IMPACTS OF REACTIVITY FEEDBACK UNCERTAINTIES ON INHERENT SHUTDOWN IN INNOVATIVE DESIGNS*

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The concept of "inherent shutdown" is emphasized in the approach to the design of innovative, small pool-type liquid metal reactors (LMRs)[1] This paper reports an evaluation of reactivity feedback uncertainties used in the analyses of anticipated transients without scram (ATWS) for innovative LMRs, and the associated impacts on safety margins and inherent shutdown success probabilities on unprotected loss-of-flow (LOF) events. It then assesses the ultimate importance of these uncertainties on LOF and transient overpower (TOP) events in evolving metal and oxide innovative designs.

The fundamental neutronic response of LMRs to ATWS events is governed by the following mechanisms that provide short term negative reactivity feedback to system temperature rises:

- Doppler feedback
- sodium density reduction (in some areas of the core)
- solid state fuel expansion
- radial core expansion (via load pad heating) and bowing
- control rod driveline (CRD) axial expansion

and in the event of fuel melting prior to cladding failure,

- in-pin relocation of molten fuel to above the active fuel region.

In the longer term, control rod retraction from reactor vessel heating and expansion is opposed by enhanced radial expansion from heating of the core support structure. Uncertainties in core response are a function of the uncertainties in the phenomenology and reactivity worth, as well as the relative contributions, of each mechanism to overall reactivity feedback.

To address the uncertainty in the first five mechanisms and associated reactivity coefficients, information developed for CRBR and FFTF[2,3] was supplemented with current insights from supporting innovative design analysis (core radial expansion, solid state fuel expansion, CRD expansion) and criticals experience (Doppler, Na density effects). This led to the current estimates of uncertainty, summarized in Table 1 for both metal- and oxide-based fuel systems, used in Argonne risk assessments of innovative designs.

The neutronics contributions to uncertainty simply reflect variations in calculated/measured coefficients. Slight differences in metal and oxide estimates exist because metal fuel feedback is more affected by cross-sections in the unresolved resonance range (Doppler) and has been less extensively measured; further metal critical experiments will reduce these differences. Fuel axial expansion/contraction feedback in both fuel systems is most affected by uncertainties in fuel-clad mechanical interaction. Radial core and CRD expansion uncertainties are most affected by the thermomechanical aspects. Bowing behavior, which is highly uncertain, contributes only a small amount to the overall core expansion effects and thus, is not overly critical.

The relative importance to core response of each mechanism varies according to type of ATWS event (LOF, TOP, loss-of-heat-sink, or combinations thereof), transient parameters (e.g. coastdown characteristics in an LOF), fuel system (metal or oxide), and of course, major design details (heterogeneous or homogeneous arrangement of subassemblies, core radial restraint options, control rod worths, etc.). Despite these dependencies, SASSYS[4] calculations performed over the past year in support of continuously evolving designs, show clear generic trends in the importance of feedback uncertainties in ATWS events.

LOF, fast (few second) coastdown, transients in the metal cores are characterized by monotonically decreasing power, small rises in fuel (<100K) and coolant temperatures (<250K) during flow coastdown, followed by monotonically decreasing temperatures. The negative feedback from radial expansion essentially controls the short term core response by overwhelming the positive sodium density feedback; in concert with a lesser contribution from CRD elongation it also offsets the long term positive Doppler, fuel contraction, and sodium feedbacks resulting from chilled fuel and elevated coolant temperatures to result in long term coolability with large margins to creep. The uncertainties in Table 1 propagate roughly a 5% uncertainty (1σ) in maximum LOF transient coolant temperatures. This is comparable to the uncertainty expected from "hot channel" effects as described for CRBR.[5,6] With the given margins to boiling of several hundred degrees K, predicted probabilities of inherent shutdown failure are well below 0.01.

Innovative oxide cores require design features such as flow coastdown extension and self-activated shutdown devices to achieve comparable safety margins in LOFs. As a result, the impacts of uncertainties in feedback are too design-dependent to allow rule-of-thumb characterization.

Both metal and oxide fuel designs subjected to rod withdrawal TOPs are characterized by a fairly rapid rise in coolant temperature which equilibrates at an elevated temperature. With very low rod worths due to low burnup swings in reactivity, metal system temperatures are kept, primarily by radial core expansion, hundreds of degrees K below levels where fuel melting, fuel-clad eutectic formation, or clad creep could signal the failure of early inherent shutdown. Although more work on the temperature dependence of clad failure mechanisms is required to develop quantitative predictions, impacts of feedback uncertainties on inherent shutdown comparable to those in the metal LOF are anticipated.

Higher rod worths may cause oxide centerline fuel temperatures to approach melting temperatures, but Doppler feedback turns over the transient with hundreds of degrees margin to fuel melt fractions that would signal early inherent shutdown failure. Thus, feedback uncertainties do not have much impact here either.

In summary, safety margins and probabilities of inherent shutdown success in LOFs and TOPs in both metal- and oxide based innovative designs are robust with respect to reactivity feedback uncertainties, moreso in the metal designs because of less reliance on engineered safety devices.

References

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Table 1.

UNCERTAINTY[1] ASSIGNMENTS IN REACTIVITY FEEDBACK
USED IN ANL RISK ASSESSMENTS OF ADVANCED LMR CONCEPTS

Reactivity Feedback Mechanism	Metal	Oxide
Doppler	20%	15%
Na Density	20	20
Fuel Axial Expansion/Contraction	30	25
-- neutronic	20	15
-- thermo-mechanical	20	20
Net Radial Expansion and Bowing	20	20
-- pure expansion (75% of net)	15	15
-- neutronic	10	10
-- thermal-hydraulic and structural	10	10
-- bowing (25% of net)	50	50
Control Rod Expansion	20	20
-- neutronic	10	10
-- thermal-hydraulic	<20	<20
Pre-clad failure, in-pin, molten fuel relocation	Not evaluated	Not evaluated
Vessel Axial Expansion	Not evaluated	Not evaluated

1 Values shown represent 1σ deviations from the mean of a normal distribution expressed as percentages of the best estimate reactivity coefficient. "Subeffect" contributions are statistically combined to develop the five major short term reactivity feedback uncertainties, which are rounded to the nearest 5%.