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This paper briefly describes the progress to date on the joint UKAEA/USDOE program of fast reactor fuel safety testing and the definition of the future tests. The program involves transient tests in the TREAT reactor on fresh and irradiated mixed oxide fuel pins. The tests simulate transient overpower (TOP) accidents, which result from an unintentional addition of reactivity and transient undercooling followed by overpower (TUCOP) accidents, which arise from an unintentional stoppage of the primary sodium circulating pumps, both with failure to scram. Thirteen tests have been performed to date, all on UK pins. Future plans include five tests, all on US pins which have been irradiated in FFTF. Much has been learned about the behavior of fuel driven to conditions well beyond those existing during normal reactor operation.

INTRODUCTION

A collaboration between the UKAEA and USDOE in the field of fast reactor fuel safety testing and analysis, called PFR/TREAT, was established in 1979 to make use of the PFR reactor to pre-irradiate mixed oxide fuel pins fabricated by the UK and the US and the TREAT reactor to carry out safety tests (ref. 1). These safety tests are designed to produce conditions similar to those which arise in very low-likelihood unprotected power reactor faults in which the automatic shut-down system is assumed to fail to operate. In these tests, the most significant information is the time and location of cladding failure and the redistribution of fuel. This is obtained by the interpretation of loop instrumentation (thermocouples, flowmeters, pressure transducers) data and by the analysis of data from the fast neutron hodoscope (ref. 2). The aim of the program is to produce an experimental data base which can be used to validate and improve the methods and codes used for safety analyses of the behavior of fast reactors.

TESTS COMPLETED TO DATE

Thirteen experiments have been performed to date. Three of the tests have been done on fresh fuel and the remainder have been performed on pre-irradiated fuel pins. The pins employed have been of standard PFR driver fuel design with annular fuel pellets, clad in M316 stainless steel and with a knitmesh plug of refractory metal separating the fuel stack from the lower annular breeder pellets. The gas plena on these pins are at the bottom. The tests which have been run simulate transient overpower conditions resulting from an accidental addition of reactivity, and transient undercooling followed by overpower conditions arising after unintentional stoppage of the primary sodium circulating pumps. The variables are: (i) the type of test, that is TOP or TUCOP; (ii) the conditions at the start of the power pulse, that is the pin rating in a TOP test and the state of the sodium coolant in a TUCOP test; (iii) the power ramp rate during the overpower; (iv) the fuel burnup; and (v) whether the test uses a single fuel pin (C-series) or bundle of 7 pins (L-series). The matrix of completed tests is shown in Table I.

Table I: Matrix of Completed Tests

Test Type	Start Conditions	Power Ramp Rate	Burnup: Fresh 1-Pin	Burnup: Fresh 7-Pin	Burnup: Medium 1-Pin	Burnup: Medium 7-Pin	Burnup: Goal 1-Pin	Burnup: Goal 7-Pin
TOP	High Rating	High	C01	L01	C02	L02	C03	
		Low			C04	L03	C05	
TUCOP	Voided	Nominal		L06		L04		
	Unvoided				C06R	L07		
	Part-Voided					L05		

SINGLE PIN HIGH RAMP RATE TOP TESTS

Three single pin high ramp rate TOP tests, [C01, C02, C03], (ref. 3) were run to determine the time, location and mode of failure. C01 employed unirradiated fuel and C02 and C03 used, respectively, $\simeq$ 4 and 9% peak burnup fuel, the pre-irradiations having been performed in the PFR reactor. The transients that were used in these tests simulated a 5 \$/s reactivity ramp hypothetical accident. The single pin test vehicle used for the three experiments was a capsule containing static NaK as coolant. The nickel heat sink containing the fuel pin and NaK was instrumented with thermocouples at the inner and outer surfaces to monitor the thermal response during the transient. In the experiments, the capsule test assembly was heated, using electrical heaters, to give a pre-determined axial temperature profile. The power transients were qualitatively the same for all three experiments. The overall conclusion that was reached after a study of the results from the three high ramp rate TOP capsule tests is that three mechanisms were operating during these three tests, namely fuel melt-through, internal pressurization, and fuel-cladding mechanical interaction. However, the capsule test vehicle did not provide an ideal environment to study pin failure and it was not possible to unambiguously determine the degree of non-prototypicality in the test conditions.

SEVEN-PIN HIGH RAMP RATE TOP TESTS

Tests L01 and L02 were similar tests done with seven-pin bundles performed with fast TOPs to simulate 5\$/s reactivity ramp hypothetical accidents in a large fast reactor (ref. 4). L01 used fresh fuel, while L02 used PFR fuel irradiated to $\simeq$4% peak burnup, to determine any differences in the failure mechanism and subsequent fuel behavior due to irradiation. They were performed in flowing sodium in the Mark IIIA version of a TREAT integral loop. Test objectives were to obtain information on: (i) fuel motion in the central hole of the annular pellet fuel stack prior to cladding failure, (ii) the time, location and mode of failure, and, (iii) material motion in the channel after failure, in all cases having particular regard to the effect of irradiation. L01 and L02 were the seven-pin counterparts to the C01 and C02 single pin capsule tests described above, seven pins in flowing sodium being a more representative environment for the post failure events. From the results it was concluded that the fuel pin failure found in the seven-pin tests L01 and L02 were consistent with those in the C01 and C02 tests. From the post-test examinations done on the L01 and L02 test sections, it has been found that there are no major differences between fresh and irradiated fuel in the extent of fuel disruption, cladding failure, and flowtube failure (all approximately in the upper two-thirds) under high ramp rate TOP conditions. Upper and lower metal blockages were formed in both tests.

Among the low probability fast reactor accident scenarios addressed by the collaborative PFR/TREAT transient testing program is the slow TOP resulting from a control rod runaway with failure to trip. This has been simulated with three tests on irradiated fuel (ref. 5). Tests C04 and C05 were single pin experiments designed as a pair to study the effect of burnup on the time, location, and mechanism of cladding failure and initial fuel escape. The C04 fuel had a peak burnup of $\simeq$4% while the C05 fuel had reached a maximum burnup of $\simeq$9%. The L03 test studied pin failure and post-failure fuel dispersal in a bundle of seven pins nominally identical to that used in test C04. The test vehicle used for C04 and C05 consisted of a Mark III flowing sodium loop containing a test train designed to accommodate a bottom plenum test fuel pin supported by grids in a flowtube with prototypic flow area. Instrumentation was provided to measure the sodium flows, temperatures, pressures, and fuel motion. Test L03 was performed using a Mark III 7-pin loop similar to that used for tests L01 and L02, but the coolant flow area increased around the outside of the pin bundle to encourage fuel pin failure into the center of the bundle. The transients used for C04, C05, and L03 simulated a hypothetical accident with a period of 15 seconds. From the hodoscope results for these tests, it has been found that fuel motion from both fresh and irradiated fuel pins is dispersive under test conditions. The conclusions reached from these tests are: (a) as predicted, there are no phenomenological differences in failure behavior between the two burnups tested and (b) a slow overpower accident in a fast reactor would result in fuel pin failure near the top of the fuel column, followed immediately by rapid upward fuel dispersal and a large reduction in reactivity.

SINGLE PIN TUCOP TESTS

The C06R test was a single-pin test to study the mechanism, time and location of cladding failure and first fuel escape in a TUCOP accident (ref. 6). The test fuel was a single irradiated fuel pin with $\simeq$4% peak burnup. The test vehicle was a specially designed single pin test loop with flowing sodium coolant, and the test fuel was supported by simulated grid supports in the test train flowtube. Instrumentation was provided to measure inlet and outlet flows, temperatures, pressures and acoustic signals, and the fast neutron hodoscope was used to monitor fuel motion. In this test it was observed that when the fuel pin failed in the upper part, emerging fuel accumulated in the vicinity of the failure site for 30 ms and then dispersed upward. Even with the momentary accumulation of fuel outside the failure site, the in-pin motion of molten fuel to the breach produced a decrease in the net fuel worth. The subsequent upward dispersal of the accumulated fuel produced further worth reduction leading to a total decrease of ~ 15%. In summary, this test has produced evidence that postfailure internal and external fuel motions produce net fuel worth decreases that would help reduce the effects of a TUCOP accident in a fast reactor.

SEVEN-PIN TUCOP TESTS

Four TUCOP tests have been performed on seven-pin bundles in Mark III loops (refs. 7, 8). Three of them (tests L04, L05, and L07) used fuel pins of ≃4% peak burnup, from the same PFR subassembly, and one (L06) tested fresh fuel. The three tests on irradiated fuel covered the spectrum of conditions expected in a power producing fast reactor undergoing an unprotected loss-of-flow accident. Test parameter values were chosen to emphasize the differences in the motion of reactor-core materials that would result from the range of power-to- flow conditions to be found across the core. Moreover, by initiating the overpower bursts at different fuel-coolant thermal-hydraulic states, the three tests yielded distinct differences in fuel and coolant response, providing a wide range of behavior useful in verifying accident models and codes. In test L04, fuel escape was into mostly-voided coolant channels, with the cladding weak or molten. In L05, escape was into partly-voided channels with partly intact but weak cladding, and in test L07, escape was into channels just beginning to void with the cladding still strong. Test L06 was the fresh fuel equivalent of test L04. There were some differences in the fuel dispersal in these two tests. In general, the fuel motion is dispersive; however, in L06 there is evidence of a small compactive event. This event has a much lower magnitude that the offsetting dispersive events. Tests L04, L05 and L07 form a triplet which can be studied for similarities and differences since they had, as their chief parameter, the channel condition at time of failure. The fuel movement in these three tests was, in general, dispersive. However, there were some differences in the observed behavior. The voided channel test, L04, was the most dispersive; in the partly voided test, L05, dispersal was similar to that for L04 in the early phases, but it terminated with only approximately one-half the dispersal observed in L04. The dispersal in the third test, L07, was terminally similar to that in L05 but it began appreciably later.

Several general conclusions can be drawn from the results of the tests that have been completed. A major overall observation is that in every test there has been axial dispersive redistribution of fuel, which, in an actual fast reactor fault, would have a very significant effect in reducing reactivity and shutting down the core power. However, the seven-pin bundle tests have shown blockages of the coolant flow passages after this axial dispersal of fuel and cladding. This may be a small bundle effect; if it occurred in full-scale subassemblies of a fast reactor, it might tend to inhibit in-situ cooling of the core after a major fault. In modeling fuel pin failure, it is clear that predictions of failure time and location using present methods are generally in good agreement with the experiments. The importance of cladding melt-through as a failure mechanism has been demonstrated and some progress has been made toward a better understanding of this phenomenon. Fuel pin burnup does not appear to be a very important parameter. Four sets of similar tests, three (C01, C02, and C03), (L01 and L02), (C04 and C05) simulating TOP conditions and a fourth (L04, L06) simulating TUCOP conditions, with pin burnup the only major variable, have been run. Although the magnitude of the fuel motion appears to be a function of burnup, the trends in all cases are very similar. Further tests are needed to explore this point. If the initial indications are confirmed, it would be possible to simplify reactor safety analysis considerably and to have greater confidence in the assessments.

Further details of tests results, analyses, evaluations and conclusions for the matrix of completed tests are reported in references 3-10.

STRATEGY FOR FUTURE TREAT TESTING

The tests that have been completed in the PFR/TREAT program cover portions of ranges of parameters needed to establish a sufficiently complete mixed oxide fuel data base useful to both the UK and the US reactor programs. Consequently, those tests alone cannot be considered to be a complete data base. It is appropriate at this point to consider the matrix that was given in Ref. 1 and the parameters in that matrix and to evaluate the values that are currently pertinent for those parameters. It is still necessary to consider both TOPs and TUCOPs. However, the conditions considered for testing for both test types have changed. Currently, the interest in the TOP is stronger for the low ramp rate TOP than for the medium or high ramp rate TOP because less information is available world-wide on the effect of low ramp rates. With respect to the TUCOP, although single pin tests give important information on the time and location of first cladding failure during the TUCOP scenario, the large mass of flow tube wall relative to the mass of a single pin inhibits the post failure fuel motion within the coolant channel, which is of most interest in accident analysis. A TUCOP test with a seven-pin bundle provides a more prototypical environment. Consequently future TUCOP tests will be done with seven-pin bundles. Although a seven-pin test configuration can be used to simulate, in TREAT, most situations of interest, a seven-pin TUCOP test in which the flow channel is unquestionably completely unvoided at fuel failure is actually not achievable in TREAT because the power period that can be achieved with a seven-pin test cannot be made short enough to guarantee no boiling and voiding before fuel failure. Consequently, seven-pin tests for the unvoided channel situation are not being considered in the further development of the test program.

One must consider not only the transients which form the data base but also the parameters of the fuel pin which are used in the testing. One of those parameters is the power level at which fuel pins are irradiated. The original test matrix specified two power levels, HIGH and MEDIUM. During the past several years, it was recognized that the matrix is not realistic with respect to the power level at which the fuel pins are irradiated. For example, a subassembly of pins being irradiated in PFR must be rotated 180 degrees during irradiation in order to achieve uniformity in stainless steel swelling; because there is a marked flux gradient across a bundle it is difficult to characterize the power level during irradiation as either HIGH or MEDIUM. Another irradiation site for fuel pins used in this program is FFTF. The pins that are available from that site for this program have all been irradiated at nominally the same power levels.

Another parameter related to the fuel pins used in the testing is the burnup. The values specified for this parameter in the original test matrix for the PFR/TREAT Program were 0, 1/3, 2/3, and Goal. When the irradiation conditions of the available fuel pin were considered, the values were reduced to Fresh, Medium, and Goal. Also, the US has developed, subsequently, a strong interest in Near-Fresh fuel. Such fuel would be irradiated for 5 to 10 full-power days, to produce a condition in which the fuel is restructured with some gap closure and essentially no fission gas content. The use of such pins in a testing program would permit a study of the impact of fission gas on the dispersal of restructured fuel. Although fuel pins with such low burnup cannot be provided from fuel irradiated in PFR because of PFR operational considerations, they are available from FFTF.

Other parameters are related to the pins that are available for consideration. There are three basic sources of pins; one is UKAEA pins irradiated in PFR, another is USDOE pins which have been irradiated in PFR, and the third is USDOE pins irradiated in FFTF. The UKAEA pins have annular pellets, grid-supports and bottom gas plena. the US pins irradiated in PFR have wire-wrap supports and bottom gas plena. Some have annular pellets but most have solid pellets. The US pins irradiated in FFTF have solid pellets, wire-wrap supports and top gas plena. A viable approach to the development of an appropriate testing data base is one that accepts the information that has been developed in the thirteen tests that have been completed with PFR fuel, but continues in a direction that will broaden the data base, to make it applicable to a wide variety of fuel pin designs. Use of several types of pins to examine safety characteristics of oxide fuel systems provides a more comprehensive data base with which design features can be compared and evaluated with respect to safety. Similarly, the use of a multi-parameter test matrix to address generic safety issues and validate analytical models and computer codes requires parametric variation of important variables, including fuel design features. Therefore, there are strong motivations to strengthen the test matrix to include the effects of fuel pin design alternatives. Use of both PFR- and FFTF-type fuel pins in the test matrix will most broadly accomplish that purpose. The strategy that completes the test matrix by using US-fabricated pins irradiated in FFTF enhances the total matrix because it complements the completed tests, which were done with fuel pin design features which are pertinent to UK concepts, with a set of tests done with fuel pins with design features pertinent to US concepts. This strategy addresses the safety implications associated with top vs. bottom plenum, wire-wrap vs. grid-support, and solid vs. annular fuel pellets.

Based on the above strategy, five additional tests are planned to complete a reference mixed oxide fuel (mixed oxide; 316 stainless steel cladding) data base for accident analysis code validation. These five tests, all with FFTF pins, will include three low ramp rate TCPs and two voided channel TUCOPs. The three TOP tests will assess the effect of burnup over the full range from near-fresh to goal burnup. The two TUCOP tests will be done at near-fresh and medium burnup. All five tests will be done with seven-pin bundles. The matrix of these tests, superimposed on the matrix of completed tests is given in Table II. In that table, the future tests are designated by F.

Table II
Matrix of Completed and Future Tests

Test Type	Test Conditions	Burnup							
		Fresh		Near Fresh		Medium		Goal	
		1-Pin	7-Pin	1-Pin	7-Pin	1-Pin	7-Pin	1-Pin	7-Pin
TOP	Ramp Rate								
	High	C01	L01			C02	L02	C03	
	Low				F	C04	L03,F	C05	F
TUCOP	Channel Conditions								
	Voided		L06		F		L04,F		
	Unvoided					C06R	L07		
	Part-Voided						L05		

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