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Quasistatic Reactivity Balance Equation to meet inherent safety requirements

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1. Introduction

The three inherent safety shutdown requirements previously developed and proved from the fast reactor systems and LMRs have been used to check if the fast reactors can go critical depending on these requirements without any external reactivity intervention such as control rod or shutdown systems.

In this paper, the same requirements and procedures were used to check if the thermal reactors satisfy these requirements using data from Younggwang unit 7 as a reference.

For various power level, the value of the three inherent safety shutdown requirements were evaluated where positive reactivity, $\boldsymbol{\rho_{ext}}$, is inserted by control rod ejection incident. Even though typical PWRs do not satisfy these requirements and cannot be stabilized at equilibrium power, fast Doppler feedback and subsequent drop of control rods shutdown the reactors.

We have fuel temperature and moderator temperature coefficients where the moderator temperature coefficient is affected by the boron concentration and the fuel temperature coefficient is affected by fuel burnup then these values could be more or less positive or negative reactivity insertion depending on those variables.

2. Process of work and Quasistatic Reactivity Balance Equation.

From the Quasistatic Reactivity Balance Equation, the core can be influenced through coolant inlet temperature in term of feedback reactivity:

$$0 = -\Delta\rho = (p-1)A + \left(\frac{p}{F} - 1\right)B + \delta Tin * C - \Delta\rho_{ext} \quad (1)$$

Where:

A, B, C are typical coefficients of reactivity, the general definition of A, B, C are as follow:

$A = \frac{\partial\Delta\rho}{\delta P}$, $B = \frac{\partial\Delta\rho}{\partial\frac{p}{F}}$, $C = \frac{\partial\Delta\rho}{\delta Tin}$, A implies prompt power coefficient, B is power over flow reactivity coefficients and C is coolant temperature reactivity coefficient.

δTin = the change of coolant inlet temperature from normal value and P = power, F = coolant flow, $\Delta\rho_{ext}$= externally imposed reactivity.

From this equation (1) if we want to decrease reactor power in case of fast reactor, small power decrement would be better than large power decrement because we can avoid too large Na coolant temp increase.

- From Eq. (1), P and F constant, $\delta Tin = \frac{A+B}{C}$, $\delta T_{out} = \delta T_{in} - \Delta Tc$, ΔTc = rise in coolant Temp at nominal (P/F) ratio.
- If we have loss of heat sink accident, we can minimize the core temperature rise by designing (A+B), power decrement, to be small and designing C to be large.

For thermal reactor same equations with corresponding inputs of A, B, C are used but with minor modification of assumptions on their reactivity inputs and this assumptions will be mentioned in the following sections.

2.1. Data of Younggwang unit 7 as a reference

The hot leg and cold leg temperature in Younggwang unit 7 are 329c^o, 295.8c^o giving the temperature difference, **Δ**T, 33.2c^o.

Because thermal reactors have small **Δ**T compared to the fast reactor and the coolant inlet does not directly contact the core structure, we can assume the reactivity insertion by radial expansion of the core and fuel assembly are neglected from the feedback reactivity calculation.

2.2 equations of A, B, C coefficients

$A = \frac{\partial\Delta\rho}{\delta P}$ = DPC * $\mathbf{\Delta Tf}$ / $\mathbf{Tf}$

DPC is Doppler power coefficient, $\mathbf{\Delta Tf}$ is Fuel temp rise and $\mathbf{Tf}$ is average fuel temperature

$$\boldsymbol{B} = \frac{\partial\Delta\rho}{\partial\frac{P}{F}} = \left(\frac{\mathbf{A}}{\mathbf{\Delta Tf}} + \mathbf{MTC} * \mathbf{0.000214} + \mathbf{CRDE}\right) * \frac{\mathbf{\Delta Tc}}{\mathbf{2}},$$

MTC is the moderator temperature coefficient. CRDE is the control rod drive expansion coefficient and assume this value equal to zero so this is the second assumption and 0.000214 volume expansion coefficient for the moderator H_2O.

$C = \frac{\partial\Delta\rho}{\delta Tin} = \frac{A}{\Delta Tf} + \frac{B}{\Delta TC/2}$, pcm/c

$\mathbf{CRDE} = \left(\frac{d\rho}{dL}\frac{1}{\beta}.\boldsymbol{L}\right) \cdot \boldsymbol{a}$

$\boldsymbol{\beta}$ **is physicl parameter (depend on the material temp),**

L is the rod height . a is linear thermal expansion coefficient

$\mathbf{\Delta Tf}$ = Fuel temp rise = 142.48 c^o

$\mathbf{Tf}$ = Tin + $\frac{\mathbf{\Delta Tc}}{\mathbf{2}}$ + $\mathbf{\Delta Tf}$

$\mathbf{\Delta Tc}$ (**coolant temp rise**) =33.2 c^o,

Tin = 295.8 c^o

$\mathbf{\Delta Tf}$ = 142.48 c^o, $\frac{\mathbf{\Delta Tc}}{\mathbf{2}}$ = 16.75 c^o

$\mathbf{Tf}$ = 295.8 + 16.75 + 142.48 = 455.03c

$$\frac{\mathbf{\Delta Tc}}{\mathbf{2}} = \mathbf{ave. coolant - Tin\ temp}$$

* Note for oxide fuel in LMR $\Delta\mathbf{Tf}$= 750 c^o, and $\Delta\mathbf{TC}$ = 150 c^o

We start with, control rod ejection accident, positive reactivity insertion, so power increase, P/F increase with fixed F and Tin, Tout increase then we got the following equation from equation (1):
P = 1- $\left(\frac{\Delta\rho_{RIA}}{A+B}\right)$ But if Tin, and if the Quasistatic Reactivity Balance Equation is unable to reject higher power P then P/F reaches to unity, P reach to one, finally Tout followed by the increasing at Tin so we can got another equation from same equation (1) $\boldsymbol{\delta Tin}$ = $\left(\frac{\Delta\rho_{RIA}}{c}\right)$ and by this equation the reactor can be controlled inherently.

3. Values of A, B, C for Younggwang unit 7

Table.1 evaluated values of A, B and C

at 100%P	BOC	MOC	EOC
A	-2.55	-2.6237	-2.946
B	-0.3054	-0.3279	-0.39
C	-0.03613	-0.03799	-0.04396

at 60%P	BOC	MOC	EOC
A	-4.811	-4.8267	-5.2444
B	-0.5773	-0.59855	-0.68732
C	-0.06823	-0.06961	-0.0778

at 20%P	BOC	MOC	EOC
A	-16.75	-16.3438	-17.173
B	-2.0105	-2.0475	-1.9806
C	-0.2375	-0.2369	-0.2387

4. Equilibrium condition without intervention results

Table.2 Evaluated safety shutdown requirements of Yoogwang Unit.7

Requirements 100%p	BOC	MOC	EOC
$\frac{A}{B} \leq \mathbf{1}$	8.3481	8.0015	7.5538
$\mathbf{1} \leq \frac{C\,\Delta TC}{B} \leq \mathbf{2},$	3.9624	3.8812	3.7760
$\frac{\Delta\rho_{RIA}}{/B/} \leq 1$	-	-	-

Requirements 60%p	BOC	MOC	EOC
$\frac{A}{B} \leq \mathbf{1}$	8.3329	8.0639	7.63021
$\mathbf{1} \leq \frac{C\,\Delta TC}{B} \leq \mathbf{2},$	3.9589	3.8959	3.7939
$\frac{\Delta\rho_{RIA}}{/B/} \leq 1$ *	-	-	-

Requirements 100%p	BOC	MOC	EOC
$\frac{A}{B} \leq \mathbf{1}$	8.3312	7.9823	8.6708
$\mathbf{1} \leq \frac{C\,\Delta TC}{B} \leq \mathbf{2},$	3.9588	3.8768	4.038
$\frac{\Delta\rho_{RIA}}{/B/} \leq 1$*	-	-	-

*Blank means the value is big or the value is not important since already two of conditions don't meet the requirements, all the above values depending on the assumption that we assumed in advance.

5. Conclusions

We can conclude from the results shown in table.2 that Yunggwang unit7 can't meet the safety shutdown requirements of fast reactors during the whole cycle without any external intervention. In case of control rod ejection accident, the power increase causes the fuel temperature increase so the negative reactivity insertion by Doppler effect shutdown the reactor only temporarily not steadily. So we have to insert negative reactivity by the shutdown system to bring thermal reactor into the safe state in case of rod ejection accident.
But from this kind of study we suggest that most inherent safety shutdown requirements strongly depending on the high fuel temperature and moderator differences then from this point any modification into the design to bring the thermal reactor to meet the requirements if can be achieved is the engineers should take care about this point of design .

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