CONF-900804--32

Fast Reactor Safety Testing in TREAT in the 1980s*

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CONF-900804--32

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Submitted to the 1990 International Fast Reactor Safety Meeting, August 12-16, 1990, Snowbird, Utah.

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* Work performed under the auspices of the U.S. Department of Energy.

Work supported by the U.S. Department of Energy Technology Support Programs Contract W-31-109-Eng-38.

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FAST REACTOR SAFETY TESTING IN TREAT IN THE 1980s

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ABSTRACT

Several series of fast reactor safety tests were performed in TREAT during the 1980s. These focussed on the transient behavior of full-length oxide fuels (U.S. reference, UK reference, and U.S. advanced design) and on modern metallic fuels. Most of the tests addressed fuel behavior under transient overpower or loss-of-flow conditions. The test series were the PFR/TREAT tests; the RFT, TS, CDT, and RX series on oxide fuels; and the M series on metallic fuels. These are described in terms of their principal results and relevance to analyses and safety evaluations.

INTRODUCTION

The Transient Reactor Test (TREAT) facility is the principal U.S. facility for safety testing of fast reactor fuel. Located on the Idaho National Engineering Laboratory site, TREAT has been operated by Argonne National Laboratory-West for the U.S. Department of Energy (USDOE) since it was built in 1959. During the first decade of its use, the experiments performed were relatively simple and very numerous. Between 1961 and 1971 approximately 175 tests were performed on metal fuels, mostly in support of the early liquid-metal fast breeder reactors (LMFBRs) EBR-II and Fermi. TREAT testing of LMFBR oxide fuels also began soon after TREAT was commissioned, and by the late 1960s oxide fuel testing dominated the TREAT program. Test objectives focused on meltdown behavior of fuel pins and on energetics associated with molten fuel-coolant interactions. Capsules with stagnant-sodium or sodium-potassium (NaK) and transparent vehicles without coolant (for photographic diagnostics) were used. In the late 1960s and early 1970s, programmed control of reactor power, the 0.5-meter fast-neutron hodoscope, and the development of flowing-sodium loops (the Mark-I and Mark-II loops) provided new horizons for experimentation. The exceptionally-high rate of test performance during the 1960s was diminished in the 1970s as the tests became more complex with broader objectives and greater prototypicality relative to reactor behavior. Nearly all of the tests in the 1970s were on oxide fuel, studying fuel damage potential during protected transients, failure margins, local-faults issues, and postfailure material motions under hypothetical accident conditions. Most of the tests utilized single-pin capsules with stagnant sodium or NaK coolant or else tested multi-pin bundles in flowing-sodium loops. With few exceptions, the fuel pins tested had fuel columns shorter than prototypic of a commercial design since irradiated full-length fuel was not available until the 1980s.

In the 1980s the testing programs in TREAT focussed on the behavior of full-length oxide fuel of reference and advanced designs and, in the last half of the decade, on modern-design metal fuel. Preparations for tests on full-length fuel began in the 1970s with the construction of a new hodoscope[1] with enlarged (1.2 m high) field of view and with the design of longer sodium loops for single and multiple-pin tests. An agreement was established between the USDOE and the United Kingdom Atomic Energy Authority (UKAEA) whereby full-length oxide fuel irradiated in the UK Prototype Fast Reactor (PFR) would be tested in TREAT. This PFR/TREAT program,[2] with 13 tests, dominated the first half of the 1980s. Tests on FFTF-irradiated fuel also began early in the 1980s in support of FFTF safety evaluations. Preparations that began in the late 1970s for performing 37-pin tests and that would utilize a new vehicle (the Advanced TREAT Loop) and a partial new TREAT core were halted in the middle of the decade as the direction of the LMR program in the U.S. turned to the investigation not only of advanced oxide fuel designs[3] but also of improved-design metal fuel[4] that had been developed and proven in EBR-II since the 1960s. This paper describes the purpose, results and applications of the fast reactor safety testing programs during the past decade in TREAT. Those programs were conducted by Argonne National Laboratory (ANL) and by Westinghouse Hanford Company (WHC).

EXPERIMENT PROGRAMS

Severe-Accident Initiating-Phase Tests on Oxide Fuel (PFR/TREAT Series)

Under an agreement established in 1979 between the UKAEA and USDOE (the PFR/TREAT Agreement), researchers in the UK and U.S. collaborated in a program of 13 severe hypothetical accident simulation tests in TREAT using UK-design (bottom-plenum, annular pellet) full-length mixed oxide fuel pins irradiated in PFR and tested in grid-spaced geometry. Basic characteristics of the tests are listed in Table I. Six of the tests (C01 through C06) were single-pin tests performed by Westinghouse Hanford Company, three in stagnant capsules and three in single-pin test loops. Seven of the tests (L01 through L07) were performed by Argonne National Laboratory, all being seven-pin-bundle tests in Mark-III loops. Two principal types of severe accidents were simulated. One was the transient overpower (TOP) without scram accident, for which both slow (15-sec period) and fast (0.15-sec period) exponential power increases were of interest. The other was the TUCOP, i.e., unprotected transient undercooling accident which involved an overpower burst simulating a coolant-voiding-induced reactivity increase that would occur during the accident sequence. Coolant channel conditions at the time of cladding failure were an important variable among the TUCOP tests. Fresh, medium burnup, and high burnup (9 at.%) pins were tested. Although the PFR fuel was of a different enrichment than U.S. FFTF fuel and employed a bottom plenum design as opposed to U.S. top plenum design, this was the first opportunity in the U.S. LMR safety program to perform transient tests on full length fuel pins (0.9-m fuel column height).

The objective of the PFR/TREAT program was to obtain data useful for developing and validating a number of UK and U.S. fuel-behavior models and codes, fuel-pin/coolant-channel thermal-hydraulic codes, and integrated severe-accident codes. U.S. codes TEMECH, FPIN, FSTATE, COBRA, SAS4A, and SIMMER-II and UK codes PINEX-AR, TRAFIC, and SABRE were applied in the test analyses. Independent analyses performed in the UK and U.S. were compared. The tests provided data in time and location of failure cladding, fuel failure mechanisms, prefailure in-pin fuel motion,

Table I. PFR/TREAT Tests on Oxide Fuel

Test	Vehicle	No. of Fuel Pins	Burnup at.%	Test Type[a]
C01	NaK capsule	1	0	TOP, Fast
C02	"	1	4%	TOP, Fast
C03	"	1	9%	TOP, Fast
C04	SPTL loop	1	4%	TOP, Slow
C05	"	1	9%	TOP, Slow
C06	"	1	4%	TUCOP[b]
L01	Mark-III loop	7	0	TOP, Fast
L02	"	7	4%	TOP, Fast
L03	"	7	4%	TOP, Slow
L04	"	7	4%	TUCOP[c]
L05	"	7	4%	TUCOP[d]
L06	"	7	0	TUCOP[c]
L07	"	7	4%	TUCOP[b]

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a. Transient overpower (TOP) of 0.15 s period (fast) or 15 s period (slow); transient undercooling with overpower burst (TUCOP) with burst occurring at the indicated cladding and coolant conditions.

b. Fuel escape into channels just beginning to void with cladding still strong.

c. Fuel escape into mostly-voided coolant channels with cladding weak or molten.

d. Fuel escape into partly-voided coolant channels with partly intact, but weak, cladding.

postfailure motion in the coolant channel, and postfailure metal blockage formation. In the TOP tests in flowing sodium, failure was generally near the fuel top in the slow-ramp tests and just above midplane in the fast-ramp tests. (Location of failure was not well represented in the stagnant-coolant tests.) Prefailure in-pin fuel motion generally occurred in the TOP tests but not in the TUCOP tests. Measured timing and location of cladding failure provided a basis for determining the relative importance of the several potential failure mechanisms (melt-through, internal pressurization, and fuel-cladding mechanical interaction). Typically, blockage formed during fuel-pin disruption, which may have been an effect due to small-bundle geometry but suggested that coolability might be inhibited in a full subassembly under those conditions. Fuel pin response was found to be only weakly dependent on burnup. In all tests, the reactivity consequence of the postfailure fuel motion was negative. Plans to perform several complementary tests on FFTF-irradiated fuel of U.S. design remained unfulfilled as the U.S. fast reactor program shifted emphasis to advanced oxide designs and to metallic fuel.

Transient Overpower Tests on Reference FFTF Oxide Fuel (RFT and TS Series)

In support of FFTF operations throughout the 1980s, the Reference Fuel Transient (RFT) and Transient Safety (TS) series of tests were performed by Westinghouse Hanford Company using full length fuel pins previously irradiated in the FFTF. A listing of these tests is shown in Table II.

Table II. Transient Testing in the 1980s on FFTF and Advanced-Oxide Fuel

Experiment Designation	Burnup (at.%)	Transient Rate	Power Ratio Peak/Steady-State	Results
RFT-CAL-L	0	1$/s	N/A Fresh Fuel	Damage
	"	"	"	"
	"	"	"	"
RFT-L1	0.2	50¢/s	5.9	Damage
	"	"	5.7	Damage
	"	"	9.3	Failure
RFT-L2	0.2	5¢/s	3.7	Damage
	"	"	1.8	"
	"	"	3.4	"
RFT-L3	2.7	5¢/s	2.3	Damage
	5.3	"	2.0	"
	5.3	"	1.9	"
RFT-L4	2.7	1$/s	8.5	Damage
	5.3	"	7.5	"
	5.3	"	7.3	"
TS-1	0.2	5¢/s	3.0	Failure
TS-2	5.8	5¢/s	3.4	Failure
CDT-1	12.5	5¢/s	4.5	Damage
CDT-2	11.5	1$/s	16.5	Damage
	6.2	"	16.5	Failure
	6.4	"	16.5	Failure
CDT-3	6.3	5¢/s	4.5	Damage

Notes: 1. Fuel pin cladding material was 20% CW 316SS in the RFT and TS series and HT9 in the CDT series.
2. Three-pin tests were performed in Mark-III sodium loops. Single-pin tests were performed in Single-Pin Test Loops (SPTLs).

The RFT-CAL-L Experiment was the first TREAT transient test with FFTF driver fuel pins. This test provided data useful for determining the fuel pin power-to-TREAT-reactor power coupling for calibrating TEMECH (a thermal/hydraulic/mechanical code used in transient analysis) and for studying the transient performance of various fuel types.

The specimens for RFT-CAL-L were unirradiated fuel pins of FFTF prototypic size and material. Two of the fuel pins were standard FFTF driver fuel pins; the third pin was fabricated to rigid dimensional specifications with each pellet characterized. The pin contained both solid and annular pellets with variations in void deployment and smear densities. In addition, one fuel type was radially slotted to simulate cracking.

In tests RFT-L1, RFT-L2, RFT-L3, and RFT-L4 a total of 12 FFTF fuel pins, with fuel burnups ranging from 2 to 54 MWd/KgM, were transient tested at overpower ramps rates of 5¢/s, 50¢/s and 1$/s in flowing sodium. Among the specific test objectives were: 1) to demonstrate the capability of the fuel pins to accommodate a secondary plant protective system (PPS) terminated transient without damage, 2) to verify that a significant failure margin exists by extending transient overpower beyond the secondary PPS limit of 1.25 normal rated power, and 3) to establish transient-induced measurable changes in the test pins as a basis for pin performance code correlation and validation. The majority of the fuel pins in this test series incurred measurable cladding strain and substantial fuel melting as a result of the overpower transient. The test series was successful in establishing the transient performance capability of reference FFTF driver fuel pins.

The TS-1 and TS-2 experiments were conducted to determine the time and location of failure of FFTF fuel pins subjected to hypothetical unprotected 5¢/s transient overpower conditions. These tests were conducted in flowing sodium. Transient conditions between the two tests were closely matched to provide a direct comparison of burnup effects on the failure response. Each experiment was terminated upon fuel pin rupture.

The fuel pin in the TS-1 experiment ruptured at 127 kW/m while the fuel pin in TS-2 failed at 120 kW/m. The slightly higher threshold of the TS-1 pin relative to the TS-2 pin was attributed to the higher fission gas pressure in the TS-2 pin as a result of its higher burnup. In both tests, the failure thresholds exceeded three times nominal FFTF power.

For the reference fuel design, at the slower (5¢/s) transient ramp rate, it was necessary to exceed three times nominal power to induce fuel pin failure. At intermediate (5¢/s) and fast (1$/s) transient ramp rates, overpower levels of eight and nine times nominal FFTF power respectively were survived without breach. For the margin-to-failure tests TS-1 and TS-2, the cause of failure was identified as internal fission gas pressure combined with reduced cladding strength at the elevated temperatures developed during the transient. Failure locations, in all cases, were in the upper one-third of the fuel column, which is considered favorable from the standpoint of negative reactivity feedback for unprotected events. Under the conditions tested, failure threshold appears to be relatively independent of fuel pin burnup.

Transient Overpower Tests on Advanced Oxide Fuel (CDT Series)

The CDT series of tests was conducted by Westinghouse Hanford Company to obtain transient performance data to support irradiation of advanced CDE type fuel in the FFTF to its goal burnup of 900 equivalent full power days and beyond. The advanced CDE design featured larger diameter

(0.686 mm), PuO_2-UO_2 fueled, HT9 clad fuel pins. In the CDT tests, these FFTF-irradiated fuel pins sustained 5¢/s overpower transients in TREAT of up to 4.5 nominal FFTF power levels without failure, and 1$/s transient ramp rates were conducted to overpower levels of over sixteen times nominal power before fuel pin rupture. These long lifetime fuel pins also demonstrated a propensity for pre-failure axial fuel relocation, a highly desirable inherent safety characteristic which can serve to mitigate or, potentially, terminate transient overpower accidents. The failed pins exhibited breaches attributable to cladding melt-through just above the fuel column mid-plane. The transient overpower performance capability of both CDE and the reference fuel design are presented in Figure 1.

The CDT-1 and CDT-3 experiments provided the opportunity to compare the relative transient performance of solid versus annular fuel pin designs. The two fuel pins, while having different burnup levels, were subjected to similar 5¢/s overpower transients. Post-test evaluations suggested that the maximum fuel enthalpy reached in the CDT-3 pin with annular fuel was over 20% greater than the CDT-1 with solid fuel. In spite of the higher power level and higher cladding temperature, the annular fuel pin showed less transient-induced strain than did the solid pin: 1.4% versus 2.5%. Results from the experiment suggest that the central hole in the annular design serves as an effective pathway to the plenum, thus alleviating pressure buildup in the fueled region during overpower transients.

Severe-Accident Transition-Phase Tests on Oxide Fuel (RX Series)

Two tests (RX-1 and RX-2) were performed by Argonne National Laboratory to investigate the behavior of a pool of molten urania fuel and steel subjected to decay-heating rates to simulate the transition phase of an LMFBR hypothetical core disruption accident. Both tests utilized dry capsules containing a fuel-steel mixture located within a fission-heated urania wall. The mixture was originally in the form of a 0.13-meter high stack of urania-steel slugs. The objective of the tests was to demonstrate the boilup of the mixture due to steel vapor production. In test RX-1 the pool was vertically unconfined; in RX-2 it was confined to a volume approximately ten times the volume of the pool. Fuel motion data taken during the tests by the fast neutron hodoscope confirmed the ability of analyses to predict the onset of boilup. Application of later fuel motion data was limited, however, by the development of a spurious vapor source in the first test and penetration of the pool through the urania wall in the second test.

Transient Overpower Tests on Metallic Fuels (M Series)

Testing of metallic fuels resumed in 1984 under the Integral Fast Reactor (IFR) Program at Argonne National Laboratory. Advances in metal-fuel design since the 1960s had allowed for higher swelling, higher burnup, and greater margin to failure, thereby making much of the database from the earlier TREAT tests obsolete. After a preliminary test M1 on a small fuel sample in a dry capsule, six tests (M2 through M7) on modern metallic fuel were performed in Mark-III sodium loops. All six investigated the response of the fuel to anticipated transient without scram (ATWS) transient overpower (TOP) conditions, in particular the fuel

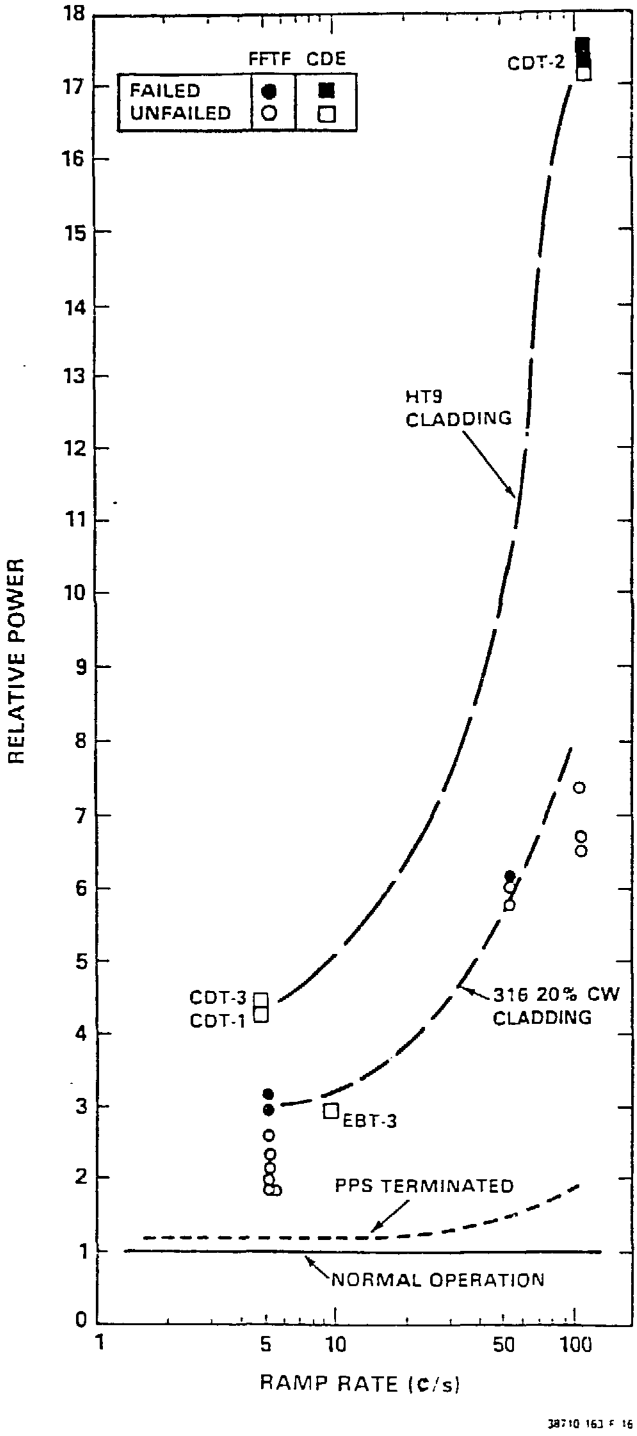

Figure 1. Safety Margins Demonstrated by Transient Tests on Oxide Fuel (U.S. Design)

failure mechanisms, prefailure fuel expansion, and early post-failure fuel movement. The parameters in the tests were fuel composition, burnup, and fuel conditions at test termination, as indicated in Table III.

Table III. IFR Tests on Metallic Fuel Pins

Test	Fuel Composition	Burnup (at.%)	Posttest Condition
M2	U-5Fs	0.3	intact
	"	4.4	failed
	"	7.9	failed
M3	U-5Fs	0.3	intact
	"	4.4	intact
	"	7.9	intact
M4	U-5Fs	fresh	intact
	"	2.4	failed
	"	4.4	intact
M5	U-19Pu-10Zr	0.8	intact
	"	1.9	intact
M6	U-19Pu-10Zr	1.9	intact
	"	5.3	failed
M7	U-19Pu-10Zr	9.8	failed
	U-10Zr	2.9	intact

Note: Cladding was 316SS for U-5Fs fuel pins, D9 for U-19Pu-10Zr pins, and HT9 for the U-10Zr pin.

Until irradiated fuel pins of IFR reference fuel (U-Pu-Zr alloy) were available, the fuel that was the EBR-II driver fuel in the early 1980s (U-5 wt.% fissium) was tested. (Fissium is a mixture of metals representing an equilibrium composition of solid fission products that would result using a simple pyrometallurgical fuel cycle.) In all of the six loop tests, each of the fuel pins was located in a separate flowtube and an overpower transient with 8-s period exponential rise was used. Data from the tests were instrumental in developing models of cladding failure and prefailure fuel elongation. In the relatively-short time frame of the tests, cladding failure was caused by a combination of pin plenum pressure acting hydrostatically through weak partially-molten fuel on cladding that had been thinned by transient-induced formation of a low-melting-temperature fuel-cladding alloy. The relative importance of pressure and cladding thinning was found to be a strong function of burnup. At low burnups, it was necessary for peak cladding temperatures to reach a value at which the rate of metallurgical attack of the cladding increased sharply by two or three orders of magnitude. In general, cladding failure is a function of time at temperature. For the heating conditions applied in these tests, failure of both U-5Fs and U-19Pu-10Zr fuel in austenitic cladding consistently occurred at conditions corresponding to 4.0 - 4.4 times IFR reference operating power. The failure threshold for HT9-clad U-10Zr fuel was not measured but was found to exceed 4.8 times nominal conditions. Cladding failure consistently occurred at the very top of the fuel column and was very localized. Nearly all of the molten-alloy (roughly half of the fuel) that was present in the pin at the time of failure was expelled through that small breach and was carried upward out of the core region by the flowing sodium. The non-molten alloy at the bottom of the fuel pin remained in place. Although the test geometry did not well represent a pin-bundle configuration, the observed propensity of the fuel to monotonically disperse in a manner that would be a strong advantage in mitigating or preventing hypothetical severe accidents can be considered to be a basic characteristic of the metal fuel.

Prefailure fuel elongation was found to be sensitive to fuel composition and preirradiation power level. In addition, where those parameters led to potentially high elongations, there was strong dependence on burnup. The U-5Fs fuel irradiated at 8 kW/ft expanded up to 17% axially at low burnups, but the reference U-Pu-Zr fuel expanded during the tests by only 2-4% and nearly independently of burnup. Models that were developed to predict the transient-induced elongation were quite simple and accurate.

EXPERIMENT HARDWARE

With the exception of three single-pin static capsule tests (C01, C02, and C03) and the two transition-phase capsule tests (RX1 and RX2), all transient tests in the 1980s were performed in integral flowing sodium loops. Two basic loop designs were used: the Single Pin Test Loop (SPTL) and the Mark-III loop which is capable of testing up to seven-pin bundles. Figure 2 shows a schematic comparing the TREAT testing vehicles.

All multiple-pin transient tests were conducted in Mark-III integral flowing sodium loops. The Mark-III loop is a test vehicle for testing fast reactor fuel pins in TREAT under representative reactor conditions of sodium flow, temperature, and fuel pin power. With the exception of the outfitting details, the loops used by WHC were identical to those used by ANL. The major components of the loop consist of the main piping body, a single or dual Annular Linear Induction Pump (ALIP), three magnet type flowmeters, (at least two being permanent-magnet flowmeters) thermal-neutron-filter shaping collars, heaters, and chromel-alumel thermocouples. The loop is housed in a 0.10 m x 0.20 m x 3.45 m long secondary containment can which replaces two TREAT fuel elements at the center of the reactor core. Mark-III loops were used in the PFR/TREAT (L) test series, in the RFT and CDT series, and in the M-series.

The Single Pin Test Loop (SPTL) is basically similar to the Mark-III but was designed with lower mass and reduced shielding for use in slow (typically 5¢/s) transient-to-failure experiments on individual FFTF fuel pins. Its design includes a single ALIP for circulating coolant, and all-welded construction. The SPTL was used in the TS and CDT test series.

Test trains for experiments are designed to provide an instrumented assembly into which irradiated fuel pins can be remotely inserted. They are long cylindrical assemblies which, when inserted into the loop, make axial contact at the loop's test section seat resulting in sodium flow up through the test train. An inert-gas filled "adiabatic" annulus surrounding the flow tube(s) in the test train serves to reduce radial heat losses. Test trains are typically instrumented with chromel-alumel thermocouples (12 in the SPTL, up to 18 in the Mark-III loop) to record temperatures at various axial locations along the coolant channel, particularly adjacent to the fuel pin(s). A ceramic liner (Al_2O_3) was used in single-pin test trains to protect the SPTL containment from molten fuel contact in the event of a fuel pin failure. In the multi-pin fuel-disruption tests in the PFR/TREAT series using Mark-III loops, a ZrO_2 liner in the test trains formed a radial boundary for the fuel motion. In some of the tests in Mark-III loops (e.g., the M-series), each pin's flowtube was orificed to provide the required relative coolant flow rate between or among the two or three pins in the test. In the two-pin M-series tests, miniature permanent-magnet flowmeters measured the flow rate along each pin.

CONCLUSIONS

TREAT tests in the 1980s provided a large amount of information on transient performance of oxide and metallic fuels. The tests demonstrated that modern fuel-pin designs of both fuel types are excellent in withstanding overpower levels well beyond protected levels. Detailed information was obtained regarding fuel melting, prefailure fuel motion, cladding damage and failure, and postfailure fuel motion that was important in developing and verifying fuel behavior models and transient analysis codes.

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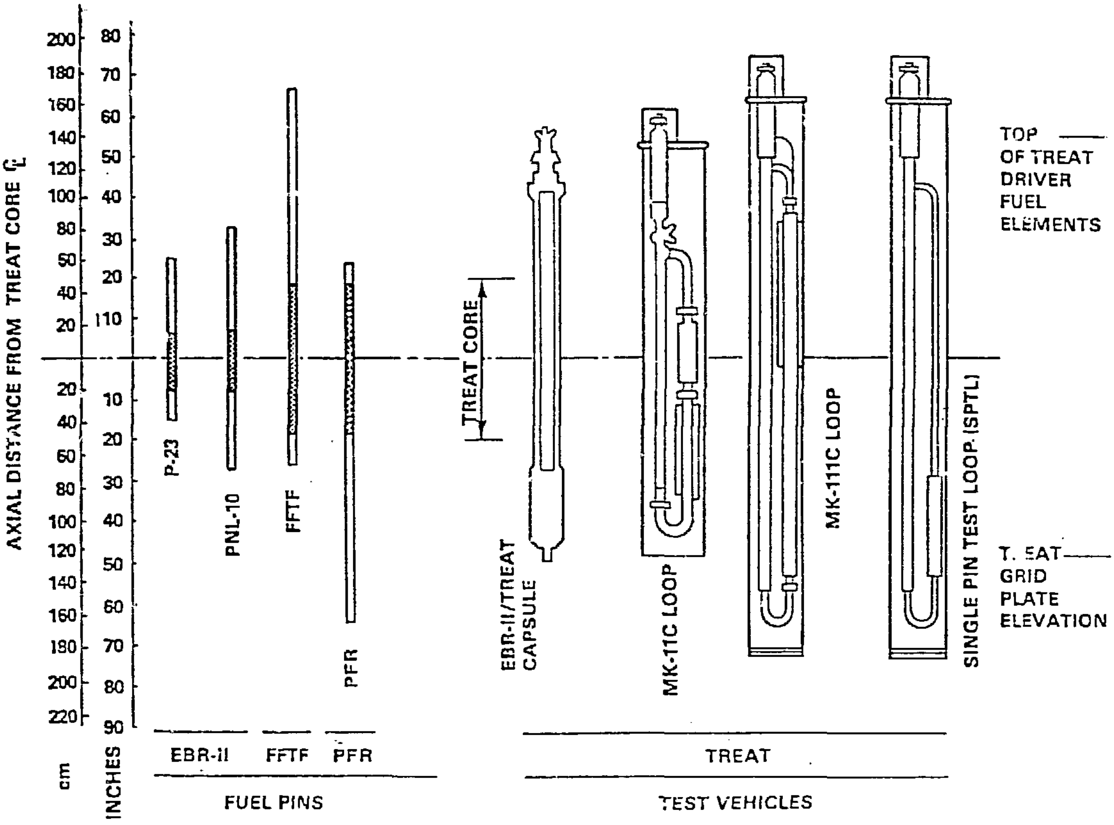

Figure 2. Comparison of TREAT Test Vehicles.