CONF-930401--11

Paper to be submitted for Topical Meeting on Nuclear Plant Instrumentation, Control and Man-Machine Interface Technologies, Oak Ridge, TN, April 18-21, 1993.

Plant Control Impact on IFR Power Plant Passive Safety Response

by

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Work supported by the U.S. Department of Energy, Nuclear Energy Programs under Contract W-31-09-ENG-38.

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ABSTRACT

A method is described for optimizing the closed-loop plant control strategy with respect to safety margins sustained in the unprotected upset response of a liquid metal reactor. The optimization is performed subject to the normal requirements for reactor startup, load change and compensation for reactivity changes over the cycle. The method provides a formal approach to the process of exploiting the innate self-regulating property of a metal fueled reactor to make it less dependent on operator action and less vulnerable to automatic control system fault and/or operator error.

I. INTRODUCTION

Advanced reactor concepts having passively safe characteristics have emerged within the past few years as engineers have moved to develop designs with a greater degree of demonstrable safety. These concepts, to varying degrees, make use of intrinsic design features to improve safety over what is achievable using active systems alone. Such features have the potential to perform more reliably since they do not depend on electro-mechanical components but only on the natural laws governing heat, fluid flow and neutron production. Their introduction, however, causes the previously clear demarcation between the role of engineered safety systems and systems required for normal operation to blur. A passive system that serves a safety function may also play a role in aiding normal operation. Conversely, an active system used for normal operation may continue to operate during an upset thereby affecting the operation of passive systems designed to protect the plant during the upset. A very important issue thus arises: can the active system ever operate to confound proper operation of the passive safety system during the upset? To successfully address this issue, a disciplined, structured approach to plant design is required, one that explicitly treats the integration of passive and active systems in achieving safety and normal operation goals.

Despite the clear need for such an approach, there is little evidence in the literature for the existence or use of such design methods. Perhaps part of the reason lies in the nature of the passive systems that appear in many of the new designs. Many of these are not purely passive but require the operator to perform a task, open a valve for example. Still, for those reactors with passive systems that are an integral part of the physics at normal operation, the fundamental need for a design approach remains.

In this paper, we describe a design methodology that was developed to address these issues for reactor designs based on the Integral Fast Reactor (IFR) concept. The key features of the IFR are the use of metal fuel, sodium coolant and a pool configuration. Designs based on the IFR concept are marked by the use of passive safety systems that are an inherent part of the plant physics at normal operation and do not require operator initiation following an upset. The hallmark of our design method is the systematic manner in which we arrive at a reactor design that is optimal with respect to unprotected safety while constrained by normal operating requirements. Our approach is not plagued by the need to identify the potentially infinite list of upset initiators and for each to determine the safety consequence. Rather, we show that all initiators fall into a small and manageable number of accident classes. We show that each class has associated physical mechanisms that limit the severity of any accident in the class. By defining a safety functional as the difference between maximum temperatures associated with these limits and actual failure limits, initiator consequences are analyzed implicitly by class rather than explicitly by enumeration. This ensures that all challenges to the passive safety system have received consideration. This functional is minimized subject to normal operating requirements which are introduced as constraints.

The design methodology has its roots in the analysis of open-loop safety by Wade (Ref. 1) and in the identification of candidate control strategies for plants with passive safety characteristics by Planchon (Ref. 2). Wade showed that the open-loop plant, that is the plant operating without a power control system, could present to the reactor at most five accident classes. In turn, the response of the plant for each of these classes is dependent on just a few integral plant parameters whose values could be adjusted to give favorable safety trends. Planchon suggested plant control strategies that reduced the safety consequence of a control failure and reduced the potential for the plant control system to override a safe passive response to an upset. What we have done in this work is to extend Wade's ideas to the closed loop plant and show how they lead to the types of control schemes suggested by Planchon.

An objection might be made that optimization should be performed not only in terms of a safety goal, but also an economic goal. Therefore, the design methodology we have developed is deficient or incomplete. We address this objection as follows:

1. To optimize not only with respect to safety, but also an economic goal, one of these goals must be translated into units of the other. However, there does not seem to be a uniformly accepted treatment for doing this.
2. The methodology does allow economic goals to be introduced as constraints to which the safety optimization is subject and future work will take this direction. For example, the inventory of stainless steel, a commodity that correlates highly with the cost of the plant, can be made a constraint. Other factors that influence cost such as availability and maintainability can be similarly treated. Treating economic goals in this way leads to a solution that is optimal with respect to safety at a given cost.

This paper presents one solution to the problem of designing the closed-loop system so that it cannot override a safe passive response to an upset. While the problem has been identified previously (Ref. 2 and 3), this appears to be the first time it has been solved.

II. INTEGRAL FAST REACTOR

The methods described in this paper were developed to address design issues associated with the Integral Fast Reactor (IFR) concept. The IFR concept consists of a pool plant layout, metallic fuel, a high internal conversion ratio core and pyrometallurgical fuel reprocessing. These first three elements allow for the design of inherent processes to bring the core to a safe shutdown condition and remove decay heat in response to off-normal conditions.

The IFR concept must be coupled to a balance of plant system and a plant control system if it is to be used to produce electricity. The concept does not define these systems since the essential safety and fuel cycle characteristics exist independent of them. This paper focuses on the development of a suitable control strategy that at once preserves the safety characteristics of the open-loop plant and meets normal operating requirements, the ability to startup, change load and compensate for reactivity changes over the cycle.

There is general agreement on what constitutes an appropriate balance of plant system (Refs. 4, 5 and 6). The main features are shown in Fig. 1. The plant consists of a primary system and an intermediate system, both using molten sodium as a coolant, and a conventional steam system. The primary system is located inside a large pool. Primary system pumps take their suction from the pool and deliver the sodium to the reactor. The intermediate system sodium is driven by a pump and the heat is transferred to the steam system. Superheated steam is used in a conventional turbine-generator to produce electricity. The steam is produced in either a once through steam generator or recirculating steam generator and a superheater.

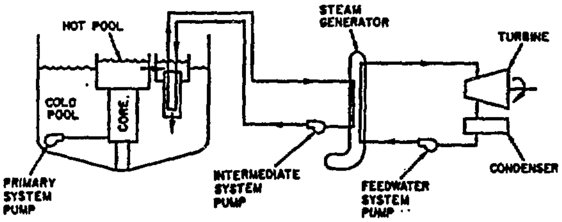

Figure 1 Liquid Metal Pool Type Reactor

III. OBJECTIVE AND SCOPE

The objective is to develop a strategy for designing and operating an IFR type plant so that conventional control requirements and some new requirements are met. The conventional requirements include the ability to manage reactivity to startup and to shutdown, to change load, and to compensate for reactivity changes over the cycle. The new requirements are to (a) exploit the innate self regulating property of an IFR core to passively shutdown the core without damage in response to unprotected upsets in the closed-loop plant and to (b) minimize the probability of the upset. The result would be a simplified control system and a reactor whose safety is less dependent on operator action and less vulnerable to automatic control system fault and/or operator and maintenance crew errors.

The scope is limited to exclude assigning a weighting to the sodium void worth. The void worth, which is design dependent, is a factor in core disruptive accidents and from that standpoint may ultimately be a factor influencing the design direction. At the present time, however, its exact role in metal core accidents is still the subject of active research. The scope further excludes assigning a weighting to commodities costs, availability or maintenance costs. These economic issues will all be addressed in future work.

IV. PHYSICS AND MODELS

The choice of reactor materials to a large extent determines the characteristics of any reactor type. In the case of the IFR, it is the use of metallic fuel and sodium coolant that provide for its unique safety characteristics. However, even though the physics of reactor operation are largely determined by this initial selection, the designer must still understand the physics and exploit them to the best advantage. Part of this task involves the development of models to be used to optimize the design.

The combination of metal fuel and sodium coolant permit the design of a reactor that inherently adjusts power to a level that is safe for the inlet temperature and flowrate presented to it by the heat sink. This self regulating property is the result of a large negative reactivity vested in the coolant temperature rise compared to the fuel temperature rise. Too much power raises the coolant temperature which in turn causes the power to drop. The size of the effect is what differentiates the IFR from other reactors; a relatively small change in coolant temperature can be used to compensate a relatively large change in power or reactivity change over the cycle. This self regulating property is what the design engineer can make use of to limit temperatures during accidents and to change load and compensate for burnup with minimal need to rely on external reactivity.

The relationship between the conditions presented to the reactor by the outside world and the associated reactivity, which determines reactor power, can be represented through a reactivity balance. There are only three channels through which the outside world can influence the reactor (excluding the passage of a gas bubble through the core): inlet temperature, flowrate and external reactivity (control rods). The time constants of the temperature feedback processes are such that the feedback temperatures are essentially in equilibrium with the instantaneous power, flowrate and inlet temperature. A reactivity balance on the reactor then gives, relative to some equilibrium zero reactivity reference state,

$$\rho = (P - 1)A + (P/W - 1)B + C\delta T_{pc} + \delta\rho_{ext} \quad (1)$$

where

P = normalized power,
W = normalized reactor flowrate,
δT_{pc} = change in primary system cold leg temperature,
$\delta\rho_{ext}$ = externally imposed reactivity, and
A,B,C = integral reactivity feedback parameters that are measurable at the full power operating point.

When nonequilibrium of the delayed neutron population can be precluded, as in the asymptotic state following an upset, the left-hand side of the above equation can be set to zero. The equation can then be solved for the new power level.

A. Unprotected Accidents

A simple yet powerful safety case can be developed for the IFR with Eq. (1) serving as its basis. By virtue of the fact that: (a) there are only three communication channels through which the core can be affected, and (b) the signal into each of these channels either increases or decreases, then all unprotected accidents are contained in the union of five generic accident classes. These classes are given in Table I. In each of these five classes, the signal input through the channel is limited in its amplitude by a physical mechanism as listed in Table I. The reactor power in the asymptote then is bounded and is given by Eq. (1). Safety analyses have shown that by proper choice of core design and primary system layout, one can achieve a safe response for these classes when taken one at a time (Refs. 1 and 7).

The above result, while rather remarkable, is one step removed from practical application since it applies to the open-loop plant. It remains to be seen what the closed-loop behavior of the plant is, that is, the plant operating under a control system. The complicating factor in the case of the closed-loop plant is the hierarchical relationship between the control system and the actuators; a control system failure can initiate through actuator motion simultaneous occurrence of more than one of these classes.

A simple extension of the ideas from the open-loop case, however, leads to an upper bound for the conditions reached for all closed-loop accidents. Taking all possible combinations, two and three at a time, of the five open-loop accident classes envelopes all closed-loop accidents. The bottom of Table I summarizes the four bounding events. Eq. (1) can again be used to compute the asymptotic power for each of these four events.

The example at the end of this paper adopts as the safety functional during an upset the cladding inside diameter temperature at the location of the peak value at normal full power conditions. The functional can be computed by substituting the power from Eq. (1) into

$$T_{clid} = T_{pc_0} + \delta T_{pc} + \frac{P}{W_p}\left(\Delta T_{sub_0} + \Delta T_{film_0}\right) + P\Delta T_{clad_0} \quad (2)$$

where

ΔT_{sub_0} = subchannel temperature rise at location of peak cladding ID temperature in peak pin at full power,
ΔT_{film_0} = film temperature rise at location of peak cladding ID temperature in peak pin at full power, and

Table I. Unprotected Accident Classes

	Accident Classes	Physical Mechanism Limiting Signal Amplitude
open-loop plant	1. reactor flow runup 2. reactor flow rundown 3. reactor inlet temperature chilling 4. reactor inlet temperature heatup 5. external reactivity insertion	- cavitation of pump coolant - establishment of natural circulation conditions - freezing of intermediate system cold leg sodium - loss of primary system heat removal capability - BOC excess reactivity
closed-loop plant	combined 1, 3 and 5 combined 2, 3 and 5 combined 1, 4 and 5 combined 2, 4 and 5	

ΔT_{clad_o} = cladding temperature rise at location of peak cladding ID temperature in peak pin at full power.

The various factors contributing to the subchannel temperature rise are related by

$$\Delta T_{sub_o} = \Delta T_{P_o} f_{driver} f_{stage} f_{intra} f_{inter} \qquad (3)$$

where

ΔT_{P_o} = reactor temperature rise,
f_{driver} = ratio of temperature rise in driver region to reactor temperature rise,
f_{stage} = ratio of power in maximum power driver at beginning of life to its average power,
f_{intra} = ratio of peak subchannel temperature rise to subassembly mixed mean temperature rise, and
f_{inter} = ratio of temperature rise in driver subassembly to reactor temperature rise at current conditions divided by same ratio at full power conditions.

B. Load Change

A design goal for any type of power plant limits the rate of change of temperatures during load changes to values that produce allowable thermal stresses on plant components. To design for allowable stresses, it is helpful to view the plant response to a load change as composed of the asymptotic response to the new condition onto which is superimposed the dynamic response. Each of these is controlled by different mechanisms and so, to some extent, the temperature swings for each can be independently set. The asymptotic response can be set in part by (a) adjustment of inherent feedbacks so that the reactor more closely follows changes in the imposed heat sink load, and by (b) the coordination of control variables - steam, primary system and intermediate system flowrate as functions of steady-state load. The dynamic component is controlled in part by (a) plant component time constants, and by (b) the dynamic order of the control equations. We focus on the asymptotic response, or the load schedule as it is known, and leave the transient component for future work.

A set of equations can be derived that express the load schedule as a function of the above parameters. Note that the coolant temperature out of each plant component can be described by an equation of the form

$$\frac{dy}{dt} = \frac{-1}{\tau}\left[\, y + F[\underline{u}(t)]\right] \qquad (4)$$

where

$\underline{u}(t)$ = vector of input forcing functions,
F = function of $\underline{u}(t)$,
τ = time constant, and
y = component output.

Setting the left hand side to zero and coupling all such equations for the plant leads to a system of equations for the plant state vector at steady state expressed in terms of the control variables

$$[T_{PH}\ T_{PC}\ \ldots T_{SH}\ P]' = A_o(w_P,w_I,w_S,\rho_R)^{-1}\, b_o(w_P,w_I,w_S,\rho_R) \qquad (5)$$

where

T_{PH} = primary system hot leg temperature,
T_{PC} = primary system cold leg temperature,
T_{SH} = superheater steam outlet temperature,
w_P = primary system flowrate,

w_I = intermediate system flowrate,
w_S = steam flowrate, and
ρ_R = control rod reactivity.

Defining the control variable schedule

$$
\begin{aligned}
w_P &= m_P\, w_S + b_P \\
w_I &= m_I\, w_S + b_I \\
\rho_R &= m_R (w_S - w_{S_0})
\end{aligned}
\tag{6}
$$

where m_P, m_I, m_R, b_P and b_I are constants and then differentiating Eq. (5) with respect to power gives a set of load schedule coefficients that define the load schedule about an operating point

$$
\left[\frac{dT_{PH}}{dP} \ \frac{dT_{PC}}{dP} \ \cdots \ \frac{dT_{SH}}{dP} \ \frac{dw_S}{dP} \right]' = A_1(m_P,m_I,m_R)^{-1}\, b_1(m_P,m_I,m_R) \tag{7}
$$

One sees from the above equation that three load coefficients can be arbitrarily assigned through the three parameters m_P, m_I, m_R.

C. Compensation for Cycle Reactivity Changes

Any change in reactivity that occurs over the course of a cycle as a result of a change internal to the reactor can be compensated for through any of the three communication channels. Mathematical relationships can be written that describe what can be achieved. Assume that the method of compensation satisfies the general set of equations

$$
\begin{aligned}
w_P &= n_P\, w_S + c_P \\
w_I &= n_I\, w_S + c_I \\
\rho_R &= n_R\, (w_S - w_{S_0}), \quad n_R = 0 \\
\rho_B &= n_B\, (w_S - w_{S_0})
\end{aligned}
\tag{8}
$$

where n_P, n_I, n_R and n_B are constants where we have set n_R to zero because it corresponds to a trivial case. To maintain power we require

$$
\frac{dP}{d\rho_B} = \frac{dP}{dw_S}\,\frac{dw_S}{d\rho_B} = 0 \tag{9}
$$

which implies dw_S/dP be infinite, a constraint. Eq. (7) still applies but with the m's replaced by n's. With three parameters, two additional constraints of the form dx/ρ_B can be set where x is a state variable.

V. OPTIMIZATION OF DESIGN AND OPERATION

The objective as defined earlier contains no reference as to how we are to proceed. Quite obviously there are degrees of freedom available in the way the reactor is designed and operated. To exploit these, one defines a functional that measures the degree of safety and then maximizes this functional with respect to these degrees of freedom subject to the constraints of the conventional control requirements. The functional is defined as the smallest margin that exists over the four worst case closed-loop accidents in Table I. The margin is the difference between a safety limit, cladding eutectic temperature for example, and the corresponding peak temperature.

A. Design

In practice, there is enough flexibility in the constraints and enough degrees of freedom in the parameter space that the solution to the above constrained optimization problem can be obtained by performing a single pass through a series of unconstrained optimizations. Each successive optimization involves a set of parameters of which there is a subset that controls the value of the current functional with the value that went before largely independent of these. One sees this in Table II where we have listed three optimization steps and their associated parameters. This single pass serial optimization is preferred because it is simpler to implement.

Step one of the three unconstrained optimizations deals exclusively with the safety of the plant response to unprotected upsets. The value of the functional is defined as the smallest value of the safety margins over the four worst case accidents defined in Section IV. Maximization of this functional is performed with respect to the parameters shown in Table II. These divide into two sets. In the first set are those parameters that determine the amplitude of the signal communicated through each of the three paths to the reactor. In the second set are the reactor feedback parameters that control the size of the asymptotic response given fixed amplitude signals.

The above step quickly requires specialization of the reactor design and the use of control rods in its operation. Note that the definition of the functional strongly penalizes any BOC reactivity excess for the following reason. When this quantity exceeds a few tens of cents, the flow and inlet temperature coefficients are not of sufficient magnitude to provide compensation and still maintain acceptable temperatures. We see this in the following example. Table III shows four design points for a 900 MWt reactor where power density and peak linear heat rate are constant across the designs (Ref. 8). The different designs correspond to different height to diameter ratios. As one sees, a flow change of many multiples of the full power value or an inlet temperature change of many hundreds of degrees are needed to provide the needed reactivity compensation for any but the low burnup swing case. Changes of these magnitudes are, however, unacceptable. Thus, for all but small burnup swings, the BOC excess must be suppressed by rod worth. This worth when withdrawn results in higher core temperatures than if it were not present to begin with. We conclude that the optimality search in step one will quickly route us to nominally zero burnup swing cores.

Table II. Design Parameters Available for Optimization of Reactor Response

Optimization Step	Communication Channel	Parameters Controlling Response	
		Fixed by Prior Step	Free to Vary
1. Unprotected accident asymptotic response			
a. signal amplitude input to channel	w δT_i ρ_{ext}		w_{min}, w_{max} $T_{SOLIDUS}$, K_{1IHX}, K_{2IHX} ρ_{excess}
b. channel sensitivity	w δT_i ρ_{ext}		B/A C/A 1/A
2. Load change asymptotic response	w δT_i ρ_{ext}	B/A C/A, K_{1IHX}, K_{2IHX} 1/A	m_P m_I m_R
3. Cycle reactivity change compensation	w δT_i ρ_{ext}	B/A C/A, K_{1IHX}, K_{2IHX} 1/A	n_P n_I n_R

Table III. Comparison of Passive Safety Characteristics:
H/D Parametric Study for 900 MWt Reactor

Parameter	Case			
	1	2	3	4
H/D ratio	0.484	0.299	0.192	0.060
BOC excess reactivity, $	0.45	6.18	10.4	12.3
A, cents	-15	-14	-12	-15
B, cents	-37	-49	-63	-94
C, cents/°C	-0.27	-0.37	-0.50	-0.76

The second optimization step (Section 2 of Table II) is performed with respect to load change asymptotic behavior. From Section IV, up to three load schedule coefficients can be arbitrarily assigned through the parameters m_P, m_I and m_R. The required parameter values are those that minimize a functional defined as the sum of the squares of the difference between the desired load coefficient values and the actual values. Searching over m_P, m_I and m_R to minimize the functional yields the required values. The other parameters shown in Table II that affect load behavior were set in the first optimization step. Consistent with our one pass approach, their values are held fixed in the present search.

In the third optimization step (Section 3 of Table II) we find those parameter values that will introduce reactivity to exactly compensate for the change in reactor reactivity induced by burnup, pin axial growth and other cycle effects. From Section IV, the reactivity change can be compensated for through the parameters n_P, n_I and n_R. The required parameter values are found by defining a functional as the square of the difference between the desired burnup coefficient value and the actual value. Searching over n_P, n_I and n_R to minimize the functional yields the required values. The other parameters shown in Table

II that affect burnup compensation were set in the previous optimization steps. Consistent with our one pass approach, their values are held fixed in the present search.

B. Operation

In general, if the number of search parameters in each of steps two and three above exceeds the number needed to achieve acceptable burnup compensation and load schedule behavior, then these extra degrees of freedom should, according to our goals, be used to implement the burnup compensation and load schedule control schemes in the way that minimizes the probability of an unprotected accident. While there may be any number of ways to proceed, it seems quite obvious that the probability can be reduced by minimizing the probability of failure of three systems: the reactor flowrate control system, the reactor inlet temperature control system, and the rod control system. Both the inlet temperature and flow are controlled by pumps and electrical circuits whose failure rate should be relatively independent of setpoint change frequency since this equipment operates continually. Changing a setpoint does not cause additional circuits to energize or moving parts to be put in motion. On the other hand, the rod control system need not necessarily be energized except when rods are moved. Minimizing the demand for motion would seem to minimize the probability for rod worth insertion through an equipment failure. Thus, the probability of an unprotected accident could be reduced by minimizing the demand frequency placed on rods during either load changes or when compensating for cycle reactivity changes. In practice, we can achieve this by de-energizing the rods and using reactor inlet temperature and flowrate, rather than rods, to change load and compensate for cycle reactivity changes. Moreover, to transport the reactor heat we must have the primary and intermediate pumps operating. We see that only the control rods are available for elimination.

In the simplest context, the zero burnup swing core required by step one implies no rod worth available for insertion once full power is reached. This, however, neglects the presence of uncertainties and the need for some worth to cover these. There are two components. First, the worth that must be inserted into the core to take the reactor from cold subcritical to the low end of the load range is subject to the uncertainty in the calculated temperature defect, the calculated critical position and the actual fissile loading. Second, over the course of a cycle, the nonlinear component of the reactivity due to fuel axial growth and the calculational uncertainty in predicting the burnup swing need to be covered. These various factors must be taken care of and thus there must unavoidably be some amount of worth available for insertion while at load.

There are two ways that we can operate the reactor given that some reactivity is needed at full power to cover these uncertainties. In the first approach, the reactivity needed to get to the low end of the power range (50%) can be vested in one set of rods, for conceptual purposes, Rods A. Once at partial power, the Rods A drive motors are electrically de-energized and access to the motor controller restricted. The reactivity needed for maintaining power operation (50-100%) through the cycle is vested in Rods B. The positions of Rods B need be changed only as frequently as is needed to compensate for axial growth reactivity loss and uncertainties in the nominally zero burnup swing. If reactor flowrate and inlet temperature are to provide compensation on the short term, of the order weeks, until they reach the limits of their ranges, then Rods B can be energized for a time long enough to move them so that flow and inlet temperature can be returned to their original values.

In the second approach, we build in a positive burnup swing equal to the worth of Rods B above. Then imagine a set of poison rods suspended above the core that enter the core under the force of gravity and a compressed spring. An electro-mechanical ratcheting mechanism on the rods allows us to insert negative reactivity a small increment at a time. A charging device physically separate from the rods is used to raise the rods during startup. Under this scheme, positive reactivity can be added only by the charging device and, under strict administrative controls, only during startup. Should the reactivity that builds into the core exceeds the rate at which it is lost through axial fuel growth, the rods can be lowered into the core to make up the difference. Load control is achieved the same way as in the previous scheme.

VI. AN EXAMPLE

The degree to which core damage can be eliminated during unprotected upsets by appropriate optimization was investigated for a 900 MWt advanced liquid metal reactor representative of those being developed in the U.S. The design, originally optimized with respect to three of the five open-loop accidents shown in Table I with the result appearing as Case 1 in Table III, was reoptimized with respect to the four closed-loop accidents of Table I. The resulting values for A, B, C and ρ_{excess} are, respectively, -15 cents, -45 cents, -0.24 cents/°C and 0. In the optimization, we elected to use the concept of Rods A and B for control rods as described in the previous section. The estimated two-sigma worth of these rods is shown in Table IV.

The reactor response for the bounding closed-loop accidents proved rather remarkable. The results summarized in Table IV show for runout limited to Rods B, the only rods ever energized after ascension to the low end of the power range, the peak cladding temperature remains below 710°C, a temperature that leads to cladding failure only after many hours. If both Rods A and B runout, then temperatures still remain substantially below the sodium boiling temperature of 950°C. The fuel axial growth component of Rods B is based on FFTF experimental data for 15 kw/ft IFR type pins. Lower power ratings would increase the worth of Rod B and perhaps favor the alternative control scheme of the previous section. The temperature swings over the load schedule shown in Fig. 2 are acceptable.

Table IV. Asymptotic Temperatures for Unprotected Closed-Loop Accidents in 900 MWt Plant

Case	Accident	Peak Cladding ID Temperature, °C (nominal)	
		Rods B Runout, 32¢	Rods A and B Runout, 56¢
1	chilled inlet[a], primary pump overspeed[b], rods runout	680	774
2	chilled inlet, loss of reactor flow[c], rods runout	709	808
3	heating of inlet[d], primary pump overspeed, rods runout	706	804
4	heating of inlet, loss of reactor flow, rods runout	706	804

[a] Sodium solidus intermediate cold leg [b] Cavitation at 115% [c] Natural circulation
[d] Loss of heat sink, zero power quasi-static reactivity balance

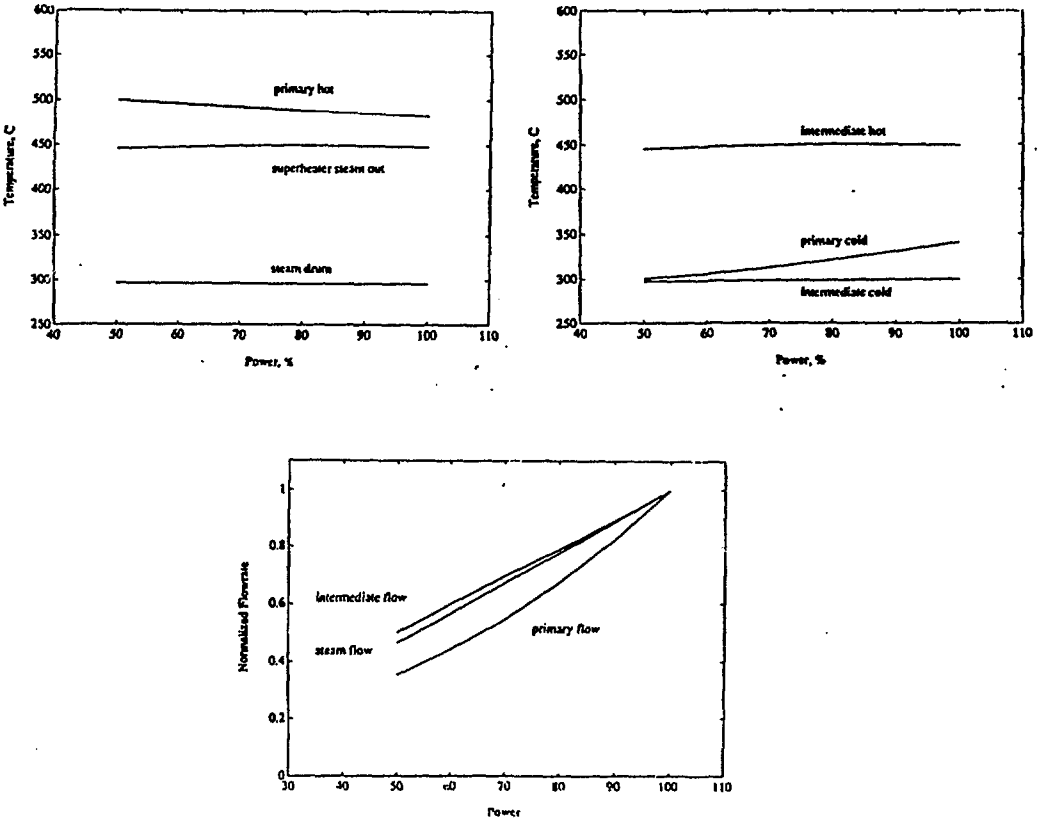

Figure 2 Load Schedule for 900 MWt Plant

VII. FUTURE WORK

The present work suggests the potential for passively protecting against virtually all control system failures and operator errors if the closed-loop plant is appropriately optimized. It is clear that the needed values of A, B and C are achievable. A number of issues, however, were not addressed in this work and remain to be investigated. For the example considered, some fuel melting does occur during the chilled inlet/loss of flow/rod runout accident and the consequences of this as a source of possible reactivity addition needs to be studied. Finally, while an acceptable steady-state load schedule was shown to be possible, the transient response during load changes still needs to be investigated and the structural response of the heat transport system components shown to be acceptable.

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