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THE LMFBR FUEL-DESIGN ENVIRONMENT FOR ENDURANCE TESTING, PRIMARILY OF OXIDE FUEL ELEMENTS WITH LOCAL FAULTS

by

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ABSTRACT

The U.S. Department of Energy LMFBR Lines-of-Assurance are briefly stated and local faults are given perspective with an historical review and definition to help define the constraints of LMFBR fuel-element designs. Local-fault-propagation (fuel-element failure-propagation and blockage propagation) perceptions are reviewed. Fuel pin designs and major LMFBR parameters affecting pin performance are summarized. The interpretation of failed-fuel data is aided by a discussion of the effects of nonprototypicalities. The fuel-pin endurance expected in the US, USSR, France, UK, Japan, and West Germany is outlined. Finally, fuel-failure detection and location by delayed-neutron and gaseous-fission-product monitors are briefly discussed to better realize the operational limits.

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INTRODUCTION

The intent of this paper is to set the framework within which we deal in the design of fuel elements to withstand expected local faults through 1) a brief review of the liquid-metal-cooled fast-neutron breeder nuclear-reactor (LMFBR) lines-of-assurance, 2) a review, history, and definition of local faults, 3) the fuel designs and major reactor-design parameters in decommissioned, operating, and planned reactors, 4) a summary of what the U.S. and other nations expect for fuel-design performance, and 5) a review of failed-fuel detection. The companion paper, reference 1, will then review international testing and operating experience with cases of the most serious local faults encountered.

These papers focus on fuel failure and fuel degradation as subsets of local faults, although cases of other local faults are also reviewed. To improve the fuel design, we must not only gauge where the fuel has fallen short of the design expectation, but also note how design changes, such as increased diameter, fuel-chemistry change, and change from pellet to vibratory-packed fuel, might have affected the operating performance of the fuel, particularly in the presence of local faults. We cannot provide such definitive design-change results here, but we can review the operation of some reactors and experiments [1] and leave impressions of how the fuel performed; one can then ascertain in a gross sense what trends appear to possibly meet the design goal and what R&D remains to ensure that the lines-of-assurance goals are met. Reference 2 provides a more step-by-step review of the fuel-element design process.

THE LMFBR LINES-OF-ASSURANCE (LOA)

An explanation of the LOA concept used by the U.S. Department of Energy (DOE) to guide LMFBR safety R&D will help our understanding of the ultimate constraints on fuel design. (See references 3 and 4 for more thorough explanations of the LOA approach.) The use of LOAs also ensure proper interpretation of our use of the words "incredible" and "highly unlikely" by defining these terms in a context that can be scientifically accepted. The LOAs are divided into the following groups with their associated assigned (not expected) frequencies per reactor year of full-power operation.

LOA-1	Prevent Accidents (prevent any event leading to substantial fuel melting and/or cladding breach)	$\leq 10^{-6}$
LOA-2	Limit Core Damage (maintain in-place coolability; no damage to primary containment even if an accident were to occur)	$\leq 10^{-2}$
LOA-3	Control Accident Progression (mitigate severity in case of damage to primary containment, and control radioactive releases to environment)	$\leq 10^{-2}$
LOA-4	Attenuate Radiological Consequences (in case containment systems fail to control radioactive releases)	$\leq 10^{-2}$

The LOAs are structured independently so that the health and safety of the public are assured a probability of at least $1-10^{-12}$. For a potentially damaging coolant blockage, we could assume an occurrence and damage probability of $\leq 10^{-8}$ if the blockage were deemed incredible. This suffices to define "incredible."

The impact of the LOA approach on fuel behavior is seen in the necessary design goal to avoid a cladding breach with a probability of 10^{-6} throughout the residence time of the fuel pin. This can be changed to another number as long as LOA-1 and LOA-2 combined can be ensured to be $\leq 10^{-8}$ (for local faults only).

REVIEW OF LOCAL FAULTS

To put the local-fault problems into better focus, we succinctly define local faults and pin-to-pin and blockage propagation, and summarize the findings of analyses and out-of-pile studies completed on local faults. The companion paper, Ref. 1, will review the in-pile experiments and operating experience. Reference 5 presents a status of local faults, and proposes the R&D needed to resolve the remaining issues, at least for oxide fuel. The subject, ill-defined to many as an accident initiator, needed to be placed in perspective; this was the goal of Reference 5. The members of International Working Group on Fast Reactors (IWGFR) specialists on fuel-failure mechanisms last met in 1975 and were to document a state-of-the-art review on fuel-element failure-propagation (FEFP) studies and experience [6] -- a task unfulfilled as of this writing. In 1976, Fauske et al. [7] summarized analyses and reasoned why rapid local-fault propagation could be ruled out. During the past four years, more analyses and in- and out-of-pile work have been reported. Upon reviewing this recent information in concert with an overall review of LMFBR oxide-fuel and local-fault experience, Warinner and Cho [5] suggest that we can be more comfortable with previous statements made about the unlikelihood of widespread core-damage from local faults. One key statement was that a necessary (but not sufficient) result for serious consequences from normal operations with local faults is contact between liquid coolant and molten fuel; however, to even deliberately design molten-fuel release into the LMFBR coolant is no easy task. It appears that the plausible intuitive hypothesis of small causes producing small effects is again at work.

A Brief Look at Two Local Faults and Pin-to-Pin and Blockage Propagation

Since neutron flux irradiation embrittles stainless steel, one could (quite simplistically) imagine closely spaced LMFBR fuel-pins to bow, fail mechanically, strike the neighboring pin causing it to bow, and so on; such a process would march, domino-like, across the subassembly (S/A) rapidly. Similarly, a pin with a high-inventory of gaseous fission products (GFP) has been postulated to burst and eject a gas jet that blankets an adjacent pin which in turn bursts; the process is postulated to continue or cascade through the S/A [8,9]. The first process, presented here only to more easily envision FEFP, is unrealistic; the second process, more complex, can be dismissed. To postulate FEFP (in this case rapid) to be a natural safety issue which deserved attention must have seemed only reasonable. Coolant-channel blockages reared their heads as possibly posing a safety threat because the closely packed LMFBR-bundle appears as an effective filter for the primary-circuit coolant during normal operation. Blockage accidents (e.g., in Fermi and the Sodium Research Experiment (SRE) reviewed in reference 1) made the issue more difficult to dismiss. (We have often spoken of FEFP and blockage propagation synonymously.) Indeed, Argonne National Laboratory's (ANL's) first in-reactor attempt to address this issue began with the Fuel-Element Failure-Propagation Loop (FEFPL) project, now called the Sodium-Loop Safety-Facility (SLSF) program. In 1973, the Atomic Energy Commission listed nine priority R&D issues; fuel-failure thresholds and FEFP ranked 2 and 3 after "criteria, codes, and standards." However, while the FEFPL or SLSF was being built, domestic out-of-pile research (at Oak Ridge National Laboratory (ORNL) and ANL), foreign research (British and West German), and more operating experience with failed fuel (French and Soviet) had begun to dismiss aspects of FEFP in the early 1970s. This progress was striking. A blockage or fuel-failure test, scheduled to be the first SLSF test, was postponed while analyses and out-of-pile experimental results here and abroad indicated that FEFP was not only of less consequence than once believed, but also perhaps entirely benign. Doubters remain, however. Without a complete in-pile program to add credibility to the out-of-pile work and analyses completed, the challenge to stand before an LMFBR licensing board and assert that either rapid propagation cannot occur, or would be accommodated if it could occur, remains.

Has slow propagation ever been observed? Possibly, in Manufacture-Franco Belge-au-Bouche-Sodium (MFBS)-6, Mol 7B, EBR-II Run-Beyond-Cladding-Breach (RBCB)-1, BOR-60, and DFR, for examples; however, we will cite only the experimenters' conclusions as such. In each possibly observed case of FEFP, the conditions were extreme and, in RBCB-1, the additional failure would be called self-limiting if one could call it propagation. (It is noteworthy that "propagation," used alone, has recently taken a new meaning with respect to fuel failure -- crack propagation or extension.)

The following sections present 1) a definition and summary of local faults (the generic term given to FEFP initiators, blockages, and other S/A anomalies), 2) a review of local-fault perceptions, 3) a review of fuel and reactor designs, 4) design expectations, and 5) failed-fuel detection. The companion paper, reference 1, presents the status of analyses and out-of-pile experiments and prototypic fuel-failure experience and in-pile experimental results (e.g., from DFR, BR2 Mol 7 series, and EBR-II RBCB program).

Definition of Local Faults

For the purposes of this paper, local faults are those off-design conditions at the entrance and within a subassembly that could potentially cause core damage, i.e., those operational or constructional divergences which alter the intended geometry or material distribution to such a degree that they can be (or have been) considered possible *initiators* for structural, hydraulic, thermal, and neutronic *consequences* (phenomena) which could possibly result in either a damaged core or unacceptable contamination. To have a damaged core (i.e., cause more than mere fuel failure with in-situ fuel-deterioration) implies the local accident might have involved some degree of power/flow mismatch to cause local events analogous to those involved in a core-wide accident. The question is, will this local event remain localized or will it (perhaps when coupled with an upset transient) spread or cascade to involve the whole core. This cascading is generally termed FEFP (although some call it "autocatalytic pin-failures") and S/A-to-S/A propagation. All consequences of local faults should result in localized (self-limiting) damage, if any, except possibly for certain faults with a concurrent transient. To explain this conclusion, credible local faults and a history of FEFP, the most oft-cited consequence, are set forth. (*In some cases "credible" means the fault has been taken seriously enough to warrant treatment in either the Fast-Flux Test-Facility Final Safety-Analyses Report (FFTF-FSAR), the CRBRP- Preliminary Safety-Analyses Report (PSAR), or elsewhere in the open literature for sometime(s) during the past fifteen years.*) These local faults are listed in Table 1.

Table 1

Possible LMFBR Local Faults and Their Consequences

Local Fault (Initiator)	Consequence (Phenomena)	Operational Status
cladding defect	fuel failure	observed
cladding swelling	fuel failure	observed
local over-enrichment	fuel failure with possible molten fuel ejection	observed (not observed)
inert coolant-channel blockage	fuel failure	observed
S/A inlet blockage	S/A-to-S/A propagation	observed
loose spacer wire	fuel failure (local line hot spot)	observed
broken spacer wire	benign	observed
pin bowing	local hot spots, fuel failure	observed
pin distortion	local hot spots, fuel failure	observed
excess Na oxygen	local blockages	observed

Table 2

Possible Local-Fault Consequences and End State(s)

Consequences	Further Consequences & End State(s)	Operational Status
fuel failure	severe breach, loss of fuel, damage of adjacent pin, $Na_3(U,Pu)O_4$ formation, blockage formation	observed
molten fuel ejection	e.g., mild FCI, mechanical failure of other pins, and overheating to saturation if flow halted long enough	not observed
local heat-generating blockages	fuel failure, et seq. or, much less likely, molten fuel ejection, et seq.	either not observed or not reported
S/A-to-S/A propagation	whole-core involvement; meltdown beyond initiated S/As	not observed

Fuel-failure severity, and thus fuel performance, depends on the local fault. A random failure will more likely occur near EOEC or end of life (EOL) than near beginning of life (BOL) when quality control is effective. This case would have damage potential from gas-blanketing or pin deflection causing FEFP. However, such cases have been shown to be highly unlikely [10]; the pin's natural period exceeds the minimum thrust time from fission-gas exhaust by three orders of magnitude. It has also been shown that sudden emission of gas from a lower plenum, sufficient to fully surround a pin, would not raise the coolant temperature enough to cause another failure [11].

Cladding swelling has been negligible except in cases where the fuel failed with concomitant sodium ingress, uranate formation increasing the breach severity, and so on.

Historical Perceptions of Local Faults

To review the status of FEFP is interesting and instructive; this helps place the problem in perspective and thereby helps to focus our attention on further needs.

Many expressed skepticism early about the fuel-pin integrity, and properly so, given the lack of operating experience. Yet, others who closely studied FEFP concluded early on that no problem existed. The 1965 Fast Reactor Conference was marbled with both pessimism and optimism about FEFP [12]. Several papers presented studies on vented fuel to coolant, a concept clearly pursued primarily to avoid FEFP. Gas-Cooled Fast Reactors (GCFRs) were highlighted on ability to *view* a local fault (vs. opaque sodium systems); shorter doubling time and "voided" channels added incentive.

Although the 1966 British Nuclear Energy Society (BNES) Conference was less FEFP-oriented, the discussions reveal many striking statements about FEFP. Examples are [13]:

> "We regard the propagation of subassembly faults as the *most pressing problem* facing the fast reactor designer today as far as core design is concerned, and we have assumed that we cannot detect certain types of faults,..." (emphasis added) and
> "...Our biggest concern is the rate of propagation of the fault. This is the big uncertainty in subassembly behavior at the present time." Also, we find; "...and the safety system must be capable of detecting the onset of any local fault and shutting the reactor down before any serious propagation has occurred."

Echoes of this FEFP devil (not lacking advocates of FEFP possibility) appear in the 1974 BNES conference on Fast Reactor Power Stations [14, 15] and in the CRBR-PSAR which states, "It will be shown that pin-to-pin failure propagation would be very remote in CRBRP for an initiating event such as stochastic fuel pin failure or even for the postulated event of a small release of molten fuel or a postulated local flow blockage in the fuel assembly." Many pages of the CRBR-PSAR and the FFTF-FSAR are devoted to FEFP and blockages (e.g., [16]).

Later, to detect true concern requires a keener eye. The results of reactor experience, out-of-pile studies, and analyses have calmed the cautious and cautioned the calm. Overall, the results for oxide fuel can be judged to be encouraging--indeed, impressive, particularly in the reactors in which the pins were not driven hard during tests (e.g., 0.03% fuel failure in Phenix vs. 5.0% in DFR [1]). Even so, we find that a decade after the aforementioned FEFP caution, propagation and blockages are still feared. Examples are:

1. "Under these conditions the calculation, very conservative, shows that a faulty pin should preferably be left in place *no longer than a week* if its burn-up is more than 20,000 MWd/t, or *no longer than a day* if its burn-up exceeds 40,000 MWd/t. However, these periods are certainly very much under-estimated and, it is probably quite safe to leave defective pins in place for a week." (emphasis added) -- Gatesoupe et al., 1975 [17].

2. "With these values, the 'clean-reactor' operating option can be respected. This decision is extre-

mely important from the accident prevention viewpoint since plugging risks are considerably reduced if reactor operation with cladding failures is prohibited," and

(Discussion) "It is preferable to devote effort to developing a fuel clad which permits high fuel burn-up without failure. This also gives a wide margin against subassembly blockage by plugging, which enhances safety." -- Megy et al., 1977 [18].

3. (Mol-7B experiment) "The blockage in that axial position was about 38%," "...One cannot neglect the possibility of blockages in a defect bundle," and "...We propose...to remove the defective bundle within the first week after discerning a pin failure." -- Weimar, 1977 [19].

4. "Important and mostly unavoidable abnormal operation conditions for fuel elements in power stations can be:

   coolant blockage in a fuel bundle.

   ..."The objectives for the fuel pin performance in normal operation are that:

   No gross propagation from a blockage coolant channel region to the whole bundle." -- Kummerer, 1979 [20].

The first two quotes above imply pessimism with regard to public safety for operation with failed fuel. Kummerer, who also cites limited experience with failed-fuel operation, cites a blockage problem. The natural question is: are the above views warranted based on analyses, out-of-pile experiments, and finally, in-pile experience? To answer this question requires an extensive review of reactor experience; let us first review the designs from which the conclusions were drawn and the designs to which the conclusions would be applied.

FUEL DESIGNS AND MAJOR REACTOR-DESIGN PARAMETERS

The Soviets and French have led in LMFBR implementation of the wire-wrap hexagonal, oxide-fuel assemblies now favored in the U.S., U.S.S.R., and France; the design has passed the test of time beginning with the BR-5 in the 1950s and continuing with Phenix, Super-Phenix, BOR-60, BN-350, and FFTF in the 1970s and the foreseeable '80s. Great Britain and West Germany have chosen to alter this somewhat by replacing the wire-wrap spacers with grid spacers. Table 3 summarizes the pertinent reactor-design parameters which influence fuel performance. Figure 1 summarizes the fuel designs for several reactors [2].

Table 3

Major LMFBR Design Parameters Affecting Fuel-Element Performance

	BR-5	BR-10	EBR-II*	BOR-60	DFR*	JOYO	FFTF	PFR	PHENIX	BN-350	MONJU	SNR-300	CRBRP	SUPER PHENIX	BN-600
Date Critical	1959	1973	1963	1970	1959	1977	1980	1974	1973	1972	1985?	1982?	?	1983?	1980?
Power, MWt	5	7.5	62.5	60	60	100	400	559	563	650	714	736	975	3000	1470
Coolant	Na	Na	Na	Na	NaK[b]	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na
Pot/Loop	Loop	Loop	Pot	Loop	Pot	Loop	Loop	Pool	Pool	Loop	Loop	Loop	Loop	Pool	Pool
Core Length, mm	280	320	343	400	304	600	914	914	850	1060	900	950	914	1000	750
Spacer	Wire	Wire	Wire	Wire	Grid	Wire	Wire	Grid	Wire	Wire	Wire	Grid[d]	Wire[c]	Wire	Wire
Spacer pitch or interval, mm							305	102	150			150	305	180	
No. Core S/As	81			80			73	78	103	211	196	195	198	364	
No. S/A pins	19	19	61	37	77	127	217	325	217	169	169	169	217	271	127
Pitch/O.D.	1.08	1.08		1.10	1.26	1.18	1.25	1.26		1.15	1.22	1.32	1.25		1.17
Pin O.D., mm	5.0	5.0	5.84	6.1	5.84	5.5	5.84	5.84	6.55	6.1	6.5	6.0[e]	5.84	8.6	6.9
Peak linear power, kW/m	25.0	25.0	46.0	56.0	43.5	40.2	42.5	46.0	45.0	44.0	46.5	46.0	47.5	48.0	53.0
Inlet temp, °C	430	230	372	340	230		316	400	400	280	390		388	395	375-410
Exit temp, °C	500	440	483	615	450		459	600	560	410	540		535	545	545-580
Peak flux, 10^{15} n/cm^2s	1	1.9	3	3.7	3.8	5	7	8.5	7.2	8.0	4[a]		8		10
Local max. b.u., MWd/kg			80	100	100	60	80	75	75	50	72	90	150	70	100
Peak Fluence, 10^{23} n/cm^2				0.75					2	2.2				3	3.5
Peak Fast Fluence to b.u., 10^{22} $n/cm^2/a/o$													2.2		
Cladding Type	321		316	316	M316	316	316	M316	316L	316	316	1.4970	316	316	316
Cladding Wall, mm	0.4	0.4	0.40	0.38	0.35	0.38	0.38	0.45	0.45	0.35	0.47	0.38	0.38	0.4	0.4
Max. O_2, ppm		3		20				10		30					
Max. C, ppm				40					43	40					
Smear Density, % T.D.	50		85.5	73.5		80	85.5	80	80	73.5	79	80	85.5		77

*For test fuel only; the driver fuel not considered
[a] Average
[b] 1.0-4.8 m/s downflow vs. ~7.5 m/s upflow for PFR, for example
[c] Advanced cores planned to be gridded as of 1974
[d] Wire spacer for radial blanket elements
[e] To be increased to 7.6 mm with 205 fuel S/As

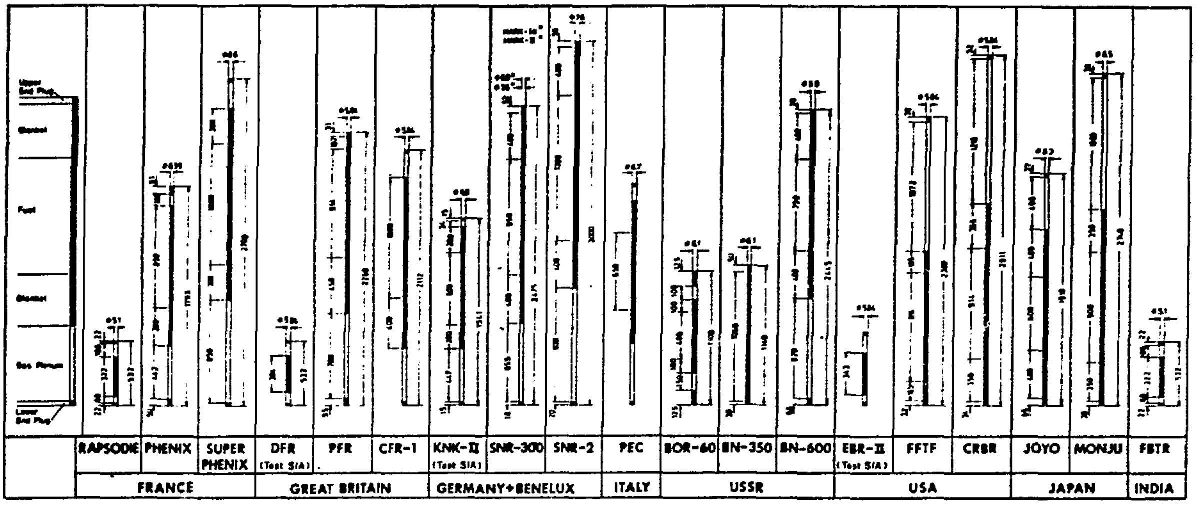

Fig.1 Fast reactor fuel pins -- synopsis of the different designs [2]

All reactors except DFR used upflowing sodium as the primary coolant. It is important to keep DFR's downflowing NaK in mind while reviewing the DFR test data. Although the in-pile experience covers a broad range of such parameters as stoichiometry, smear density, and linear pin power, enough anomalies with this experience exist to be open to criticism if the results were applied directly to a reference U.S. design. Even some aspects of the experience gained in the primary U.S. fuels test-bed, EBR-II, could be challenged. Table 4 lists the major nonprototypicalities.

Table 4

Characteristics of Variables and Effects of Results from Failed-Fuel Experience

Characteristics Which Might Be Nonprototypic	Examples, Values; Test or Facility	Results Conservative? Comment
COOLANT		
Downflow	DFR	Yes; fuel-failure due to gas blanketing or entrained gas bubbles. No; for blockage formation
NaK	DFR	No; less $Na_3(U,Pu)O_4$ formation than for Na. Yes; surface bubbles tend to form.
High O_2 content	Varies; high in Mol 7B	Yes; more O_2 available for $Na_3(U,Pu)O_4$ formation; NaO_2 blockages have formed.
High impurity content	Varies	Yes; could affect results depending on impurity (e.g., carburize cladding or begin local blockage).

Table 4 (cont'd)

Characteristics of Variables and Effects of Results from Failed-Fuel Experience

Characteristics Which Might Be Nonprototypic	Examples, Values; Test or Facility	Results Conservative? Comment
High velocity	Varies	Yes; for wastage. No; for blockage formation.
High temperature	Varies	Yes; infers clad temperature.
Low pressure at midcore	Varies	Yes; pin to coolant ΔPs and lower coolant saturation point.
High axial dT/dz	Varies	Yes; indicates higher power/flow mismatch.
PIN DESIGN		
Fuel		
UO_2	Mol 7C, Some BR-5 S/As,...	No; less O_2 produced through fissioning to be available for uranate formation.
PuO_2	BR-5	Yes; more O_2 available.
Higher %Pu in $(U,Pu)O_2$	Varies ~15 to 40%	Yes; Pu variation probably negligible *for impact on local* faults (as are many of these parameters) except above ~25%.
High O/M	Varies	Yes; $Na_3(U,Pu)O_4$ formation.

Table 4 (cont'd)

Characteristics of Variables and Effects of Results from Failed-Fuel Experience

Characteristics Which Might Be Nonprototypic	Examples, Values; Test or Facility	Results Conservative? Comment
Annular Pellets	e.g., BOR-60 & DFR & GETR tests	No; low smear density.
Dished-end pellets	Fairly standard	No.
Vibrocompacted (vipak) fuel	DFR tests (preferred in U.K.)	Results nonconservative before failure; may be conservative after failure.
Small gas-bond gap (fabricated)	Varies	Yes; more FCMI.
Large pellet O.D.	Varies	Yes.
Low smear density	BR-5	No.
Short active core length	Mol 7, EBR-II, & DFR tests	No; except for impedance to plenum gas flow.
Cladding		
Long overall pin length	Varies (see Fig. 1)	Yes; for sweepout.
Fuel vented to coolant	DFR	No; for pin-to-pin propagation.
High fill pressure	Varies	Yes.
Fill gas other than helium (and purity)	Rare	Yes; any other fill gas (argon or xenon) conservative.
Pin-plenum space and location(s)	Varies (see Fig. 1)	Smaller plenum more conservative.
S.S. other than 20% C.W. 316	In USSR and West Germany	Effect differs for each material. Ti-stabilized preferred.
Cladding O.D.	Varies little	Has increased 1.9 mm in 20 years in USSR.
Thinner cladding	Fairly standard at ∿0.38mm	Yes; results should be fairly sensitive as thickness decreases to reduce number of grains; irradiation embrittlement and swelling more severe.
SUBASSEMBLY (OR PIN-BUNDLE) DESIGN		
Smaller pin pitch	Varies little	Yes.
Fewer number of pins per bundle than 217 for U.S. design	Varies from single pin to trefoil to 19 pins, etc.	Yes; little difference down to ∿19 pins; difficult to infer effect with smaller bundle.
Nonuniform enrichment distribution	Varies (e.g., high variation for Mol 7C)	Yes; for high radial variation of enrichments (adverse effects of radial fuel motion).
Grid instead of wire-wrap spacers	In U.K. & Germany (DFR & Mol series)	Yes; for blockage formation in upflow. No; for pin deformation (bowing and distortion).
Reconstituted bundles	EBR-II RBCB & DFR series	Yes; results require careful interpretation.
Dummy central tube with coolant flow	Mol 7C series	Results require careful interpretation.
Dummy pins (e.g., S.S.)	Mol 7C series	Results require careful interpretation.
REACTOR DESIGN AND OPERATION		
Irradiation history with many startups	Varies	Yes; important to determine effect of sodium ingress.
Number of S/As	Varies	Important for impurity distribution, for example.
Small sodium volume	20 L in Mol 7B and C	Affects impurity concentration and DN signals.
Flat radial power-profile	Usually flat in S/A	Conservative for radially graded enrichments.
High average pin power	Varies	Yes.
High Max/Ave. power (axial)	Varies	Yes; more Cs migration.
High fluence	Varies	Yes; high displacement per atom (dpa) on cladding.

Table 4 (cont'd)

Characteristics of Variables and Effects of Results from Failed-Fuel Experience

Characteristics Which Might Be Nonprototypic	Examples, Values; Test or Facility	Results Conservative? Comment
Low fluence-to-b.u. ratio	Varies	No.
Neutron flux spectrum	Varies	Effects on cladding and fuel differ for high thermal-flux vs. high fast-flux.
FAILURE CHARACTERISTICS		
Higher linear pin-power at time of failure	Varies	Yes.
High burnup at failure	Varies	Yes.
Neighboring pins failed if any (location and time of such failures)	MFBS-6, Mol 7B	Yes.
High b.u. (and dpa) before failure removed	Mol 7B	Yes.
Nature of failure (size, shape, location) or other local fault	BOR-60, BR-5, DFR-435	Important to recognize.

Table 4, lengthy as it is, probably omits some nonprototypicalities. The broad range of parameters involved will caution us to more properly interpret the fuel failures observed. The section on historical perceptions has indicated the cautious French and German positions on failed fuel. We now turn to the U.S. and USSR to help round out, but not complete, the picture; some nations have yet to take a firm position on permissible fuel-failure.

EXPECTATIONS OF THE DESIGNED FUEL ELEMENTS

While the fuel provides the power, it must also meet the LOA criteria which concentrate on preventing accidents. Primarily, then, the fuel must not degrade to the point of initiating a course of events endangering public safety. This means that a flow blockage must not form to threaten FEFP or blockage propagation. Further, operational safety must be ensured; e.g., plant contamination must be minimized. Thus, ideally, the fuel should not lose hermeticity. However, this is not practical for economic operation of LMFBRs.

The U.S. has imposed the most stringent criteria on the CRBRP fuel to demonstrate safe and economic benefits. The following is excerpted from the CRBRP-PSAR:

"In the first core loading the fuel rods are limited to a peak pellet burnup of 80,000 megawatt days per metric ton of heavy metal (MWd/T). For later cores the peak burnup increases to 150,000 MWd/T with an average burnup of 100,000 MWd/T. ....The duration of the first cycle is 128 full power days (FPD) and the second cycle is 200 FPD. ....For all operating cycles after the first two, the cycle length is increased to 274 FPD and the maximum fuel assembly residence time is subsequently increased to three cycles. ....Maintenance of fuel rod structural integrity is a design basis should an Unlikely Fault occur during the fuel residence time."

Although the CRBRP-PSAR cites the cleanup systems to be capable of handling the failure of 1% of the fuel, the failure limit allowed is not clear (although a concensus existed in the DOE LOA local-faults committee that 0.1% should be the permissible limit for DN-receipt failures). Operation with failed fuel is permitted, but the permissible degree of sodium contact with fuel remains to be established. The French have established a DND sensitivity of 0.1 - 0.2 cm^2 equivalent exposed fuel area and scram on a DND of 2.5 cm^2 equivalent area.

The Soviets allow only 5.8% b.u. in the BN 350; even this is a recent increase [21]. The failure limit (loss of hermeticity) is 400 pins in the BN-350 (~1% of the reactor's fuel pins) and they shut down the reactor upon receipt of a delayed-neutron (DN) signal indicative of sodium contact with fuel [22]. The BN-600 will be permitted $\leq$ 0.1% fuel failure. As experimental facilities, BR-5 and BOR-60 were allowed much higher b.u. and much higher failure rates. In view of this and the historical review of local faults, the U.S. appears to hold the most liberal view on failed-fuel operation and b.u. limit. [It should be noted that the French and Soviets differentiate between "failures" and "gas-leakers;" sodium must contact the fuel before they consider that to be a fuel-element failure.] A hint of West Germany's approach comes from the KNK-II fuel permitted to operate to 80 MWd/kg with up to 43.5 kW/m [23]. The British approach is as stringent as the French; PFR has each S/A monitored for DNs and six TCs are installed at the exit of each S/A to detect such anomalies as blockages. As of 1974, Japan planned to add individual S/A flow meters to monitor for blockages, but West Germany did not have a definite arrangement for the fuel failure detection system, and location techniques were in the "thinking" stage. The official posture of each country is not clearly defined, perhaps because the technology is evolving.

The detection of failed fuel by GFP and DN monitors, key elements in the philosophy of failed-fuel operation, is discussed next.

FAILED-FUEL DETECTION

A discussion of fuel-failure detection may well begin with why such detection is needed. Besides structural integrity, impervious cladding is required to prevent coolant contamination and fuel-coolant chemical reactions. As a cladding failure develops, the fission gas is first released to the coolant; this gas may be tagged with a unique xenon- or krypton-isotope blend to help locate the detected failure. (The detection time is usually on the order of tens of minutes whereas location requires hours or days without a sophisticated location system.) As the failure worsens or conditions become such that fuel daughters

(DN precursers) enter the coolant stream, a downstream monitor detects the emitted DNs within tens of seconds (thirty seconds is commonly cited). This can produce the unexpected results of a high DN signal for a not-visible-to-the-naked-eye pinhole failure and a low DN signal for particulate fuel washed by the coolant. The results must be carefully interpreted, particularly when a "background" or "noise" DN signal exists from several previously failed pins. Reference 24 reports some interesting experience with failed fuel in the BR-10. The DNM is sensitive to many variables, including coolant transit time (from the failure site to the monitor), exposed-fuel temperature, fuel type, porosity of exposed fuel, failure geometry (size, shape, and location), sodium "rinsing" of hot fuel, burnup, and linear pin-power.

Briefly, the DN and tag-gas detection and location techniques permitted the increase of not only the irradiation, but also the operating temperatures and total specific powers. We might be expecting too much from our present systems, however. Although we have hoped to be able to depend on the DNM for early warning of potentially serious events, we need much more research and development to realize that goal. We also have less hope on gas tagging as a fast, reliable failed-fuel locator when operating with failed fuel. (The U.S. is seriously considering the Soviet off-line location-technique of capping an individual S/A, pressurizing it to lower the Na level and gas-blanket the S/A pins, and sniffing to detect a failure within that S/A [21-28].) While the DN receipt in Mol 7C has provided valuable information, translating the loop DN receipt to what a global monitor would receive in a prototype LMFBR does not appear easy. Finally, to infer that such a signal would always be seen in a prototype remains to be demonstrated (or reported). (See references 29, 30, and 31 for more thorough discussions on failed-fuel detection.)

CONCLUSIONS

Warinner and Cho [3] concluded from their summary of out-of-pile experiments and analyses (coupled with previously published summaries) that:

- rapid FEFP has been deemed extremely unlikely, if not incredible
- slow FEFP should be 1) detectable, and 2) self-limiting
- slow blockage propagation is unlikely
- slow blockage growth appears nonmechanistic from within and highly unlikely even for external debris
- in-core planar blockages can be ruled out as a credible local fault
- molten-fuel release is very improbable, but even given a small release, resultant failure propagation or subassembly damage is unlikely
- although pin distortion and vibration, wire-wrap breakage, and other faults are possible--indeed, likely--the basic conclusions from the analyses and out-of-pile studies appear to be relatively insensitive to such perturbations.

Whether the consequences of an in-core local-fault will always be contained within the S/A will remain in question until many years of prototypic operating experience have been witnessed. The conclusions, based on analyses and prototypic out-of-pile experiments, often with a critical parameter or characteristic bounding, can be challenged to be conjectures. However, the in-reactor experience summarized in reference 1 lends credence to these conclusions.

The LMFBR LOAs have been briefly outlined to show the constraints of fuel-pin design, local faults reviewed, fuel designs and reactor parameters summarized, requirements of the fuel discussed, and failed-fuel detection reviewed. Outstanding are the trends toward larger pin diameter for economic benefit and titanium-stabilized 20% C.W. 316 S.S. cladding, the many parameters affecting fuel failure, and the stringent constraints set by the U.S. in comparison with other countries (e.g., 150 MWd/kg b.u. and $\leq$ 0.1% failure). Whether that goal will be met, with confidence of detecting all other safety hazards with such a high DN-signal background, remains to be seen.

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