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Development of a Methodology for Evaluation of Core Disruptive Accidents in KALIMER

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Abstract

A methodology was developed to investigate the core disassembly process following a meltdown accident as part of the analysis work to demonstrate the inherent safety of a conceptual design of Korea Advanced Liquid Metal Reactor(KALIMER). In the methodology, the core kinetics and hydraulic behavior is followed over the period of the super-prompt critical power excursion induced by the ramp reactivity insertion, starting at the time that the sodium-voided core reaches the melting temperature of the metallic fuels. For this purpose, the equations of state of the pressure-energy density relationship are derived for the saturated- vapor as well as the solid liquid of metallic uranium fuel, and implemented into the formulations of the disassembly reactivity. Mathematical formulations are then developed, in the framework of the Modified Bethe-Tait method , in a form relevant to utilize the improved equations of state as well as to consider the Doppler effects. Using the numerical program developed, scoping analyses were performed for the KALIMER core behavior during super-prompt critical excursions induced by various reactivity insertion rates up to 100 $/s, which are considered the upper limit of ramp rates due to fuel compaction.

1. Introduction

Liquid Metal Fast Reactors(LMFRs) can be very sensitive to dimensional changes or relocation of materials since the intact LMFR core is not in its most reactive configuration. Therefore it is theoretically possible that a rearrangement of geometry can lead to prompt-critical reactivity excursions and to hydrodynamic disassembly of the reactor resulting in an explosive energy release to the reactor system and containment. The analytic method used in the evaluation of this type of super-prompt critical core disruptive accident(CDA) in a fast reactor was originally developed by Bethe and Tait [1], further elaborated by Jankus[2] and used in early safety studies of small uranium metal reactors like EBR-II and Fermi Reactor[3]. They developed a simple procedure for estimating the energy release in reactor explosions, subject to several simplifying assumptions. They assumed a simple relation between pressure generation and energy density, taking the vapor pressure to be negligible until the energy density reaches a threshold value of single-phase liquid and increasing linearly thereafter. Other simplifications of the method include the use of the first-order perturbation theory for the reactivity changes and the assumption of constant material

density in the hydrodynamics equation for core disassembly.

Many improvements and modifications had subsequently been made on the basic method by a number of authors[4,5,6] and they are often classified as Modified Bethe-Tait Methods. The two main modifications which have been made to the original method are the inclusion of the Doppler reactivity effect and the use of a more realistic equation of state of the fuel. It had been shown that the vapor pressure becomes significant while the power is varying much less rapidly, and core dispersion is then due to much lower pressures acting for a much longer time. The difference was particularly marked with large oxide-fuelled power reactors having a large Doppler constant.

In this study, a simple methodology was developed to investigate the core kinetics and hydraulic behavior during the super-prompt critical power excursion induced by the ramp reactivity insertion, starting at the time that the sodium-voided core reaches the melting temperature of the metallic fuels. The equation of state for pressure as a function of energy was derived by curve fitting relevant data for uranium to a fourth-order power series in the saturated vapor region, whereas a straight-line pressure-energy density relationship based on the principle of corresponding states was used in the single-phase region. The Doppler effect is taken to have a temperature dependency of $T^{-3/2}$ due to hard neutron spectrum of the reactor core with metallic fuels. Using the numerical program developed, scoping analyses were performed for the KALIMER core behavior during super-prompt critical excursions induced by various reactivity insertion rates up to 100 \$/s, which are considered the upper limit of ramp rates due to fuel compaction.

2. Method of Analysis

Basic Approach

It is assumed that the power excursion begins with the reactor prompt critical at time zero and the energy density generated during the excursion is governed by the reactor kinetics equation with no delayed neutrons and the source,

$$\frac{d^2Q}{dt^2} = \frac{k-1-\beta}{\ell}\frac{dQ}{dt} \tag{1}$$

where $Q(t)$ is the time dependence of the energy generation density

$$E(\vec{r},t) = N(\vec{r})Q(t) \tag{2}$$

and $N(\vec{r})$ is the normalized spatial power distribution. The other quantities in Eq.(1) is expressed in standard notation; k for multiplication constant, ℓ for prompt neutron lifetime.

The neutron multiplication constant as a function of time may be expressed in the form

$$k(t) = k_0 + k_1(t) + k_2(t) + k_D(t) \tag{3}$$

where k_0 is the initial multiplication constant(at prompt critical, $k_0 = 1+\beta$), $k_I(t)$ is the reactivity insertion responsible for initiating the excursion, $k_d(t)$ is the reactivity feedback resulting from material displacement during disassembly process, and $k_D(t)$ is the feedback from Doppler effect.

The rate of reactivity insertion initiating the excursion is assumed constant and

$k_I(t)$ may be written as; $\mathrm{k}_1(t) = [\frac{dk}{dt}]t = at$. In the case that a ramp insertion of reactivity initiates the accident, an equivalent step insertion is frequently used in Bethe-Tait analysis. For the purposes of determining the equivalent step insertion, it is convenient to divide the power excursion into two phases. During the first phase, reactivity is added at an assumed constant rate and the power rises until the time t_1 , when the total energy generated becomes sufficiently large to produce pressures that bring about significant material movement. During Phase 1, therefore, reactivity feedback is neglected. Once the core begins to disassemble it goes very rapidly, and it is found that one can safely neglect any further addition of reactivity afterward. Taking Eq.(1) for the reactivity insertion, the energy density generated during this phase is given by

$$\frac{\ddot{Q}}{\dot{Q}} = \frac{(dk/dt)t}{\ell} = \frac{at}{\ell} \tag{4}$$

Equation (4) may be utilized to obtain an explicit representation of the time t_1 as a function of Q to give

$$t_1 \approx \sqrt{\frac{\ell}{a}}\sqrt{\ln X + \ln(\ln X)} \tag{5}$$

where

$$X \equiv \frac{aQ^2(t_1)}{\ell}[\dot{Q}(0)]^{-2} \tag{6}$$

The total reactivity inserted by the ramp prior to the large burst in power is given by

$$k_1(t_1) = at_1 = \sqrt{a\ell}\sqrt{\ln X + \ln(\ln X)} \tag{7}$$

For the initial conditions of Q and $\dot{Q}$, the core is assumed initially at prompt critical in the molten state, and the initial energy content of the core, $Q(0)$, is taken to be about 0.250 KJ per gram of uranium, which corresponds to the internal energy to heat uranium from room temperature to the melting point(1,400K). We also need to know $\dot{Q}(0)$, the initial power level at prompt critical. Since the power at the delayed-critical steady state is usually known, we need estimate the increase in power from there on to the prompt critical state. A simple formula for the power at the prompt critical state brought by introducing reactivity at the constant rate of a dollars per second to an initially delayed critical reactor of the power level, $\dot{Q}_{ss}$, may be derived by solving the one-group point kinetics equations with constant delayed neutron precursor concentrations. The result is [7],

$$\dot{Q}(0) = \dot{Q}_{ss}(\frac{pb}{2a\ell})^{1/2} \tag{8}$$

We may interpret that the total amount of reactivity insertion, $k_I(t_1)$, is the reactivity beyond prompt critical , which drives the power excursion along to its termination. It is assumed that t_1 comes when the fuel boiling occurs at the peak power location of the core. The boiling temperature of the uranium fuel is assumed to be about 4,100K and the corresponding energy $Q(t_1)$ is taken to be 0.8 KJ/g. Since the net reactivity is

initially at its maximum and reduced with the negative reactivity feedback from the Doppler effect and /or core disassembly during the excursion, $k_I(t_1)$ is termed $k_{\max}$ in the following for clarity as well as for convenience.

Development of Equations of State

The equation of state plays an important role in calculations of the course of a hypothetical fast reactor excursion, for it serves as the link between the neutronic relations and the dynamic behavior of a core which leads to ultimate shutdown. The principal relation necessary for such calculations are the pressure as a function of energy and volume for hydrodynamic calculations. There exist, however, considerable uncertainties in our knowledge of the equation of state as well as material properties at extreme conditions of temperature and pressure, occurring during the power excursion of fast reactors. Resort has therefore been made to theory and correlation for the estimation of these physical properties at extreme conditions. The equations of state described in the following are based on the calculations of R.H.Brout[8], with modifications that extend his calculations for single-phase conditions into the saturated-vapor region. We start with liquid uranium, just above the melting point, interspersed with void spaces left in the core when the coolant is expelled. As the temperature rises, the voids are filled with the expanded liquid producing saturated vapor pressure. If the liquid reaches the threshold energy to fill the voids completely, the pressure then begins to rise rapidly.

First, an equation of state is derived in the Bethe-Tait type linear threshold equation for the liquid region. Use is made of the equation-of-state data calculated by Brout for the uranium density of 7.44 g/cc[8]. The result is

$$p = 5{,}939\,(E - 1.44) \tag{9}$$

where pressure is measured in MPa and the liquid energy is in KJ/g. The threshold energy Q^* is fitted to be 1.44 KJ/g.

A vapor pressure equation for uranium is given by Raugh and Thorn[9] as,

$$\log p\,(atm) = 5.702 - (23{,}300 / T) \tag{10}$$

We need, however, an expression relating pressure to energy rather than to temperature. The specific heat of uranium is not well known in the high temperature region. It is believed that it is close to 2.0 J/gK and stays constant above the melting point of uranium. We do not know for certain what will happen above the vaporization temperature. Under these circumstances, a constant value of 0.11 J/gK(6.06 cal/g) was chosen as the specific heat of uranium at the vapor region, in line with the works by Brout and Nicholson[4]. The resulting values of pressure as function of energy were curve-fitted to a fourth-order power series,

$$p = \sum_{i=0}^{4} B_i E^i \tag{11}$$

where

$B_0 = 1.297 \times 10^3$, $B_1 = -6.018 \times 10^3$, $B_2 = 10.495 \times 10^3$,

$B_3 = -8.182 \times 10^3$, $B_4 = 2.416 \times 10^3$,

and pressure and energy are in the units of MPa and KJ/g. The saturated-vapor-pressure curve, fitted by Eq.(11), starts from the boiling point of uranium Q_b, which is assumed 0.8 KJ/g, and is smoothly connected to the linear equation of state at the energy of 1.55KJ/g for the consistency of two different equations of state, as illustrated in Fig.1.

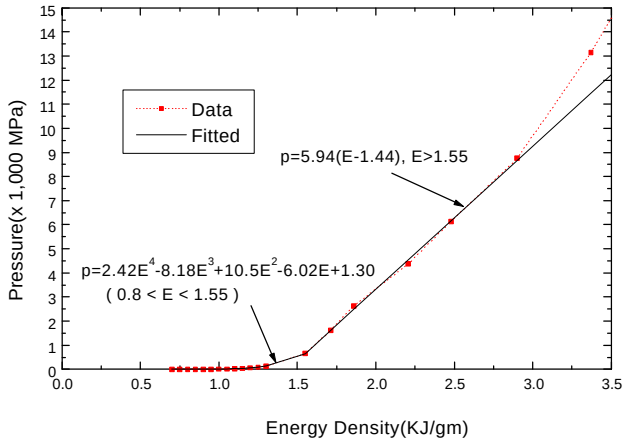

Fig.1. Pressure-energy relations of uranium core

Disassembly Reactivity

The equations of state developed in the above can be utilized to obtain the expressions for the disassembly reactivity. For the single-phase liquid region, we may substitute Eq.(9) into the Bethe-Tait form of expressions for the disassembly reactivity[2,3]. In the saturated vapor region, the curve-fitted equation of state Eq.(11) is used and we get the second derivatives of the reactivity in time as follows ;

$$\ddot{k}_{\mathrm{d}} = 0 \qquad , \qquad \text{for} \quad Q < Q_{\mathrm{b}}$$

$$\ddot{k}_{\mathrm{d}} = -\left(\frac{1}{x}\frac{k_{\max}^{3}}{\ell^{2}}\right)\sum_{\mathrm{i}=0}^{4} \mathrm{A}_{\mathrm{i}}(z)Q^{i} \quad , \qquad \text{for} Q_{\mathrm{b}} < Q < \frac{Q_{b}}{1-q} \tag{12}$$

$$\ddot{k}_{\mathrm{d}} = -\left(\frac{1}{x}\frac{k_{\max}^{3}}{\ell^{2}}\right)\sum_{\mathrm{i}=0}^{4} \mathrm{A}_{\mathrm{i}}(q)Q^{i} \quad , \qquad \text{for} \quad \frac{Q_{\mathrm{b}}}{1-q} < Q < Q_{b}$$

where X is a constant characterizing the reactor core, q is a power shape factor, Q_b is the energy density at the boiling temperature of the core, and

$$A_0(z) = \frac{2}{3} z^{2/3} B_0$$

$$A_1(z) = \left(\frac{2}{3} z^{2/3} - \frac{2}{5} z^{2/5}\right) B_1$$

$$A_2(z) = \left(\frac{2}{3} z^{2/3} - \frac{4}{5} z^{2/5} + \frac{2}{7} z^{2/7}\right) B_2 \tag{13}$$

$$A_3(z) = \left(\frac{2}{3} z^{2/3} - \frac{6}{5} z^{2/5} + \frac{6}{7} z^{2/7} - \frac{2}{9} z^{2/9}\right) B_3$$

$$A_4(z) = \left(\frac{2}{3} z^{2/3} - \frac{8}{5} z^{2/5} + \frac{12}{7} z^{2/7} - \frac{8}{9} z^{2/9} + \frac{2}{11} z^{11/2}\right) B_4$$

and,

$$z = 1 - Q_0 / Q \tag{14}$$

where Q_0 is the initial energy density of the core. The coefficients $A_i(q)$ are obtained

replacing z with the power shape factor q in Eq.(13).

It is convenient for numerical analysis to define the following dimensionless variables

$$y = \frac{Q - Q_0}{Q_0} \tag{15}$$

$$k(t) = \frac{k(t) - 1 - b}{k_{\max} - 1 - b} \tag{16}$$

$$t = \frac{k_{\max} - 1 - b}{\ell} t \tag{17}$$

Eq.(12) may be reduced to a simple set of differential equations in terms of the above dimensionless variables,

$$\frac{d^2k}{dt^2} = 0, \qquad \text{for} \quad y < \frac{Q_b - Q_0}{Q_0}$$

$$\frac{d^2k}{dt^2} = -\frac{1}{x}\sum_{i=0}^{4} A_i \left(\frac{y}{y+1}\right) Q_0^i (y+1)^i, \qquad \text{for} \frac{Q_b - Q_0}{Q_0} < y < \frac{Q_b/Q_0}{1-q} - 1 \tag{18}$$

$$\frac{d^2k}{dt^2} = -\frac{1}{x}\sum_{i=0}^{4} A_i(q) Q_0^i (y+1)^i, \qquad \text{for} \quad \frac{Q_b/Q_0}{1-q} - 1 < y < \frac{Q^* - Q_0}{Q_0}$$

where Q^* is the threshold energy of the single-phase liquid region. Likewise, it can be written for the single-phase liquid region,

$$\frac{d^2k}{dt^2} = -\frac{y+1}{x}\left(\frac{Q_0}{Q^*}\right)\left(\frac{y+1-Q^*/Q_0}{y+1}\right)^{5/2}, \text{ for } \quad \frac{Q_b - Q_0}{Q_0} < y < \frac{Q^*/Q_0}{1-q} - 1$$

$$\frac{d^2k}{dt^2} = \frac{5q^{3/2}}{2x}\left[\left(1 - \frac{3}{5}q\right)\left(\frac{Q_0}{Q^*}\right)(y+1) - 1\right], \quad \text{for } y > \frac{Q^*/Q_0}{1-q} - 1 \tag{19}$$

Doppler Reactivity Feedback

If T_0 is taken as the initial temperature at which the energy density Q_0 is achieved, then Doppler effect can be written as

$$\frac{dk_D}{dt} = -\left(\frac{dk_D}{dT}\right)_{T_0} \left(\frac{T_0}{T}\right)^n \frac{dT}{dt} \tag{20}$$

where $(dk_D/dT)_{T_0}$ is the Doppler temperature coefficient at temperature T_0. The Doppler effect is assumed to decrease in magnitude inversely as the n[th] power of the temperature T, measured from absolute zero. With the use of a constant value of the heat capacity at constant volume C_v, Eq.(20) can be rewritten in terms of the dimensionless variables as[6],

$$\frac{d\Gamma}{dt} = \frac{-a_D}{k_{\max}} \frac{q^{n-1}}{(q+y)^n} \frac{dy}{dt} \tag{21}$$

where

$$\Gamma = \frac{k_D}{k_{\max}} \tag{22}$$

$$q = \frac{C_v T_0}{Q_0} \tag{23}$$

$$a_D = -T_0 \left(\frac{dk_D}{dT}\right)_{T_0} \tag{24}$$

The fuel temperature (Doppler) coefficients are evaluated for sodium-flooded/voided cases. It is estimated to vary as $0.11T^{-1.49}$ for the sodium-voided case, whereas it varies as $0.10T^{-1.43}$ in the case of the sodium-flooded core[10]. The Doppler coefficient does not show any substantial change with burnup. It results in between –0.002 and –0.003, but close to –0.003, in the broad range above the melting temperature.

Excursion Phases for Numerical Analysis

In previous sections , a set of differential equations were established in terms of dimensionless variables, taking into account the reactivity feedback due to the Doppler effect as well as core disassembly in the framework of the Modified Bethe-Tait methods. Rewriting Eq.(1) into the dimensionless form likewise, we obtain the equation for energy density

$$\frac{d^2 y}{dt^2} - (k + \Gamma)\frac{dy}{dt} = 0 \tag{25}$$

with the initial conditions

$$y(0) = 0, \quad k(0) = 1, \quad \Gamma(0) = 0,$$

$$\frac{dy(0)}{dt} = 1, \quad \frac{dk(0)}{dt} = 0 \tag{26}$$

which, together with Eqs.(18),(19) and (21), constitute a complete set of equations to have a unique solution of the problem. Starting with the initial conditions, the above equations can be numerically integrated using the Runge-Kutta method on a digital computer. The integration is continued until the reactor power falls below a preset value.

The power excursion may be divided into three phases in our analysis. During the first phase, the power rises until the time when the core begins to boil. The reactor power change as well as the reactivity reduction due to Doppler reactivity feedback are followed in time using Eq.(25) and (21), starting with the initial conditions of Eq.(26). Phase 2 starts upon the inception of boilng at the center of the core , when the vapor pressure begins to build up causing material displacement. Eq.(18) is employed for estimating the disassembly reactivity feedback along with Eqs.(21)and (25). Depending on the magnitude of the initial reactivity insertion rate and the Doppler effect, the power excursion may be terminated either in Phase 2, by gradual dispersion of the fuel vapor or weak explosion , or progress to the next phase of the excursion, where the more severe disassembly should occur as the single-phase liquid core expands., for which Eq.(19) is to be utilized for obtaining the disassembly reactivity.

3. KALIMER Reactor Model

The KALIMER core system is designed to generate 392MWt of power. The reference core utilizes a heterogeneous core configuration with driver fuel and internal blanket zones alternately loaded in the radial direction. As shown in Figure 2, the core consists of 48 driver fuel assemblies, 18 internal blankets, 6 control rods, 1 ultimate shutdown system(USS) assembly self-actuated by a Curie point electromagnet, 6 gas

expansion modules(GEMs), and is surrounded by layers of 48 radial blanket assemblies, 48 reflector assemblies, 126 shield assemblies, and 54 in-vessel storage(IVS) of fuel assemblies, in an annular configuration. There are no upper or lower axial blankets surrounding the core. The reference core has an active core height of 120 cm and a radial equivalent diameter(including control rods) of 172 cm[10].

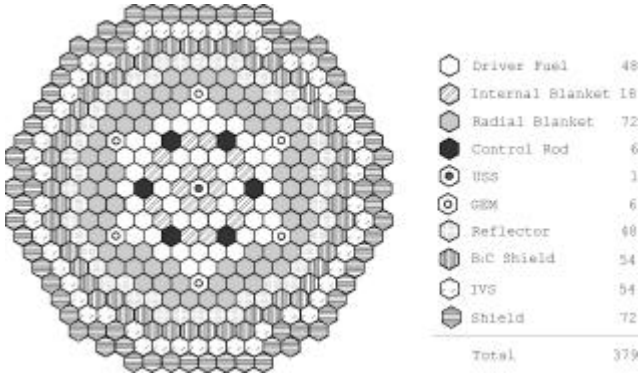

Fig. 2 KALIMER Core configuration

The driver fuel assembly includes 271 fuel pins. The fuel pins are made of sealed HT-9 tubing containing metal fuel slug of U-Pu-10%Zr in columns. The driver fuel and blanket have smeared densities of 75% and 85%, respectively. The power fractions for the driver fuel, inner blanket and radial blanket at the beginning of the equilibrium cycle (BOEC) are 0.773, 0.093 and 0.121, respectively. The power fractions of the internal blankets significantly increase with burnup and, consequently, the location of the peak linear power shifts from the inner driver fuel zone to the innermost internal blanket region. The peaking factor is close to 1.5, which provides a basis for using the power-shape factor q of 0.6 in this study. The peak linear power is 286.5 W/cm, which is equivalent to a specific power of about 60 W per gram of fuel. It is assumed ,as a base case of this study, that the hypothetical meltdown process involves the central 18 assemblies including 6 inner blankets and 12 inner driver fuel assemblies. Whole-core meltdown is also considered for completeness. Table1 lists the KALIMER reactor parameters used in this study for the base cases and whole- core meltdown cases as well.

Table 1. Reactor Parameters of KALIMER

Reactor Parameters	U-Pu-Zr Core	
	Base Case 18-Assemblies	Whole Core Case
Σ_{tr} $n\Sigma_f$	1.004×10^{-3}	1.030×10^{-3}
q	0.6	0.6
ℓ (sec)	2×10^{-7}	2×10^{-7}
b	0.035	0.035
b (cm)	49.7	77.8
Volume Fraction(%)		
Fuel Slug	32.16	29.75
Coolant	42.53	42.91
Structure	25.31	27.34
Core Density		
r_{hyd} (g/cm^3)	7.17	6.64
r_c (g/cm^3)	5.36	4.70
Fuel Loading(MT)	2.60	9.23

4. Analysis Results

A number of calculations have been performed to analyze the hypothetical super-prompt-critical power excursion of KALIMER for various Doppler constants as a function of reactivity insertion rates using the formalism described in the previous sections and the reactor parameters listed in Table 1. It is assumed in line with the Bethe-Tait model that the step reactivity equivalent to a ramp reactivity insertion is initially provided to drive the power excursion. Table 2 shows the results for the peak values of energy generation density and pressure for reactivity insertion rates in the range of 10 to 100 dollars per second, with three different values of Doppler constants considered; a_D = 0(no Doppler effect), –0.001 and –0.002. The results with the cases of a_D equal to –0.003 are not included in Table 2, because in no case does the energy density go beyond the boiling point of the core.

Table 2. Calculation of Energy, Pressures and Powers at the Core Center for Various Doppler Constants and Reactivity Insertion Rates

Ramp Rate ($/s)	k_{max} ($)	Doppler Constant(a_D)		
		0.0	- 0.001	-0.002
10	0.097	1.66 (1) 13.10 (2) 4.93 (3)	0.67 0.001 1.19	0.48 0.001 1.09
20	0.145	1.92 28.56 5.55	0.90 0.063 1.30	0.57 0.001 1.13
30	0.184	2.08 38.12 6.00	1.08 0.248 1.41	0.65 0.001 1.18
40	0.217	2.20 45.40 6.34	1.23 0.855 1.63	0.72 0.001 1.21
50	0.246	2.30 51.43 6.65	1.36 2.18 1.63	0.79 0.001 1.24
60	0.273	2.39 56.66 6.90	1.47 4.36 1.74	0.86 0.045 1.28
80	0.321	2.54 65.60 7.31	1.66 13.39 1.99	0.98 0.115 1.34
100	0.363	2.67 73.25 7.65	1.83 23.36 2.25	1.10 0.30 1.41

Note: (1) the first line of each column lists energy density in KJ/g at the peak location of the core, and
(2) second line shows peak-spot pressure in Kbar,
(3) third line showing the ratio of maximum power to the initial power at prompt critical

A few observations can be made from Table 2 as follows; Without the Doppler effect considered, the excursions are terminated, regardless of the reactivity insertion rates assumed in this study, with fairly large energy releases of 1.66 to 2.67 KJ/g accompanying strong pressure rises(in the range of a few tens of thousands atmosphere)for quite a short time, with the core in the single-phase liquid region. The power typically rises a few times of the initial value and rapidly drops down below the order of 10^{-5} of the initial value in one or two hundred microseconds, once the core disassembly starts to work, as can be seen in Fig.3. As with the Bethe-Tait method, the results of the magnitudes of pressure and energy release are weakly dependent on the reactivity inserted.

We can also see from the table the significant influences of the Doppler effect on the

power excursion, even with a low value of the Doppler constant. The effects are more pronounced with the excursions initiated by low rates of reactivity insertion. The peak powers are considerably reduced near to the level of the initial values and pressure rises dramatically drop down. For the Doppler constant of -0.002 taken as the reference value for KALIMER in this study , the power excursions are terminated even before the core reaches the assumed energy density of the boiling point(0.8KJ/g) for reactivity insertion rates up to 50 $/s. The reactor would shutdown without any significant energy release.

With the reactivity insertion rates assumed above 50$/s, the energy densities at the peak location of the core go over the boiling point but stays well below the threshold value of the solid liquid region, which is assumed 1.44KJ/g in this study. Only the peak spot of the core would boil, whereas most area of the core would be in the pre-boiling liquid state. The power initially increases by up to 20-40 % of the initial value and gradually decreases due to the Doppler feedback, before the peak location of the core boils. As the fuel vapor generated there fill some of the voids left out of sodium coolant, the pressure gradually rises, while the power continues to be in decline under the influence of Doppler feedback. The core dispersion would be then with the fuel of low energy density driven by much lower pressure acting for much longer times, the extent of which depends on the specific reactivity insertion rates.

Figures 3 and 4 compare the influence of Doppler reactivity feedback on the increase of normalized power and energy generation density, respectively, during the excursions initiated by the reactivity insertion rate of 100$/s. We can see that , as the magnitude of the Doppler constant gets larger, the longer the excursion lasts and both the power rise and energy generation density decrease. In case of the Doppler constant –0.002,. power excursion is terminated by a gradual fuel dispersion or a mild explosion, with an energy generation density of 1.10 KJ/g and a pressure of 300 atm. At the core center. The total energy release is estimated to be 1,840 MJ for the base case. Considering that

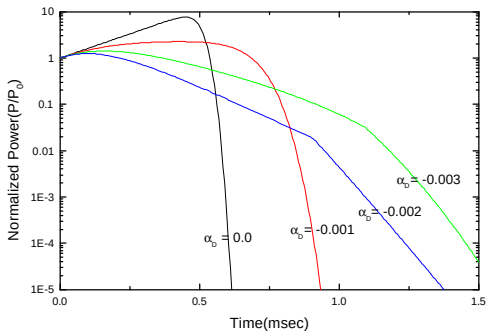

Fig.3 Power changes for 100$/s Ramp Reactivity Insertion Rates

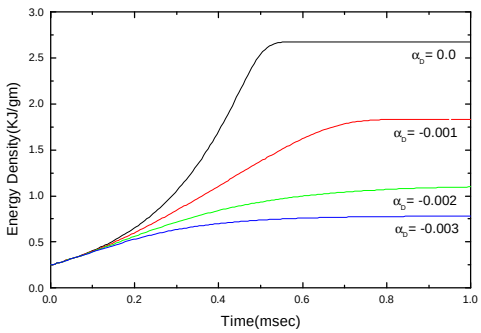

Fig.4 Energy-Density Rise for 100$/s Reactivity Insertion Rates

the thermal energy converted into the work energy is in the range of a few per cent for a isentropic expansion of fuel vapor to 1 atmosphere, the maximum work energy available for mechanical damage is expected far less than 500 MJ, the design limit of the reactor vessel of KALIMER. Even in the case of whole-core meltdown , the work energy is expected to be below the design limit of the reactor vessel.

A limited scope of parametric studies was also performed to investigate the

sensitivity of the results of our study. Power(or energy) shape factor, q ,is among the reactor parameters which considerably affect the results of power excursions. The smaller the value of q, the flatter the power distribution will be and ,hence, resulting in a higher energy release. With the value of q assumed to be 0.3, reduced by half from the reference value 0.6, the energy density at the core center resulted in 1.22 KJ/g. The peak-spot energy density increases by only about 10%, but the total energy by 40% or so from the base case. Other reactor parameters do not greatly affect the observations made above on the results of our study.

4. Conclusions

In this study, a simple methodology was developed to investigate the core kinetics and hydraulic behavior during the super-prompt critical power excursion induced by the ramp reactivity insertion, starting at the time that the sodium-voided core reaches the melting temperature of the metallic fuels. The equations of state of the pressure-energy density relationship were derived for the saturated- vapor as well as the solid liquid of metallic uranium fuel, and implemented into the formulations of the disassembly reactivity. Mathematical formulations were then developed, in the framework of the Modified Bethe-Tait method , in a form relevant to utilize the improved equations of state as well as to consider the Doppler effects. Using the numerical program developed, scoping analyses were performed for the KALIMER core behavior during super-prompt critical excursions induced by various reactivity insertion rates up to 100 $/s, which are considered the upper limit of ramp rates due to fuel compaction.

Significant influences of the Doppler effect on the power excursion were confirmed, particularly with that initiated by the lower rates of reactivity insertion. Without the Doppler effect, the excursions are terminated, regardless of the assumed reactivity rates, with fairly large energy releases accompanying strong pressure rises for quite a short time, with the core in the single-phase liquid region. . The peak powers are considerably reduced near to the level of the initial values and pressure rises dramatically drop down. For the Doppler constant of -0.002 taken as the reference value for KALIMER in this study , the power excursions are terminated even before the core reaches the assumed energy density of the boiling point(0.8KJ/g) for reactivity insertion rates up to 50 $/s. With the reactivity insertion rates above 50$/s, the energy densities at the peak location of the core go over the boiling point but stays well below the threshold value of the solid liquid region. In the upper-limit case of the 100$/s reactivity insertion rate, the power excursion is terminated by a gradual fuel dispersion or mild explosion over the extended duration, with the core center remaining at an energy density of 1.1 KJ/g

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References

1. H.A.Bethe, J.H. Tate, ” An Estimate of the Order of Magnitude of the Explosion when the Core of a Fast Reactor Collapses”, UKAEA-RHM(56)/113., 1956

2. W.J McCarthy,.R.B.Nicholson, D.Okrent, V.J. Jankus, “Studies of Nuclear Accidents in Fast Power Reactors,” *Proceedings of Second UN Int’ l. Conf. on Peaceful Uses of Atomic Energy*, A/CONF.15/P/2165, New York, 1958
3. V.J. Jankus, “A Theoretical Study of Destructive Nuclear Bursts in Fast Power Reactors,” AN L-6512.,1962
4. R.B.Nicholson, “Methods for Determining the Energy Release in Hypothetical Fast-Reactor Meltdown Accidents”, *Nucl. Sci. and Eng*., 18, 207-219 ., 1964
5. E.P..Hicks, D.C.Menzies,” Theoretical Studies on the Fast Reactor Maximum Accident,” *Proceedings of a Conference on Safety, Fuels, and Core Design in Large Fast Power Reactors*, ANL-7120, 654-670, 1965
6. B.Wolfe, N.Friedman, D.Riley,” Influence of the Doppler Effect on the Meltdown Accident,” *Proceedings of a Conference on Breeding, Economics and Safety in Large Fast Power Reactors*, ANL-6792, 171-192., 1963
7. J.E. Wilkins, “The Behavior of a Reactor at Prompt Critical when the Reactivity is a Linear Function of Time, *Nucl. Sci. and Eng*.,5, 207.,1959
8. R.H Brout, “Equation of State and Heat Content of Uranium”, USAEC Report APDA-118, Atomic Power Development Associates, Inc. ., 1957
9. E.G. Rauh, R.J. Thorn, “ The Vapor Pressure of Uranium,” *J. of Chem.Phys*., 22, 1414.,1954
10. Y.I Kim., “KALIMER Equilibrium Core Conceptual Design and Analysis,” LMR/CD120-ER-01,KAERI(1999)