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SUMMARY AND CONCLUSIONS - SLSF LOCAL FAULT SAFETY EXPERIMENT P4*

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Sodium Loop Safety Facility (SLSF) experiment P4 was performed to investigate the consequences of an upper-bound or "worse-than-worst case" local fault configuration. P4 was intended to bound the consequences of credible subassembly faults by ejecting molten fuel into a 37-pin bundle of full-length Fast Test Reactor (FTR)-type pins and failing fuel with the potential for further cladding and fuel-pin damage. In addition to ejecting a large amount of molten fuel at or near full power, experiment objectives were to evaluate the severity of molten fuel-coolant interactions (MFCIs) and to demonstrate that any resulting blockage could either be tolerated during continued power operation or detected by global monitors in time to prevent significant fuel failure propagation.

SLSF was a large, double-contained sodium loop test vehicle for testing LMFBR fuel pins under hypothetical accident conditions. It was operated in the Engineering Test Reactor (ETR) at the Idaho National Engineering Laboratory by EG&G Idaho, Inc. Experiment P4, conducted under the direction of Argonne National Laboratory, was the seventh, and last, in the series of large-scale SLSF experiments sponsored by the U.S. Department of Energy to resolve technical issues affecting licensing of LMFBR plants.

The 37-pin P4 test subassembly contained 34 standard FTR-type fuel pins and three fuel pins with a sealed 10-cm-long fuel canister located at their fuel-column midplanes. Two canisters were cylindrical and the third was fluted. The diameter of the cylindrical canisters was selected to produce line contact with the adjacent fuel pins in an undistorted bundle geometry. The fluted canister occupied the area of six coolant flow subchannels; 120° of the periphery of each adjacent pin nested in the cusps of the fluted canister. The canisters were loaded with high density, fully enriched UO_2 pellets and contained a total of 170 grams of fuel, the same as that in one fuel pin. Cladding of the fluted canister was designed to fail via sodium boiling, voiding and cladding dryout. Cylindrical canisters were designed to fail and release molten fuel via cladding rupture due to fuel-cladding mechanical interaction.

Full-power operating conditions for P4 were a peak linear power of 45 kW/m and a coolant velocity of 6.4 m/s. Bounding operating conditions for P4 were emphasized by selection of an undercooling operating condition (power/flow ratio = 1.24 times that of a central FTR core subassembly), high coolant inlet temperature (695 K), and use of half-diameter wire wrap spacers on the outer row of fuel pins to reduce the "cold" peripheral flow. Design goal for molten fuel release was 10 to 30 g per cylindrical fuel canister, an order of magnitude margin over the minimum required for damage.

Experiment Operation

Two full-power days of irradiation were accumulated during initial low power ETR operation to build up fission products in the initially fresh fuel for subsequent failure detection. Full power was then reached with a programmed power transient that increased ETR power from 40 MW to 175 MW on an 18.8-s period, followed by a 5-s hold at 175 MW and a 5-s ramp down to 156 MW for subsequent steady state operation. First evidence of fluted canister failure was observed at 15.2 s. There was an increase in the delayed neutron signal and some temperature perturbations, but no evidence of gross molten fuel release or flow blockage. Molten fuel release from a cylindrical canister occurred at 34 s. The molten fuel was directed toward outer row pins and adjacent hex-can flats. It was accompanied by a sharp increase in DN level and by perturbations in acoustic noise, local coolant temperature levels, and in inlet and outlet flow. Pin failures resulted from this release of molten fuel; some of the fuel formed a local blockage and the remainder solidified on the hex-can above the upper end caps of the canisters. Inlet flow was reduced to 93% of nominal, but recovered to 97% at 54 s. Molten fuel was ejected toward the center of the bundle from the fluted canister at 86 s and was accompanied by a further reduction in test section flow to 86%. This molten fuel caused failure of the second cylindrical canister. One thermocouple that formed a new junction as a result of this fuel release indicated sustained local boiling and dryout in the blockage wake. At 110 s, the hex-can failed locally where it was in contact with once-molten fuel and a blowdown of the pressurized gas in the insulator region occurred. This caused large oscillations in indicated bundle exit and loop coolant flowrates for several seconds. After gas passage, the test section bundle flowrate recovered to the 86% level.

An incorrect helium operation resulted in an unreversed increase in test-subassembly inlet sodium temperature during the power transient and subsequent steady power operation. By 110 s, the inlet temperature had increased by ~55 K. Output of the SLSF annular linear induction pump and the non-temperature compensated signal from the inlet magnetic flowmeter to the protective system were both influenced by the increase in inlet temperature. This resulted in a total reduction of 5 to 6% in inlet flowmeter signal to the protective system. ETR scram occurred when the preset 80.3% inlet-flow setpoint was reached at 118 s.

ETR power operation resumed later with a lower (68%) inlet-flow setpoint. A blockage reconfiguration occurred as reactor power was being trimmed near 100 MW, after power increases in 10- and 20-MW increments in a step-and-hold manner. Delayed neutron signals began to increase about three minutes prior to the reconfiguration and flow reduction. The DN signals rose in an exponential manner to a level nearly 6 times nominal prior to the blockage extension and peaked at about 11 times nominal after the blockage extension. ETR scrammed on the drop in test subassembly flow and no further high power operation followed.

Disassembly and Posttest Examination

The SLSF loop and P4 test assembly were transported to the Hot Fuel Examination Facility (HFEF) for initial disassembly and nondestructive examination. Full-length neutron radiographs were produced of the P4 fuel bundle. They provided evidence that a significant portion of the test-section flow area became blocked by fuel expelled from the fuel canisters during the power transient. The 28-cm-long blockage region extended from 13 cm below to 15 cm above the fuel midplane. The blockage region was neutron radiographed from thirty-six views at 5° azimuthal increments to permit computer-assisted tomographic reconstruction of the blockage. Evidence from this extensive radiography identified an 8 mm x 25 mm hole in the hex-can ~8 cm above the tops of the fuel canisters. This hex-can failure occurred where molten fuel had solidified on the hex-can; frozen fuel was found adjacent to the hole. A 36-cm-long fuel-bundle segment, containing the entire blockage region, was cut from the P4 test section and transferred to the Alpha-Gamma Hot Cell Facility (AGHCF) for detailed posttest examination.

A routine SLSF-type macroexamination was performed on the fuel-bundle segment for the purpose of evaluating the extent of fuel expulsion from the blockage canisters and failure propagation to adjacent fuel pins, characterizing the blockage morphology, and developing an accident-simulation scenario consistent with on-line instrumentation data. A series of closely spaced transverse cuts were made throughout the segment, and each newly exposed surface was photographed at 2X magnification with both flat and highlight illumination.

Examination of the macrosections revealed that full-length breaches were present in all three canisters that permitted expulsion of all the UO_2 from the central three-fourths of the fluted and one cylindrical canister and a lesser amount from the other cylindrical canister. Expulsion of the molten UO_2 from the fuel canisters directly caused the failure of cladding and fuel disruption of the central seven pins. Over twenty percent of the pins remained intact throughout the experiment, and many more experienced only slight cladding failure with no fuel disruption. Cladding melting was observed from 64 mm below to 73 mm above fuel midplane and from 110 mm to 165 mm above fuel midplane (i.e., adjacent to the breach in the hex-can). Maximum cladding disruption was observed within a 20-mm-long region centered on the fuel midplane where up to 40% of the cladding was melted and relocated. A voided region, once containing the central pins, extended from 38 mm below to 47 mm above midplane where a cap of cast fuel and metal had frozen against the existing pin structure.

Metallographic examination of specimens selected from throughout the blockage region identified a wide range of microstructures. Fuel exposed to sodium (either as disrupted fuel in the coolant channels or as intact fuel in pins with melted cladding) contained a grain-boundary phase near the exposed fuel surface, identified as sodium uranate. In many regions, cast fuel and metal were intimately mixed where metal filled the cracks and voids in the cast fuel, and other fuel structures contained 1-2 micron diameter metal spheres within a very dense fuel matrix.

Conclusions

1. Fresh fuel pins are tough. Even though operated at an undercooled condition and subjected to an overpower, three molten fuel releases, modest MFCIs, and a massive gas release, over 20% of the pins survived the entire P4 operation intact. Damage to the other pins was localized.

2. Molten fuel ejected from the P4 fuel canisters did not fragment and sweep-out, as predicted, but produced local heat-generating flow blockages. This lack of fuel sweepout was also observed in the CAMEL II 37-pin C5 test[1] and is attributed to two dimensional effects (sodium bypass, etc) in 37-pin test subassembly.

3. The measured P4 inlet coolant response was in excellent agreement with slug-response coolant behavior driven by the 14.4 MPa peak pressure predicted by PLUTO pretest calculations. This provides additional confirmation of the earlier conclusion that MFCIs resulting in greater than 20 MPa pressurization with measurable impulses simply have not occurred.[2]

4 The local hex-can failure resulted from the nonprototypicalities (small bundle size, graded fuel enrichment, and lack of external hex-can cooling) inherent in P4.

5. Although the extended steady-state operation at full power was not realized, there was no evidence of any failure propagation following the initial molten fuel releases.

6. Uranate which formed in the fuel blockage during the extended shutdown at temperature reduced blockage coolability and contributed to the blockage reconfiguration during return-to-power operation. DN detectors provided up to three minutes warning of the impending change. The developing configuration was not sensed by other instruments.

References

1. R. J. Wilson et al., CAMEL II 37-Pin/7-Pin Intra-Pin Fuel Injection Test, *Trans. ANS 46*: 504-505, June 1984.

2. C. J. Mueller, ANL, personal communication, August, 1979.