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INHERENT CONTROLLABILITY IN MODULAR ALMRs*

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Introduction

As part of recent development efforts on advanced reactor designs ANL has proposed the IFR (Integral Fast Reactor) concept. The IFR concept is currently being applied to modular sized reactors which would be built in multiple power paks together with an integrated fuel cycle facility. It has been amply demonstrated that the concept as applied to the modular designs has significant advantages in regard to ATWS transients. Attention is now being focussed on determining whether or not those advantages deriving from the traits of the IFR can be translated to the operational/DBA (design basis accident) class of transients. Inherent operability, the scheme proposed by Sackett et al. [1], where reactor power control is effected through the usage of primary pumps and BOP (balance of plant) swings rather than through the active motion of control rods, is a proposal to utilize the enhanced inherent feedback response of the IFR to improve the operating characteristics of LMRs. The scheme has associated with it potential advantages in the areas of plant control and design simplification. Furthermore, in examining the various PCS (Plant Control System) strategies possible for this alternative it became evident that the results were directly translatable to the area of control system feedback on inherency effects during the ATWS transients. This study on inherent operability in modular LMRs therefore has implications both for operational and ATWS events. Current intentions are to analytically explore possibilities of applying various schemes to ALMRs with the aid of the SASSYS [2] system code and then to test viable alternatives in the EBR-2 plant under the auspices of the ISOT program.

Table 1 shows the various plant operating modes which any plant operating/control scheme would have to account for in order to provide a comprehensive response. Modes (1) and (2) are being investigated primarily at the EBR-2 plant and primarily through the implications for operator procedures. Mode (4) will not be addressed in this study. The study initially focussed on the steady state aspects of mode (3). Dynamic questions of load adjustments were then investigated. Mode (5), the scram transients, was investigated through a combination of high setpoints and a controlled runback by the PCS. The question of whether or not the approach could be extended to preclude a reactor scram function was addressed. For the purposes of this study a modular sized 900 MWt plant is selected as the reference plant.

The unique features of the IFR concept consists of two salient characteristics; (A) Pool configuration: The pool configuration manifests itself during upset transient conditions through its large thermal inertia and a large time constant. (B) Metal fuel: The use of metal fuel in the reactor core leads to feedback coefficients very different from those derived by the use of oxide fuel in the core. Much smaller changes in reactivity are sufficient for the same change in power in the metal system.

Table 1. Plant Operating Modes

1) Startup	4) (N-1) Loop Operation
2) Shutdown	5) Scram Transients/Duty Cycle Events
3) Steady State/Load Adjustment	6) ATWS Events

We choose to actively focus on trait (B) for reactivity control and regard trait (A) as an accompanying feature.

Reactor plants consist of many components and systems selected and configured to reflect a number of constraints such as economics, safety, etc. The ground rule for this study is that with the exception of the PCS and the plant protection system (PPS) no other plant component or system will be modified or reconfigured to optimize the control strategy. This paper concentrates on the strategy for the choice of the superheated steam cycle and the once through steam generator (OTSG) for the water side of the balance of plant (BOP). Table 2 summarizes a number of the reference plant design parameters important for the plant response. With the exception of the load pad material, none of these design parameters were altered for the purposes of this study.

Two plant operating strategies are proposed: (a) Use the control rods only in the PCS circuit (termed "semi-innovative" alternative). There should be no use of the rods in the PPS for scram. (b) Remove the control rods entirely from the PPS/PCS circuits (termed "innovative" alternative). Operate the plant only through the PHTS pumps and BOP swings.

Table 2. Reference Plant Nominal Power Design Parameters

Core Power MWt	900
Core Inlet Temperature, °F	675
Core Outlet Temperature, °F	950
IHX Intermediate Inlet Temperature, °F	620
IHX Intermediate Outlet Temperature, °F	900
SG Steam Outlet Nozzle Temperature, °F	855
SG Feedwater Temperature, °F	495
Fuel	Metal
Clad	HT9
Duct/Load Pads	HT9 or 316 SS
Grid Plate	316 SS

It may well be that the most acceptable strategy is neither strategy (a) nor strategy (b) but a combination of strategies. It is envisioned that as a possible backup procedure the scram alternative would still be incorporated but with higher setpoints so if PCS runback is for some reason insufficient to mitigate the initiator fast shutdown would still be available.

Steady State/Load Adjustment

Figure 1 shows the conventional part load balance developed for the reference plant over the power range 40%-100% which utilizes control rods to effect the change in reactor power. With the exception of the steam generator outlet steam temperature which remains constant by design, all temperatures decrease with decreasing load. Decreasing load reduces turbine extraction steam. To obtain reasonably smooth axial temperature profiles in the heat transfer components the flows on the source and sink sides are kept in balance as total flow is reduced. All temperatures therefore decrease with decreasing load. The conventional balance acts in the exact opposite direction which an inherent operability scheme would require. Furthermore, the maximum core outlet plenum temperature is only 15°F below the level A limit for structural components. For a control scheme which depended upon increasing primary temperatures to decrease power the core outlet structural design margins would be a very tight restriction.

The quasistatic reactivity balance equation for the core can be written in terms of a different set of independent thermal hydraulic variables as

$$A[1-\bar{P}] - \frac{B}{\Delta T_c^o}\,\delta T_{op} - \left(\alpha_I - \frac{B}{\Delta T_c^o}\right)\delta T_{ip} = 0 \qquad (1)$$

with δT_{op} = core outlet temperature rise
δT_{Ip} = core inlet temperature change
$\bar{P}$ = normalized power
ΔT_c^o = initial core ΔT
A = power coefficient*
B = flow coeffcient
α_I = core inlet temperature coefficient

This equation is exact for transitions between different steady state load conditions. This form of the reactivity balance makes it possible to conveniently relate operating points to design constraints such as structural limits.

Using Eq. (1), a comprehensive search was made for schemes which would adjust the plant power in the 40%-100% load range only through the use of sodium pump flow and balance of plant maneuvers and simultaneously satisfy the design criteria for the core, the primary components, the IHXs, the steam generator and the BOP. Due largely to the small core outlet margin available it proved only possible to construct a scheme which would satisfy core and hot pool limits. BOP limits were also satisfied and steam cycle efficiency preserved. However, it was necessary to shift the burden of providing the

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*Defined with core power/flow kept constant.

temperature increases required onto the IHX and cold pool. This resulted in thermal stresses considered to be beyond design limits in the IHX and the primary piping. Schemes which require a change in the ground rules had to be considered.

Given the restriction of limiting design changes it was decided to run the PHTS (primary heat transport system) pump controller to maintain the core temperature drop constant. Opening up this temperature drop results in reduction of margins at the core outlet while closing it leads to difficulties with inlet piping and plenum structural stresses. Figure 2 is a reasonable choice for the partial load balance with this PHTS pump strategy. The reactivity coefficients used correspond to a design where 316 SS load pads or ducts were utilized instead of HT-9. A deliberate decision was made to select a strategy which would not alter the BOP design. Apparently nonregenerative feedwater heating at high temperatures bears a high economic disadvantage. However, there is a resulting mismatch of flows across the IHXs and the steam generators. Axial temperature profiles are fairly skewed and sensitive to flow control inaccuracies. These issues will have to be further explored. The upper temperature limits on HT-9 cladding may also have to be reexamined unless the power range is restricted to a ~10% swing of nominal. The temperature swings are reasonable for the component stress limits concerned.

Figure 3 presents results for a power rampback of 3%/min from 100% to 60% power without the usage of control rods. The PHTS flow is controlled to maintain the core ΔT constant while the feedwater flow follows a flow/load schedule.The results show good load following capability. At these slow rates the passive reactivity feedbacks are perfectly capable of a coherent inphase response. The initial 15 second null transient needs to be run further to numerically stabilize, and additional tuning of the PHTS pump controller gains will be required.

Future work will have to be concentrated on the alternatives of either (a) plant redesign for higher margin, (b) derating of the 100% power conditions or a combination of the two, or (c) restricting the inherent operability schemes to the power range of ±5% load swings which certainly is one of the more frequent class A duty cycle events.

Duty Cycle Events

Mode (5) forms the category of transients which are commonly analyzed for compliance with NRC licensing criterion and are referred to as FSAR Chapter 15 events. In the terms of the plant duty cycle, these are the service Conditions B, C and D events. All of these events can be categorized by event initiator type which in the standard FSAR format is as shown in Table 3. For this study, a mild transient and a severe transient in each of these categories were selected for analyzing the effects of different control strategies. In this manner, the entire spectrum of probable initiators and plant responses can be bracketed. Since this is a preliminary envelope further work may be necessary depending upon the acceptability of the conclusions drawn.

While, in general, event initiators which were not control system malfunction driven, were selected in order to avoid the question of control system parameters, it proved difficult to do so in the case of the secondary side induced overcooling category. The choice of the once through steam generator (OTSG) with the superheated cycle strictly limits the severity of the driving cooldown which can be induced by "breaks" on the waterside. Steam line breaks very quickly (~couple seconds) become overheating events instead of overcooling events. The enveloping cooldown event selected is the MFW (main feedwater) overfeed event. Results with the SASSYS plant model were obtained for the two alternative control strategies for the preliminary set of enveloping duty DBAs. A preliminary set of sensor signal and delays were used to obtain the SASSYS transient results. The following conclusions for the reference plant can be drawn from this initial study.

For the semi-innovative strategy a plant runback of a few %/sec is an acceptable response for the category of secondary side induced undercooling events if a thermal transient of a few °F/sec at the heat transfer components is tolerable. The SCS (Supervisory Control System) response to the category of reactivity transients and to the category of secondary side induced overcooling transient should be one of no action. For the loss of coolant flow combination event categories if the PCS control rod ramp rate is not significantly increased, a flow initiated plant scram is required.

Table 3. Plant Duty Cycle

Operating Mode	FSAR Chapter 15 Category	Service Condition	Transient
5	Reactivity Insertion	B	Uncontrolled control rod withdrawal
	Loss of Flow (LOF)	B	1 PHTS pump trip
		C	1 PHTS pump seizure
	Secondary Side Undercooling	B	1 IHTS pump trip
		B/C	2 steam generator FW valve closure
	Secondary Side Overcooling	B/C	2 steam generator FW valve overfeed
	*Multiple Initiators	B	Loss of Offsite Electric Power (LOEP)
		D	Safe Shutdown Earthquake (SSE)

*While not totally consistent with the FSAR format, this category represents combination events.

The innovative control strategy shows good load following capabilities for the required design load cycling with only BOP/sodium pump maneuvers. The neutronic power follows the imposed load changes well for a core using 316 SS ducts/load pads. For the rest of the duty cycle conclusions similar to those drawn for the semi-innovative strategy can be inferred for the innovative control strategy with a few modifications; the thermal transient rates at the heat transfer components is of the order of several °F/sec for the plant runback response to secondary side induced undercooling initiators; for the loss of coolant flow/combination event categories a flow initiated plant scram is required. If there is a need to reduce the thermal rates, alternative schemes can be examined with the implied possibility of PCS complications. The SCS response to the reactivity and secondary side overcooling events should be one of no action. Eventually operating procedures for these events will require the plant to be shutdown but the shutdown issue is not addressed in this study.

If either of these control strategies are pursued further, there will be a need to reexamine the waterside control algorithm to prevent steam generator overfill and a better definition of the "standby" conditions. In addition, some effort will have to be made to examine the possibilities of improved flow control techniques through the use of digital controllers and adaptive control.

ATWS Events

The effort on designing a plant control system (PCS), based on the understanding achieved through the inherent operability work, which would under no transient circumstances lead to the defeat of the inherency effects found to be so beneficial for ATWS events can be divided into two areas: (A) choice of local control parameters for the local controllers; (B) choice of strategy to link the local controllers. This study focuses on area (B).

Noninterference or nondefeat of inherency effects by the plant control system is best translated, in practical terms, as nonreduction of margins by specific actions of the PCS. For the purposes of this study this is regarded as minimization of the core outlet coolant temperature rise, since cladding temperature follows it closely, and margin to sodium freezing for the core inlet coolant temperature. The experience has been that clad eutectic temperature is the index for fuel performance so core outlet coolant temperature is a good measure to use. As the work on DBAs has shown the need for a conventional PPS, malfunctions in the PCS during duty cycle events will be adequately covered by the presence of the PPS. This means that the only importance of duty cycle events in the study of nondefeat of inherency by the PCS is in the setting of the stage for the ATWS events. Assuming that the critical stages of the ATWS (~minutes) is survived without SCS (supervisory control system) action then further SCS action can be divided into a short term ATWS phase where quasistatics prevail and a long term phase where additional equipment failures and noncriticality may occur. For these phases it is proposed that the following SCS strategy to link the remaining active local controllers, PHTS/BOP, be utilized. (a) Maximize PHTS flow; (b) BOP controller to follow the PHTS flow.

Quasistatic analysis, Eq. (1), shows for the short term ATWS phase that as long as the LOHS/ATWS response is acceptable the control strategy while not optimally maximizing margin for the core outlet coolant temperature will not deliberately exceed those limits. A reactor in the 1000 MWt (SAFR) range would fall within this class. Nonreduction of margins for all conditions is not always possible, but given an appropriate LOHS/ATWS response margins will always be present. The analysis also shows that the same conclusion holds for the core coolant inlet temperature both for maximum and minimum limits for a reactor of the SAFR class if a factor of three is considered to be the power load range. Structural limits may have to differ between the cold pool and the hot pool for the proposed strategy but that will have to be further examined. If reactivity coefficients change during a transient for a specific design, perhaps resulting from changes in core radial expansion regimes, then there may be a need to run the BOP controllers off PHTS monitored variables. This issue will be addressed in a future study on selection of control variables for the local controllers to implement the proposed SCS strategy for controller linkup.

For the long term ATWS phase, quasistatic analysis shows that the proposed control strategy would either try to increase margin or in the case of reducing margins lead to acceptable consequences if the initial phase of the ATWS is survivable. Long term dominance of the neutron power by decay heat maintains subcriticality but leads to the vulnerabilities of a classical startup condition. Decay heat removal systems have to be appropriately designed.

Stage setting for the ATWS events by the spectrum of duty cycle transients is in the main, as far as SCS strategy is concerned, consistent with the proposal presented here if the SCS responses for DBAs outlined in the previous section are adopted. The DBA transient categories where some inconsistencies will be encountered are the secondary side induced undercooling and the loss of flow event categories. A delay of pump trips/valve closing until confirmation of control rod motion is acquired would resolve these inconsistencies. Addition of this feature to PPS actuated rod scram would also be required.

Conclusions

In general it appears that without design modifications, except possibly for load pad material, a combination of strategies may be in order. For inherent operability schemes: the design load swing range should be limited to within a 10% swing of nominal; design load rate changes are feasible depending upon the BOP design; the loss of flow events may require a traditional PPS scram function with traditional settings; the reactivity events and secondary side overcooling events can tolerate higher settings for the traditional PPS scram; a "fast" power runback by the PCS for the secondary side undercooling events could be acceptable depending upon component design rate limits. For the short term ATWS phase, depending upon the LOHS/ATWS response, the control strategy which maximizes PHTS flow and runs the BOP controller to follow PHTS flow will not deliberately exceed the core outlet coolant temperature limits. For the long term ATWS phase, the proposed control strategy would either try to increase margin or in the case of reducing margins lead to acceptable consequences if the initial phase of the ATWS is survivable. However, the response of the BOP equipment requires further examination. An effort was initiated to expand the BOP modelling capability of the SASSYS code to clarify these issues. Results of that effort are reported in references [3,4,5] presented at this conference.

REFERENCES

1. H. P. Planchon et al., "Implications of the EBR-2 Inherent Safety Demonstration Test," Nuclear Engineering and Design, Vol. 101, pp. 75-90 (1987), North Holland-Amsterdam.

2. F. E. Dunn, F. G. Prohammer, D. P. Weber, and R. B. Vilim, "The SASSYS-1 LMFBR Systems Analysis Code," Proc. Intl. Topical Meeting on Fast Reactor Safety, CONF-850410, Knoxville, TN, pp. 999-1006, April 1985.

3. P. A. Pizzica, "An Improved Steam Generator Model for the SASSYS Code," submitted to the 1989 ANS Winter Meeting.

4. L. L. Briggs, "A New Balance-of-Plant Model for the SASSYS-1 LMR Systems Analysis Code," submitted to the 1989 ANS Winter Meeting.

5. J. Y. Ku, "SASSYS Balance-of-Plant Component Models for an Integrated Plant Response," submitted to the 1989 ANS Winter Meeting.

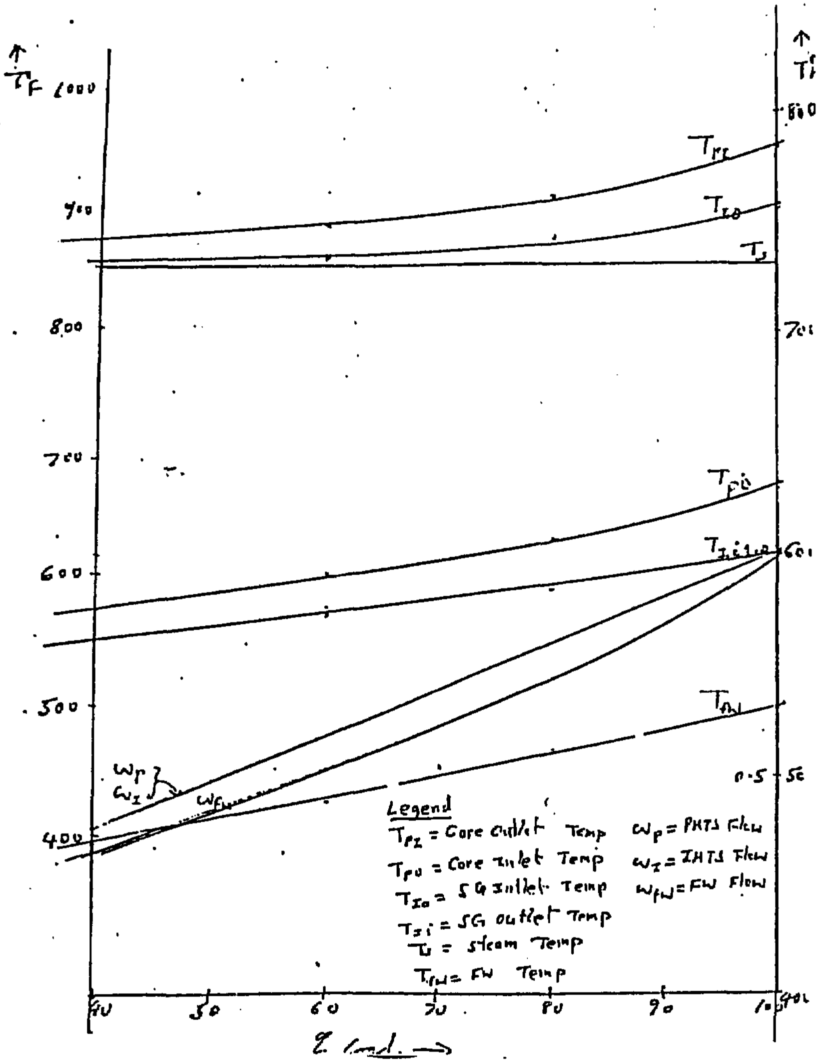

Fig. 1. Conventional Load Balance

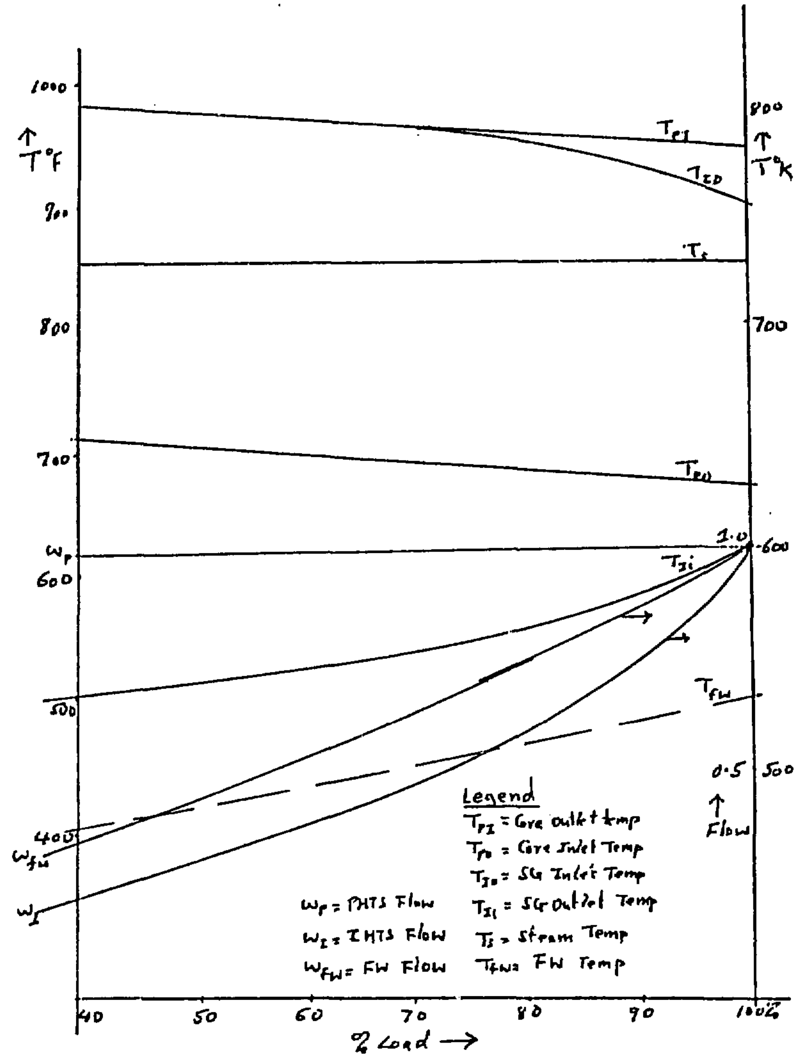

Fig. 2. Inherent Operability Load Balance

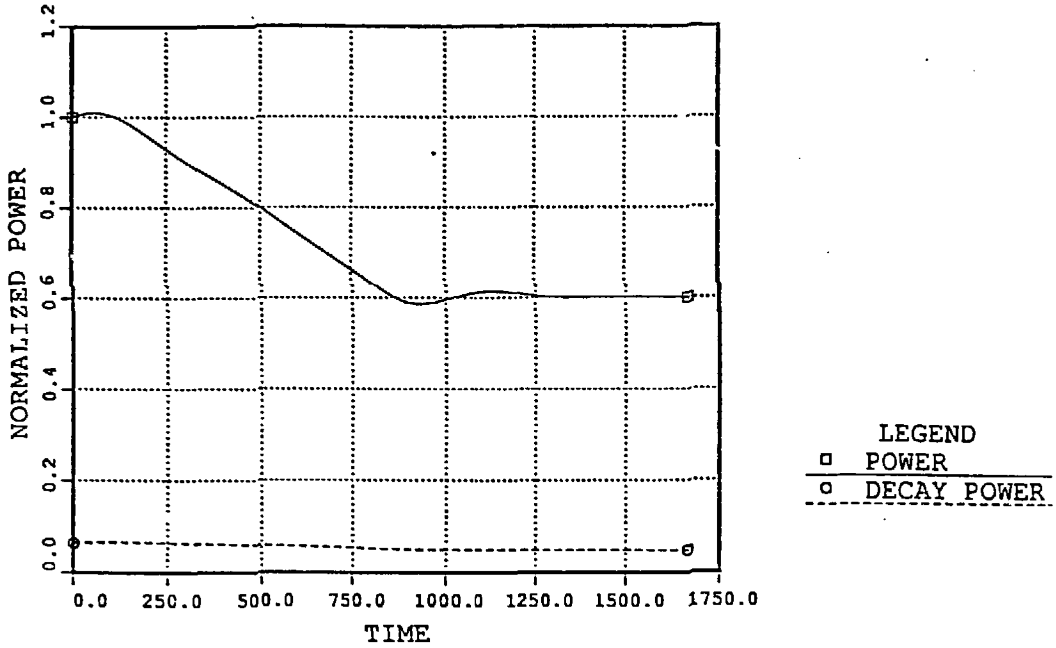

Fig. 3. Inherent Operability 3%/min Power Ramp - Reactor Power