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Stability Analysis of the EBR-I Mark-II Core Meltdown Accident

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1. Introduction

The Experimental Breeder Reactor I (EBR-1) at Argonne National Laboratory was designed to demonstrate fast reactor breeding and to prove the use of liquid-metal coolant for power production and reached criticality in August 1951. The EBR-I reactor was undergoing a series of physics experiments and the Mark-II core was melted accidentally on Nov. 29, 1955. The experiment was going to increase core temperature to 500C to see if the reactor loses reactivity, and scram when the power reached 1500 kW or doubling of fission rate per second. However the operator scrammed with a slow moving control and missed the shutdown by two seconds and caused the core meltdown. [1]

The Korea Atomic Energy Research Institute (KAERI) has developed the NuSTAB code for stability analysis of the sodium cooled fast reactor. In the NuSTAB code, the coupled neutron-kinetic and thermal-hydraulic equations are linearized to form the characteristic equation, which is solved as a generalized eigenvalue problem for determining the decay ratio, an indicator of the system stability. NuSTAB was used to analyze stability of the U and final TRU fueled cores of the Prototype Gen-IV Sodium-Cooled Fast Reactor (PGSFR) under development at KAERI. [2]

The purpose of this paper is to analyze the stability of the EBR-I core meltdown accident using the NuSTAB code. The result of NuSTAB analysis is compared with previous stability analysis by Sandmeier using the root locus method [3]

2. Method

1.1 NuSTAB Method

The NuSTAB code solves the coupled neutron-kinetics, fuel heat conduction, and coolant thermal-hydraulic equations, namely

Neutron kinetic equations:

$$\frac{1}{v_g}\frac{\partial \phi_g(r,t)}{\partial t} = \boldsymbol{\nabla}\cdot D_g(r,t)\boldsymbol{\nabla}\phi_g(r,t) - \Sigma_{rg}(r,t)\phi_g(r,t)$$

$$+\sum_{g'\neq g}^{G} \Sigma_{sg'\to g}(r,t)\phi_{g'}(r,t)$$

$$+(1-\beta)\chi_{pg}\sum_{g'=1}^{G}\nu_{g'}\Sigma_{fg'}(r,t)\phi_{g'}(r,t)$$

$$+\textstyle\sum_{j=1}^{J}\lambda_j\chi_{dg}C_j(r,t) + Q_g(r,t) \qquad (1)$$

$$\frac{\partial C_j(r,t)}{\partial t} = \beta_j\textstyle\sum_{g'=1}^{G}\nu\Sigma_{fg'}(r,t)\phi_{g'}(r,t) - \lambda_j C_j(r,t) \qquad (2)$$

Heat conduction equation:

$$\rho c\frac{\partial}{\partial t}T_f(r,t) = \nabla\cdot k\nabla T_f(r,t) + q'''(r,t) \qquad (3)$$

Thermal-hydraulic equation:

$$\rho c_p A\frac{\partial T_{CL}(t,z)}{\partial t} = \frac{1}{R_{wc}}[T_w(t,z) - T_{CL}(t,z)] - \rho c_p \bar{u} A\frac{\partial T_{CL}(t,z)}{\partial z} \qquad (4)$$

Here $\phi_g(r,t)$ represents the neutron flux of energy group g, and T_f and T_{CL} are temperatures of fuel and cladding, respectively. Other notations in the above equations are usually defined [2].

The differential equations can be expressed in a matrix equation as

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{f}(\boldsymbol{x}) \qquad (5)$$

The Taylor's theorem is used to expand the above equation:

$$\frac{d(\boldsymbol{x}_o + \boldsymbol{\Delta x})}{d\boldsymbol{t}} = \boldsymbol{f}(\boldsymbol{x}_o u_o) + \frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}}\boldsymbol{\Delta x} + \boldsymbol{O}(\,\boldsymbol{\Delta x^2}) \qquad (\boldsymbol{6})$$

Using the steady state condition, $\frac{d(x_o)}{dt} = \boldsymbol{f}(\boldsymbol{x}_o u_o)$, and ignoring terms higher than the first order for small $\boldsymbol{\Delta x}$ leads to

$$\frac{\boldsymbol{d\Delta x}}{\boldsymbol{dt}} = \boldsymbol{A\Delta x} \qquad (\boldsymbol{7})$$

The characteristic equation of the above equation and algebraic equations for variable feedbacks forms a generalized eigenvalue problem, which has the eigenvalues and right/left generalized eigenvectors:

The right eigenvector $\boldsymbol{e_i}$ satisfies:

$$\boldsymbol{A}\boldsymbol{e_i} = \lambda_i \boldsymbol{B}\boldsymbol{e_i} \quad (\mathbf{8})$$

The left eigenvector $\boldsymbol{f_i}$ satisfies:

$$\boldsymbol{f}_i^H \boldsymbol{A} = \lambda_i \boldsymbol{f}_i^H \boldsymbol{B} \quad (\mathbf{9})$$

λ_i is the *i-th* generalized eigenvalue, and $\boldsymbol{f}_i^H$ denotes the conjugate transpose of $\boldsymbol{f_i}$.

As a measure of stability of a dynamic system, the decay ratio (*DR*) can be used, The decay ratio is defined as the ratio of two consecutive maxima of the impulse responses of the oscillating variable, and if DR<1.0 a dynamic system is considered to be stable.[5,6] The dominant eigenvalue of the system can computed from $\lambda = \frac{f^H A_s e}{f^H \boldsymbol{B_s} e}$, and the decay ratio can be computed from $DR = e^{2\pi\frac{\sigma}{|\omega|}}$ where $\lambda=\sigma+j\omega$ and $j=\sqrt{-1}$.

1.2 Root-Locus Method

The Root-Locus method was used by Sandmeier to analyze the EBR-I accident. [Ref.3] The load power transfer function LP(s) can be expressed as

$$\mathrm{LP(s)} = \frac{ZP(s)}{1 - ZP(s)PK(s)} \quad (10)$$

where the zero power transfer function, ZP(s), assuming using one delayed neutron group, is

$$\mathrm{ZP(S)} \approx \frac{10.8(40\,s + 1)(2.76\,s + 1)}{s(9.09\,s + 1)} \quad (11)$$

and the power coefficient, K(s) for the Mark-II core is approximated as

$$\mathrm{PK(s)} = \mathrm{P}\ 10^{-3}\left[\frac{2}{1+\frac{s}{2}} - \frac{3}{\left(1+\frac{s}{2.0}\right)\left(1+\frac{s}{0.2}\right)}\right] \quad (12)$$

The poles of LP(s) start at poles of ZP(s)PK(s) and end at the zeroes of ZP(s)PK(s). The root-locus method allows determination of the complete range of poles and zeros as the power level P is increased.

3. Numerical Results

The Mark-II core of EBR-I contained U-2wt% Zr alloy in the fuel and blanket. Enriched fuel was used in the core, and top and bottom blanket used natural uranium. Inner blanket consisted of natural-uranium slugs. The core and the inner blanket were cooled by circulating sodium-potassium alloy. Table 1 lists the reactor parameters for EBR-I that were used in the stability analysis.

The dominant eigenvalues determined by running NuSTAB are listed in Table 2. The frequencies, ω, of dominant eigenvalues were found to be very small indicating that the system is hardly oscillatory. Therefore, the decay ratios were extremely small due to such small frequencies. For this reason, the sign of the real part of the dominant eigenvalue is used to determine the system stability instead of using the decay ratio. That is, if the real part of the dominant eigenvalue is negative, the system is stable and vice versa. The dominants eigenvalues in Table 2 indicate that the reactor is stable until P=3.0 full power and the reactor becomes unstable at and above P=3.5 full power.

Table 1: EBR-I Reactor parameters

Parameters	Value
Power,kW	1203
Core Height, cm	21.59
Core Radius, cm	9.996
fuel rod radius, cm	0.48768
Clad thickness, cm	0.0565
Gap thickness, cm	0.02478
NaK temp, in, C	230
Nak temp, out, C	322
Coolant velocity, cm/s	198.12 cm/s
Flow area per rod, cm2	0.3199 cm2
Reactivity coefficients:	
Doppler, $\frac{\Delta k}{kC}$	2.0 x 10^{-6}
Bowing, $\frac{\Delta k}{kMw}$	2.0 x 10^{-3}
Thermal expansion, $\frac{\Delta k}{kC}$	-3.5 x 10^{-5}

In addition, Table 2 lists the roots of the feedback function LP(s) for different power levels computed using the root-locus method by Sandmeier [3]. The polynomial describing the poles of LP(s) is of 4th order and there will be four roots. Table 2 shows that at low power level, all roots are negative real and the reactor is stable. As the power level is increased, two of the roots remain negative real and the other two become negative conjugate complex until P=3.0 full power and the reactor is stable. As the power is further increased, the conjugate complex roots have positive real parts and the reactor becomes unstable.

Table 2 shows that the results of stability analysis for Mark-II core of EBR-I are in good agreement between NuSTAB and the root-locus method by Sandmeier. Furthermore the analyses suggest that the reactor became unstable above 3.5 times full power and had the core melted.

4. Conclusion

The NuSTAB code has an advantage of analyzing space-dependent fast reactors and predicting regional oscillations compared to the point kinetics. Also, NuSTAB can be useful when the coupled neutronic-thermal-hydraulic codes cannot be used for stability analysis. Future work includes analyses of the PGSFR for various operating conditions as well as further validation of the NuSTAB calculations against SFR stability experiments when such experiments become available.

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Table 2: Roots by Root – Locus method and dominant eigenvalues

Power level	NuSTAB	Root -Locus method			
	Dominant eigenvalue	s_1	s_2	s_3	s_4
1.0	-0.5928E+00 +0.1411E-10j	-1.4805	-0.0086	-0.1481+0.1246j	-0.1481-0.1246j
2.0	-0.3537E+00 +0.1872E-10j	-0.9929	-0.0134	-0.1271+0.2348j	-0.1271-0.2348j
3.0	-0.1146E+00 -0.1703E-10j	-0.6529	-0.0162	-0.0334+0.3652j	-0.0334-0.3652j
3.5	0.5009E-02 -0.1090E-10j	-0.5682	-0.0172	+0.0559+0.4086j	+0.0559-0.4086j
3.8	0.7674E-01 +0.7797E-12j	-0.5393	-0.0176	+0.1203+0.4181j	+0.1203-0.4181j
4.0	0.1246E+00 -0.1064E-10j	-0.5181	-0.0179	+0.1624+0.4213j	+0.1624-0.4213j

P=1 Full Power