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NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

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

FROM: Saul Levine, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER # 38, "RESULTS OF THE INITIAL SERIES OF ACPR EXPERIMENTS ON PROMPT-BURST ENERGETICS WITH FRESH OXIDE FUEL"

INTRODUCTION AND SUMMARY

Transmitted by this memorandum are the results of the initial series of single-pin in-core tests on the pressures generated and the work potential resulting from the failure of fresh oxide fuel pins in sodium under prompt-burst disassembly conditions in an LMFBR. These results are the most definitive currently available on this subject. They are given in detail in the enclosed Sandia report.

In seven of the tests in which the fuel failed (out of a total of 12), the largest measured conversion of the fuel thermal energy into work (damage potential) by the short very-high pressure pulse occurring upon fuel failure was 0.04%. This prompt-failure pressure pulse can be accounted for by fuel vapor pressure alone, without requiring significant sodium vaporization from molten fuel-sodium interaction. In several of the tests, however, delayed pressure pulses occurred that had to be the result of sodium vaporization from fuel-coolant interaction. The thermal energy-to-work conversion in these delayed interactions could not be measured directly, but in one case the estimated conversion was 0.5%. Two of these delayed interactions were triggered by an extraneous shock pressure associated with the experiment. This result raises questions about the possibility of shock-propagated fuel-coolant interactions in mixtures of molten fuel and sodium under reactor meltdown conditions.

Axial fuel motion of potential reactivity significance is inferred from post-test examination.

DISCUSSION

The experiments on Prompt-Burst-Energetics (PBE) considered here were performed by Sandia Laboratories in the Annular Core Pulse Reactor (ACPR). In these experiments, single clad pins of fresh UO_2 fuel in a stagnant-sodium capsule that contained an inertial loading piston, (representing a sodium head), were exposed to the neutron flux of a 1.4 m sec. power excursion in the experiment cavity of the ACPR, resulting in melting and partial vaporization of the test fuel. These are the first experiments to be performed on the real time scale of a postulated extreme prompt-burst disassembly accident in an LMFBR ($\sim$ \$100/sec.). The axial-maximum, radially-averaged fuel energy depositions ranged from 2550 to 2900 J/g UO_2, with a 500°C initial capsule temperature. Time histories of the capsule pressure, loading piston position, and sodium temperatures were measured.

At energy depositions where fuel failure occurred promptly during the ACPR power excursion, failure produced a sharp but quickly damped pressure pulse in the sodium. The largest peak source pressure was 32 MPa (4700 psi) and the decay time constants were about 4 m sec. From the measured kinetic energy of the capsule loading piston and its associated sodium, the largest conversion of the thermal energy in the fuel into work was 0.04%. These single pressure events that occurred upon fuel failure can be accounted for by the bursting of the fuel-pin cladding under fuel vapor pressure, with rapid quenching of the fuel vapor source by the cladding and sodium heat sinks. With the uncertainties in the fuel equation of state, however, significant pressure contribution from sodium vaporization can be neither established nor excluded.

Two different modes of significant pressure generation by sodium vaporization from fuel-coolant interaction also occurred in some of these tests. In one test at an energy deposition marginal for fuel failure, a series of moderate pressure pulses followed by sustained pressurization occurred 25 m sec. after peak power following sodium boiling and clad heating and failure. The largest thermal energy-to-work conversion of these delayed fuel-coolant interactions was 0.03%.

In two of the tests, the hydrodynamic pressurization of the upper sodium column produced by the rapid deceleration of the capsule loading piston at its limit of travel triggered a sharp fuel-coolant interaction in the post-failure mixture of sodium and molten fuel. In one of these tests, the pressure pulse had a peak source pressure of 20 MPa (3,000 psi) and was followed by a 5 MPa (700 psi) sustained pressurization for 10 m sec. When the measured impulse ($\int Pdt$) is used to estimate the work potential of this fixed-volume pressurization, the thermal energy-to-work conversion was 0.5%, which is an order of magnitude greater than the work conversion from the prompt-failure pressure pulses alone. This method overestimates the work potential of the experiment, because the pressure decrease from continued expansion does not occur, but it may underestimate the work potential of the reactor case of coherent failure in an array of fuel pins because of extraneous wall heat losses in the experiment.

The fuel-coolant interaction events triggered by piston-deceleration shock are extraneous to the experiments on prompt-burst work potential. Their significance is the demonstration that a shock pressure can trigger a significant fuel-coolant interaction in a mixture of molten UO_2 and sodium, and in showing, with these reactor materials, that a potential mechanism does exist for producing a large-scale coherent UO_2 sodium interaction under reactor meltdown conditions.

Sandia, in a joint project with KfK of the Federal Republic of Germany, performed three preliminary tests in the PBE capsule in ACPR with fresh carbide fuel pins with results that differed strongly from the oxide fuel tests. A preliminary report of these carbide tests was given in a topical report, "Prompt Burst Energetics Experiments, Uranium Carbide Series, Preliminary Results" by K. O. Reil, M. F. Young, and W. J. Camp of Sandia, and H. Plitz, KfK, NUREG/CR-0137, SAND 78-0758 (1978).

In these carbide tests, very-high pressure events occurred both promptly during the ACPR power excursion (one test) and delayed by tens of milliseconds (two tests at lower energy depositions). Fuel vapor pressures were small, so that fuel-coolant interaction had to be the source of the pressure events. The largest measured peak source pressure was 130 M Pa (19,000 psi). The largest conversion ratio of fuel thermal energy into work was about a factor of 5 greater than in any of the oxide tests. These results showed the effect of the difference in fuel thermal conductivity upon the energetics of prompt-burst disassembly, and upon fuel-coolant interaction mechanisms.

The EXPAND fuel-failure model developed at Sandia agrees well with the failure times and energy depositions in these fresh oxide fuel tests. Failure is by stress rupture of the cladding, and is highly dependent upon the cladding temperature and temperature gradient. The pre-failure in-clad prompt axial fuel motion predicted by EXPAND was observed in post-test examination of in-clad scratch gauges. This fuel motion could represent a significant prompt negative reactivity feedback in the reactor system which could lead to a significant reduction in the accident fission energy. The voiding of fuel toward the cladding failure location that is implied by the post-test examination and is predicted by EPIC could also result in significant reactivity changes. The sign and magnitude of these changes would depend upon the axial failure location and upon the movement of fuel in the coolant channel after exiting the cladding break.

Verified mechanistic models for the work potential under prompt-burst disassembly conditions do not currently exist. The SIMMER code is being used to model the disassembly work potential from fuel vapor pressure, but several of the relevant mechanisms and exchange coefficients are uncertain and require further verification. Mechanistic models do not exist for the mixing, fragmentation, and heat transfer processes necessary to describe the work potential of fuel-coolant interactions under prompt-burst disassembly conditions. In this situation, parametric models are used that require an a priori assignment of parameters that cannot be determined experimentally.

EVALUATION AND APPLICATION

The results of these ACPR tests are the best experimental data currently available on the work potential resulting from the failure of fresh oxide fuel in the sodium - filled fraction of an LMFBR core under prompt-burst disassembly conditions. They are the only data available on the real, millisecond period, prompt-burst disassembly time scale. Irradiated-fuel data are needed and will be obtained in the upgraded ACPR in the near future, but the opinion of workers in the field is that fresh fuel represents the worst-case upper limit on the prompt-burst pressures and work potential.

These results show that the prompt-failure pressures and work potential can be accounted for by fuel vapor only, with an observed rapid quenching process that needs further research. The conversion of fuel thermal energy into work in this process is quite low, 0.04% being the greatest observed in these tests.

Delayed rapid thermal interactions between the molten oxide fuel and sodium coolant definitely do occur however. Thermal energy to work conversions as high as 0.5% have been observed, and the occurrence of shock-triggered interactions gives rise to concern about the possibility and energetics of a large-scale shock-triggered delayed fuel-coolant interaction under reactor meltdown conditions. Further research to resolve these questions is needed.

The EXPAND code, with its agreement with these oxide fuel test results, gives the best available predictions on the failure energy deposition, location, and time under rapid transient conditions with fresh fuel. For irradiated fuel, the Los Alamos code LAFM should be used.

These test results verify the existence of pre-failure in-clad axial fuel motion in rapid transients, as predicted by EXPAND. The reactivity effects of this axial fuel motion in reducing accident fission energy may be significant.

FUTURE WORK

Considerable further work is needed before verified models of the processes that determine the prompt-burst work potential are available for fast-reactor safety assessment over the full range of accident conditions. Major areas requiring research are:

1. Fuel-coolant interactions: governing processes, work potential
2. Fuel-vapor quenching
3. Irradiated fuel effects
4. Sodium-in, sodium-out, partial sodium effects
5. Scale effects, large-bundle size.

The near-future research in the upgraded ACPR that is presently planned includes the following:

1. Prototypic radial temperature distributions in the fuel (centerline vaporization).
2. A low vapor pressure coolant (tin) test to separate out fuel-coolant interaction effects.
3. A low sodium subcooling test.
4. Irradiated fuel tests (start FY 79)
5. 7-pin tests: scaling, wall heat loss (not FY 79)

Flowing-sodium loop tests for proper radial and axial temperature distributions are deferred pending funding availability for a sodium loop. (The major purpose of the loop is fuel-dynamics experiments.) Also under consideration are phenomenological experiments with molten oxide fuel and sodium on fuel-coolant interaction mechanisms, with emphasis on propagation phenomena. The extent and timing of this needed future research will be determined by available future funding.

RECOMMENDATIONS

The results of these ACPR tests on prompt-burst energetics give NRR a much improved data base for assessing the work potential and the resulting threat to the integrity of the primary system and eventually the containment of a hypothesized prompt-burst disassembly accident in an LMFBR. The existence of a rapid thermal interaction between molten oxide fuel and sodium has been definitely demonstrated. The observed conversion of fuel thermal energy into work, however, was less than one percent. The shock-triggered delayed fuel-sodium interactions observed in these experiments raise questions about the possible occurrence of a large scale propagating fuel-coolant interaction under core meltdown conditions, as proposed by Board. The current experimental results do not, however, 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 absence of verified mechanistic models of fuel-coolant interactions when assessing accident work potential.

The EXPAND fresh fuel failure code has been verified for the range of conditions covered by these experiments, and is the best accident analysis code available for these conditions. The pre-failure in-clad axial fuel motion predicted by EXPAND has been verified by post-test examination in these experiments. This fuel motion may have reactivity effects that are significant in assessing the accident work potential and the threat to the integrity of the primary system and eventually the containment. EXPAND is recommended to NRR as the best available tool for safety assessment for fresh oxide fuel in these areas.

For further information on the results of these tests, on their use, and on the continuing research in this area, please contact Robert W. Wright of my staff.

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Enclosure: NUREG/CR-0367

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Enclosure: NUREG/CR-0367

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