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PROBABILITIES OF INHERENT SHUTDOWN OF UNPROTECTED EVENTS IN INNOVATIVE LIQUID METAL REACTORS*

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Probabilities of Inherent Shutdown of Unprotected Events in Innovative Liquid Metal Reactors

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The uncertainty in predicting the effectiveness of inherent shutdown (ISD) in innovative designs results from three broad contributing areas of uncertainty: (1) the inability to exactly predict the frequency of ATWS events with potential to challenge the safety systems and require ISD; (2) the approximation of representing all such ATWS events by a selected set of "generic scenarios"; and (3) the inability to exactly calculate the core response to the selected generic scenarios. The full report will discuss the work being done to address each of these contributing areas, identify the approaches being used at Argonne National Laboratory to reducing the key contributions to uncertainties in ISD, and present results, to date. In this summary, we will focus on the third item by illustrating the methodology and associated results of work used to establish probabilities of failure of inherent shutdown of innovative LMRs to the unprotected loss-of-flow (LOF) accident.

Nominal responses of the innovative metal core reactors to ATWS events are characterized by transient temperatures with large safety margins to short term boiling during coastdown (LOF), long term temperatures with large margins to fuel temperature regimes capable of leading to fuel-clad eutectic penetration and/or creep rupture (LOF, transient overpower (TOP)), and long term temperatures with large margins to creep of the reactor vessel or its internals (loss of heat sink (LOHS)). The risk of irreversible core disruption or severe structural failures from these events [1,2] comes about as a result of anomalous behavior or unexpected design deviations such as

-- accelerated flow coastdowns (LOF) due to pump lockup or, depending on design, flow extension failure

-- hypothetical structural failures retarding radial core or axial control rod driveline (CRD) expansion feedback (all ATWS)

-- multiple rod withdrawals (TOP) that through some combination of structural, electrical, or design failures proceed at speeds and to levels beyond which are nominally limited by design

-- hypothetical core distortion events that place the core in a more reactive configuration (catastropic events)

-- the composite of core response effects, of which reactivity feedback is dominant, failing to perform as expected and predicted (all ATWS)

For all but extremely improbable, massive seismic or similarly catastrophic initiators, the top four items can be addressed by careful design and should have slight importance to risk relative to the fifth. Accordingly, the three generic scenarios, the unprotected LOF, TOP, and LOHS events, have traditionally been analyzed, both individually and in combination, to provide an envelope of calculations to cover all unprotected and ATWS sequences. Key parameters are then varied to explore the sensitivities of core temperature fields and concomitant safety margins for these reference cases.

Figure 1 illustrates the results of an LOF analysis [3] using the SASSYS code [4] which demonstrate several aspects of LMR innovative designs pertinent to the themes discussed herein: (1) The margin to boiling, one measure of the failure of inherent shutdown for an LOF, is several hundred degrees K. (2) The dominant contributor to inherent shutdown is negative reactivity feedback from radial expansion of the core [5]; thus uncertainty in this feedback mechanism is particularly important to core response. (3) The other feedback mechanisms taken individually are relatively unimportant.

The overall uncertainty in core response predictions comes about as a result of (1) uncertainties and limitations in ATWS modeling, as in calculating the various reactivity feedback effects; (2) uncertainties in steady state characterizations of neutronic (e.g. rod worths and positions, nominal power ratings) and thermal-hydraulic (e.g. inlet and outlet temperatures, flow distributions) parameters; (3) variations due to manufacturing, installation, and operating tolerances; and (4) uncertainties in the conditions needed to result in core disruption or vessel failure, i.e. the "criteria" to signal the defeat of inherent shutdown. Sources of uncertainty (2) and (3) are often lumped together and referred to as "hot channel effects"[6,7]. The full paper will discuss current estimates and their bases for all four sources.

All these uncertainties, as well as stochastic variations in actual operations, can be propagated through accident analysis codes using published response surface [8] or other approximating techniques to the uncertainty in core response to uncertainties in key phenomena. The results are used to produce probability distributions for maximum temperatures that have the potential for being reached in an ATWS event by fuel pins, flow channels, or key structural parts. The probability of failure of inherent shutdown is the fraction of this distribution of maximum temperatures that exceed safety limits keyed to the onset of core disruption or severe irreversible damage to the vessel or its internals.

Using SASSYS as the reference code, analyses [9] of a series of various designs have provided probability distributions for core temperatures used to signal failure of inherent shutdown. One sigma (1σ) uncertainties of 25-50K in overall safety margin have been obtained, depending on particular design, type of transient, and choice of transient parameters (e.g. flow coastdown characteristic in an LOF). As a result, the probabilities of achieving temperatures capable of defeating inherent shutdown are generally predicted to range from ~1% to negligible for current designs.

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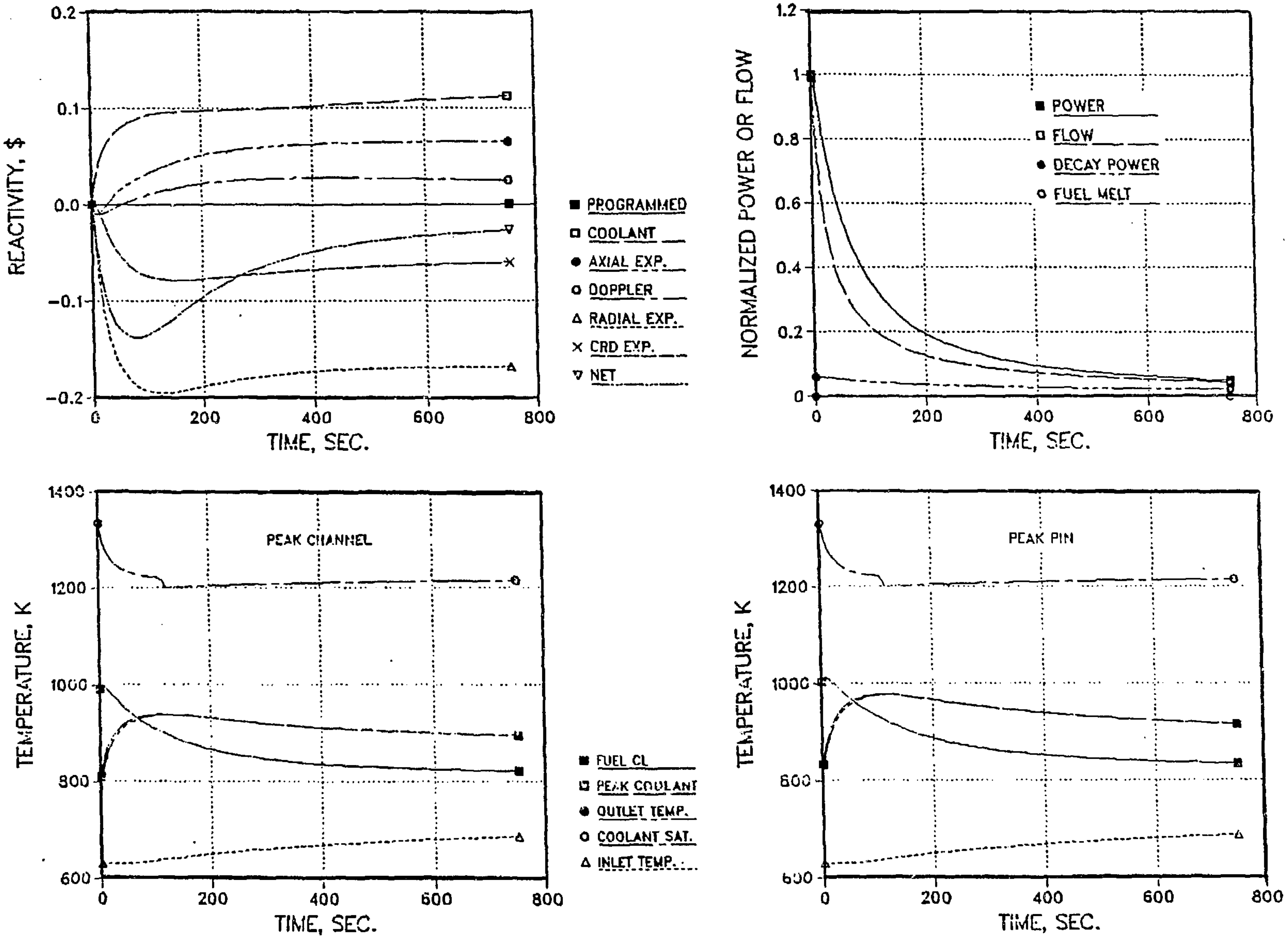

Figure 1. Illustration of Inherent Response of Innovative Liquid Metal Reactor to Unprotected Loss-of-Flow Event.