponds to a nuclear-to-mechanical energy conversion ratio of 0.038%.

A post-test photograph of the fuel rod is shown in Figure 9. The rod had a 3/8-inch split, 4-1/2 inches from the bottom of the rod. The rod was blackened over the active region except at the split where the opening of the rod resulted in a large space between the cladding and the fuel.

Fig. 8 Reactor power, energy deposition, axial displacement, fuel rod internal pressure, and capsule pressure during Test 555.

Fig. 9 Waterlogged SPXM-B fuel rod after Test 555.

3.3 Test 558 - Annealed Zr-2 Cladding - 5.5 msec Reactor Period

A waterlogged SPXM-B rod having annealed Zircaloy-2 cladding subjected to a 5.5 msec period test, which would have resulted in a maximum energy density of 225 cal/g of UO_2 if the rod had not failed. However, the rod failed before the maximum energy density was reached. The rod failed in the form of a 1/4-inch split in the cladding. The rupture occurred 13.6 msec after peak power at an energy density of 157 cal/g of UO_2 . Figure 10 illustrates axial cladding displacement, fuel rod internal pressure, reactor power, and fuel rod energy deposition. The time of the rupture is distinguished by a sharp pressure pulse in the capsule, a rapid negative axial cladding displacement and movement of the water column. The fuel rod internal pressure increased as the energy density increased to a level of about 1500 psi. At this point the measured internal pressure leveled to a near constant value until after the failure. After the failure the measured internal pressure decreased slowly showing no linkage with the rupture of the rod.

The maximum measured fuel rod internal pressure was 1580 psi, and the maximum capsule pressure was 530 psi. The maximum water column velocity was 9.4 fps, which corresponds to a nuclear-to-mechanical energy conversion ratio of 0.059%.

A post-test photograph of the fuel rod is shown in Figure 11. The rod had a 1/4-inch split, 5-1/2 inches from the bottom end. The rod was blackened over the active length. Less than one gram of fuel was expelled from the fuel rod.

Fig. 10 Reactor power, energy deposition, axial displacement, fuel rod internal pressure, and capsule pressure during Test 558.

Fig. 11 Waterlogged SPXM-B fuel rod after Test 558.

3.4 Test 547 - Cold-Worked Zr-2 Cladding - 3.0 msec Reactor Period

A waterlogged SPXM-B fuel rod having cold-worked Zircaloy-2 cladding was subjected to a 3.0 msec power burst, which would have resulted in a maximum energy density of 430 cal/g of UO_2 if the rod had not failed. However, the rod failed before the maximum energy density was reached. The rod failed in the form of a 2-inch long split. The rupture occurred about 4.0 msec before peak power at an energy density of 85 cal/g of UO_2 . Figure 12 illustrates axial cladding displacement, fuel rod internal pressure, capsule pressure, reactor power, and fuel rod energy deposition. The time of the rupture is distinguished by a sharp pressure pulse in the capsule, a rapid negative axial cladding displacement and movement of the water column. A second significant pressure pulse was generated in the capsule about 7.5 msec after the first pressure pulse. This pressure pulse was broad and multi-peaked and was initiated at an energy deposition of 285 cal/g of UO_2 . Coincident with this pressure pulse, the water column was accelerated. The measured fuel rod internal pressure increased and decreased in a smooth manner showing no linkage with the rupture.

The maximum measured fuel rod internal pressure was 1830 psi and the maximum capsule pressure was 170 psi. The maximum water column velocity was 27.5 fps, which corresponds to a nuclear-to-mechanical energy conversion ratio of 0.25%.

A post-test photograph of the fuel rod is shown in Figure 13. The rod had a 2-inch split, 4 inches from the top. The cladding was blackened and wrinkled over the active region. The edges of the split were badly burned. All the fuel was expelled from the rod.

Test 547
 Rod SPXM-B-508
 Cladding Zr-2(cold worked)

Fig. 12 Reactor power, energy deposition, axial displacement, fuel rod internal pressure, and capsule pressure during Test 547.

Fig. 13 Waterlogged SPXM-B fuel rod after Test 547.

3.5 Test 556 - Cold-Worked Zr-2 Cladding - 5.5 msec Reactor Period

A waterlogged SPXM-B fuel rod having cold-worked Zircaloy-2 cladding was subjected to a 5.5 msec period power burst, which would have resulted in a maximum energy density of 225 cal/g of UO_2 if the rod had not failed. However, the rod failed before the maximum energy density was reached. The rod failed in the form of a 3/8-inch split in the cladding. The rupture occurred about 13.1 msec after peak power at an energy density of 150 cal/g of UO_2 . Figure 14 illustrates axial cladding displacement, fuel rod internal pressure, capsule pressure, reactor power, and fuel rod energy deposition. The time of the rupture is distinguished by a sharp pressure pulse in the capsule, a rapid negative axial cladding displacement, a sharp decrease in the fuel rod internal pressure and movement of the water column.

The maximum measured fuel rod internal pressure was 11,000 psi and the maximum capsule pressure was 530 psi. The maximum water column velocity was 6.9 fps, which corresponds to a nuclear-to-mechanical energy conversion ratio of 0.031%.

A post-test photograph of the fuel rod is shown in Figure 15. The rod had a 3/8-inch split, 4-1/2 inches from the bottom of the rod. The rod was blackened over the active region at the split where the opening of the rod left the cladding out of contact with the fuel. Less than one gram of fuel was expelled from the rod.

Test - 556
 Rod SPXM - B - 509
 Cladding Zr-2 (cold worked)

Fig. 14 Reactor power, energy deposition, axial displacement, fuel rod internal pressure, and capsule pressure during Test 556.

Fig. 15 Waterlogged SPXM-B fuel rod after Test 556.

3.6 Test 559 - Cold-Worked Zr-2 Cladding - 5.5 msec Reactor Period

A waterlogged SPXM-B fuel rod having cold-worked Zircaloy-2 cladding was subjected to a 5.5 msec period power burst, which would have resulted in a maximum energy density of 225 cal/g of UO_2 if the rod had not failed. However, the rod failed before the maximum energy density was reached. The rod failed in the form of a 1/4-inch split in the cladding. The rupture occurred 5.6 msec after peak power at an energy density of 121 cal/g of UO_2 . Figure 16 illustrates axial cladding displacement, fuel rod internal pressure, reactor power, and fuel rod energy deposition. The time of the rupture is distinguished by a sharp pressure pulse in the capsule, a rapid negative axial cladding displacement and movement of the water column. The measured fuel rod internal pressure increased as the energy density increased to a level of about 1000 psi. At this point, the measured internal pressure leveled to a near constant value until after the failure. After the cladding failed, the internal pressure decreased slowly, showing no linkage with the rupture of the cladding.

The maximum measured fuel rod internal pressure was 1115 psi and the maximum capsule pressure was 406 psi. The maximum water column velocity was 5.7 fps, which corresponds to a nuclear-to-mechanical energy conversion ratio of 0.022%.

A post-test photograph of the fuel rod is shown in Figure 17. The rod had a 1/4-inch split, 6 inches from the bottom end. A hole was burned through the cladding, 1-1/2 inches from the bottom end. This hole did not appear to be caused by internal pressure. The rod was blackened over the active length. Less than one gram of fuel was expelled from the rod.

Fig. 16 Reactor power, energy deposition, axial displacement, fuel rod internal pressure, and capsule pressure during Test 559.

Fig. 17 Waterlogged SPXM-B fuel rod after Test 559.

3.7 Test 538 - Annealed 304-Type Stainless Steel - 3.0 msec Reactor Period

A waterlogged SPXM-B fuel rod having annealed 304-type stainless steel cladding was subjected to a 3.0 msec period power burst which would have resulted in a maximum energy density of 380 cal/g of UO_2 if the rod had not failed. However, the rod failed 11 msec after peak power at an energy deposition of 330 cal/g of UO_2 . Figure 18 illustrates axial cladding displacement, fuel rod internal pressure, capsule pressure, reactor power, and fuel rod energy deposition. The composite plot shows that as the reactor power and resultant energy deposition increased, the fuel rod internal pressure and length increased. The time of failure is distinguished by the generation of a pressure pulse in the capsule, a sharp decrease in the fuel rod internal pressure, and a decrease in the axial cladding displacement. The water column was accelerated at the time of failure and reached a constant velocity after about two inches of travel. The water column then maintained approximately a constant velocity over the remaining 7 inches of travel to the upper limit of displacement.

The maximum measured internal pressure of the fuel rod was 5260 psi and the maximum measured capsule pressure was 1340 psi. The maximum velocity of the water column was 60 fps, which corresponds to a nuclear-to-mechanical energy conversion ratio of 1.2%.

A post-test photograph of the fuel rod is shown in Figure 19. The rod was split open over 1-1/2 inches of the length at the top end. The cladding over the remaining active portion of the rod was discolored. All the fuel was expelled from the rod. The expelled fuel burned away a portion of the upper positioning spacer.

Test 538
 SPXM - B - 524
 Cladding 304SS(annealed)

Fig. 18 Reactor power, energy deposition, axial displacement, fuel rod internal pressure, and capsule pressure during Test 538.

Fig. 19 Waterlogged SPXM-B fuel rod after Test 538.

3.8 Test 546 - Annealed 304-Type Stainless Steel - 3.0 msec Reactor Period

A waterlogged SPXM-B fuel rod having annealed 304-type stainless steel cladding was subjected to a 3.0 msec period power burst, which would have resulted in a maximum energy density of 380 cal/g of UO_2 if the rod had not failed. However, the rod failed before the maximum energy was reached. The rod failed in the form of single, widely opened split. The rupture occurred about 10 msec after peak power at an energy density of 352 cal/g of UO_2 . Figure 20 illustrates axial cladding displacement, fuel rod internal pressure, capsule pressure, reactor power, and fuel rod energy deposition. The time of the rupture is distinguished by a sharp pressure pulse in the capsule, a decrease in the fuel rod internal pressure, a rapid negative cladding axial displacement, and acceleration of the water column. The water column reached a maximum velocity after about four inches of travel.

The maximum measured fuel rod internal pressure was 3000 psi and the maximum capsule pressure was 1690 psi. The maximum water column velocity was 59 fps, which corresponds to a nuclear-to-mechanical energy conversion ratio of 1.1%.

A post-test photograph of the fuel rod is shown in Figure 21. The rod had a 1-1/4-inch split, 4 inches from the top. All the fuel was expelled from the rod.

Test 546
Rod SPXM-B-526
Cladding 304SS (annealed)

Fig. 20 Reactor power, energy deposition, axial displacement, fuel rod internal pressure, and capsule pressure during Test 546.

Fig. 21 Waterlogged SPXM-B fuel rod after Test 546.

3.9 Test 540 - Cold-Worked 304-Type Stainless Steel - 3.0 msec Reactor Period

A waterlogged SPXM-B fuel rod having cold-worked 304-type stainless steel cladding was subjected to a 3.0 msec period power burst which would have resulted in a maximum energy density of 380 cal/g of UO_2 if the rod had not failed. However, the rod failed before the maximum energy was reached. The rod failure was in the form of two separate ruptures. The first rupture occurred at about 2.7 msec before peak power at an energy deposition of 110 cal/g of UO_2 . The second rupture occurred at about 2.4 msec after peak power at an energy deposition of about 240 cal/g of UO_2 . Figure 22 illustrates axial cladding displacement, fuel rod internal pressure, capsule pressure, reactor power, and fuel rod energy deposition. The time of the first rupture is distinguished by a sharp pressure pulse in the capsule, a negative axial cladding displacement, a slight decrease in the measured fuel rod internal pressure, and movement of the water column. The time of the second rupture is distinguished by a sharp pressure pulse in the capsule, a sharp decrease in the fuel rod internal pressure, and movement of the water column. Immediately following the second rupture, a multi-spiked pressure pulse occurred in the capsule during which time the water column was accelerated.

The maximum measured internal pressure of the fuel rod was 7500 psi, and the maximum measured capsule pressure was 505 psi. The maximum velocity of the water column was 25 fps, which corresponds to a nuclear-to-mechanical energy conversion ratio of 0.20%.

A post-test photograph of the fuel rod is shown in Figure 23. The rod had a 3/4-inch split, 1-1/2 inches below the top and a 1-inch split, 5 inches below the top. All the fuel was expelled from the rod.

Test 540
 Rod SPXM-B-531
 Cladding 304SS(10% cold worked)

Fig. 22 Reactor power, energy deposition, axial displacement, fuel rod internal pressure, and capsule pressure during Test 540.

Fig. 23 Waterlogged SPXM-B fuel rod after Test 540.

3.10 Test 544 - Cold-Worked 304-Type Stainless Steel - 3.0 msec Reactor Period

A waterlogged SPXM-B fuel rod having cold-worked 304-type stainless steel cladding was subjected to a 3.0 msec period power burst which would have resulted in a maximum energy density of 380 cal/g of UO_2 if the rod had not failed before the maximum energy was reached. The rod failure was in the form of two separate ruptures. The first rupture occurred about 2.3 msec before peak power at an energy density of 116 cal/g of UO_2 . The second rupture occurred at about 2.4 msec after peak power at an energy deposition of about 270 cal/g of UO_2 . Figure 24 illustrates axial cladding displacement, fuel rod internal pressure, capsule pressure, reactor power, and fuel rod energy deposition. The time of the first rupture is distinguished by a sharp pressure in the capsule, a sharp decrease in the fuel rod internal pressure, and movement of the water column. The axial displacement showed no indication of the failure. After the sharp decrease in the fuel rod internal pressure at time of failure, the fuel rod internal pressure again increased for about three msec and then leveled off at a pressure less than the pressure before the failure. The time of the second rupture is distinguished by sharp decreases in the axial cladding displacement and fuel rod internal pressure followed by a multi-spiked pressure pulse in the capsule. At the time of the second rupture, the water column was accelerated. The water column reached a maximum velocity after about four inches of travel.

The maximum measured internal pressure of the fuel rod was 6700 psi and the maximum measured capsule pressure was 330 psi. The maximum velocity of the water column was 23 fps, which corresponds to a nuclear-to-mechanical energy conversion ratio of 0.18%.

A post-test photograph of the fuel rod is shown in Figure 25. The rod had a 3/4-inch split, 3 inches from the top and a 1-inch split, 6 inches from the top. The immediate area around the split at 3 inches from the top was burned and discolored. All the fuel was expelled from the rod.

Fig. 24 Reactor power, energy deposition, axial displacement, fuel rod internal pressure, and capsule pressure during Test 544.

Fig. 25 Waterlogged SPXM-B fuel rod after Test 544.

4. DISCUSSION AND CONCLUSIONS

Results from the tests performed are summarized in Tables IV and V. These data allow the following testative statements to be made regarding the transient behavior of waterlogged SPXM-B fuel rods. It should be emphasized that these conclusions apply to a particular fuel rod (SPXM-B) and to the environment and geometry within the capsule, and application or extrapolation to other fuel rods and other situations should be done with care.

4.1 Failure Threshold

Failure thresholds for the waterlogged fuel rod cladding types tested were in the following ranges: 85 to 150 cal/g for cold-worked Zr-2; 157 to 164 cal/g for annealed Zr-2; 110 to 116 cal/g for cold-worked stainless steel; and 330 to 352 cal/g for annealed stainless steel. These data clearly indicate that the failure threshold is lower for Zr-2 than for 304-type stainless steel, and that cold-worked material fails at lower energies than does annealed material.

4.2 Effect of Period on Response and Consequences

Tests on Zircaloy clad rods were conducted at both 3.0 and 5.5 msec periods. For the different reactor periods, the fuel rods reached the failure threshold at different power levels and at different times relative to peak power. Fuel rods subjected to 3.0 msec period power bursts failed during the upper portion of the peak while fuel rod subjected to 5.5 msec period power bursts failed far down on the back side of the peak. Therefore, the neutron density in the capsule and hence the fission density in the fuel remaining in the rod and that expelled from the rod was as much as 10 times greater after the time of failure for the 3.0 msec than for the 5.5 msec tests.

As might be expected, some differences in behavior were detected as a function of period, particularly following fuel rod failure. There was no observable effect on the failure threshold for the annealed Zr-2 cladding, both 3.0 and 5.5 msec period causing the rods to fail at about the same energy deposition. For the cold-worked Zr-2 cladding, however, the one test at a 3.0 msec period failed at 85 cal/g compared with 120 and

150 cal/g for the two tests at 5.5 msec periods. This would indicate that the failure threshold might be sensitive to the reactor period, but the data are insufficient to verify this conclusion.

More kinetic energy was imparted to the water column for the 3.0 msec period than for the 5.5 msec period tests even though the energy densities were about the same at the time of the initial phase of the failure. The dynamic behavior within the capsule during the tests shows that the only significant amount of kinetic energy imparted to the water column occurred during a second, broad, multi-peaked pressure pulse, which occurred about 10 msec after the initiation of the failure. These delayed pulses occurred only for the 3.0 msec period tests and are believed to have resulted from the expulsion of the fractured fuel pellets through the rupture in the cladding. The total energy deposition for the 3.0 and 5.5 msec period tests was 430 and 225 cal/g of UO_2 respectively; however, failure occurred prior to the deposition of these amounts of energy. For the 3.0 msec tests a considerable amount of the energy was deposited in the UO_2 after the rupture of the cladding. It is believed that the post-rupture energy deposition is responsible for the generation of the forces causing the expulsion of the fractured fuel after the initiation of the failure. These results indicate that the bursting of the cladding and the associated pressure pulse contribute very little to kinetic energy imparted to the water column, while the expulsion of the fragmented fuel into the capsule water contribute the major portion. Also, the energy content of the fuel at the threshold of failure may not be as important with respect to the consequences of failure as the power level at the time and shortly after the failure.

4.3 Post-Test Condition of Fuel Rods

With regard to the post-test condition of the fuel rods, those clad with 304-type stainless steel were undamaged except for a split in the cladding where the rod failed, while the rods having Zr-2 cladding were discolored and embrittled over the active region. The Zr-2 clad rods were fragile and easily broken by handling. They also showed some wrinkling of the cladding, indicating the onset of melting.

5. REFERENCES

- (1) J. E. Grund et al, Subassembly Test Program Outline for FY 1969 and 1970, IDO-17277 (August 1969).
- (2) L. A. Stephan and C. S. Olsen, Transient Irradiation of 0.446-Inch OD Stainless Steel Clad Oxide Fuel Rods to 300 cal/g of UO_2 , IDO-ITR-101 (November 1968).
- (3) L. A. Stephan, The Response of Waterlogged UO_2 Fuel Rods to Power Bursts, IDO-ITR-105 (April 1969).
- (4) J. A. McClure and L. J. Siefken, Transient Irradiation of 1/4-Inch OD Stainless Steel Clad Oxide Fuel Rods to 570 cal/g UO_2 , IDO-ITR-100 (October 1968).
- (5) Z. R. Martinson and R. L. Johnson, Transient Irradiation of 1/4-Inch OD Zircaloy-2 Clad Oxide Fuel Rods to 590 cal/g UO_2 , IDO-ITR-102 (November 1968).
- (6) R. W. Miller and W. G. Lussie, The Response of UO_2 Fuel Rods to Power Bursts, 5/16-Inch OD, Pellet and Powder Fuel, Zircaloy Clad, IDO-ITR-103 (January 1969).
- (7) R. W. Miller and W. G. Lussie, The Response of UO_2 Fuel Rods to Power Bursts, 9/16-Inch OD, Pellet and Powder Fuel, Zircaloy Clad, IDO-ITR-104 (April 1969).
- (8) W. G. Lussie and R. W. Miller, The Response of UO_2 Fuel Rods to Power Bursts, Detailed Tests on 5/16-Inch OD, Powder Fuel, Zircaloy Clad Rods, IN-1302 (IDO-ITR-106) (June 1969).
- (9) Z. R. Martinson, Behavior of 5-Inch Long, 1/4-Inch OD, Zircaloy-2 Clad Oxide Fuel Rods Subjected to High Energy Power Bursts, IN-ITR-107 (August 1969).
- (10) C. S. Olsen, Measurements of the Reaction of UO_2 with Water for Transient Energy Depositions to 550 cal/g of UO_2 , IN-ITR-108 (November 1969).
- (11) R. W. Miller, "Effects of Burnup on the Reactivity Accident - Tests of Fuel Rods with Low Burnup," Trans. Am. Nuc. Soc., 12, 2 (December 1969).