UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

JUN 2 1980

MEMORANDUM FOR: Harold R. Denton, Director
Office of Nuclear Reactor Regulation

FROM: Robert J. Budnitz, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER #91 , "ACPR EXPERIMENTS ON PROMPT-BURST ENERGETICS WITH FRESH URANIUM CARBIDE FUEL."

Introduction and Summary

This memorandum transmits the results, and the analysis thereof, of a series of three single-pin, in-reactor experiments on the pressures generated and the work-potential resulting from the failure of fresh uranium carbide fuel pins in sodium under prompt-burst disassembly conditions in a liquid metal fast breeder reactor (LMFBR) that uses carbide fuel. Conclusions relevant to assessing the safety implications of the use of carbide fuel in LMFBRs and in fuel test facilities are also presented. These experiments, performed in the Annular Core Pulse Reactor (ACPR) at Sandia Laboratories, were a joint cooperative research program between Sandia Laboratories, as a contractor for the U. S. Nuclear Regulatory Commission (NRC), and Kernforschungszentrum Karlsruhe (KfK) of the Federal Republic of Germany. The experiments and analysis were performed by a joint Sandia-KfK team, and are reported in detail in the enclosed Sandia topical report, "Prompt-Burst Energetics Experiments: Fresh Uranium-Carbide/Sodium Series," NUREG/CR-1396.

These were separate-effects experiments on the pressure generation and work potential from molten-fuel-coolant interactions in the unvoided region of the core of a carbide-fueled LMFBR during a prompt-critical power excursion. Except as upper limits, therefore, the work-conversion numbers are not directly applicable to an entire core where voided regions, non-coherence effects, possible venting of the constraining slug, and frictional loss to structure must also be considered. The high thermal conductivity of carbide fuel had lead to the hypothesis that molten-fuel-coolant interactions would be both more likely and more energetic with carbide fuel than with oxide fuel; this proved to be the case. Related earlier work with oxide fuel was reported in RIL #38, "Results of the Initial Series of ACPR Experiments on Prompt-Burst Energetics with Fresh Oxide Fuel," and in NUREG/CR-0367 (Ref. 1).

Post-fuel-failure molten-fuel-coolant interactions produced sharp, short, very high pressure pulses of up to 130 MPa (19,000 psi) source pressure, but the conversion ratios of fuel thermal energy to mechanical work were all less than 2%. Both these values are about a factor of 5 greater than in the corresponding experiments with oxide fuel. Two features of these experimental results were in agreement with the thermal detonation model of molten-fuel-coolant interactions developed by Board and Hall (Ref. 2). These were the delays in all three cases between fuel failure and the occurrence of the initial large fuel-coolant interaction pressure pulse, and the triggering of two fuel-coolant interaction pressure pulses by extraneous shock pressures associated with the experiment. Analysis of the highest-pressure event with the MURTI parametric model of fuel-coolant interactions gave reasonable agreement with the measured pressure histories (Ref. 3). A development of the EXPAND model for the failure of fresh fuel in power transients gave excellent agreement with the measured fuel failure times and energy depositions (Ref. 4).

A preliminary report, "Prompt Burst Energetics Experiments: Uranium Carbide Series, Preliminary Results," NUREG/CR-0137, was issued on the results of this series of three ACPR carbide-fuel experiments (Ref. 5). A meeting of the Advanced Reactor Safety Research (ARSR) Accident Energetics Review Group was held on January 20, 1978 to consider the results of these experiments, as given in the preliminary report, the analysis of the results then available, and the relevant implications of these results for assessing the safety of LMFBRs with carbide fuel. The meeting included representatives of KfK, the Department of Energy (DOE) and its contractors, and reactor vendors, as well as representatives of the NRC Offices of Nuclear Regulatory Research (RES) and Nuclear Reactor Regulation (NRR) and NRC contractors. Analysis of the results by Sandia and by others, and plans for DOE supported carbide-fuel experiments in the TREAT reactor at Argonne National Laboratory (ANL) were presented. There was general agreement that these results showed that the magnitude and possibly also the probability of energetic fuel-coolant interactions is significantly greater with carbide than with oxide fuel, at least under the conditions of these experiments. Input from this meeting as well as more extensive analysis of the results of the three ACPR carbide-fuel experiments are included in the enclosed Sandia topical report, NUREG/CR-1396, and in this Research Information Letter.

Discussion

The experiments considered here were performed in the ACPR test reactor before it was upgraded by installation of a new high-performance core. As in the previous series of 12 similar experiments with fresh oxide fuel, single clad pins of fresh fuel were placed in a stagnant-sodium capsule that contained an inertial loading piston (representing sodium head). In the experiment cavity of the ACPR, the capsule was exposed to the neutron flux of a self-limited power excursion on a prompt-burst time scale. The fresh UC fuel had an enrichment of 15% and was of 84% theoretical density. Time histories of the capsule pressure above and below the fuel pin, the loading-piston position, sodium temperatures, and the ACPR power were measured. In two of the tests, SG1 and SG3, the calculated peak fuel temperatures were about 4550K, which is well above the 3050K melting point of UC, but the fuel vapor pressure was negligible. In the more energetic test SG2, the calculated peak fuel temperature was 6650K with an estimated fuel vapor pressure of 12.5 MPa (1810 psia). The axial-maximum radially-averaged energy depositions in SG1, SG2, and SG3 were respectively 1500, 2420, and 1950 J/gUC. Because of flux depression in the test fuel pins, the ratio of the energy deposition at the surface of the pin to that at the center was 1.6 for tests SG2 and SG3, and somewhat less for SG1, which used less moderator around the test capsule. In order to reduce the resulting inverted-from-normal radial temperature profile, a double-pulsed mode of operation was used in SG3 with a delay of 185 milliseconds between the two pulses. During this time, the inverted temperature profile from the initial pulse was normalized by surface cooling and thermal relaxation before the second pulse occurred. In this test, the magnitude of the fuel temperature inversion at the time of fuel failure was significantly reduced. The power excursions in all three of these experiments were on the time-scale of $100/sec super-prompt-critical power excursions in an LMFBR, with minimum periods of 1.3 milliseconds for the single pulses in tests SG1 and SG2, and 2.6 milliseconds for the second (failure) pulse in SG3. All experiments started from a 773K initial capsule temperature. This was also effectively the sodium temperature at fuel failure in single-pulse tests SG1 and SG2, while in SG3 the average sodium temperature at fuel failure was 60K higher.

Fuel failure, in all three experiments, occurred near the end of the power burst (the second one in SG3), but with barely detectable pressurization of the capsule. After a delay, which ranged from 3 milliseconds in the energetic test SG2 to 28 milliseconds in SG3 and 78 milliseconds in SG1, a sharp, short, very high pressure pulse occurred that had to be the result of the thermal interaction between the molten carbide fuel and the sodium (fuel-coolant interaction). The measured peak pressures at the bottom of the capsule ranged from 36 MPa (5200 psi) in SG1, to 182 MPa (26,400 psi) in SG3, and to 255 MPa (37,000 psi) in SG2. These pressures are well above the sodium critical pressure of 26 MPa, particularly for the SG2 and SG3 cases. Although these peak pressures significantly exceeded the 5,000 and 10,000 psi ratings of the pressure transducers, subsequent calibrations indicate that the transducer readings were reasonably correct. Because of the rigid-wall reflection at the bottom of the capsule where the transducers were located, the actual source pressures were of about half these magnitudes. The pressure pulses decayed in a few milliseconds, so despite these very high peak pressures, the conversion of the total thermal energy in the fuel into work, as measured by the kinetic energy of the loading piston and the upper sodium slug, was only 0.16 percent in SG2, and considerably less in SG1 and SG3. The occurrence of a sharp pressure pulse from fuel-coolant interaction that is delayed from fuel failure is consistent with the detonation model of fuel-coolant interactions developed by Board and Hall (Ref. 2). In this model, there is a premixing phase of vapor-blanket insulated molten fuel and coolant before the propagating thermal detonation occurs.

In both SG2 and SG3, pressurization of the upper sodium slug produced by deceleration of the loading piston and the upper sodium slug when the piston reached its limit of travel triggered an additional fuel-coolant-interaction pressure event in the upper sodium slug (but not in the unconnected lower sodium slug). In SG3, the impulse in the upper sodium slug from this delayed triggered fuel-coolant interaction considerably exceeded the impulse from the original pressure event. Similar delayed pressure pulses from fuel-coolant interactions triggered by rapid piston deceleration were observed in two of the twelve similar ACPR tests with fresh oxide fuel. The occurrence of these triggered interactions is also in accord with the Board and Hall detonation model of fuel-coolant interactions (Ref. 2). In the piston-stop triggered interactions in SG2 and SG3, as well as in the untriggered pressure event in SG1, fixed-volume pressurizations from fuel-coolant interactions occurred after the piston had reached its limit of travel, so these pressuizations could not actually do work. The work potential of these events, however, can be estimated by applying the measured impulse ($\int Pdt$) to the mass of the piston and the upper sodium slug. When this is done, the estimated work potential of experiments SG2 and SG3 is increased to about 2% of the total thermal energy in the fuel pin.

The very high, super-critical pressure pulses in these experiments occurred when voids were present in the capsule sodium. This indicates that some of the sodium was heated to super-critical temperatues (above 2508K) during the fuel-coolant interactions. The pressure pulses, particularly the 255 MPa one in SG2, were analyzed with the German MURTI parametric model of fuel-coolant interactions (Ref. 3). This is a development of the original Cho-Wright parametric model (Ref. 6), and it is particularly well suited for use with carbide fuel because it includes non-infinite thermal conductivity in the interaction zone sodium. The MURTI calculations were able to reproduce rather well the magnitudes and general shapes of the measured SG2 primary pressure pulses in both the upper and the lower sodium slugs, and also the mechanical work. Parameters giving the best fit were:

Fraction of interacting fuel	0.30
Interacting fuel-sodium mass ratio	8.2
Partical radius - 1,000 μm decreasing with time to	350μm
Fragmentation and mixing time constant	1.0 msec

Only a limited investigation was made of the sensitivity of the results to variations in these parameters.

Post-test radiographs of the capsule showed significant fuel dispersal from the axial hot spot in the fuel upward with the moving piston and sodium. In the more energetic tests, SG2 and SG3, most of the test channel was voided of fuel. This might have a significant reactivity effect in an LMFBR prompt-burst accident, but quantitative rate measurements would be needed to assess its importance. Such rate measurements would be feasible with the high-precision coded-aperture imaging fuel-motion-diagnostics system that has been installed in the upgraded ACPR (now renamed the Annular Core Research Reactor, or ACRR).

The EXPAND model for the failure of fresh fuel in transient power excursions, that was developed at Sandia for analysis of the Prompt-Burst Energetics experiments with fresh oxide fuel, required some development in order to fit the failure times and energy depositions for the carbide fuel experiments (Ref. 4). EXPAND is similar to the Los Alamos LAFM irradiated-fuel-failure code in using the Larson-Miller-Parameter life-fraction rule developed at the Hanford Engineering Development Laboratory (HEDL) (Ref. 7, 8). The improvements in EXPAND, that are now also being used in analysis of an improved series of Prompt-Burst Energetics experiments with fresh oxide fuel in the upgraded ACRR, are a non-infinite contact conductance between molten fuel and clad, and the use of the effective stress, which includes axial as well as hoop stress, rather than just the hoop stress alone in the Larson-Miller life-fraction correlation. These additions add two parameters, one of which is essentially free, to EXPAND, which previously had no free parameters. With these additions to the model, the differences between the calculated and measured failure times in the three carbide fuel experiments were all less than 4 milliseconds, and the differences in the energy deposition at fuel failure were all less than 45 J/gUC. In these carbide-fuel experiments, the internal pressure loading of the clad was always small, and failure was dominated by thermal-stress loading and reduction in strength of the cladding late in the power burst as the cladding temperature increased.

Evaluation and Application

The results of these ACPR experiments and the analysis of these results are the only available data on the work potential resulting from the failure of fresh carbide fuel in the sodium-filled region of an LMFBR core on the actual millisecond-period, prompt-burst disassembly time scale. They are nearly the only data available at all on the work potential of the rapid thermal interaction of molten carbide fuel and sodium (fuel-coolant-interaction). The results of these three experiments have been compared with the results of a similar series of twelve ACPR experiments with fresh oxide fuel. This comparison showed that, at least under these prompt-burst conditions, the peak pressures and conversion ratios of fuel thermal energy into work were about a factor of 5 greater for molten carbide fuel than for molten oxide fuel. Even for carbide fuel, however, the measured conversion ratios of fuel thermal energy into work in the three carbide fuel experiments were less than 2%, and these separate effects experiments did not include mitigation effects potentially operative in a whole core accident. Such effects include non-coherence, frictional loss to structure, possible venting of the constraining slug, and pressure relief into voided regions of the core. A detailed accident analysis code such as SIMMER is necessary to integrate these effects for whole-core accident analysis (Ref. 9). Models developed from the results of experiments, such as the current ones, furnish the pressure source term for such accident analysis codes.

Calculations with the MURTI parametric model of fuel coolant interactions were able to match the general features of the measured pressure histories in both the upper and lower sodium slugs in the highest-pressure event observed, the initial pressure event in SG-2 (Ref. 3). These calculations indicate that a large fraction of the molten fuel (about 30%) interacted with the sodium. MURTI is a parametric, not a mechanistic model, and, in fact, no verified mechanistic model of molten fuel-coolant interactions exists. Advanced hydrodynamics codes such as SIMMER can accurately treat the effects of constraining fluids during the work-producing-expansion phase of a fuel-coolant interaction, including venting, mixing, and friction losses, but they too require a parametric input of the fuel-coolant interaction process itself. A true mechanistic model of the fuel-coolant interaction process would have to include premixing, triggering, and propagation as well.

With two recent additions, the EXPAND model for the failure of fresh fuel in power excursion transients gives good agreement with the failure time and the failure energy deposition or fuel temperature for both carbide and oxide fuel (Ref. 7) These additions to EXPAND include use of the cladding effective stress, which includes the axial stress as well as the hoop stress, in the Larsen-Miller lifetime correlation, and use of a non-infinite contact conductance between molten fuel and cladding. A topical report detailing the EXPAND model will be issued soon.

Future Work

There is currently little development work underway on carbide fuel. There is no near-term prospect for a licensing application to NRC involving the use of carbide fuel. Therefore, no further safety research is planned on carbide fuel beyond completion of the post-test examination of the debris from experiments SG-1, 2, and 3, and ACRR experiments on the Equation-of-State (vapor pressure) of fresh carbide fuel. Both these activities were part of the joint KfK-NRC cooperative research program on carbide fuel.

Recommendations

The results of these ACPR experiments on prompt-burst energetics with carbide fuel give the Office of Nuclear Reactor Regulation (NRR) the only available data for assessing the pressure generation and work potential from a hypothesized prompt-burst disassembly accident in a carbide-fueled LMFBR, and the resulting threat to the integrity of the reactor primary system and eventually the containment. These results, along with those of previous ACPR experiments with oxide fuel reported in RIL No. 38, show that the generated pressures and work potential under prompt-burst conditions are about 5 times greater with fresh carbide fuel than with fresh oxide fuel. Although the current data are not applicable directly, they do indicate that molten fuel-coolant interaction may also be considerably more energetic with carbide than with oxide fuel under other LMFBR accident conditions, and also during in-reactor fuel testing accidents. In all these carbide fuel experiments, however, the conversion of fuel thermal energy into work was less than 2%, although the measured peak source pressures were very high (up to 130 MPa). These experimental results do not include work mitigation effects that would be present in an actual LMFBR accident.

In all these experiments, the observed pressure pulses following fuel failure were produced by molten-fuel-coolant interactions; and, unlike the oxide-fuel experiments, the fuel vapor pressure was always negligible. In two of the three experiments, as in two of the oxide experiments, an energetic fuel-coolant interaction pressure pulse was triggered by an extraneous shock pressure associated with the experiment (piston stopping). This triggering is in agreement with the thermal-detonation model of molten-fuel-coolant interactions developed by Board and Hall (Ref. 2). These shock-triggered events raise questions about the possible occurrence of a large-scale propagating fuel-coolant interaction under fuel meltdown conditions in a reactor accident. The current experimental results, however, do not give information on the extent (mass involvement) of such a propagating interaction, or on the work potential of such an interaction. It is recommended that consideration be given by NRR to these uncertainties and to the current lack of a verified mechanistic model of molten-fuel-coolant interactions when assessing the accident work potential for carbide as well as oxide fuel. It is also recommended that consideration be given by NRR to the greater measured fuel-coolant-interaction peak pressures and work potentials with carbide fuel (a factor of 5 greater than with oxide fuel) in the safety review of any proposed reactor or fuel tests that use carbide fuel.

The EXPAND model for fresh-fuel failure, with the two recent additions previously described, has been verified for both oxide and carbide fuel for the range of prompt-burst conditions covered in these experiments. It is our opinion that EXPAND is the best fresh fuel-failure code available for these conditions, and its use is recommended to NRR. For irradiated fuel, use of the Los Alamos code LAFM, which shares many features with EXPAND, is similarly recommended.

For further information on the results of these experiments, or on the EXPAND code, please contact Robert W. Wright of my staff.

Robert Budnitz

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Enclosure:
K. O. Reil, M. F. Young, H. Jacobs, and H. Plitz, "Prompt Burst Energetics Experiments: Fresh Uranium Carbidel Sodium Series," NUREG/CR-1396, SAND-0820, (May, 1980)

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(9) L. L. Smith et al., Los Alamos Scientific Laboratory, "SIMMER-II: A Computer Program for LMFBR Distrupted Core Analysis, " USNRC Report NUREG/CR-0453, (October 1978).*

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* Available for purchase from National Technical Information Service, Springfield, Virginia 22161

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Robert B. Budnitz, Director
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Enclosure: NUREG/CR-1396

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RECORD NOTE: At the Review Group meeting on the preliminary results of these experiments on January 20, 1978, I informed J. F. Meyer of NRR that we intended to issue a RIL on this work when analysis of the results had been completed and a typed report issued. I discussed the principal results of this RIL with Meyers by telecom on April 24, 1980, and told him that the RIL was in typing. RWW

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