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PROMPT BURST ENERGETICS EXPERIMENTS:
FRESH OXIDE/SODIUM SERIES

K. O. Reil, M. F. Young

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ABSTRACT

A series of in-pile experiments has been performed to provide information on thermal energy to work conversion under prompt burst excursion (PBE) conditions. These consisted of single pin tests using fresh uranium oxide or uranium carbide fuel in a capsule geometry, with either stagnant sodium or helium in the coolant channel. The experiments were irradiated with single or double pulses in the Annular Core Pulse Reactor (ACPR) to provide energy depositions up to 2900 J/g. This report covers the seven single and five double pulse UO_2 sodium-in tests. Experimental data includes pressure and linear motion transducer histories, measured work-energy conversion efficiencies, and post-irradiation examination. Analysis includes derived work-energy conversion efficiencies (up to 0.54%), pin failure modeling, hydrodynamic analysis of pressure pulse propagation in the channel, and piston stopping effects. Initial pressure events in the single pulse experiments appear to be dominated by fuel vapor pressure. Definite fuel-coolant interactions were observed in several experiments, including some that were coincident with stopping of the linear motion transducer piston, suggesting a possible triggering effect by the deceleration pressure.

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1. INTRODUCTION

1.1 Purpose and Scope

The current program in Prompt Burst Energetics (PBE) at Sandia Laboratories involves an in-pile experimental and complementary analytical investigation of the energetics of fuel-clad-coolant systems subjected to energy deposition conditions associated with super-prompt critical excursions. In particular the emphasis to date has been on autoclave tests of single intact fuel pins in the presence of stagnant sodium in the experiment cavity of the Annular Core Pulse Reactor (ACPR) and on the supportive analysis of those tests. Future tests will include flowing sodium, advanced and alternative fuels and coolants, multi-pin and disrupted geometries. Prior to these experiments, no experiments had been conducted with periods in the range of a few milliseconds and no experimental basis existed for determining the potential of short-time energy transfer from fuel to coolant in the "few millisecond" time frame. This environment is characterized by the following features not generally present in other scenarios involving fuel-coolant interaction (FCI).

- (1) At the moment of fuel-coolant contact, there is a high ambient pressure due to the fuel vapor pressure and/or fission gas pressure responsible for clad failure.
- (2) Internal fuel vaporization provides a special mechanism for fuel ejection and fuel-coolant mixing, at least in the immediate vicinity of the clad failure region.
- (3) Except at the clad failure location, remaining, intact clad inhibits fuel coolant contact.
- (4) The neutronic burst itself provides a source of reactor-wide coherence even if fuel-coolant interactions themselves are not capable of intrinsic, large-scale coherence.

For these reasons, the nature of FCI under prompt burst conditions cannot be readily inferred from the results of experiments or theories applicable to other fuel-sodium contacting modes, and separate study is needed.

The present program has as its objectives the determination of the phenomena which dominate in the conversion of thermal energy to work, development of models to accurately predict the energetics associated with such hypothetical accidents and provision of the required input data for those models. This program includes the examination of the integral effects of fuel-clad-coolant interactions, fission gas release, and fuel and fission product vapor pressures during super-prompt critical core disruptive conditions and thus serves to define the initial conditions for hydrodynamic expansion of the disrupted core.

The experimental work is closely interfaced with analytical efforts to develop models which describe the prompt burst process and to the verification of currently used and developmental disassembly codes. These experiments also provide information about the state and distribution of fuel, clad, and coolant following a super-prompt excursion. These data serve as initial conditions for post accident heat removal and inherent retention studies.

The initial PBE test series utilized an instrumented pressure vessel containing the fuel pin surrounded by coolant. The upper end of the vessel is fitted with a moveable piston. Fuel enrichment and neutron spectrum moderation are combined to yield fission energy depositions sufficient to melt and partially vaporize the fuel. Pressure, temperature, piston motion and reactor power histories are obtained during each test. A comparison of piston kinetic energy (derived from the piston motion history) and fuel energy deposition (derived from the reactor power history) results in an estimate of the work conversion efficiency. Later tests will use the coded aperture imaging fuel motion diagnostics system to provide high resolution information on failure locations, times and the interaction of the fuel with the coolant. Posttest examination provides information about the character and distribution of the debris.

The reactor could be operated in either the single pulse mode or the multiple pulse mode. In the single pulse mode, energy is deposited in the pin in a single pulse of a few milliseconds duration generated by simultaneous withdrawal of three transient rods. The resulting energy deposition is not uniform radially across the pin due to the relatively soft neutron energy spectrum of the ACPR. The resulting temperature distribution is peaked near the fuel surface. In the multiple pulse mode the energy deposition is partitioned between two or three smaller pulses generated by sequential withdrawal of the transient rods. Although the energy deposition profile is similar to that observed in single pulse operation, thermal relaxation between pulses permits tailoring of the temperature profiles by altering the times between rod withdrawals. Temperature profiles can be obtained which peak within the fuel, approximating "prototypic" temperature profiles.

The analytical work can be grouped into three categories.

- (1) Pre-experiment analysis directed at experiment design and safety analysis.
- (2) Interpretive analysis directed at identification and characterization of the underlying physical phenomena based on experimental observations.
- (3) Phenomenological modeling directed at development of analytic models which uniquely describe the observed phenomena for incorporation into predictive accident analysis.

Among the areas addressed by the analysis have been:

- (1) Time and location of clad failure;
- (2) Thermophysical states of fuel, clad, and coolant at failure;
- (3) Prefailure axial fuel motion;
- (4) Postfailure voiding of the pin;
- (5) Channel-piston effects on transducer response;
- (6) Fuel-coolant interactions, including mixing, fragmentation, and heat transfer;
- (7) Effect of piston stopping as an FCI trigger mechanism.

A pin failure model, EXPAND, has been developed at Sandia to address (1), (2), and (3) above. Area (4) is under investigation using SIMMER-II and EPIC; the CSQ-II hydrodynamic code has been used to investigate (5); HONDO, a transient finite deformation code, has been used to examine (7). No model is currently available that correctly describes all important aspects of fuel-coolant interactions (6). While parametric approaches have been developed, the input parameters are not physically observable. A mechanistic approach would utilize input variables that are experimentally definable.

To date, eighteen PBE experiments have been completed. Three experiments have been performed with fresh UO_2 fuel in a helium filled capsule.⁽¹⁾ Detailed analysis of those experiments will appear in a later report. Twelve experiments have utilized fresh UO_2 fuel in sodium, and are the subjects of this report. Three experiments involving fresh uranium carbide fuel in sodium⁽²⁾ were performed in cooperation with the Fast Breeder Reactor Project at KFK Karlsruhe, West Germany. Detailed analysis of the UC experiments will be reported later.

This report describes the series of twelve experiments utilizing fresh uranium dioxide fuel in sodium. These experiments, numbered consecutively PBE-1S through PBE-12S, were completed between January 1976 and September 1977. This document contains a detailed description of the experiment vehicle (Chapter 2), a summary of experiment results (Chapter 4), the results of the related analytic work (Chapter 5), and a discussion of the conclusions drawn from this work (Chapter 6). A summary of the major conclusions is given in the following section.

1.2 Summary of Major Observations and Conclusions

This section summarizes the major conclusions that have been drawn from this work. The rationale for these conclusions and the supporting experimental and analytical evidence are given in the text.

Experimental evidence is derived from pressure transducer, linear motion transducer, and reactor power histories, radiography, and postmortem examination. Analytic evidence comes from application of several types of computer codes to various aspects of the experiment. The analysis includes hydrodynamic and heat transfer modeling of the pin, and channel, post-pin failure modeling using the EPIC FCI code, and prefailure modeling with a pin model, EXPAND. This last code was specially developed to incorporate those phenomena important during prompt burst excursions and provides a unique tool capable of both experimental and reactor accident analysis.

The observed pressure histories associated with these prompt burst tests include single and multiple high pressure, short duration transients (up to 64 MPa), followed, in some experiments, by lower amplitude sustained pressurizations. The source of the initial pressurization appears to be dominated by the fuel vapor pressure present at clad failure, although uncertainties in the fuel equation-of-state could mask an equal contribution from coolant vapor. The character of the observed pressure signatures including differences observed at top and bottom of the capsule are primarily due to channel acoustics and piston motion.

The secondary pressure events result from sodium pressurization caused by thermal interaction between fuel and coolant (FCI). The triggering of FCI by hydrodynamic pressurization of the upper sodium slug upon piston deceleration is observed. Like the nuclear burst itself, this triggering of FCI is a possible source of coherence in a larger system.

Small thermal to mechanical energy conversion efficiencies were inferred from piston motion ($<4.2 \times 10^{-4}$). Since in several experiments the piston stopped while the channel was still pressurized, higher efficiencies are implied by the measured pressure histories. The values extend up to 0.54% for PBE-9S but, due to experimental limitations, represent a lower limit of conversion efficiencies. Although these values are still quite small compared to the theoretical thermodynamic limit, it is important to note that the experimental conditions under which these initial single pin capsule tests were conducted tend to reduce the energy conversion because of the rapid quenching of fuel and sodium vapor by the "cold" experiment capsule wall.

Two potential reactivity effects have been identified. The first, a negative effect, is prefailure axial fuel expansion which is predicted by EXPAND

and is evident in post irradiation examinations (PIE). The second, a positive or negative effect depending on the failure location and subsequent fuel motion, is the nearly total voiding of the fuel pin towards the break after clad failure which is seen in PIE and is indicated by preliminary analysis with the EPIC FCI code. The magnitude and timing of these reactivity effects as well as their importance to HCDA energetics is dependent on analysis which is not complete.

The major obstacle to postfailure analysis of the experiments and extrapolation to the reactor system is the lack of a model which describes the important aspects of the observed fuel coolant interactions in terms of physically observable parameters. To be meaningful, this model should include mixing, fragmentation, and heat transfer.

2. EXPERIMENT DESCRIPTION

The series of PBE experiments described herein was performed using an instrumented, stagnant sodium-filled autoclave irradiated in the Annular Core Pulse Reactor (ACPR). This chapter contains descriptions of the ACPR, the experimental fuel pins, the two types of experiment assemblies that were used, and the diagnostic instrumentation.

2.1 ACPR Description

The ACPR⁽³⁾ was a swimming pool reactor based on TRIGA technology with approximately 150 fuel elements 381 mm long using U-ZrH fuel with 20% enriched uranium. It was operated in the steady-state mode or the pulse mode, with a pulse energy release of 108 MJ and a peak power of 15,000 MW. The minimum initial reactor period was 1.3 msec. The central experiment cavity was 240 mm in diameter and extended vertically to the top of the tank. The pulse neutron fluence was approximately 2.3×10^{15} n/cm² with half of the fluence above 10 keV. The usefulness of the ACPR for fast reactor safety experiments has been examined previously.⁽⁴⁾

In October, 1977, the ACPR was shut down for major modifications including a totally new core and control system. The upgraded ACPR will result in greatly enhanced pulse and steady-state capabilities.

2.2 Fuel Pin Description

Fresh uranium dioxide fuel pins were fabricated for these experiments by Hanford Engineering Development Laboratory (HEDL) and Los Alamos Scientific Laboratory (LASL). The pins, shown schematically in Figure 1, were fabricated with EBR-II length (343 mm) fuel columns and utilized FTR-type cladding and cross-sectional dimensions. The pin design incorporates a scratch gauge assembly in the upper plenum to provide a passive indication of total axial fuel expansion occurring during the experiment. This indication is accomplished with a spring loaded stylus that leaves a mark on the inside cladding surface which can be examined posttest. (The plenum portion of the cladding remained intact in all experiments.) The pins were helium bonded and included a wire wrap spacer. Two enrichments (14 and 20%) were utilized to permit examination of different fuel energy conditions during similar ACPR transients. Characteristics of the fuel pins are summarized in Table I.

PBE EXPERIMENT UO₂ FUEL PIN CONFIGURATION

Figure 1. PBE Fresh UO₂ Fuel Pin.

Table I
PBE Fresh Oxide Fuel Pin Characteristics

Fuel Material	UO ₂
Uranium Enrichment (%)	14 and 20
Fuel Mass (g)	64
Planar Smeared Density (%TD)	84.7
Fuel Pellet Diameter (mm)	4.93
Fuel Length (mm)	343.7
Fuel-Clad Bond	Helium
Plenum Length (mm)	90
Spring Solid Height (mm)	39.4
Cladding Material	316SST
Cladding Outside Dia. (mm)	5.83
Cladding Thickness (mm)	0.38
Wire Wrap Diameter (mm)	1.39

2.3 Experiment Capsule

A cross-section of the fueled portion of the PBE experiment capsule is shown in Figure 2. The fuel pin is surrounded by a sodium annulus bounded by a molybdenum liner (0.51mm wall thickness) which simulates the geometry of six adjacent fuel pins and serves as a refractory liner for the Inconel pressure vessel (1.27 mm wall thickness). The spaces between the molybdenum liner and the pressure vessel were filled with sodium.

The fluted molybdenum liner shown in Figure 2 contains a sodium cross-sectional area of 52.0 mm² compared to the sodium area in an FTR subassembly of 17.3 mm² per pin. Cylindrical molybdenum liners, having the same minimum inside diameter as the fluted design, were used in two experiments (PBE-8S and PBE-11S). The sodium area in the cylindrical geometry was 33.7 mm².

The fuel pin is located in the lower portion of the inner pressure vessel as shown in Figure 3. The experiments through PBE-11S were performed in the PBE Experiment Assembly I (shown in Figure 3). In PBE-12S, an improved design was utilized, which is described below.

The experiment contains approximately 55 g of sodium below a tungsten alloy piston which forms the upper boundary of the test channel and serves as an inertial constraint on the system. The piston mass (including the armature for the linear motion transducer) is 436 g, and the cross-sectional area of its face is 236 mm². The total piston travel is approximately 63 mm and displaces ~1500 mm³. The top of the piston is a tapered mandrel which engages and

PBE SINGLE PIN EXPERIMENT

Figure 2. Cross-Section of PBE Fuel Pin Housing.

PROMPT BURST EXCURSION EXPERIMENT

Figure 3. Prompt Burst Energetics Experiment Assembly I.

plastically deforms a steel sleeve to dissipate the piston kinetic energy at the end of its travel.

An isothermal initial condition is established by means of electric heater tapes wrapped on the outside of the beryllium heat sink in the fueled region and on the pressure vessel above and below the fuel pin housing. The capsule includes a receiver volume, rupture disc and orifice assembly to prevent sustained over-pressurization of the test channel. The experiment is surrounded by a polyethylene moderator sleeve (32 mm thick) to enhance the fission rate in the fuel pin.

2.4 Diagnostic Instrumentation

The diagnostic instrumentation consists of six grounded junction thermocouples of tantalum sheathed W-Re or stainless-steel sheathed Ch-Al (1.02 mm O.D.) spaced in pairs at the bottom, middle, and top of the fuel pin channel. The pressure transducers mounted at the top and bottom of the test channel are Kaman Sciences Corporation's Model KP 1911 or KP 1913 high temperature pressure transducers rated at 34.4 and 68.9 MPa, respectively, with frequency response greater than 46 kHz. The high temperature linear motion transducer is a variable reluctance device with a solid armature manufactured by Moxon, Inc.

The transducer outputs, reactor power signal, and a fiducial generated when the reactor power exceeds ~1 kW are recorded on FM tape. The data are digitized from the tape and processed via the Sandia Data Acquisition and Display System (DADS)⁽⁵⁾.

2.5 Experiment Assembly II

The PBE-12S experiment was performed in a new experiment configuration which was designed to accommodate pre-irradiated oxide fuel and has been used for a series of UC Fueled PBE experiments.⁽²⁾ The new pressure vessel assembly, shown in Figure 4, differs in several significant ways from the original design. The rupture disc geometry was modified to reduce the volume of the horizontal plenum at the face of the piston and to eliminate a trapped gas volume at the rupture disc. Redundant pressure transducers were added at the top and bottom of the sodium channel. Most importantly, the methods of fuel pin installation and constraint were altered to permit installation of the fuel as the last step of assembly rather than early in the assembly procedure. In Assembly I, the fuel pin is constrained axially by a spoke against the piston housing and against a spring in the lower end cap (see Figure 3). In Assembly II, a spoke on the bottom of the pin is locked at the bottom of the fuel pin housing, but the upper end of the pin is not constrained axially at all.

All other aspects of the experiment capsules, including the piston, containment, moderator structure, and instrumentation, are the same in the two designs.

Figure 4. Prompt Burst Energetics Experiment Assembly II.

3. DOSIMETRY AND ENERGY DEPOSITION CALIBRATION

A series of dosimetry experiments was performed to define the axial energy deposition profile in the PBE tests and to quantify the maximum radially-averaged energy deposition for the UO_2 pins used in these tests. Fuel pins were irradiated during low-level ACPR pulses. The energy deposited in each pellet was determined by fission product inventory techniques. These results were then scaled by the ratio of measured neutron fluences to yield estimates of the energy deposition in the PBE tests. The validity of the scaling technique was verified by the use of uranium-loaded aluminum dosimetry wire which can be irradiated during maximum ACPR pulses. The use of fluence values for scaling was found to be accurate to within 0.5 percent. The uncertainty in the fission product inventory results is estimated to be 5 percent.

The axial profiles determined by these experiments are shown in Figure 5. The maximum radially averaged energy depositions were found to be 2350 J/g and 2900 J/g for 14% and 20% enriched UO_2 , respectively, for a maximum ACPR pulse. (In the figure position 0.0 mm is the top of the fuel column.)

The radial fission energy deposition profiles were obtained from neutron transport calculations using DTF-IV.⁽⁶⁾ The resulting profiles, normalized to the measured maximum radially averaged energy depositions are shown in Figure 6 for 14% and 20% enriched fuel. The parameters describing the energy deposition profiles are summarized in Table II.

Table II

Energy Deposition Parameters

Fuel Enrichment (%)	14	20
Maximum Radially Averaged Energy Deposition ⁽¹⁾ (J/g)	2350	2900
Axial Deposition Profile (Peak/Average)	1.16	1.16
Radial Deposition Profile (Peak/Minimum)	1.43	1.72
Radial Deposition Profile (Peak/Average)	1.22	1.34

(1) Maximum ACPR Pulse

Figure 5. Axial Fission Energy Deposition in 14% and 20% Enriched UO_2 Irradiated in the PBE Experiment with 32-mm Thick Polyethylene Moderator.

Figure 6. Radial Fission Energy Deposition Profiles in PBE Experiments (Maximum ACPR Pulse).

4. EXPERIMENT RESULTS

This chapter describes the experiments, experimental observations, and results drawn from those observations. Of the experiments with oxide fuel and sodium, seven experiments were conducted utilizing single pulse operations in the ACPR, and five experiments were double pulse irradiations. The experiments spanned a range of total energy depositions and experiment conditions. As described in the previous section, the irradiation of enriched fuel pins in a thermalized neutron flux results in a non-uniform fission density distribution that is peaked at the pin surface and depressed towards the center. When fuel pins are irradiated during the short time intervals of single ACPR pulses, this fission density profile results in temperature distributions peaked at the fuel surface. The double pulse mode of irradiation (which combines a small reactor pulse and thermal relaxation time to establish initial temperature conditions for the test transient) provides a means of obtaining more prototypic temperature distributions that are peaked inside the fuel (see Section 4.2 below).

The significance of the fuel temperature profile extends beyond questions of prototypicality. Maximum fuel temperature implies maximum fuel vapor pressure which, for fresh fuel, is the driving force for initial fuel motion following clad rupture. If the peak fuel vapor pressure were inside the fuel column (double pulse ACPR irradiation), it is probable that upon pin failure, molten fuel would be driven through the clad rupture into the coolant channel. This is in contrast to the situation with a fuel temperature profile peaked at or near the surface (single pulse ACPR irradiation) in which a high quality two phase fuel mixture would initially contact the coolant. The first situation should lead to greater fuel-sodium heat transfer and a greater probability of an energetic FCI.

This chapter contains descriptions of the experimental objectives, initial conditions, and results. It includes descriptions of the single pulse experiments, a detailed discussion of the double pulse method, descriptions of the double pulse experiments, a discussion of the results of posttest radiography, and an overall summary of experimental observations.

4.1 Single Pulse Experiments

Seven single pulse experiments were conducted in the oxide/sodium series. These are summarized in Table III. All but one of these experiments (PBE-1S) were irradiated during maximum ACPR transients and all except PBE-1S resulted in cladding failure.

The objectives of the single pulse experiments were to examine energetics associated with several fuel energy states and to evaluate experimental effects on the results. PBE-1S was the first PBE experiment containing sodium and as such was a scoping experiment. Two fuel-energy states were examined in single-pulse experiments: One resulted in a maximum, radially averaged energy deposition

Table III. PBE Single Pulse Oxide Experiments

Experiment	Total Energy Deposition ⁽¹⁾ (J/g)	PWHM ⁽²⁾ (ms)	Reactor Yield (MJ)	Initial Temperature (K)	Pin Enrichment (%)	Comments
1S	1380	8.3	61	323	14	No Pin Damage
4S	2350	4.9	102	773	14	
5S	2350	4.8	103	773	14	
6S	2900	4.8	104	773	20	
7S	2900	4.8	103	773	20	
11S	2350	4.8	104	773	14	Cylindrical Spacer Sleeve
12S	2350	4.8	103	773	14	Capsule Assembly II

(1) Maximum Radially Averaged Energy Deposition

(2) Reactor Pulse Width at Half Maximum Amplitude

of 2350 J/g (PBE-4S, -5S, -11S, and -12S); the other yielded 2900 J/g (PBE-6S and -7S). PBE-11S and -12S were directed at understanding the effects of the coolant channel and fuel pin geometries on the experimental observations.

4.1.1 PBE-1S

The first oxide/sodium experiment (PBE-1S) was a scoping experiment which served to evaluate experiment methods and procedures. It involved a 14% enriched fuel pin irradiated during a moderate yield ACPR transient from an initial experiment temperature of 323K. Posttest examination indicated no pin damage and no fuel melting.

4.1.2 PBE-4S

The first experiment in which pin failure was expected was PBE-4S. To obtain the desired energy deposition (2350 J/g), a 14% enriched pin was irradiated during a single maximum pulse in the ACPR. The initial temperature was 773K. The pin failed about 2 ms after the peak of reactor power.* The piston displacement history and pressure histories from the top and bottom of the capsule are shown in Figure 7. A single high amplitude pressure transient was observed at the top and bottom of the capsule. A delayed pressure event was observed at the bottom of the capsule and is believed to have occurred when sodium reflooded the hot test section. The pressure history at the bottom of the capsule exhibits a train of pressure maxima decaying in amplitude. An explanation of this behavior is given in Section 5.3. Posttest examination of the experiment indicated that the rupture disc had broken during the experiment permitting the test channel to communicate with the safety plenum. This rupture reduced the pressure history at the top of the capsule and, hence, reduced the kinetic energy imparted to the piston.

4.1.3 PBE-5S

The amplitude of the observed pressure transient in PBE-4S was greater than anticipated. Since the same experiment assembly, including the fuel pin, had been used for PBE-1S, PBE-2S and PBE-4S, it was postulated that the pin had been damaged during the earlier transients and that such damage may have contributed to the observed PBE-4S pressure history. Therefore, the PBE-4S experiment conditions were repeated in PBE-5S except that the safety head assembly was modified to permit the rupture disc to survive high amplitude pressure transients but to still protect against sustained over pressurization. (As a result of these modifications, the rupture discs survived in all subsequent oxide/sodium experiments.) In PBE-5S the pin failed 2.8 msec after the peak of the power pulse (see footnote). The piston displacement and pressure histories

*Experimentally, pin failure was taken as the time the first significant pressure transient was indicated by the pressure transducers.

Figure 7. PBE-4S Data Histories (time of peak power, $T_p = 30.7$ ms).

are shown in Figure 8. A single large pressure transient was observed at both the top and bottom of the capsule. A delayed pressure transient was observed at the bottom. Note that the bottom pressure histories in PBE-4S and PBE-5S are nearly identical (see Figures 7 and 8). The negative going transient observed in the top transducer history in PBE-5S, after the piston was displaced, was the result of a thermal effect in the transducer as hot sodium and fuel moved past the sensing diaphragm. This effect contaminates the "later" portions of the measured pressure histories at the top of nearly every experiment. The oscillatory nature of the observed pressure histories can be explained by the channel acoustics (see Section 5.3).

4.1.4 PBE-6S

The PBE-6S experiment was designed to examine the effects of fuel energy deposition greater than that obtained in PBE-4S and -5S (2900 J/g compared to 2350 J/g). To accomplish this, a 20% enriched fuel pin was subjected to a single maximum ACPR pulse. The initial temperature was 773K. The piston displacement and pressure histories for PBE-6S are shown in Figure 9. A small pressure transient (~ 6 MPa) was observed at the bottom of the capsule ~ 1.6 ms after the peak of reactor power. A pressure disturbance was also recorded at that time at the top transducer. A very large pressure transient is noted 5 ms after the initial transient. Following the stoppage of the piston, a low amplitude pressure transient was observed at the top of the capsule. The exact nature of that transient, however, is lost in the thermal noise affecting the top transducer. The difference in pressure responses between the top and bottom of the capsule is most probably due to a channel obstruction. The cause of the delay between apparent pin failure and pressurization is not currently known.

4.1.5 PBE-7S

Because of the unusual pressure histories (particularly the delay between the initial pressure event and the large transient) observed in PBE-6S, the experiment was repeated in PBE-7S. Clad failure (see footnote on page 28) occurred 1.5 ms after the peak of reactor power. The piston displacement and pressure histories for PBE-7S are shown in Figure 10. The pressure history recorded at the bottom of the capsule is very similar to that observed in PBE-4S and PBE-5S. At the top of the capsule, however, a small pressure transient (~ 9 MPa) was observed coincident with the event at the bottom transducer. A second larger transient is recorded ~ 3 ms later. Again, as in PBE-6S, there appears to have been some isolation between the top and bottom of the test channel, and, perhaps, two different pressure sources were operant.

4.1.6 PBE-11S

The PBE-11S experiment was performed to investigate the effects of different sodium-to-fuel volume ratios. The original fluted molybdenum spacer sleeve

Figure 8. PBE-5S Data Histories (time of peak power, $T_p = 28.6$ ms).

Figure 9. PBE-6S Data Histories (time of peak power, $T_p = 30.1$ ms).

Figure 10. PBE-7S Data Histories (time of peak power, $T_p = 29.3$ ms).

includes three times the sodium volume per unit height of fuel that will be present in an FTR or CRBR subassembly. A cylindrical tube with an inside diameter (ID) equal to the minimum ID of the fluted tube (8.89mm) includes twice the prototypic amount of sodium and is compatible with existing PBE fuel pin designs.

The PBE-11S test was identical to the PBE-5S test except that the fluted molybdenum spacer sleeve was replaced by a 8.89 mm-ID cylindrical tube. The piston displacement and pressure histories for PBE-11S are shown in Figure 11. A single pressure event with peak amplitude of approximately 50.0 MPa was observed at the bottom transducer. A broad, low-amplitude pressure event (<2.0 MPa) was observed at the top pressure transducer. This low-amplitude pressurization was also reflected in the low-energy piston motion. The difference in response between the upper and lower pressure transducers may indicate the occurrence of a channel blockage between the pressure source and the top of the test channel. The posttest radiograph (see Section 4.4) shows evidence of such a blockage.

A comparison of the bottom pressure history shown in Figure 11 with the corresponding history from PBE-5S (Figure 8) indicates several differences. The pressurization occurred approximately 2 ms later relative to the reactor power pulse in PBE-11S. The pressure event had greater amplitude but shorter duration in PBE-11S. Finally, the acoustic "ring-down" observed in PBE-5S is much less apparent in PBE-11S. It is not yet possible to determine whether or not the differences observed between PBE-11S and -5S, aside from the apparent channel blockage, are a result of differences in molybdenum spacer sleeves.

4.1.7 PBE-12S

The PBE-12S experiment was performed to investigate the effects of the new pressure vessel geometry and single-ended fuel pin restraint on experimental results. This experiment involved irradiation of a 14 percent enriched fresh uranium dioxide fuel pin in sodium during a maximum ACPR pulse. A fluted molybdenum spacer sleeve was used, resulting in a cross-section through the fueled region identical to PBE-5S. The fission energy deposited in the fuel was the same in PBE-12S and PBE-5S.

A fuel pin identical to that used in PBE-5S was modified to be compatible with the new pressure vessel. The top spoke was removed. A stainless-steel extension was attached to the small spoke at the bottom of the fuel pin to provide a geometry similar to the German carbide PBE pins.⁽²⁾ This extension serves as the axial restraint for the fuel pin.

The piston displacement and pressure histories from PBE-12S are shown in Figure 12. (Note that two pressure transducers were located at the bottom of the capsule. Transducer A was rated 0-34.5 MPa and transducer B was rated 0-68.9 MPa by the manufacturer. The slight differences in the measured pressure histories

Figure 11. PBE-11S Data Histories (time of peak power, $T_p = 31.8$ ms).

Figure 12. PBE-12S Data Histories (time of peak power, $T_p = 30.9$ ms).

may be due to differences in frequency response between the two transducers. These histories are quite different from those obtained in PBE-5S (see Figure 8). A substantial delay (approximately 25 ms) is observed between the reactor pulse and the onset of pressurization, although the piston is accelerated by a low amplitude pressurization occurring 4-6 ms after the reactor pulse. Unlike other oxide/sodium experiments, multiple pressure transients are observed over a 15 ms time interval. A low amplitude sustained pressurization, decaying in ~25 ms, follows the high amplitude transients. There are substantial differences between the transducer responses at the top and bottom of the capsule, indicating some isolation between the ends. It is noted that the onset of pressure transient observed at the top of the capsule (indicated by the arrow in Figure 12) is coincident with the stop of the piston. An explanation of this coincidence is given in Section 5.2. It is important to note that the piston moved full travel and stopped while the channel was still pressurized. Thus the measured piston motion does not reflect the total work potential in the system.

As outlined below in Section 5.1, with a suitable vapor pressure model, it is possible to describe the PBE-5S results solely in terms of fuel vapor pressure. The long delay (approximately 25 ms after peak of reactor power) and the multiplicity of pressure events in PBE-12S are not consistent with a fuel vapor pressure explanation alone. Thus the observed pressure transients most probably result from sodium pressurization caused by localized thermal interactions between sodium and molten fuel.

4.2 Rationale for Double Pulse Irradiations

The irradiation of enriched fuel pins in a thermalized neutron flux results in a non-uniform fission density distribution that is peaked at the pin surface and depressed towards the center, as shown in Figure 6. Because of the very short heating times in the PBE experiments, this fission density profile results in temperature distributions that are peaked near the fuel surface. This can be seen in Figure 13 which displays the results of a thermal analysis (using TAC-2D⁽⁷⁾) of a 20% enriched pin irradiated during a single maximum pulse in the ACPR. These temperature profiles are very different from those expected during a severe LMFBR accident in which peak fuel temperatures would occur on the pin centerline.

The effects of the depressed fission density distribution were mitigated and the "prototypic" temperature profiles were approximated by using a double pulse mode on the ACPR. In this mode the transient control elements of the ACPR were ejected sequentially to yield a small burst followed, after a suitable delay by a larger second pulse. Typical temperature histories (from TAC2D analyses) during an "ideal" double pulse irradiation are shown in Figure 14. Note that the first pulse and subsequent thermal relaxation time result in a temperature distribution before the second pulse which is peaked at the center with a steep gradient

Figure 13. Typical Temperature Profiles - Single Pulse Experiment.

Figure 14. Temperature Histories During an "Ideal" Double Pulse Irradiation.

to the surface. This profile was combined with energy deposited during the second pulse to yield temperature profiles during the second pulse that are always peaked at the fuel centerline as shown in Figure 15. The actual temperature profiles attained during an experiment are dependent on the total energy deposition, the portion of energy between the two pulses, and the delay between pulses.

4.3 Double Pulse Experiments

Double pulse irradiation was the only operating mode permitted in the ACPR control system which would yield approximately prototypic fuel temperature distributions during the PBE test transient (see Section 4.2). Failure of a pin in which the peak fuel temperature and, hence, vapor pressure are inside the pin should yield more substantial mixing of molten fuel and sodium before the channel is voided than in a single pulse PBE-experiment in which the peak temperature is near the fuel surface. Thus the probability of a molten fuel-coolant interaction is increased. The object of the double pulse experiments was to examine prompt burst energetics in such an environment.

Five double pulse irradiations were performed in the series of oxide/sodium experiments. These are summarized in Table IV. (Note that the experiments were performed in the order listed with PBE-10S preceding PBE-8S.) As shown, these experiments spanned a range of total fission energy deposition and reactor power histories.

An energetic pin failure occurred only in one double pulse experiment, PBE-9S. Since the double pulse experiments paralleled the development of the EXPAND pin failure model, pre-experiment modeling consisted primarily of thermal analysis with emphasis on the fuel temperatures and vapor pressures. These experiments ultimately demonstrated the importance of the thermal state of the cladding to pin failure. Thus, although information about accident energetics was obtained only in PBE-9S, the results of the other experiments greatly aided the development and validation of the EXPAND pin failure model.

PBE-2S was the first double pulse experiment and, like PBE-1S, was a scoping experiment. The reactor transient used for PBE-3S resulted in the maximum reactor yield obtainable in the double pulse mode using the normal ACPR transient control rods. A program was subsequently undertaken to enhance the reactor yield by increasing the reactivity worth of the two fast transient control elements. Three experiments (PBE-10S, -8S, and -9S) utilized the upgraded transient rods, and these followed a progression of reactor power histories leading to an energetic failure in PBE-9S.

4.3.1 PBE-2S

PBE-2S, a scoping experiment, involved a 14% enriched fuel pin and an initial temperature of 523K. The interval between pulses was 0.800s but slight errors in the transient rod timing resulted in a reduced reactor yield. Posttest examination of the experiment indicated no pin damage and no melting of fuel.

Figure 15. Temperature Profiles During an "Ideal" Double Pulse Irradiation.

Table IV. PBE Double Pulse Oxide Experiments

Experiment	Total Energy Deposition ⁽¹⁾ (J/g)	Interval Between Pulses (sec)	Reactor Prompt Yield		Comment
			First Pulse (MJ)	Second Pulse (MJ)	
PBE-2S	1390	0.800	18.1	14.8	No Pin Damage
PBE-3S	2180	.779	18.1	29.8	Pin Deformed-No Failure
PBE-10S	2530	1.448	28.6	30.1	Pin Deformed-No Failure
PBE-8S	2580	1.461	17.0	46.4	Pin Deformed-No Failure
PBE-9S	2680	0.459	17.0	49.1	Gross Pin Failure

(1) Maximum Radially Averaged Energy Deposition

4.3.2 PBE-3S

In PBE-3S a 20% enriched pin was subjected to a maximum yield double pulse using the normal ACPR transient rods. The interval between pulses was 0.825 sec and the initial temperature was 600K. The pin did not fail but posttest radiographs (see Section 4.4) indicated substantial fuel melting and deformation of the pin away from the wire wrap.

4.3.3 ACPR Transient Rod Upgrade

The total reactor yield (and, thus, the energy deposition in the experiment) is reduced during double pulse operations compared to single pulse operations. This decrease results from negative reactivity feedback due to ACPR fuel heating during the first pulse. From PBE-3S it was apparent that greater energy deposition was necessary to fail the cladding. Because of the already steep radial fission density profile in the 20% enriched fuel, it was not desirable to increase the fuel enrichment. The polyethylene moderator thickness was already optimal. Thus, increased energy deposition could be obtained only by increasing the reactor yield.

To increase the reactor yield during double pulse operations, a program was undertaken to increase the reactivity worth of the ACPR fast transient rods. This was accomplished by replacing the two normal fast transient rods which contain natural B_4C with rods containing 93 percent ^{10}B enriched B_4C . All mechanical design characteristics of the rods were identical. The net result was to increase the reactivity worth of the transient rod bank from \$4.50 to nearly \$5.00, thus increasing the reactor yield during pulse operations. Three double pulse experiments were performed using the upgraded transient rods.

4.3.4 PBE-10S

In PBE-10S a 20% enriched fuel pin was used with an initial temperature at 773K. In the experiment, one upgraded fast transient rod was ejected to produce the first pulse followed ~1.5 s later by a slightly larger second pulse derived by ejection of the other upgraded fast transient rod and the adjustable transient rod. The thermal analysis described above (Figures 14 and 15) indicated that this distribution of energy between the two pulses coupled with the 1.5 s delay would yield the optimum fuel temperature distributions peaked at the fuel centerline throughout the second pulse.

The experiment did not result in clad failure. Posttest radiographs (see Section 4.4) showed distortion of the pin away from the wire wrap, much as was observed in PBE-3S. A large central void extending over about half the length of the fuel pin did appear, indicating gross fuel melting.

4.3.5 PBE-8S

In an attempt to cause pin failure, the pulse sequence used in PBE-10S was modified for PBE-8S. For PBE-8S, the adjustable transient rod was ejected

first, followed at 1.5 s by the two upgraded fast transient rods. This resulted in a smaller first pulse and a considerably larger second pulse compared with PBE-10S but with the same thermal relaxation time. The difference in distribution of energy between the two experiments yielded higher fuel temperatures in PBE-8S, resulting in higher fuel vapor pressure, a steeper temperature gradient in the clad, and thus higher stress in clad. The peak fuel temperature was still near the fuel centerline.

In PBE-8S, as in the previous double pulse experiments, the clad did not fail. Posttest radiography showed the pin to be more severely distorted than in PBE-10S, again twisted away from the wire wrap. A central void was again apparent extending nearly the full length of the fuel column. These differences in distortion and central void are consistent with the differences in energy input described above.

While PBE-10S and -8S yield little information about energetics of disrupted fuel-coolant systems, they did provide information useful to the development of clad stress-strain models and failure criteria important to the analysis of all PBE experiments.

4.3.6 PBE-9S

The overall intent of these double-pulse experiments was to create an environment in which liquid or solid fuel could be driven into the sodium-filled channel by fuel vapor pressure inside the fuel. In PBE-10S and -8S, optimum temperature distribution (that is, ones peaked at the fuel centerline) were produced, but the pins did not fail. In PBE-9S, that distribution was compromised to yield an environment in which the peak fuel temperature was inside the fuel (but not necessarily at the centerline) and which would result in pin failure.

In this experiment, the same pulse sequence as PBE-8S was used except the interval between pulses was reduced to 0.5 s. The first pulse was thus the same as in PBE-8S, but the second pulse was somewhat larger due to a decrease in temperature reactivity feedback in the ACPR fuel. As is shown in Figure 16, the result was a temperature distribution, at the time of pin failure, that is peaked about one-fourth of the distance into the pin.

The pin failed slightly before the peak of the second reactor pulse (see footnote on page 28). The piston displacement history and pressure histories measured at the top and bottom of the experiment are shown in Figure 17. Two large pressure events ~8 ms apart are observed at the top of the capsule. A sustained lower amplitude pressurization is observed for about 25 ms after the second pressure event. (Negative transient thermal effects in the top transducer contaminate the later portion of the measured pressure history.) Only the first large pressure event and the sustained lower amplitude pressurization are observed at the bottom of the capsule. It is noted that the onset of the second pressure

Figure 16. Temperature Profiles Predicted for PBE-9S.

Figure 17. PBE-9S Data Histories (time of peak power, $T_p = 540.4$ ms).

transient at the top transducer is coincident with the stop of the piston. An explanation of this coincidence is given in Section 5.2. Clearly, since the channel remains pressurized long after the piston stops, the piston motion does not reflect the total work potential of the system.

4.4 Posttest Radiography

Before and after irradiation, each experiment assembly is X-radiographed. Ultimately each assembly will be disassembled and a detailed postmortem examination will be completed. The PIE's are in progress with work completed on PBE-3S, -4S and -7S. However, the results of the PIE's are deferred to a later report, and only information extracted from the post irradiation radiographs is presented here.

Copies of the posttest radiographs of the experiments PBE-3S through PBE-12S are shown in Figures 18 and 19. Note that the images in Figure 18 appear as they do in the radiograph (fuel appears white), while in Figure 19 the images are reversed (fuel appears black).

The radiographs of the experiments where pin failure occurred (PBE-4S, -5S, -6S, -7S, -9S, -11S, and -12S) show gross disruptions of the fueled region of the experiment. For PBE-4S and -5S and PBE-6S and -7S, significant voiding of fuel and cladding from the hottest regions of the experiment is noted. The lengths of the voided regions are greater in PBE-6S and -7S than in PBE-4S and -5S. Accumulations of debris above and below the voided portion of the experiment is evident, with quantities of fuel along the outside of the unheated portion of the clad above the insulator pellet. Intact segments of clad remain at the top and bottom of the pin. These segments originally contained enriched fuel but now are nearly voided of fuel. Axial expansion of the fuel column sufficient to totally compress the plenum spring is indicated by the scratch gauge positions. This implies an axial expansion of approximately 50 mm which represents 15% of the original fuel height.

For PBE-11S much less voiding of the hot region is evident. A significant length of intact cladding containing fuel is noted in the top half of the radiograph indicating that portion of the pin remained in sodium. A concentration of fuel is noted at 5-6 cm above the core midplane. This may be a channel blockage as suggested in Section 4.1.6. An axial expansion of approximately 25 mm is indicated by the scratch gauge position.

The pin used in PBE-12S was modified with a "standoff adapter" to position and constrain the pin in the Assembly II capsule. The radiograph indicates that the weld joining the two parts of the adapter failed permitting the bottom of the pin to move upward ~45 mm. The top of the pin in the Assembly II configuration is not constrained axially after pin disruption. The radiograph shows that the top of the pin was displaced ~100 mm upward. Intact segments of cladding, ~90 mm

PROMPT BURST EXCURSION EXPERIMENTS
POST TEST RADIOGRAPHS

Sandia Laboratories

Figure 18. Posttest Radiographs of PBE-3S, -4S, -5S, and -6S.

Figure 19. Posttest Radiographs of PBE-7S, -8S, -9S, -10S, -11S, and -12S.

long at the bottom and ~50 mm long at the top are observed. These segments are partially voided of fuel. Much fuel debris remains in the hot portion of the channel with a region nearly voided of fuel and clad appearing near the top of the fuel pin housing. This voided space may just reflect the upward displacement of the top of the pin.

The radiographs of the three double pulse experiments (PBE-3S, PBE-10S and PBE-8S) in which the clad did not fail, all show the pins to be distorted away from the wire wrap resulting in a helical shape. Longitudinal voids can be seen at the centers of the fuel pins. These reflect the relocation of fuel porosity following melt and resolidification. The lengths of the voids (a quarter of the fuel length in PBE-3S, one half the fuel length in PBE-10S, and nearly the entire fuel length in PBE-8S) are consistent with the relative amounts of energy deposited (PBE-8S greater than PBE-10S, greater than PBE-3S).

The radiograph of PBE-9S indicates a breach in the Inconel pressure vessel which permitted most of the sodium and fuel to escape the pressure capsule and to flow into the containment canister. The breach location corresponds to a point at which a channel thermocouple penetrates the molybdenum liner, permitting fuel to reach the pressure vessel. A flaw in the beryllium heat sink at that point also contributed to the failure. An examination of the breach indicated that the failure was by melting and was not a pressure driven rupture.

4.5 Summary of Experiment Results

Measured experiment results from the seven oxide/sodium experiments which resulted in pin failure are summarized in Table V. With the exception of PBE-12S, pin failure, as indicated by significant pressurization, occurred near the peak of reactor power in all experiments. A substantial delay (24.3 ms) was observed in PBE-12S.

In most experiments (PBE-9S and -12S excepted) single short duration pressure transients were observed. In PBE-9S and PBE-12S multiple pressure events and lower amplitude sustained pressure "tails" were observed. The maximum pressure observed at the top transducers was less than 32 MPa; while the peak pressure observed at a bottom transducer was 64 MPa. In all experiments the measured pressure at the top of the capsule was less than at the bottom. These differences were due largely to acoustics and piston motion as is described in Section 5.3. Some of the differences as noted, can also be attributed to channel obstructions.

The maximum radially averaged energy depositions (line 4) ranged from 2350 J/g to 2900 J/g resulting in total energy depositions ranging from 130 to 162 kJ per pin (line 5). The minor differences between total energy depositions is due to small differences in the mass of fuel in each experiment.

Table V. PBE Oxide Experimental Results

	PBE-4S	PBE-5S	PBE-6S	PBE-7S	PBE-9S	PBE-11S	PBE-12S
1) Time to Significant Pressurization ⁽¹⁾ (ms)	2.2	2.8	1.6	1.5	-1.8	3.7	24.3
2) Maximum Pressure Amplitude at top (MPa)	28.0	31.2	14.8	27.2	31.1	1.3	7.8
3) Maximum Pressure Amplitude at Bottom (MPa)	45.5	47.3	64.0	37.4	53.9	55.7	13.0/27.2
4) Maximum Radially Averaged Energy Deposition (J/g)	2350	2350	2900	2900	2680	2350	2350
5) Total Energy Deposition (KJ)	129.7	130.0	158.1	161.5	147.9	129.8	129.8
6) Maximum Measured Piston Velocity (M/S)	5.4	11.4	9.8	9.2	13.8	2.2	9.8
7) Measured Piston Kinetic Energy (J)	6.4	28.5	20.8	18.5	41.5	1.0	20.9
8) Total Energy Deposited at Peak Piston Momentum (kJ)	102.4	123.1	131.2	132.4	98.9	107.7	107.9
9) Measured Energy Conversion Ratio	6.3×10^{-5}	2.3×10^{-4}	1.6×10^{-4}	1.4×10^{-4}	4.2×10^{-4}	9.4×10^{-6}	1.9×10^{-4}

(1) Time from Peak of Power Pulse to Significant (≥ 3 MPa) Pressurization

From the measured piston displacement histories, piston velocities (line 6) and, hence, piston kinetic energies (line 7) can be derived. The kinetic energies shown were based on only the masses of the piston and linear motion transducer armature. If the mass of the sodium column above the core midplane is included the kinetic energy values would be about 5% greater. As shown in the Table, maximum piston velocities ranged from 2.2 to 13.8 m/s and maximum kinetic energies ranging from 1.0 to 41.5 J.

The total fission energies deposited in the experiment at the time of maximum piston momentum (line 8) were derived from the measured power histories and the energy deposition calibrations. An estimate of the fraction of fission energy that is converted to work can be derived as the ratio of the value shown in line 7 to the value shown in line 8 for each experiment. These energy conversion ratios (line 9 in Table V) are small for all of the experiments. The greatest value is 4.2×10^{-4} for PBE-9S. As was noted earlier, however, the pistons in PBE-9S and -12S stopped while the channels were still pressurized. Thus the energy conversion ratios derived from piston motion do not reflect the total work potentials of those systems.

As is shown in Appendix A, estimates of piston kinetic energy and energy conversion ratio can be derived from integrals of the pressure histories. The results of that analysis are shown in Table VI. It is noted that a comparison of the values of piston velocity and kinetic energy derived from this analysis with the measured values in Table V shows very good agreement for PBE-4S, -5S, -6S, and -7S. (The integral for PBE-11S could not be evaluated because of a lack of resolution for the top pressure history.) For PBE-12S the derived kinetic energy is approximately 50% greater than the measured value. For PBE-9S the estimate of the kinetic energy derived from the pressure integral is nearly fifteen times greater than the measured value. This translates into a thermal to mechanical energy conversion ratio of 0.54% for PBE-9S.

It should be pointed out that computation of the pressure integrals after piston motion is complicated by the thermally induced transients in the pressure transducer. Thus, some uncertainties are introduced in that analysis. It should also be noted that the system boundary condition changes when the piston stops clearly affecting the measured pressure histories.

Table VI. Results Derived from Pressure Integrals

	PBE-4S	PBE-5S	PBE-6S	PBE-7S	PBE-9S	PBE-11S	PBE-12S
1) Maximum Pressure Integral (kPa·S)	9.0	19.6	16.0	16.3	98.3	-	22.2
2) Derived Piston Velocity (m/s)	4.9	10.6	8.7	8.8	53.2	-	12.0
3) Derived Piston Kinetic Energy (J)	5.2	24.5	16.4	17.0	613.	-	31.4
4) Derived Energy Conversion Ratio	5.1×10^{-5}	2.0×10^{-4}	1.25×10^{-4}	1.28×10^{-4}	5.4×10^{-3}	-	2.9×10^{-4}

5. PBE ANALYSIS

The principle phenomena under investigation in the PBE experiment are as follows:

- (1) Prefailure axial fuel motion toward the pin ends. This is of interest as a feedback mechanism adding negative reactivity during a prompt burst. Total internal motion is recorded on an internal passive scratch gauge; this amounts to 15% of the fuel column length, which is the maximum travel of the gauge.
- (2) Time and location of clad failure. This influences subsequent voiding of the fuel pin.
- (3) Thermophysical state of fuel and coolant at failure. This gives initial conditions for fuel-coolant motion, mixing, and heat transfer.
- (4) Fuel voiding from the pin into the channel. It has been observed in postmortem examination that the intact clad ends (roughly 5-10 cm long) are completely voided of fuel. This is a possible mechanism for adding reactivity via fuel motion toward the break location, possibly prolonging the prompt burst and increasing the severity of the disassembly.
- (5) Fuel-coolant interactions, including mixing, heat transfer, and fragmentation mechanisms. No model is available at the present time that correctly describes all important aspects of fuel-coolant interactions. While parametric approaches have been done, the parameters are not physically observable. A mechanistic approach would utilize input variables that are experimentally observable.
- (6) Channel-piston effects on pressure transducer response. This must be determined to evaluate the break pressure source from the transducer data.
- (7) Effect of piston stopping as an FCI trigger. This was observed in several tests, and the magnitude of the sodium pressurization as a result of piston deceleration was evaluated.

Of the above topics, (1), (2), and (3) have been analyzed with the EXPAND pin failure model. Item (4) is under investigation with SIMMER-II and EPIC. A model has yet to be developed for (5). The CSQ-II hydrodynamic code was used to investigate (6), and (7) was examined with HONDO, a transient finite deformation code.

5.1 Pin Failure Modeling

Fuel motion before failure and the temperature and pressure in the pin and channel are modeled by the EXPAND pin model.⁽⁸⁾ The code is described in detail in Appendix B; this section will deal with the results obtained.

Table VII compares EXPAND calculations for time of failure and fuel vapor pressure at failure to experimental data. Tests selected for comparison are PBE-5S, -7S, -3S, -10S, -8S, and -9S.

Failure times for the single pulse tests -5S and -7S are in excellent agreement with experiment. Fuel vapor pressures are calculated using a true lower pressure bound; uncertainty in the fuel equation-of-state is about a factor of 2, so actual pressures could be up to a factor of 2 higher. There is an additional doubling effect at the lower pressure transducer due to channel geometry effects (discussed in Section 5.3). The fuel vapor pressure in the single pulse tests is comparable to that recorded on the lower transducer, taking these factors into account.

In the double pulse tests, the no failure experimental result was duplicated in -3S and -10S. Experiment PBE-8S was calculated to fail at 58 ms past the main power peak, whereas the -8S experiment did not fail, although experimental data indicates it was very close. Experiment PBE-9S was predicted to fail at 11 ms, considerably longer than the experimental time of -1.8 ms.

The EXPAND results for -5S, -7S, -3S, -10S, -8S, and -9S are summarized in more detail in Table VIII. The failure times in parentheses are the result of varying energy depositions and (for the single pulse tests) radial peaking factors. For a $\pm 10\%$ variation in energy and peak/minimum ratio (together), the single pulse tests show less than ± 1 ms variation in failure time, which is excellent. Varying the energy deposition $\pm 5\%$ for -3S and -10S produced no failure, and variations in the life fraction integral from 0.3 to 0.7. PBE-8S failed at the same time in all cases, and -9S exhibited an asymmetric behavior, that is, $+5\%$ in energy produced a 2 ms decrease in failure time, but reducing energy input by 5% resulted in a 49 ms increase. This difference is due to the fuel surface melting in the $+5\%$ cases increasing heat transfer to the cladding and resulting in early failure, and not melting in the -5% case. If the fuel surface does not melt, the normal contact resistance and gas conductance is assumed for the clad-fuel gap, hence, much less heat is transferred and the clad fails much later.

The calculation of -8S invariably failing at 58 ms is probably also due to the fuel surface melting. As noted elsewhere, failure time is very sensitive to heat transfer in the fuel-clad-coolant system.

During the transient, an extreme thermal gradient of about 800K is developed across the clad, peaking on the inner clad surface. This can be seen in Figure 20. The figure shows calculations for 3 and 11 finite difference nodes in the clad for PBE-5S at failure; the coarser 3 node case results in failure about 0.4 ms earlier. The effect of this extreme thermal gradient on the clad stress is shown in Figure 21. The curve marked "EXPAND" shows a compressive hoop stress on the inner clad region and a tensile hoop stress on the outside;

Table VII. Comparison of EXPAND Results with Experiment

PBE Case	Total Energy Deposition (J/g)	Failure (1) Time (ms)		Energy In At Failure (J/g)		Pressure At Failure (MPa)	
		A	B	A	B	A	B ⁽²⁾
5S	2350	3.0	2.8	1790	1760	9.7	47.3
7S	2900	1.7	1.5	2450	2400	22.5	37.4
3S	2180	None	None	-	-	-	-
10S	2530	None	None	-	-	-	-
8S	2580	58.1	None	1970	-	1.5	-
9S	2680	10.9	-1.8	1880	985	4.4	53.9

(1) Referenced to Main Power Peak

(2) Measured at Lower Pressure Transducer

A = EXPAND calculation

B = Experimental Result

Table VIII. EXPAND Results

Case	Failure Time ⁽¹⁾ (ms)	Pin Pressure At Failure (MPa)	Maximum Clad Strain (%)	Average Clad Temperature At Failure (K)	Energy Deposited To Failure (J/g)
5S	3.0 (2.2-3.8) ⁽²⁾	9.7	2.1	1090	1790
7S	1.7 (0.9-2.5) ⁽²⁾	22.5	1.9	1050	2450
3S	Life Fraction = 0.47	-	1.4	-	2180
10S	Life Fraction = 0.49	-	2.1	-	2530
8S	58.1 (58.1 - 58.1) ⁽³⁾	1.5	2.2	1150	1970
9S	10.9 (8.1 - 60.1) ⁽³⁾	4.4	2.5	1290	1880

(1) Referenced to Main Power Peak

(2) Energy and Radial Peak/Minimum Ratio Both Varied $\pm 10\%$

(3) Energy Varied $\pm 5\%$

CLAD TEMPERATURE VS RADIUS AT 3 MS (PBE-5S)

Figure 20. Clad Temperature vs. Radius at 3 ms (PBE-5S).

CLAD HOOP STRESS VS RADIUS AT 3 MS (PBE-5S)

Figure 21. Clad Hoop Stress vs. Radius at 3 ms (PBE-5S).

both stresses are in the plastic regimes. The nearly flat curve is the hoop stress resulting from the same internal pressure but without the thermal gradient. This is insufficient to cause plastic flow and large strains. Based on a Larson-Miller Parameter or burst rupture failure criterion, the pin would fail much later in the transient, if at all, in the absence of a thermal gradient causing a large hoop stress. Other general features of the PBE series that have been noted in the EXPAND results are:

- (1) The fuel fractures early in the transient (5ms before the first power peak).
- (2) The fuel melts almost completely by the time of the power peak; this is 2-5 ms before significant pressurization occurs.
- (3) Clad loading is by internal gas pressure and thermal gradient rather than differential thermal expansion.
- (4) About 50-60% of the recorded axial fuel motion is predicted to occur prior to pin failure. A fuel motion diagnostic system is necessary to confirm this.
- (5) Clad failure criteria are strongly influenced by the average clad temperature via the Young's modulus and yield surface dependence.

It has been noted that an accurate treatment of the gap conductance is essential to predicting failure time, as this factor influences both the average clad temperature and the thermal gradient across it. The EXPAND model includes temperature-dependent gas conductance corrected by accommodation coefficients, fuel-clad mechanical contact⁽⁹⁾, fuel-clad expansion, and molten fuel-clad contact.

5.2 Piston Stopping Effects

A coincidence has been observed between the stopping of the piston and a secondary pulse on the top pressure transducer in several experiments. In -9S, the secondary pulse was on the order of 30 MPa. It was hypothesized that this was an FCI triggered by a pressure pulse in the top sodium slug generated by piston deceleration.

A calculation was done using HONDO⁽¹⁰⁾, a transient finite deformation code, to determine the magnitude and duration of the pressure pulse caused by piston stoppage. The piston, deformable sleeve, and sodium column were modeled as in Figure 22.

Mechanical properties for the piston (Mallory M-1000 tungsten alloy) were evaluated at 773K, and for the sleeve (4130-D4 stainless steel) at 593K. The sodium slug was assumed to be at 773K and to have a mass of 21 grams. An initial velocity of 13.8 m/s was used, which is the same as that observed in -9S. This piston-sodium slug was calculated to stop in 0.55 ms and travel 0.54 cm into the

Figure 22. HONDO MODEL OF PISTON-SLEEVE

sleeve. The distance actually travelled in the experiment was 0.8 cm. The bulk pressurization of the sodium slug is summarized in Table IX; this gives pressure and pulse width at half maximum at several distances from the piston face. It is seen that pressure falls off linearly with distance, becoming zero at the end of the sodium column.

Table IX. Sodium Pressure at Several Distances from Piston Face

Peak Bulk Pressure (MPa)	Distance from Piston Face (cm)	PWHM (ms)
4.7	2.51	0.32
2.7	6.27	0.37
* 1.8	8.78	0.38

* Peak occurs at 0.45 ms

The last entry (8.78 cm) is closest to the pressure transducer location; comparing the bulk pressure due to deceleration (1.8 MPa) to that recorded by the pressure transducer (32 MPa), it is seen that the piston stoppage is sufficient to generate a trigger pulse, but is not enough to account for the recorded pressure. Together with the absence of fuel vapor pressure at this time in the experiment, this strongly indicates the presence of an FCI. Recent work by Patel and Theofanus ⁽¹¹⁾ in liquid-liquid systems gave an estimate of the trigger pressure necessary to cause vapor explosions in the Na-UO₂ system as around 4 MPa, of the same order as that caused by piston stoppage in -9S. The pressure pulse calculated by HONDO for -9S at the top transducer location is shown in Figure 23.

The top pressure histories recorded in PBE-5S, -6S, and -7S display pressure transients having amplitudes of 1-2 MPa occurring coincident with the piston stoppage. (See Figures 8, 9, and 10.) These transients were apparently not sufficient to trigger FCI's in those experiments, but their occurrence supports the validity of the HONDO analysis.

In PBE-12S the observed transient (coincident with piston stoppage) was ~4 MPa (see Figure 12). This amplitude is greater than the calculated bulk pressure due to piston deceleration. The piston velocity in PBE-12S was approximately the same as those measured in PBE-5S, -6S, and -7S (see Table V). However, because of differences in the PBE-12S experiment geometry compared to the other experiments, the mass of the moving sodium (and fuel) column may have been greater in -12S. Thus, it cannot be concluded that the coincident pressure maximum in PBE-12S (indicated by the arrow in Figure 12) resulted from a triggered FCI rather than from bulk pressurization of the sodium upon deceleration.

Figure 23. Sodium Pressurization.

5.3 Channel-Piston Hydrodynamic Effects

Pressures generated in these experiments were recorded by a pressure transducer located at the top and bottom of a sodium channel surrounding a single, fresh UO_2 fuel pin. Work energy conversion was measured by a linear motion transducer connected to a piston at the top of the sodium column. Since the pressure transducers were located fairly far from the location of pin failure, it becomes necessary to determine the effect of channel geometry and piston motion on the observed pressure data. A two-dimensional, hydrodynamic analysis of pressure pulse propagation in the fuel pin-coolant channel geometry was therefore performed using the CSQII computer code.⁽¹²⁾

CSQII is a coupled hydrodynamic-radiation transport code. It uses an Eulerian mesh and incorporates a very complete equation-of-state package, capable of handling liquids, gasses, elastic-plastic solids, porous media, and explosives; phase transitions are included.

The PBE-5S experiment was selected for analysis, since the data are reasonably typical of the whole sodium-in series. Figures 24a and 25a show the recorded pressure data. The failure location was about 14 cm from the bottom of the fuel column.

The model used in the calculations is shown in Figure 26. The computer simulations were started from time of failure and extended 2 to 3 ms in real time. The basic model consisted of fuel material at a constant pressure (200 bar) connected to the sodium channel via a 1.8 cm^2 break. Clad and structure were represented as fixed boundaries; initially no piston motion or heat transfer were included. Figures 24b and 25b give the results of this case. The peak pressure at both transducer locations is 2.2 times pin pressure, and pulse width and periods roughly match the experiment. Decay of the pulse train is not as rapid.

A second case, incorporating a free piston at the channel top in the model, is shown in Figures 24c and 25c. The bottom/top pressure ratio (1.57) now matches the experiment (1.52) and three pulses are seen at the top. In PBE-5S, only two pulses are seen at the top; this is probably because the driving pressure in the experiment has died away by the time of occurrence (about 33.6 ms). A second possible effect, seen in a CSQII calculation with a lower pin pressure (60 bar), is that the piston will outrun the sodium column, again resulting in no third pulse.

A third case, incorporating heat transfer between fuel and sodium, was computed but did not agree well with experimental data. High sodium pressures were generated due to the thermal equilibrium assumption of CSQII when dealing with mixed UO_2/Na mesh cells. Pulse train damping was faster than in PBE-5S. Results of the calculations are compared to experiment in Table X.

Figure 24. Comparison of Bottom Pressure Transducer to CSQII.

Figure 25. Comparison of Top Pressure Transducer to CSQII.

CSQ II MODEL OF PIN-CHANNEL GEOMETRY

Figure 26. CSQII Model of Pin-Channel Geometry.

Table X. Comparison of PBE-5S and Hydrodynamic Calculations.

	PBE-5S		CSQII FREE		CSQII FIXED	
	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM
FIRST PEAK						
P_1 (MPa)	31.56	42.31	28.57	44.90	43.40	45.37
PWHM (MS)	0.35	0.3	0.19	0.21	0.37	0.2
SECOND PEAK						
P_2 (MPa)	11.02	22.18	12.24	35.71	33.54	40.48
PWHM (MS)	0.35	0.35	0.2	0.21	0.4	0.24
P_2 / P_1	0.35	0.52	0.43	0.80	0.77	0.89
P_1 / P_{UO_2}	1.6*	2.1*	1.44	2.28	2.2	2.3
τ (MS)	1.02	0.6	0.9	0.4	0.7	0.4
BOTTOM / TOP PRESSURE RATIO:	1.52		1.57		1.1	

The hydrodynamic calculations were thus able to identify mechanisms responsible for some of the features in the recorded pressure data. The effect of the free piston in reducing the top transducer pressure was demonstrated and an upper limit on pressure multiplication obtained. Pulse widths and periods were also reproduced.

5.4 Pin-Channel Voiding Behavior

This topic is still under investigation. Preliminary calculations done with EPIC⁽¹³⁾, an FCI code, demonstrated voiding of the pin ends similar to that observed in the PBE postmortems, occurring during the piston motion. Pressure histories in the channel were not expected to be duplicated, partly due to the incompressible treatment of the sodium slugs in EPIC, and the simple Cho-Wright FCI model in the code. However, the pin voiding behavior is probably more sensitive to the overall channel voiding history and hence piston motion, than to the detailed pressure history. On this basis, somewhere between 10 and 30 grams of fuel are voided from the pin during piston motion (lasting about 8 ms), based on very rough calculations. More refined calculations will be done using a modified version of EPIC. A cooperative effort with LASL is also underway to follow the -5S experiment from initial pin failure through piston stoppage using SIMMER-II.⁽¹⁴⁾

6. CONCLUSIONS

A number of conclusions can be drawn from this work and areas of future experimentation and modeling with fresh oxide fuel in sodium can be identified.

The development of the EXPAND pin failure model, which incorporates those phenomena occurring during prompt burst excursions, provides a tool uniquely applicable to experiment and accident analysis. For the experiments described herein and for accidents representative of those conditions, pin failure is by stress rupture of the cladding with the temperature gradient and average temperature of the cladding being most important in predicting pin failure.

In the experiments high amplitude pressures up to 64 MPa were observed. The pressure histories included single and multiple high pressure short duration transients followed, in some experiments, by lower amplitude sustained pressurizations which decay in less than 35 ms. The timing and magnitudes of the initial pressure transients (except in PBE-12S) when compared with EXPAND results appear to be consistent with the fuel vapor pressure predicted at failure (within a factor of two uncertainty). The character of the pressure histories observed at the top and bottom of the capsule were described with CSQII analysis in terms of the channel acoustics with piston motion. That analysis implies that the pressure source must decay in 3-5 ms.

The rapid quenching of fuel vapor arises from prototypic mechanisms (heat transfer to clad and coolant) and nonprototypic mechanisms (heat transfer to cold vessel walls). Presently, no model exists to describe the observed quenching phenomena. The decay of the low amplitude, sustained, sodium vapor pressurization most certainly arises from heat transfer to the vessel walls.

The secondary pressure transients and sustained pressurizations cannot be described in terms of fuel vapor pressure. These certainly result from single phase sodium expansion and pressurization resulting from molten-fuel-coolant thermal interactions (FCI). FCI may also contribute to the initial pressurizations; however, a partition of the initial pressurization between fuel vapor and sodium is not now possible. The observed coincidence of high amplitude pressure transients with piston deceleration coupled with the results of the HONDO analysis, leads to the conclusion that those pressure transients result from triggered FCI with trigger pressures of the order of 2-3 MPa. The observed triggering of FCI suggests that the possibility of coherent pressurization in a larger system must not be overlooked in future safety analysis. No mechanistic model(s) exist to describe the mixing, fragmentation, and heat transfer that lead to the observed FCI. There appears to be no agreement on the conditions necessary for the occurrence of FCI.

The measured thermal energy to work conversion efficiencies were small (4.2×10^{-4}). The inclusion of the work potential represented by the channel

pressure after piston stopping implies conversion efficiencies more than an order of magnitude greater (0.54% for PBE-9S). One-half percent is, however, still a very small conversion ratio. It should be noted that the single pin experiment includes abnormally high heat losses for fuel and sodium as well as restricted mixing volumes. These experimental effects would tend to reduce the experimentally implied energy conversion.

The axial fuel expansion observed post-experiment and predicted by EXPAND could represent a significant prompt negative reactivity feedback in the reactor system which could lead to reduction of the accident excursion and thus the total energy released. The voiding of fuel toward the clad failure that is implied by the voided cladding found in the posttest examinations and which appears to be predicted by EPIC could also result in reactivity changes. The sign and magnitude of the change would depend on axial failure location and movement of fuel in the coolant channel after exiting the cladding breach.

Clearly, additional experimentation and analytic model development is needed to fully understand the response of fresh oxide fuel in sodium. Complete post irradiation examination of the experiments may aid in understanding the differences in observed pressure histories. The development of mechanistic mixing, fragmentation and heat transfer models to describe fuel coolant interaction is essential. The use of parametric models for the heat transfer requires the use of a priori assignment of parameters that cannot be experimentally determined. The modeling of fuel and sodium motion in the experiment after clad failure must be completed.

Experimentation to identify the source of the initial pressurization as fuel vapor or sodium pressurization, or the combination of the two will be performed. This will involve the use of a low vapor pressure liquid metal simulant coolant. Seven pin experiments with fresh oxide fuel will be performed to evaluate and reduce the experimental limitations of single pin experiments, particularly the effects of the "cold" vessel walls on determining the energy conversion efficiency. And lastly, the effects of fission products on these phenomena must be determined with experiments involving irradiated fuels.

APPENDIX A

ESTIMATES OF ENERGY CONVERSION RATIOS DERIVED FROM PRESSURE DATA

Since in several experiments (PBE-9S and PBE-12S) the piston moved full travel and stopped while the channel was still pressurized, it was desired to estimate energy conversion efficiencies independent of the piston displacement diagnostic. This Section describes the method used.

The impulse implied to the piston can be derived from the pressure history measured at the top of the capsule as:

$$I(T) = A \int_0^T \Delta p(t) dt$$

where

$I(T)$ is the impulse

A is the piston cross-sectional area

$\Delta p(t) = P(t) - P_o$

$P(t)$ = Measured pressure history

P_o = Original system pressure $\approx$ pressure behind piston

(It is assumed that the pressure behind the piston is a constant. Since the volume above the piston is large compared to the piston displacement, this assumption is approximately correct.)

Since the impulse represents a change in momentum, the velocity of the piston $[V(t)]$ can be estimated as:

$$V(T) = \frac{1}{M} [I(T)]$$

where M is the piston mass.

The piston kinetic energy $[KE(T)]$ is derived from the pressure integral as

$$KE(T) = \frac{1}{2M} [I(T)]^2$$

The energy conversion ratio is then estimated as

$$R = \frac{(KE)}{E}$$

where KE is the maximum derived kinetic energy and E is the total fission energy deposited when $KE(T)$ achieves its maximum.

APPENDIX B

EXPAND PIN FAILURE MODEL DESCRIPTION

Conditions during PBE experiments are fairly unique; this necessitates an analysis tool specifically designed for experimental modeling. The unique features of the experiment can be summarized as: High energy depositions of 2350-2900 J/g over a time of 10 ms, fresh fuel, presence of fuel vapor, internal axial fuel motion, and fuel melting on the surface first due to the inverted radial energy deposition profile. This last is due to the fairly soft spectrum in the ACPR.

The code is divided into five major sections:

- (1) Transient Heat Transfer. This is a Crank-Nicholson finite difference model allowing up to 26 radial temperature nodes for the clad and fuel, plus one in the sodium channel and one in the channel well. Temperature-dependent properties are included, and the sodium can be flowing or stagnant. The radial 1-D heat transfer equations are solved for up to 19 axial nodes; radial solutions are coupled only through the coolant flow. Gap conductance includes allowance for variable gap width due to fuel-clad differential expansion; heat transfer is determined via fill gas conductance with a correction for accommodation coefficients if the gap is open; if closed but with solid fuel and clad, the direct contact area and contact pressure is used to determine a direct conductance heat transfer coefficient; if the gap is closed and fuel and/or clad is molten on the surface, direct contact is assumed and the gap conductance set to a high value. Inclusion of the direct motion fuel-clad conductance in the gap model is unique to EXPAND and is necessary to predict failure time correctly. Not including it leads to late predictions or no failure.
- (2) Fuel Equation-of-State. This incorporates a fuel vapor pressure equation for UO_2 , which is K. O. Reil's lower pressure bound.⁽¹⁵⁾ This is also a unique failure in EXPAND. Fill gas pressure is included. Fuel porosity is assumed to collapse on melting and is thus available for expansion of the fuel.
- (3) Internal Fuel Motion. This is treated by a slug model of the bulk axial fuel motion before failure. The slug is driven by thermal expansion and axial pressure gradients. The gradients are generated by the assumption of plugging the fuel-clad gap following partial melting of an axial node. The actual time for this to occur is estimated to be on the order of 0.1 ms for a few atmospheres initial gradient or about 10 μs for an internally driven expansion in a node,

such as by fuel vapor. Since the fine details of the fuel motion are not modeled, the assumption of instant plugging on loss of fuel integrity (melting or extensive cracking) is deemed adequate. This is a special feature of the code.

- (4) Fuel Stress-Strain. The model assumes a solid elastic annulus of fuel in generalized plane strain. Allowance is made for molten fuel both inside and outside the annulus to account for surface melting; this is also unique to the EXPAND model and makes the code applicable both to experiment and to cases with more prototypic temperature profiles. The annulus is allowed to crack via a tensile hoop stress criterion. This constitutes a simple cracking model. On cracking, the fuel is assumed strengthless and treated hydrostatically. This assumption is valid under prompt burst experimental conditions where there is very extensive fuel cracking due to the large thermal gradients.
- (5) Clad Stress-Strain and Failure Criteria. The clad is modeled as an elastic or plastic annulus with strain hardening. This model is essentially the same as that in the LAFM code ⁽¹⁶⁾ developed by Mast.

Failure is predicted via a Larson-Miller Parameter (LMP) and life fraction rule,⁽¹⁷⁾ melt-through, or ductile failure. The LMP criterion has been found to give good agreement with experimental data.

A block diagram of the overall code structure is shown in Figure 27. This shows the calculation flow and names of the major subroutines. HYDRO is an interface that outputs EXPAND results at failure (temperature, pressure, failure location) in a form suitable for use by another code for post failure analysis (in this case, EPIC).

Figure 27. EXPAND Calculation Flow.

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