Proceedings of the Korean Nuclear Society Fall Meeting
Yongpyung, Korea, October 2003

Analysis of Mechanical Work Energy For Fuel-Sodium Interaction During A Core Disruptive Accident in KALIMER

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Abstract

Sodium expansion analysis was carried out in this study using the finite heat transfer model for a typical initial condition of a core disruptive accident. It was assumed for conservatism that no sodium is present in the core at the time of core disassembly, which provides a basis for determining the initial condition for our work energy analysis. In this scoping analysis, the two-phase mixture of vapor and droplets of molten fuels is assumed to be ejected from the core and expands in a single bubble constrained by the inertia of the sodium pool above the core. The fuel is assumed to be mixed with some amount of sodium remaining in the core or more possibly from the surrounding pool, and comes to a temperature equilibrium without heat loss from the fuel-sodium mixture. Scoping calculations with a modified Bethe-Tait method were carried out to provide the initial thermodynamic conditions for these analyses. It was shown that resulting values of the work potential for the design basis case of power excursion were less than the structural design criteria for the reactor system of KALIMER.

1. Introduction

A simple method was established in this study to determine the maximum theoretical work energy resulting from a two-phase expansion of sodium during a super-prompt critical power excursion in KALIMER(Korea Advanced Liquid Metal Reactor). The work energy resulting from the high pressures generated in core disruptive accidents(CDAs) in liquid metal fast reactor can cause structural damage of various parts of the primary system. To preclude unacceptable consequences in KALIMER, a conservative estimate of the CDA work energy has been made using a series of scoping approaches in this study. This study is part of the CDA analysis work to demonstrate the inherent and ultimate safety of the conceptual design of KALIMER, a 150 Mwe pool-type sodium cooled prototype fast reactor that uses U-Pu-Zr metallic fuel[1].

The analysis taken in this study has been performed in a two-step process; core disassembly analysis and mechanical damage evaluation. The disassembly phase analysis involves a calculation of the core neutronics and thermal behavior during a super-prompt critical excursion utilizing a modified Bethe-Tait model[2,3], where spherical core is treated as a homogeneous fluid so that the material motion during disassembly can be calculated using a hydrodynamic approach. During or following reactor disassembly, the thermal energy released in the power excursion can be

converted to mechanical work that can cause the damage to the system. It had been assumed in earlier studies that the work would be done by the expanding fuel materials in the sodium-voided core. It was however noted later on that the transfer of heat from the high temperature fuel to the sodium above the core might substantially increase the potential work since the sodium is more efficient expansion fluid than the fuel.

Historically the sodium expansion models have been divided arbitrarily into thermodynamic models and finite heat transfer models. The thermodynamic models are characterized by the assumption that the rate of heat transfer is either infinite or zero during the sodium expansion[4]. Consequently the expansion of the sodium is independent of the system geometry and can be calculated from the thermodynamic principles. In the finite heat transfer rate models, the rate of heat transfer is determined by the conduction in the fuel and sodium and geometrical constraints are utilized to determine the time available for heat transfer[5]. In this study, work potentials were calculated for sodium expansion using the SOCOOL-II code[6], in which the rate of heat transfer is calculated by conduction in the fuel and sodium and geometrical constraints are considered to determine the time available for heat transfer.

2. KALIMER Core Configuration

KALIMER is a 150 MWe pool-type sodium cooled prototype reactor that uses metallic U-TRU-Zr alloy, which brings potential benefits over oxide fuel in improved inherent safety, reduced burdens of nuclear waste, and unique proliferation resistance. The 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 1, the core consists of 54 driver fuel assemblies, 24 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, 54 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.

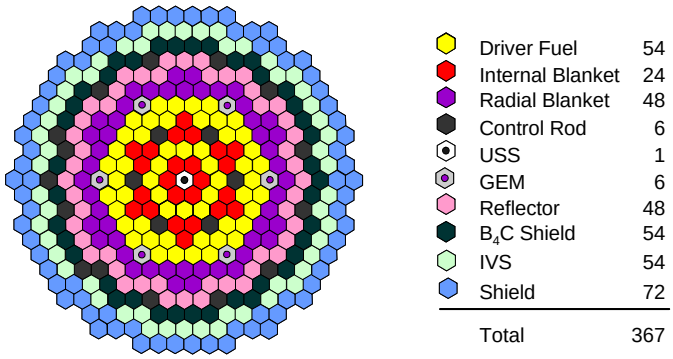

Figure 1. KALIMER Core configuration

The reference core has an active core height of 100 cm and the physically outermost core diameter of all the assemblies is 337.3 cm. The core structural material is HT9 ferretic martenstic steel[1]. It is assumed in this study that all of 54 driver fuel assemblies and 24 internal blankets, where a total amount of 8.4 MTU of U-Pu-Zr are loaded, melts down forming a sphere of an equivalent radius of about 80 cm. The sphere is assumed to consist of pure molten uranium metal fuels in this study.

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[7].

The fuel temperature (Doppler) coefficients are evaluated for the 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. The Doppler coefficient does not show any substantial change with burnup. Taking into account some uncertainty with the correlation for the Doppler coefficients, –0.002 is taken as the best-estimate value of the Doppler constant for the subsequent analyses for the sake of conservatism.

3. Core Disassembly Analysis

At the time of initiation of a super-prompt critical accident, the core is assumed to be in molten state and the energy content of the core is therefore taken to be 0.25 KJ/g, the internal energy needed to heat uranium from room temperature to the melting point(1,400 K). The boiling temperature of the core is set at around 4,100 K and the corresponding energy at 0.8 KJ/g. The specific heat of metallic fuel is assumed to be close to 0.2 J/g-K just above the melting point and assumed to stay constant beyond. The pressure-temperature relation was converted to that of pressure and energy density, which was then curve-fitted to a fourth-order polynomial, $p = \sum_{i=0}^{4} B_i E^i$. Meanwhile, for the single-phase liquid region, an equation of state is developed in a linear threshold type. The use is made of the equation-of-state data calculated by Brout for the uranium density of 10.0 g/cm^3,.which is close to the density of the sodium-voided core of the KALIMER.

Analysis results of core disassembly accidents are listed in Table 1, including the peak values of the energy generation density, temperature and pressure for various reactivity insertion rates. Energy densities and temperatures averaged over the core arte also listed. Given the maximum energy or temperature at the peak location of the

core, we can find out the average temperature of the mixture T_{avg}, using the relationship,

$$T_{avg} = T_0 + \frac{1}{c_p}(Q_{avg} - Q_0) \quad (1)$$

where

$$Q_{avg} = Q_{\max}[1 - 0.6(1 - \frac{Q_0}{Q_{\max}})] \quad (2)$$

Here

Q_{avg} = average energy density of the fuel mixture

$Q_{\max}$ =maximum energy density of the core

Q_0 = fuel melting energy(0.25 kJ/g)

T_0 = fuel melting temperature(1,450 K)

Table 1. Results of Energy, Temperature and Pressure

Ramp Rate ($/s)	Peak Values at Core Center			Core Average Values	
	Energy Density (KJ/g)	Temperature (K)	Gauge Pressure (Kbar)	Energy Density (KJ/g)	Temperature (K)
10	0.48	2,600	0.0	0.31	1,740
20	0.58	3,100	0.0	0.37	2,060
50	0.80	4,200	0.0	0.51	2,760
100	1.10	5,700	0.36	0.70	3,720
150	1.40	7,200	2.80	0.90	5,100
200	1.64	8,400	11.9	1.05	6,700

The Doppler constant of -0.002 was taken as the reference value for KALIMER in this study. For reactivity insertion rates up to 50 $/s, the power excursions are terminated even before the core reaches the assumed energy density of the boiling point (0.8KJ/g). And the reactor would shutdown without any significant pressure rise or energy release. In the case of the reactivity insertion rate of 100$/s, which has been traditionally set as the upper limit of the ramp rate, the energy density at the peak location of the core goes over the boiling point and stays around the threshold value of the solid liquid region(1.10 KJ/g). The corresponding temperature is about 5,700 K at the peak location of the core. The average temperature of the core fuel is estimated to be about 3,700 K, which is below the fuel boiling temperature. The central part of the core would boil, whereas the outer area of the core would be in the pre-boiling liquid state. As the fuel vapor generated at the peak spot of the core fills some of the voids left out of the sodium coolant, the pressure gradually rises, while the power continues to be in decline under the influence of the Doppler feedback effect. When the reactivity insertion rate is increased further beyond 100 $/s, the core peak pressure, temperature and energy builds up very rapidly.

4. Sodium Expansion Work Energy

Both the heat transfer from the fuel to the sodium and the motion of the expanding sodium are time-dependent processes. In the SOCOOL-II mode, it is assumed that fuel particles are instantaneously and uniformly dispersed in a mixing region surrounded by unheated liquid region. The expanding sodium in the mixing zone is constrained by the surrounding region like the sodium pool above the core resulting in high pressure, which suppress normal boiling. There is no heat transfer between these two regions [5,6].

The constraint of the mixing zone is modeled in two stages, an acoustic constraint followed by an inertial constraint. If the time for heat transfer is small compared to the acoustic period, which is the time for a pressure wave to travel to the nearest free surface and back, the unheated liquid assumed to be compressible and the region is considered to be under acoustic constraint. The vaporization can take place only when sufficient expansion relieves the high pressures generated by the rapid heating or if a rarefaction wave suddenly reduces the pressure in the mixing region below the saturation pressure corresponding to the temperature of the heated liquid. For the acoustic constraint time domain, the expansion of the system can be approximated by one-dimensional acoustic equation,

$$p(t) - p_0 = \rho_0 c_0 \frac{dZ}{dt} \tag{3}$$

where p is the system pressure, Z is the height of the mixing region, and p_0, ρ_0, and c_0 are the initial values of pressure, density, and sonic velocity in the constraining sodium.

For times which are large compared to the acoustic period of the heated region, the mixing region can be assumed to be under inertial restraint. The unheated liquid can be assumed to be incompressible and the expansion of the system can be determined using Newton's law of motion,

$$p(t) - p_0 = \rho_0 L \frac{d^2 Z}{dt^2} \tag{4}$$

where L is the height of the sodium being accelerated above the mixing zone, p_0 is the pressure in the cover gas over the sodium.

The rate of heat transfer is determined by considering a single spherical fuel particle concentrically surrounded by sodium. The parabolic heat conduction equation in spherical coordinate r with internal heat generation Q''',

$$\rho c_p \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r}\right) + Q''' \tag{5}$$

is solved using an implicit numerical technique assuming the thermal resistance at the fuel-sodium interface is negligible.

The rate of pressure increase is obtained by the relationship,

$$\frac{dp}{dt} = \gamma_V \frac{dT}{dt} - \frac{1}{\beta_T V}\frac{dV}{dT} \tag{6}$$

where

$\gamma_V = (\frac{\partial p}{\partial T})$ = thermal pressure constant

$\beta_T = -\frac{1}{V}(\frac{\partial V}{\partial p})$ = isothermal compressibility

The rate of temperature increase, *dT/dt* is calculated from the heat conduction equation in the above and the rate of volume increase, *dV/dt* is calculated from one-dimensional acoustic equation, Eq.(3).

In the SOCOOL-II code[6], the acoustic work is first calculated by integrating the pressure-volume curve until vaporization conditions are attained either by gradual expansion (until the pressure in the heated liquid becomes less than the saturation pressure), or when the time becomes equal to the acoustic period and the rarefaction wave reflected from the free surface returns to the heated region. The inertial work is then calculated from an adiabatic expansion of the superheated sodium assuming that there is no further heat transfer from the fuel. The heat transfer rate and the expansion work calculated by SOCOOL-II code are strongly affected by the fuel droplet size. The rate of heat transfer is determined by considering a single spherical fuel particle concentrically surrounded by sodium. For uranium metal fuel, mean particle diameter of the fragmented fuel in sodium is known to be in the order of 10.0 mm, while it is in the range of 0.1 to 1.0 mm. The thermal equilibrium case like Hicks and Menzies model corresponds to a droplet size of zero.

Table 2 shows the work energy densities per unit mass of fuel for the fuel particle diameters of 0.1 cm, 0.5 cm and 1.0 cm, respectively, as a function of sodium mass fraction during the thermal interaction of the liquid fuel at 3,700 K with sodium at 800 K. It can be seen that, as the fuel diameter gets larger, the work energy potentials rapidly decrease and are saturated with a lesser amount of sodium per unit mass of fuel. For the reference case of the fuel particle diameter of 1.0 cm, work energy reaches its maximum 10.7 J/g of fuel when the mass of sodium per unit mass of fuel is 0.06.

Since the total mass of the reference core is about 8.4 MT, the total energy release amounts to approximately 90 MJ. The peak values of work potential increase to 220 MJ as the fuel diameter decreases to 0.5 cm. These values are far less than the structural design criteria for the KALIMER reactor system, which is set at 500 MJ. It may be noted that, for the case of the fuel diameter of 0.1cm, the SOCOOL-II code predicts approximately the same value of work energy as that calculated by the zero-heat-transfer thermodynamic model (i.e., modified Hicks and Menzies method).

Table 2. Sodium Expansion Work Energy Densities

Sodium Mass per Unit Mass of Fuel	Mean Diameter of Fuel Particles (cm)			Thermodynamic Models	
	1.0	0.5	0.1	Zero Heat Transfer Model	Infinite Heat Transfer Model
0.02	6.12	11.39	33.24	18.68	107.9
0.04	8.26	16.76	52.04	32.28	153.5
0.06	10.7	21.11	66.67	42.37	161.6
0.08	6.78	24.35	76.30	49.94	154.0
0.10	4.17	25.93	84.17	55.69	148.5
0.12	2.10	21.76	89.50	60.08	143.5
0.20	0.65	9.07	92.50	69.49	127.4

5. Conclusion

Scoping studies to estimate the mechanical work energy arising from the expansion of sodium during the super-prompt critical power excursion in KALIMER was made using a set of simple methods. For the reactivity insertion rate of 100$/s, which has been set as the upper limit of the ramp rate in this study, mechanical work energy densities were calculated for the fuel-sodium thermal interaction, using the finite heat transfer rate model for a typical initial condition of a core disruptive accident. The finite heat transfer model predicted work energy less than the structural design criteria, for representative fuel particle sizes. For instance, the total amount of work energy generated is about 90 MJ for the fuel diameter of 10 mm. The energy density at the peak location of the core goes over the boiling point and stays around the threshold value of the solid liquid region(1.10 KJ/g). The corresponding temperature is about 5,700 K at the peak location of the core. The average temperature of the core fuel is estimated to be about 3,700 K, which is below the fuel boiling temperature. The central part of the core would boil, whereas the outer area of the core would be in the pre-boiling liquid state.

Acknowledgement

This work was performed under ‘the Long-Term Nuclear Energy Research and Development Program‘ sponsored by the Ministry of Science and Technology of the Republic of Korea.

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