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

FEB 2 8 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 # 81, "IRRADIATED-FUEL DISRUPTION UNDER LOF ACCIDENT CONDITIONS: RESULTS OF ACPR TEST SERIES FD-1 AND THE FISGAS CODE."

INTRODUCTION AND SUMMARY

This memorandum summarizes the results and analyses of the Fuel Disruption-1 (FD-1) series of in-reactor experiments on the swelling and disruption of irradiated fuel under the conditions of an unprotected (no-scram) loss-of-flow (LOF) accident in an LMFBR. The Sandia topical report, NUREG/CR-0914 (Enclosure 1), describes this work in detail. The Sandia report, NUREG/CR-1124 (Enclosure 2), describes the FISGAS irradiated-fuel fission-gas-behavior code. FISGAS was developed from the base of the FRAS2 code[1] with the addition of phenomena shown to be needed by the FD-1 series test results.

The fission-gas-driven post-failure motion of the reactor fuel is a principal determinant of an LOF accident sequence. Whether or not the LOF accident transient is terminated by negative reactivity feedback or whether it proceeds into a relatively energetic disassembly of the reactor core was an important issue in the Clinch River Breeder Reactor (CRBR) licensing review.[2, 3] In his accident analysis, the applicant invoked an assumed fission-gas-driven fuel dispersal with sweep-out by fission gas and sodium vapor to prevent prompt criticality from sodium voiding and to achieve a nonenergetic termination of the LOF accident transient. This assumption was rejected in the analysis by the staff of the Office of Nuclear Reactor Regulation (NRR) on the basis that "from the available experimental data and analysis it is not clear to what extent fission gases may act dispersively or via what mechanism.[3] The fuel-disruption (FD) experiment series was undertaken to provide such information to assist the staff in resolving the issue. The data and analysis obtained to date and reported here support the staff in rejecting the applicant's position.

In the FD-1 series of 12 tests, single clad pellets of irradiated mixed-oxide fuel were fission heated in a helium-containing test capsule in the experiment cavity of the Annular Core Pulse Reactor (ACPR) at Sandia Laboratories. The behavior of the cladding and fuel was observed by high-speed cinematography. The environment simulated the conditions in the voided region of an LMFBR core during an unprotected LOF accident. Two of the 12 tests used fresh UO_2 fuel to obtain base data. Each test fuel element consisted of a single fuel pellet undisturbed within its original cladding as cut from EBR-II irradiated fuel pins. A variable fraction of the fuel reached melting in each of the data tests.

No evidence was seen in these experiments of the hypothesized irradiated-fuel dispersal mechanism of dust-cloud breakup, that is incorporated in the SAS accident analysis code, or of fuel frothing.[4] Unexpected, very-rapid fuel swelling of up to 67 area/percent in about 0.1 sec was observed as the fuel approached melting. These experiments indicate that rapid and massive fuel swelling is the initial mode of fuel disruption under LOF accident conditions. This rapid swelling is not predicted by the existing FRAS-type irradiated-fuel modeling, so a new model of irradiated fuel behavior, FISGAS, was developed. FISGAS includes fuel creep, bubble disequilibrium, and grain boundary gas in addition to the intra-granular gas treated in FRAS. While FISGAS gives the qualitative features of the fuel-swelling data, the agreement is not really quantitative, which shows that significant effects are still missing from the model. Continuing modifications to the model are addressing the differences from the data. In the FD-1 experiments, the clad ballooned away from the fuel as the fuel swelled, and the ballooned clad failed by rupturing and "peeling away" from the fuel as the clad approached melting. The molten stainless-steel clad material did not wet the hot solid or molten fuel in either the irradiated or the fresh fuel tests.

The results of the FD-1 series of experiments, the irradiated-fuel-behavior modeling in the FISGAS code, and plans for future work were the subject of a meeting of the Advanced Reactor Safety Research (ARSR) Accident Energetics Review Group on September 19, 1979. Argonne National Laboratory (ANL) staff in attendance also presented results of the Department of Energy (DOE) supported program of direct-electrical-heating laboratory experiments with irradiated fuel, plans for future in-reactor experiments, and associated analytical model development. No substantive technical disagreement was expressed with the experimental and analytical results in the two Sandia reports, NUREG/CR-0914 and NUREG/CR-1124, as presented to the review group and in this Research Information Letter, although questions were raised by ANL staff about the prototypicality of the FD experiments. There was general agreement that further experiments in this area are desirable, particularly with multiple pellet fuel pins and with more prototypic heating rates, and that further analytical model development is needed.

DISCUSSION

In the voided region of an LMFBR core during an unprotected loss-of-flow (LOF) accident, the fuel temperature at fuel failure varies from melting (3020K) at the center to about 2200K at the pellet surface, and the atmosphere is sodium vapor. In the FD-1 series of fuel-disruption experiments, these conditions were simulated by fission heating a single clad pellet of irradiated mixed-oxide fuel contained in a dry, helium-filled test capsule. These experiments were performed in the Annular Core Pulse Reactor (ACPR) at Sandia Laboratories before its upgrade with a new high performance core. With the moderation in the ACPR experiment cavity that was necessary to achieve the desired temperatures in the available irradiated test fuel, the max/min radial flux depression ratios in the test fuel were about 4, with the maximum energy deposition at the fuel surface. In order to overcome this undesired radial temperature profile, a series of two or three self-limited reactor power pulses was used with delay times of about 1/2 second between the pulses during which time the radial temperature profiles were modified by surface cooling and thermal relaxation. In some of the tests this procedure achieved relative flat radial temperature profiles at the time of clad failure, but the actual temperature or enthalpy maximum occurred at a radius of about 80 percent. Calculated temperature profiles as a function of time are given in NUREG/CR-0914. Optical measurements of the fuel and clad surface temperatures agreed well with the calculated temperature distributions. The nearly prototypic radial temperature profiles made possible by the increased performance of the upgraded ACPR (now called the Annular Core Research Reactor or ACRR) are one of the major improvements in the recently started FD-2 series of experiments.

The test fuel consisted of a single pellet of irradiated mixed-oxide or fresh UO_2. Each pellet was cut, undisturbed in its original stainless-steel cladding, from a fuel pin in a nitrogen-atmosphere hot cell. The test fuel pellets were taken from pins from the PNL-9, 10, and 11 irradiations in EBR-II. The 0.57 cm long pellets had fissile heavy-atom fractions of 40 percent or 68 percent, 5 percent burn-up, either high or medium power history, and had about 90 percent of theoretical density. The test pellets were constrained by depleted UO_2 end pieces which were lightly spring loaded.

The high speed cinematography gave very graphic information on the behavior of the fuel and cladding during these experiments. This technique shows much promise for future in-reactor experiments. In the data tests, the framing rate during the final power pulse varied from 1000 to 2250 frames per second. The motion pictures from these experiments are available on request from the Office of Research (RES).

Of the 12 tests performed, 4 were low energy calibration tests in which the fuel did not fail, 2 were comparison tests with fresh UO_2 fuel, and 6 were data tests with irradiated mixed-oxide fuel. A variable fraction of the fuel reached melting in each of these 6 tests. The rate of temperature rise during the final heating pulse was $1. \times 10^4$ K/sec for the triple-pulsed runs and $2. \times 10^5$ K/sec for the double-pulsed runs. This is roughly two orders of magnitude greater than the adiabatic rate of temperature rise at the nominal LMFBR power characteristic of the unprotected LOF accident. The higher rate, however, is characteristic of an LOF-driven-TOP power burst. The average heating rate over the period of the two or three heating pulses was about 5 times that at nominal LMFBR power.

In these six tests, the cladding ballooned away from the fuel and generally failed by a rapid rupture-peeling-melting process that quickly exposed most of the fuel surface. The molten stainless steel did not wet the hot solid or liquid fuel in either the irradiated or the fresh fuel tests.

There was no fuel disruption in the three tests with the most nearly prototypic radial temperature profiles, but very rapid (0.1 sec) fuel swelling did occur with an increase of as much as 67 percent in cross-section area. In three of these tests in which the pulse-spacing was so short that the surface temperature at failure was above the centerline temperature, some fission-gas driven disruption of the liquid fuel near the pellet surface was observed. In one of these tests, the mostly-molten fuel pellet collapsed under the slight spring loading on the depleted UO_2 end caps. In none of these irradiated-fuel tests did the previously hypothesized fuel-disruption mechanisms of a solid-particle dust-cloud break up or liquid fuel frothing actually occur.[4] The clad did not rupture in the two fresh fuel comparison tests but failed only by melting, and the fuel swelling was slight.

In the DOE program at ANL, related experiments have been performed in which single pellets of irradiated fuel are heated to failure by direct electrical heating (DEH).[5] Heating rates were in the range of nominal LMFBR power. Some premelting surface spallation was observed at the higher powers, which were two to three orders of magnitude below the power at fuel failure in the fission-heated FD experiments. Pellet collapse upon complete melting occurred in both the DEH and the FD experiments.

The FISGAS analytical model that was developed during analysis of the FD-1 data and is reported in detail in the NUREG/CR-0914, is based on the fission-gas modeling in the FRAS code. Models of additional phenomena were added to the code in modular form and then tested independently against the experimental data. FISGAS was developed as a flexible research tool for use in analysis of the effect of these individual phenomena. The additional phenomena that were added during FISGAS development are grain boundary gas, bubble disequilibrium, and fuel creep.

The original FRAS modeling very seriously overpredicts the magnitude of the observed fuel swelling (factors of 2 to 3). Accounting for vacancy depletion was needed to correct this. Accounting for fuel creep was necessary to match qualitatively the very rapid swelling produced by the third heating pulse. Allowing for relief from the solid-structure constraint on swelling that occurs upon melting also appeared to be necessary from the data. The grain edge gas was the pressure source for the very rapid fuel swelling produced by the third heating pulse.

EVALUATION

The FD-1 series of experiments is unique in that the failure, swelling, and disruption of clad irradiated fuel under simulated LOF conditions in an LMFBR have been observed and measured directly. The results of these unique experiments are thus valuable for assessing the validity of the models of these processes that have been and will be used in LMFBR accident analysis codes. These results do not agree with the dust-cloud fuel-dispersal model used in the SAS analysis in the CRBR Preliminary Safety Analysis Report (PSAR), and they support the position of the NRR staff in not accepting the conclusions of this analysis. No evidence for the postulated dispersal mechanism of fuel frothing was observed in these tests. Other results applicable to LOF accident assessment are the observed rapid large swelling of the fuel as it approached melting, the rapid rupture-peeling-melting mode of cladding failure, and the lack of wetting of either hot solid or liquid, fresh or irradiated fuel by molten stainless steel.

A principal uncertainty about the applicability of these results to LOF accident analysis is the non-prototypically-high heating rate (factor of 50 to 1000 in power) at the time and temperatures of fuel failure that resulted from the double or triple pulsed mode of fuel heating necessary in these experiments. A second uncertainty is the possibility that contamination of the irradiated fuel pellets during the cutting operation in the nitrogen glove box might have contributed to the observed fuel swelling. Both these uncertainties will be eliminated in the FD-2 series of experiments in the upgraded ACRR that is now underway.

The FISGAS code, described in NUREG/CR-1124, was developed to include the FD-1 test results in modeling irradiated-fuel swelling under LOF conditions. In FISGAS, phenomena that were found to be important from the FD-1 results, primarily the effects of grain-boundary gas, bubble disequilibrium, and fuel creep, were added to the fission-gas modeling of the FRAS 2 Code. Although developed as a modular tool for experiment analysis, FISGAS is, in our opinion, the best code currently available for assessing fuel swelling under LOF accident conditions, because of its experimental verification. By using FISGAS for assessment of LOF accident behavior rather than applying the FD-1 test results directly, effects of the non-prototypically-high power at fuel failure in the FD-1 tests can largely be eliminated.

FUTURE WORK

A much-improved series of FD-2 experiments on the swelling and disruption of clad pins of irradiated oxide fuel under LOF accident conditions has been started in the upgraded ACRR test reactor. With the increased pulse fluence available in the upgraded reactor, the required energy deposition in the fuel can be achieved with a harder spectrum (less moderation) so that the undesired flux depression in the test fuel can be significantly reduced. Prototypic LOF fuel heating is achieved by an approximately constant-power heating pulse that is generated by constant-rate withdrawal of the control-rods. This eliminates the unprototypically high heating rates at fuel failure associated with the double-or-triple-pulse heating required in the FD-1 series of tests. In the FD-2 experiment series, the specimens of clad irradiated fuel are prepared in a high-purity (10 ppm impurity) argon glove box to avoid contamination of the fuel. The test specimens of clad fuel are 5 pellets long, and the high-speed cinematography views both the front and back of the test fuel element simultaneously. Samples of the gases emitted by the test fuel during the transient are collected for later analysis as to composition. These experimental improvements should produce significantly better data under more nearly prototypic conditions, and should provide a base for ongoing modeling of fission-gas effects. The FD-2 experiment series includes 10 tests, of which 7 are data tests with irradiated fuel. This test series should be completed by April 1980.

A different series of irradiated-fuel disruption experiments under high-reactivity-ramp-rate conditions (up to $200/sec) are planned for 1980. Premelting fission-gas-driven fuel dispersal has the potential for early termination of a super-prompt-critical power excursion with a significant reduction of the fission energy in the burst. The purpose of this series of experiments is to determine whether or not this hypothesized early shutdown mechanism actually exists, and to provide a data base for model development if it does exist. These experiments are a joint program between NRC and the United Kingdom Atomic Energy Authority which has considerable interest in this potential shutdown mechanism. A British visiting scientist at Sandia has played a major role in designing these experiments. These experiments will use double-pulsing of the ACRR to achieve the desired radial temperature profiles in the fuel and high power at fuel failure. A series of 6 or 7 irradiated-fuel tests is planned.

Also under discussion is a short series of 4 fuel-disruption tests, similar to FD-2, that uses zircalloy-clad irradiated PWR fuel. These tests are to be performed in cooperation with the Light Water Reactor Safety Research program. These are scoping tests to determine whether the modes of cladding failure and rapid fuel swelling observed in the LMFBR fuel tests also occur under LWR conditions.

RECOMMENDATIONS

We consider that the results of the FD-1 series of experiments on the failure, swelling, and disruption of clad irradiated-fuel pins under LMFBR LOF conditions are the best data currently available on these processes. We believe that these data, and the FISGAS irradiated-fuel behavior code that models the data, are the best tools currently available in LMFBR safety analysis for assessing these effects. We recommend that the irradiated-fuel behavior modeling of FISGAS be incorporated in codes such as EPIC for use in assessing the early stages of the LOF accident. The FD-1 data support the position of the NRR staff in the CRBR licensing review in rejecting the applicant's claim that fuel dispersal, in particular the dust-cloud model used in the applicant's SAS analysis, would produce a non-energetic termination of the LOF accident. Improved data from the FD-2 test series should soon be available and will be transmitted to NRR.

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

Robert Budnitz

Robert J. Budnitz, Director
Office of Nuclear Regulatory
Research

Enclosures:
(1) NUREG/CR-0914
(2) NUREG/CR-1124

cc: See Page 8

cc w/o encl.:
R. J. Budnitz, RES
J. T. Larkins, RES
T. E. Murley, RSE
C. N. Kelber, ARSR
M. Silberberg, ARSR
R. W. Wright, ARSR (6)
E. G. Case, NRR
D. B. Vassallo, DPM
D. Ross, DPM
W. P. Gammill, DPM
J. V. Walker, Sandia
J. E. Powell, Sandia
P. S. Pickard, Sandia
G. L. Cano, Sandia
R. W. Ostensen, Sandia
M. F. Young, Sandia
J. H. Scott, LASL
H. H. Hummel, ANL
V. K. Dhir, UCLA

cc w/encl.:
J. F. Meyer, DPM
T. P. Speis, DSS
H. Alter, DOE
H. K. Fauske, TMC/ANL

References:

1. E. F. Gruber, "A Generalized Parametric Model for Transient Gas Release and Swelling in Oxide Fuels," Nuclear Technology, 35, 619 (October 1977).

2. "Preliminary Safety Analysis Report-Clinch River Breeder Reactor Project," Project Management Corporation (1975).

3. J. F. Meyer, L. Lois, J. L. Carter, and T. P. Speis, "An Analysis and Evaluation of the Clinch River Breeder Reactor Core Disruptive Accident Energetics," NUREG-0122 (March 1977).

4. W. R. Bohl and M. G. Stevenson, "A Fuel Motion Model for LMFBR Unprotected Loss-of-Flow Accident Analysis," (CONF-730414-02, Ann Arbor, MI (April 1973).

5. G. Bandyopadhyay and J. A. Buzzell, "Cladding and Fuel Motion of Irradiated Stainless Steel-Clad Mixed-Oxide Fuels in Response to Simulated Thermal Transients," Proc. Int. Mtg., Fast Reactor Safety Technology, Seattle, Washington, Aug. 19-23, 1979, p. 1735. (1979)

RECOMMENDATIONS

We consider that the results of the FD-1 series of experiments on the failure, swelling, and disruption of clad irradiated-fuel pins under LMFBR LOF conditions are the best data currently available on these processes. We believe that these data, and the FISGAS irradiated-fuel behavior code that models the data, are the best tools currently available in LMFBR safety analysis for assessing these effects. We recommend that the irradiated-fuel behavior modeling of FISGAS be incorporated in codes such as EPIC for use in assessing the early stages of the LOF accident. The FD-1 data support the position of the NRR staff in the ~~CRBR licensing review in~~ rejecting the applicant's claim that fuel dispersal, in particular the dust-cloud model used in the applicants SAS analysis, would produce a non-energetic termination of the LOF accident. Improved data from the FD-2 test series should soon be available and will be transmitted to NRR.

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

Saul Levine, Director
Office of Nuclear Regularory
Research

Enclosures:
(1) NUREG/CR-0914
(2) NUREG/CR1124

cc w/o encl.:
~~S. Levine, RES~~
R. J. Budnitz, RES
J. T. Larkins, RES
T. E. Murley, RSE
C. N. Kelber, ARSR
M. Silberberg, ARSR
R. W. Wright, ARSR (6)
E. G. Case, NRR
D. B. Vassallo, DPM
D. Ross, DPM
W. P. Gammill, DPM
J. V. Walker, Sandia
J. E. Powell, Sandia
P. S. Pickard, Sandia
G. L. Cano, Sandia
R. W. Ostensen, Sandia
M. F. Young, Sandia
J. H. Scott, LASL
H. H. Hummel, ANL
V. K. Dhir, UCLA

cc w/encl.:
J. F. Meyer, DPM
T. P. Speis, DSS
H. Alter, DOE
H. K. Fauske, TMC/ANL

DIST:
Subj
Circ
Chron
RWWright:RDG

OFFICE ►	RSR:EFRSRB RWW MS	RSR:AD/ARSR	RSR:D	RES:PC	RES:DD	RES:D
SURNAME ►	RWWRIGHT;wh MSILBERBERG	CNKELBER	TEMURLEY	JTLARKINS	RJBUDNITZ	~~SLEVINE~~
DATE ►	12/1/79	12/1/79	12/5/80	~~12/ /79~~ 2/ /80	~~12/ /79~~ 2/ /80	~~12/ /79~~

model development if it does exist. These experiments are a joint program between NRC and the United Kingdom Atomic Energy Authority which has considerable interest in this potential shutdown mechanism. A British visiting scientist at Sandia has played a major role in designing these experiments. These experiments will use double-pulsing of the ACRR to achieve the desired radial temperature profiles in the fuel and high power at fuel failure. A series of 6 or 7 irradiated-fuel tests is planned.

Also under discussion is a short series of 4 fuel-disruption tests, similar to FD-2, that uses zircalloy-clad irradiated PWR fuel. These tests are to be performed in cooperation with the Light Water Reactor Safety Research program. These are scoping tests to determine whether the modes of cladding failure and rapid fuel swelling observed in the LMFBR fuel tests also occur under LWR conditions.

RECOMMENDATIONS

We consider that the results of the FD-1 series of experiments on the failure, swelling, and disruption of clad irradiated-fuel pins under LMFBR LOF conditions are the best data currently available on these processes. We believe that these data, and the FISGAS irradiated-fuel behavior code that models the data, are the best tools currently available in LMFBR safety analysis for assessing these effects. We recommend that the irradiated-fuel behavior modeling of FISGAS be incorporated in codes such as EPIC for use in assessing the early stages of the LOF accident. The FD-1 data support the position of the NRR staff in the CRBR licensing review in rejecting the applicant's claim that fuel dispersal, in particular the dust-cloud model used in the applicant's SAS analysis, would produce a non-energetic termination of the LOF accident. Improved data from the FD-2 test series should soon be available and will be transmitted to NRR.

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

Robert Budnitz

Robert J. Budnitz, Director
Office of Nuclear Regulatory
Research

Enclosures:
(1) NUREG/CR-0914
(2) NUREG/CR-1124

cc: See Page 8

*See attached yellow for previous concurrence

OFFICE ▶	RSR:EFRSRB*	~~RSR:AD/ARSR*~~	~~RSR:D*~~	RES:PC	RES:D RJB
SURNAME ▶	RWWRIGHT:wh MSILBERBERG	CNKELBER	TEMURLEY	JTLARKINS	RJBUDNITZ
DATE ▶				/ /80	2/28/80

NRC FORM 318 (9-76) NRCM 0240 ★ U.S. GOVERNMENT PRINTING OFFICE: 1978 - 265 - 769