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QUANTITATIVE STUDIES OF SEVERE FUEL DAMAGE USING DELAYED NEUTRON DATA

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ABSTRACT

A technique to quantify fuel damage in an LMR through analysis of delayed neutron data is presented, which is suitable for analysis of both small-scale in-pile experiments and full-scale plants. Validating analyses are described for five in-pile severe accident simulations performed within the SLSF and Mol 7C test programs. Comparison is made of measured and calculated amounts of fuel damage.

INTRODUCTION

Methods to quickly detect and diagnosis fuel damage are of considerable value to the safe operation of advanced liquid metal reactors (LMR's). Detection and analysis of a delayed neutron (DN) signal from coolant make this goal technically feasible because many long-lived DN-emitting fission products released from damaged fuel are transported efficiently in sodium coolant to locations where centralized detection is possible. In principle, fault detection only requires the damaged fuel to be a source of fission products and is limited only by time delays of coolant transport, so the technique is well-suited to small scale in-pile simulations as well as full scale LMR's. DN detection systems have been included on operating reactors, such as EBR-II, to provide diagnostic support for operation with failed fuel and special experimental subassemblies. DN detection systems were also developed within major in-pile programs of LMR severe accident safety testing to assess the ability of a DN signal to sensitively detect onset and propagation of fuel damage. These programs included the USDOE Sodium Loop Safety Facility (SLSF) at the ETR in Idaho and the Mol 7C collaboration of KfK and CEN/SCK at the BR2 in Mol, Belgium.

It is the aim of this paper to extend use of DN data beyond that of simple fault detection and demonstrate potential for true quantitative diagnosis of fuel damage. Simple techniques (first reported in Ref. 1) are proposed for modeling the release, transport, and detection of DN emitting isotopes from damaged fuel which allow fast-running computer analysis of measured DN activity in either a small-scale experiment or a large plant. Analyses explicitly accounts for plant-specific features of DN transport and detection: coolant transit times, mixing volumes, etc., and transforms the levels and trends of a measured DN signal into quantitative levels and trends of fuel exposure and damage. DN data from in-pile simulations of severe accidents, where fuel damage was measured under highly controlled and well-instrumented conditions, were analyzed and results are presented here as a validating database. Experiments analyzed include SLSF tests P4² and W2³ and Mol 7C/ 4-6⁴⁻⁶. Past reporting of the DN data from these

experiments has emphasized sensitivity in the detecting onset of fuel damage. This report emphasizes diagnostic analysis and quantitative comparisons of measured and calculated fuel release.

MODELING TECHNIQUES

Analysis of DN data was accomplished by the Delayed Neutron Release and Transport (DN/RAT) computer code which explicitly models DN-emitters from their generation in irradiated fuel, to release from damaged fuel into flowing sodium, and transport in the sodium flowstream to DN detectors¹. The diagram of Fig. 1 illustrates the logical flow of the analysis. The code explicitly follows production, transformation and decay of 17 isotopes, including 9 of the longest lived DN emitter-daughters and their immediate precursor-parents. Half-lives of these DN emitters range from 2-50 s.

A central concept in this analysis is a single quantity of "exposed fuel mass" postulated to characterize fuel damage. Within the model, exposed fuel is defined solely by its ability to release its isotope content to the flowing coolant stream. No physical relocation is assumed. Isotope inventory in exposed fuel is assumed either released promptly to sodium coolant or possibly delayed by diffusion (see below).

Figure 1. Flow Diagram of the DN Analysis (DN/RAT Code).

DN detection is assumed to take place in a "mixing plenum" which is both downstream from the damaged fuel and also included in a recirculating loop. As illustrated in Fig. 1, isotope inventory in the mixing plenum is adjusted by the calculation for (a) transformation and decay, (b) new isotopes arriving from exposed fuel after delay and decay, and (c) isotopes

exiting the plenum possibly returning again after recirculation delay and decay. (By comparison with the lifetimes of the longest-lived DN emitting isotopes, recirculation is only important to the analysis of small scale experiments where the timing is of order 50 s or less.) Transport delay and decay times are computed on the basis of coolant flowrates assuming all isotopes travel with the bulk coolant velocity.

The nature of isotope release from exposed fuel is a key controlling element of the analysis, and the particular mode assumed strongly influences both the time-dependance and amount of exposed fuel necessary to produce a given DN signal. Physically, where exposed mass is solid and stable, release to the coolant is limited by diffusion, but in the limit where exposed fuel is highly fragmented or molten, release is likely to be nearly instantaneous. (Instantaneous release is also an appropriate assumption for the special case of "recoil" emission from surfaces.) Because experiments analyzed in this report each included one or more highly-disruptive fuel releases, analyses reported here have assumed a prompt release of all isotopes from exposed fuel into the coolant. While this concept of isotope release might be appropriate for severely disrupted and/or largely molten fuel, in other stable and cooler fuel configurations isotope release may be limited by diffusion to a nearby grain boundary surface. In order to extend its usefulness into the realm of less-severe local faults and accidents, an optional diffusion-limited isotope release model has been incorporated into the DN/RAT code. With this option, an additional time-dependent isotope inventory is computed to accumulate computed within exposed fuel based on diffusion-limited release rates, transformation and decay laws, and addition of fuel not previously exposed.

DN/RAT was coded in IBM CSMP simulation language. Required input constants include DN counter efficiencies, nominal flow and mixing volumes. Time-dependent coolant flowrates, and fission rates in the fuel are needed as driving functions. CSMP programming has the advantage of allowing the principal input and output variables of DN activity and fuel mass exposure to be easily interchanged for both "forward" and "backward" operation. For exploratory studies the code is run in a "forward" mode where a postulated fuel mass exposure is input and subsequent DN activity output. For DN data analysis, the code is run "backwards" where measured DN activity is input and the fuel mass exposure responsible for this activity output.

EXPERIMENT DATABASE

The five experiments analyzed each tested small bundles of mixed oxide LMR fuel with fission heating and flowing sodium coolant under conditions that induced severe fuel damage and fuel melting. In all cases, obtaining a record of DN activity from coolant directly downstream of damaged fuel was a major objective. SLSF experiment W2 studied behavior of fuel undergoing a transient overpower (TOP) accident at full coolant flow. Experiments SLSF P4 and Mol 7C/ 4-6 were each intended to explore potential for growth and development of conservatively chosen "worst case" heat generating blockages or local faults. Both SLSF experiments tested fresh fuel, whereas the three Mol 7C experiments, 4-6, tested pre-irradiated fuel of medium, low and high burnup respectively. SLSF W2 tested an initially intact 7-pin fuel bundle. SLSF P4 and Mol 7C tested larger pin bundles of 37 and 30 pins, respectively, with built-in heat-generating "faulted

artifacts" designed to release significant amounts of molten fuel into the test bundle in the course of the experiment. In SLSF P4, this fault consisted of three 10 cm long solid fuel cannisters initially blocking about 15% of the flow cross section. In Mol 7C tests, initial conditions included a porous heat-generating blockage provided by a 4 cm long mesh cage filled with highly-enriched UO_2 spheres, covering 34% of the flow cross section

From the standpoint of fuel damage generated, differences were noted in timing and coherence of fuel damage produced. Indeed, this database spans faults which develop over many minutes down to rather coherent fuel releases occurring in just a few seconds. Local fault tests SLSF P4 and Mol 7C/ 4 and 5 were characterized by initial stage "blockage formation" events as the built-in artifacts failed, releasing debris into the coolant channel. Following initiation, complex blockage disruption or reconfiguration events were interspersed within periods of relative stability. By contrast, local fault test Mol 7C/6, and a later blockage reconfiguration event of SLSF P4 were characterized by monotonic, coherently growing fuel exposure. TOP test SLSF W2 was characterized by a single, massively coherent step increase in fuel exposure within seconds of fuel pin failure.

Table I shows some key times comparing fuel damage rates with times that characterize the performance of the SLSF⁷ and Mol 7C⁸ coolant circulation and DN data collection systems. The "fault development time" shown in Table I is intended to roughly characterize the time scale over which fuel damage evolved in each experiment and, for local faults experiments, is a rough measure of the fault stability.

The typical transit and delay times reported in Table I describe transit between the test fuel and the mixing plenum, mean residence in the mixing plenum, and recirculation around the loop. Values were generally based on nominal volumes and measured flowrates. In cases where the actual flow pattern within the apparatus was complex, measured transit times and "effective" flow volumes were substituted and included in Table I. In comparing characteristic delay and transport times of SLSF and Mol 7C apparatus, similar transit times are noted between fuel and detector, but shorter mean residence and recirculation times are noted in Mol 7C. In both cases recirculation times are well within the lifetimes of the longest-lived DN emitting isotopes (Table I).

Table I Fault Development and DN Transport/Delay Times

Test	Fault Dev. Time (approx.)	Transit Time (s)	Mean Residence Time (s)	Recirculation Time (s)
SLSF W2	2 s	4	2.5	18
Mol 7C/6	30 s	1.7	0.5	7
SLSF P4	1 m, 30 s*	2	1.4	12
Mol 7C/4	4 m	1.7	0.6	7
Mol 7C/5	15 m	1.6	0.5	6

* reconfiguration event

TEST ANALYSIS

Data from the above experiments were analyzed with the DN/RAT code, as described above. Input parameters included measured DN activity, counter efficiencies, flow and mixing volumes, measured coolant flowrates and specific (bundle average) fission rates generated in the test fuel. Also, because each experiment included one or more highly-disruptive fuel releases, analyses assumed prompt release of isotopes from exposed fuel into the sodium coolant. Exposed mass was output by the calculation. In assessing results, it should be emphasized that the modeling assumptions include (at least) three major idealizations which make quantitative determinations especially "approximate":

- 1) single quantity of "exposed" mass to characterize fuel damage,
- 2) prompt release of isotopes from "exposed" fuel to the coolant, and
- 3) efficient transport of all isotopes at the bulk coolant velocity.

In the present context of well-instrumented and controlled experiments, computed mass exposures are validated through corroboration by other test data, analysis, and post-test examination. On a transient basis, calculated mass exposures were in generally good agreement with reported test scenarios up to the point of abrupt neutronic shutdown. Indeed, before reactor scram, calculations accurately reflected and enhanced indications from other test data of onset and changing severity of fuel disruption. A sampling of such transient fuel release events from the tests, as quantified by the present analysis, are shown in Figs. 2-5. Results of the W2 analysis have already been reported in Ref. 1 and will not be repeated here. Analysis problems presented by reactor scram will be discussed subsequently.

In these analyses, DN "spikes" followed by an increased level in the DN signal were typically translated by the calculation into "step" increases in mass exposure. Despite sizable delay times indicated in Table I, the analysis is able to "resolve" very rapid changes in fuel exposure. On numerous occasions, the analysis correctly "filters out" small "secondary" peaks in the DN signal as returns of original spikes after recirculation and not indications of additional fuel exposure. In such cases, timing between peaks corresponds closely to the recirculation time given in Table I. In all analyses, a steady or slowly declining computed mass exposure indicates a period of relative stability.

Events shown in Fig. 2, prior to the indicated reactor scram, illustrate initiating behavior in SLSF P4. Computed step increases in exposed fuel mass coincide well with failures of the artifact blockage cannisters and nearby fuel pins. To place computed fuel mass exposures in some perspective, the total fuel inventory of a single pin was around 170 g with 20 or 30 g of "extra" fuel mass included in each artifact fuel cannister.

Figure 3 shows a complex late-stage blockage reconfiguration in Mol 7C/5. Perhaps two fuel exposure events are evident before the system again stabilized. These events have been associated with molten fuel away from

the built-in blockage. Post-test examination indicated a fuel loss from the blockage region of 10 - 17 g in good agreement with computed exposures.

In Mol 7C/6, computed fuel mass exposure shown in Fig. 4 displayed a multi-staged pattern of unstable growth with several different rates and occasional "hesitations" over a ~30 s time span. The peak value of computed mass exposure corresponded to about 19% of the total fuel inventory. SLSF P4 in Fig. 5 also showed a multi-stage growing mass exposure following a restart of the experiment illustrated in Fig. 2. Interestingly, both the timing and pattern of the computed mass exposures in these tests (Figs. 4 and 5) are similar. As indicated on the figures, both Mol 7C/6 and P4-reconfiguration were terminated by reactor scrams.

When reactor scram was encountered analysis of the DN data led to computations of "runaway" mass exposure several seconds later in both SLSF and Mol 7C configurations (Figs. 2, 4, and 5). Such post-scram mass exposures were not corroborated by other test indications and are considered spurious. Spurious mass exposures calculated after scram imply that the measured DN signal responds to sudden, major decreases in fission power more slowly than calculated by the model. The reason for this difficulty is not yet understood but may be related to the calculated release and transport of isotopes being assumed too highly efficient (assumptions 2 and 3, above). After a sudden power decrease by several orders of magnitude, activity from even a small fraction of "straggler" isotopes generated earlier at high power make measured DN activity much higher than modeled.

Table II provides a summary comparison of total exposed fuel mass calculated at the end of the test with best available post-test measurements. (Spurious mass exposures calculated post-scram were excluded from these estimates.) In view of the highly idealized nature of the calculations only very rough agreement would be anticipated. However, agreement shown in Table II is surprisingly good, with calculated mass exposures typically within 75% of those measured.

Table II Calculated Versus Measured Fuel Disruption

Test	Calculated Fuel Mass (g)	Measured Fuel Mass (g)
SLSF W2	380	~380
Mol 7C/6	710	~900 *
SLSF P4	~240	280-340
Mol 7C/4	100-160	173
Mol 7C/5	50-65	84

* preliminary, based on measured Cs₁₃₈ concentration in sodium

Figure 2. Measured DN Activity and Computed Fuel Mass Exposure in SLSF P4: Artifact Failure and Blockage Formation.

Figure 3. Measured DN Activity and Computed Fuel Mass Exposure in Mol 7C/5: Blockage Reconfiguration and Stabilization.

Figure 4. Measured DN Activity and Computed Fuel Mass Exposure in Mol 7C/6: Blockage Formation and Monotonic Growth.

Figure 5. Measured DN Activity and Computed Fuel Mass Exposure in SLSF P4: Blockage Reconfiguration and Monotonic Growth.

CONCLUSIONS

For the five tests analyzed, computed fuel exposures agree very well with reported test scenarios, and calculations of disrupted fuel mass at the end of the tests agree very well with measurements. Computed fuel exposures have aided interpretation and diagnosis of test events. The experiment database spans faults which develop over many minutes down to massive fuel releases occurring in seconds. Significantly, this database spans two completely independent experiment and DN detection hardware configurations (SLSF and Mol 7C programs).

The principal conclusion that can be drawn from this work is that a rather simple and idealized analysis of a DN signal shows great promise as a quantitative diagnostic tool to study severe accidents. The techniques developed for the present analyses of small-scale in-pile experiments should be directly applicable in diagnosing the operation of full-scale advanced LMR's. Computations of fuel mass exposure that correspond to stable, declining or growing mass exposures in well-instrumented experiments will help identify "DN signatures" of benign or threatening fuel behavior in large plants. We note that sample calculations performed for systems with much longer transport and residence times than these small-scale experiments show fundamentally the same relationship between fuel mass exposure and subsequent DN signal.

The single major problem area identified in the analyses was computation of runaway, spurious mass exposure shortly after a reactor scram. While not fully understood, the difficulty is believed related to idealizations in modeling efficient isotope release and transport and may only influence situations involving sudden power decreases.

To make these techniques as useful as possible to DN detection in advanced LMR's, application must be weighted towards probable fuel types and modes of fuel damage. DN data from advanced metallic fuel needs to be studied. While diffusion limited isotope release is already incorporated in DN/RAT, further analysis and validation with less disrupted, colder configurations of damaged fuel is needed.

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