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MAY 10 1979

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

FROM: Saul Levine, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER # 53
"DEBRIS-BED COOLABILITY LIMITS, RESULTS FROM IN-CORE TESTS D-1, D-2, AND D-3."


REFERENCES:
1. J. B. Rivard, "Debris Bed Studies and Experiments at Sandia Laboratories," NUREG/CR-0263, SAND 78-2299 (July 1978).
2. J. B. Rivard, "Postaccident Heat Removal: Debris Bed Experiments D-2 and D-3," NUREG/CR-0421, SAN 78-1238 (Nov. 1978).


## Introduction and Summary

This memorandum summarizes the results of the initial series of three in-core experiments on the coolability limits of post-accident particulate LMFBR fuel debris in a sodium pool. The work supplies key information for assessing risk from core-melt accidents in LMFBRs; it is responsive to questions raised by the NRR staff and the ACRS during the FFTF safety reviews and the previous CRBR reviews. It is an important element in the ARSR containment integrity program. These experiments were performed in order to measure, under the high sodium subcoolings of the LOF and TOP LMFBR accident scenarios, the specific power in the bed of fuel particulate at which dry out of the sodium coolant in the bed occurs. Local dry out had been thought to be the coolability limit of a bed, an assumption that has been used in safety evaluations. By sustained operation with local dry out of sodium in the bed, these experiments showed that local dry out is not the true bed coolability limit.

These experiments were performed in the Annular Core Pulse Reactor (ACPR) at Sandia Laboratories. They were the first experiments on post-accident core debris behavior to use fission heating to simulate the internal heating of fuel debris by fission-product decay.

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In two cases the experiment operated for more than one hour under quasi-static dry-out conditions in a portion of the bed, the volume of which increased slowly with time, thus demonstrating bed coolability under conditions of local dry out. An analytical model of bed behavior was developed that does not depend on heat transfer correlations and that agrees well with the experimental data. The experimental results and the accompanying analysis show that the mechanisms leading to bed leveling in previous laboratory experiments under saturated conditions are not present in internally heated beds of particulate fuel debris under the highly-subcooled sodium characteristic of the LOF and TOP accidents. The results of these experiments, although they cover a limited range of conditions, are the most definitive data currently available on the post-accident coolability of beds of particulate fuel debris under sodium. These experiments, the results, and the analytical models developed are described in the referenced Sandia Laboratories reports.

Substantial foreign interest exists in this work, and we will seek to benefit from any cooperative work that can be done in this area.

## Discussion

The first of the referenced Sandia reports, NUREG/CR-0263, contains the design of the experiment capsule and its associated helium cooling loop, and of the test train. The report also gives the results of the initial test, D-1, which was primarily a check out of the experimental system. The second report, NUREG/CR-0421, contains the results of tests D-2 and D-3, in which local dry out occurred in the beds, as well as the analysis of the results and the analytical model development.

### Experiment Description

The particulate fuel debris was located in the bottom of a sodium pool contained in an in-core capsule in the ACPR test reactor. The fission (and gamma) heat deposited in the fuel debris and transferred to the sodium pool was removed from the pool to an ex-reactor heat dump by a helium cooling loop. The capsule bottom and sides were insulated. The leakage heat flux from the insulated bottom of the capsule was negligible, so the insulated bottom corresponds to the maximum temperature surface in deeper beds with some bottom cooling. The diameter of the bed was 10 cm, and its depth was varied from 6 to 11 to 16 cm in tests D-1, D-2, and D-3, respectively. Because of neutron self-multiplication in the 93% enriched fuel debris used in the experiment, the radial power profile in the bed was flat to within 20%, and the axial profile was also effectively flat. With the negligible heat loss through the insulated side walls of the capsule, the experiment was essentially one-dimensional (z dependence only), so the results should be applicable to beds of indefinite radial extent. Temperature distributions were measured by five thermocouples distributed through the bed. During the tests, the power was changed in steps and the resulting new steady-state temperature distributions were measured. Local sodium dry out was indicated, during the approach to thermal equilibrium, by a sudden thermocouple temperature rise above the sodium saturation temperature.

All these tests were performed with high subcooling of the pool sodium, in a range from 300 to 500°C. This corresponds to early post-accident conditions in the loss-of-flow (LOF) and the transient overpower (TOP) accident scenarios for LMFBRs, when decay heat levels are a few percent. These results are not applicable to the low subcoolings present in loss-of-heat-sink scenarios. The maximum specific power attainable in these tests was 1.28 kw/kg$UO_2$, which corresponds to about 1.3% of nominal core-average specific power in LMFBR fuel. Future experiments at higher specific power will be possible in the newly upgraded ACPR. All the beds were composed of simulated particulate $UO_2$ debris of irregular shape, with a mass-mean particle diameter of about 500 microns. This is typical of the debris from in-core LMFBR safety tests involving fuel meltdown. The $UO_2$ particulate was poured dry into the helium-filled experiment capsule, and the bed was then flooded with sodium. The sodium was allowed to freeze and was then later remelted after the experiment capsule had been placed in the reactor. The bed porosities were about 45%, and the bed permeabilities were about 200 darcys.

## Results

In the initial test, D-1, with a 6 cm deep bed, a bed power of 1.0 kw/kg$UO_2$ (1.0% of nominal LMFBR fuel specific power) was not sufficient to reach dry out or even sodium boiling, a result that had been expected. The measured temperature distributions in the bed showed that heat transfer was by conduction only (through the sodium), with no single-phase sodium convection.

In test D-2 with an 11 cm deep bed, local dry out occurred at a bed power of 0.70% of nominal LMFBR fuel specific power. The reactor power was then lowered so that the bed reflooded with sodium. The power was again increased slowly in steps, and local dry out occurred at the same bed power as before. During a later heating cycle at reduced subcooling, a step power increase to 0.40% of nominal LMFBR specific power produced a rapid temperature "disturbance" throughout the bed which is thought to have resulted from a disruption of the bed. After this event, the bed power was increased in steps to the maximum available from ACPR, 1.28% of nominal LMFBR fuel specific power, and the bed remained in a stable boiling mode indefinitely without undergoing dry out.

In test D-3 with a 16 cm deep bed, a repeatable local dry out occurred at 0.40% of nominal LMFBR fuel specific power. In two cases the experiment was continued at power for over an hour after the occurrence of dry out with stable bed behavior. Temperatures in the dry-out zone continued to increase slowly but at a monotonically decreasing rate. This is attributed to a slow growth in the volume of the dried-out portion of the bed. Heat was removed from the dried-out region by a combination of conduction and radiation. Upon dry out, the initial rate of temperature rise of the thermocouples ranged from 18% to 36% of the calculated adiabatic rate of rise. These results show definitely that local dry out in a particulate debris bed of LMFBR fuel under sodium is not the coolability limit of the bed. The measured threshold power for local dry out in these in-core experiments is in fair agreement with the prerun predictions made by Gabor and Baker (ANL) and by Dhir and Catton (UCLA)*. In both cases, these predictions were based on correlations with their respective experimental data using the models developed from these data. When Rivard used the published Dhir and Catton correlations (NUREG/CR-0262) and his experimental particle-size distributions, however, he found the agreement with the in-core data to be considerably less satisfactory and the predictions to be non-conservative (NUREG/CR-0421). The difference appears to be connected with determination of the proper mean-particle diameter to use in the Dhir and Catton correlation. Both the Gabor-Baker and the Dhir-Catton correlations are based on laboratory experiments with saturated coolant in which vapor jets opened up channels in the beds. It is not thought that this happened in the Sandia in-core experiments, except possibly following the bed disturbance in test D-2.

The agreement with the data is much better for a model of debris-bed cooling at high subcoolings which was developed at Sandia by Hardee and Nilson and extended by Rivard. This model is given in one of the reference Sandia reports (NUREG/CR-0421). Above a maximum temperature plane (the insulated capsule bottom in these experiments), this one-dimensional model has a two-phase zone (at nearly constant temperature) topped by a conduction zone across which most of the temperature drop occurs. This is a first-principles model that does not use heat transfer correlations. The model does not incorporate channels in the bed for upward vapor flow, but all upward and downward flow percolates through the bed. The model includes, as an option, the addition of bottom cooling to the bed by adding a stagnant conduction zone below the maximum temperature plane.

*J. B. Rivard, "Preliminary Results from Initial In-Pile Debris Bed Experiments," in 'Proceedings of the Third Post-Accident Heat Removal' Information Exchange; Nov. 2-4, 1977, Argonne National Laboratory ANL-78-10, pp. 49-61 (1978).

The stagnant sodium conduction zone at the top of the bed that is observed in the D-series in-core experiments at high sodium subcooling eliminates the bed-leveling mechanism of agitation by vapor jets and bubbles that has been observed in laboratory experiments a low subcooling. Since post-accident core-debris beds would be formed under conditions of high sodium subcooling in the LOF and TOP accident scenarios, bed leveling by vapor-bubble agitation does not appear credible under these conditions.

A decrease of the sodium subcooling from 485°C to 420°C (not apparent from the numbers in the report) had a negligible effect on the specific threshold power for bed dry out in test D-3.

Evaluation and Application

The results of these in-core experiments are the only data available on the threshold specific power for bed dry out with internal heating of $UO_2$ simulated LMFBR fuel debris in sodium. The data are also unique for the high sodium subcoolings of the LOF and TOP accident scenarios. These data are thus directly applicable as check points for evaluating analysis of the local dry-out limits of LMFBR particulate core debris in sodium under the high subcoolings of the LOF and TOP accidents. The Sandia bed-cooling model in the referenced reports fits the data very well, and thus appears to be the best available for evaluating the bed dry-out threshold under highly subcooled conditions. The data and model are applicable to the assessment of the in-vessel coolability by primary system sodium of LMFBR particulate core debris located either upon primary system structure or upon core-debris retention devices in the reactor vessel. There is considerable foreign interest in the results of these and future experiments for use in assessing the performance of such in-vessel systems. The current results are also applicable to the assessment of the ex-vessel coolability, following reactor vessel failure, of particulate core debris in the reactor cavity by the plant sodium. These results are applicable only so long as extraneous gases released by the concrete beneath the cavity liner are not present in the bed.

At the same time, these results clearly show that the actual coolability limit of a particulate debris bed of LMFBR fuel under sodium occurs at a higher fuel specific power than the threshold for local dry out. How much higher the coolability limit actually is is a subject for further research.

The vapor-bubble agitation mechanism for bed leveling is not applicable under these conditions of high sodium subcooling. This is because the vapor bubbles from the two-phase zone are condensed and do not penetrate the stagnant subcooled sodium conduction zone at the top of the bed. In this respect the bed behavior at high subcoolings is thus fundamentally different from that at saturation or low subcoolings, where bed leveling by vapor bubble and jet agitation has been observed in laboratory experiments.

Future Work

Considerable further research is needed if the true coolability limits of particulate beds of LMFBR core debris under sodium over the relevant range of LMFBR post-accident conditions are to be measured and modeled. The upgrade of the ACPR, now called the Annular Core Research Reactor or ACRR, increases the available debris-bed specific power from 1.3% of nominal LMFBR average fuel specific power to 4.5% on a steady-state basis, and up to about 7% for a few hours. This capability covers the full range of fuel specific powers relevant to decay heating under LMFBR post-accident conditions. With this power capability, experiments can be performed on the dry out and coolability limits of thin beds as well as the very thick beds that were necessary to achieve dry-out in experiments D-2 and D-3.

The cooling and the characterization of the dried-out portion of the bed are a major subject for future experiments in ACRR. Extensive use will be made of recently developed techniques of ultrasonic thermometry that can measure temperature distributions at up to about 3000°C. The effect of steel particulate in the dried-out portion of the bed will be investigated. These experiments should determine the margin between the dry-out limits and the true coolabililty limits of a particulate bed of LMFBR fuel debris under sodium.

Some experiments are needed at low sodium subcooling, because laboratory experiments indicate that, near saturation, different cooling mechanisms are dominant and bed leveling will occur. Information from these experiments is also needed for assessing the consequences of the loss-of-heat-sink accident. Research is also needed upon the effect of the bed formation process upon bed coolability, as particulate segration by size while falling through sodium and the degree of bed packing affect the local bed permeability. Experiments are planned with particulate beds that are settled naturally by gravity through sodium. The effects of particle size, and the presence of $UO_2$ fines and particulate steel, need to be investigated.

Planned near-term ACRR experiments through FY 1980, consistent with current budget constraints, are as follows:

D-4 Intermediate bed depth (9 cm) at higher specific power. Predicted dry out at 2.5% of nominal LMFBR fuel specific power. Ultrasonic thermometry and additional thermocouples.

D-5 First experiment to investigate extended dry-out regions. Modified capsule for higher wall temperatures. Ultrasonic thermometry. Bed depth, 11 cm.

D-6 Naturally settled particulate bed formed under 9 meter sodium column. Fines added to particulate mix. Bed-depth, 11 cm. Results directly comparable with D-2 and D-5.

Recommendations

We consider these in-core results on the threshold specific power for the dry out of particulate LMFBR fuel debris under highly subcooled sodium to be the best data currently available. We also consider the Sandia debris-bed coolability model for high sodium subcoolings (that agrees well with these data) also to be the best available. We recommend the use of these data and this model for evaluating LMFBR debris-bed coolability under the highly subcooled conditions of LOF and TOP accidents. This work will be utilized by RES in studying LMFBR event trees. It may also be of use to NRR staff in forming judgments about end of spectrum accident scenarios in such reactors.

The fact that the true bed coolability limit occurs at a higher specific power than the dry-out limit, but by a currently unknown amount, supports an assumption of conservatism in the use of the dry-out limit in evaluations of bed coolability. On the other hand, the results of these experiments and the analysis indicate that the assumption of bed leveling under these conditions of high subcooling is both technically unwarranted and non-conservative.

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

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