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Consequences of Core Meltdown Accidents in a Medium-Sized Liquid Metal Reactor Design

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Abstract

Work energy generated by the thermal interaction of molten fuel with the sodium in the pool above the reactor core was estimated for a typical initial condition of core disruptive accidents in a medium-sized KALIMER design. Work potentials arising from sodium expansion were calculated using the SWEEP computer code, in which scoping calculations with a modified Bethe-Tait method are first carried out to provide the initial thermodynamic conditions for the subsequent thermodynamic analyses of fuel/sodium interaction. It was shown that resulting values of the work potential for the reference case of power excursion were less than the structural design criteria for the reactor system of KALIMER.

1. Introduction

A design concept of the medium-sized KALIMER, a 600 Mwe pool-type sodium cooled prototype fast reactor that uses U-TRU-Zr metallic fuel, has been developed over the past year[1]. As part of the CDA analysis work to demonstrate the inherent and ultimate safety of the core design, an effort was made to evaluate work energy arising from two-phase expansion of sodium during core disruptive accidents. A simple method was utilized 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. 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.

The SWEEP computer code[2] was developed in this study to evaluate the work energy arising from two-phase expansion of fuel or sodium during core disruptive accidents in liquid metal reactors. In the SWEEP program, scoping calculations with a modified Bethe-Tait method is first carried out in the SCHAMBETA module[3] to provide the initial thermodynamic conditions for the subsequent analyses to estimate the mechanical work energy generated in the reactor system. To estimate the work energy due to fuel-vapor expansion, a bounding approach is adopted to calculate the work potential assuming isentropic expansion to atmospheric pressure during super-prompt critical power excursions in the FXWEEP module. Work potentials are also calculated

in the SXWEEP module of the SWEEP code for sodium expansion using the simple thermodynamic models including the infinite heat transfer model during expansion(Hicks and Menzies method) or more realistic zero heat transfer model for a typical initial condition of core disruptive accident.

Calculations of the thermal energy generated during excursions in the sodium-voided core of the 600 MWe KALIMER were performed using the SCHAMBETA module for the reactivity insertion rate of 100 $/s, which has been traditionally set as the upper limit of ramp rate. Since the Doppler constant of the reference core is relatively large, the average temperature of the core fuel is estimated to be below the fuel boiling temperature at the completion of the core disruptive accidents. Work potentials were consequently calculated for sodium expansion using the zero heat transfer model for a typical initial condition of core disruptive accident.

2. KALIMER Core Configuration

The KALIMER core system evaluated in this study is a breakeven core designed to generate 1,589 MWt of power. The reference core is a homogeneous, metal alloy fuel design with 703 assemblies: 102 inner driver fuel assemblies, 126 middle driver fuel assemblies, 108 outer dirver fuel assemblies, 12 control rods, 1 ultimate shutdown system (USS) assembly, 72 reflector assemblies, 78 B_4C shield assemblies, 90 shield assemblies, and 114 in-vessel storages (IVSs). In this design, the blanket assemblies are completely removed in the core so as to exclude the production of the weapon-grade plutonium. This configuration is shown in Figure 1.

Table1 shows the overall core design parameters. The core is designed to produce 1589.3 MWt with an average temperature rise of 143.8 ^oC. The inlet temperature is 366.2 ^oC and the bulk outlet temperature is 510.0 ^oC. The active core height is 100.0 cm and there are no blankets in the core. The core structural material is HT9. This ferritic stainless steel is chosen to minimize swelling associated with long fuel burnups.

The fuel form is U-TRU-10%Zr ternary alloy. The duct pitch is 16.21 cm. The driver fuel assembly includes 267 fuel pins and 4 moderator pins. The moderator pins are used to reduce the coolant void reactivity worth by softening the core neutron spectrum. The driver fuel has smeared density of 75 %. At equilibrium, the design basis refueling interval follows 18 months of operation at 85 % capacity factor, with one-third of the driver fuel assemblies, being replaced during each outage. The fuel assemblies are not shuffled, but remain in position for the entire cycles. Following removal from the core, they decay for one operating cycle in the IVS positions.

Reactivity control for normal operations of startup, load following and shutdown is accomplished by bank (uniform) movement of the control rod system in the driver fuel region of the core. The control rod system consists of four identical culsters. Each control rod units are identical in design and consist of an array of tubes containing B_4C. The control rod clusters are designed so that each control cluster has a rapid reactor shutdown capability at a rod drop signal as well as for the four control clusters

consisting of tweleve control rods to be operated simultaneously for normal operation control. Each control rod unit provides two diverse scram methods; a gravity-driven rop drop and a powered drive-in. The control rod design satisfies both the one rod stuck condition and the unit control rod worth condition against the unprotected transient over power (UTOP) event. Positive reactivity addition by inadvertent withdrawal of the control rods is limited by the rod stop system.

An ultimate shutdown system (USS) is included as a means to bring the reactor to cold critical conditions in the event of a complete failure of the normal scram system and after the inherent reactivity feedbacks have brought the core to a safe, but critical state at an elevated temperature. For this purpose an USS is located in the core center which drops neutron absorber by gravity[1].

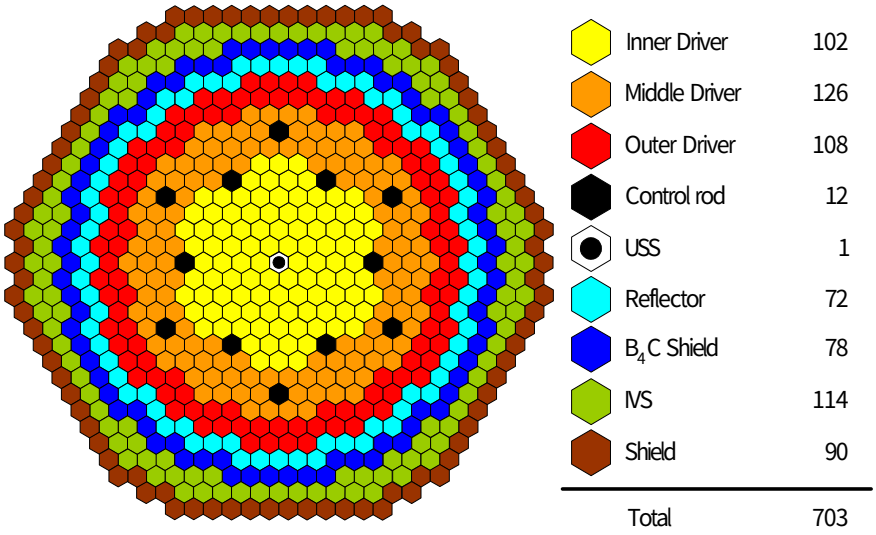

Figure 1. KALIMER Breakeven Core Configuration

Table 1. Core Design Parameters

Core Design Parameters	
] Core Thermal Power (MWt)	1589.3
Core Electric Power (MWwe)	600
Core Configuration	Homogeneous
Number of Core Enrichment Zones	3
Active Core Height (cm)	100.0
Maximum Core Diameter (cm)	471.5
Axial Blanket Thickness (cm)	None
Feed Fuel Composition	LMR Recycled
Number of Assemblies	
Inner Driver Fuel	102
Middle Driver Fuel	126
Outer Driver Fuel	108
Reflector	72
GEM	None
Control Rod	12
USS (SASS)	1
B_4C/Radial Shield	78/90
IVS	114
Total	703
Core Mixed Mean Inlet/Outlet Temperature (^{o}c)	366.2/ 510.0
Plant Capacity Factor (%)	85.0
Refueling Interval (months)	18
Effective Full Power Day (EFPD)	465
Fuel /Moderator Material	U-TRU-10Zr/ZrH_2
Smeared Density (%)	75
Active Fuel Length (cm)	100.0
Fuel Element Length (cm)	366.8
Overall Assembly Length (cm)	462.2
Duct Pitch (mm)	162.1
Duct Gap (mm)	4.0
Duct Wall Thickness (mm)	3.7
Pins per Fuel Assembly (Fuel/Moderator)	267/4
Pin Outer Diameter (mm)	7.60

3. Analysis Methods and Results

3.1 Initial Conditions and Assumptions for Core Disassembly Analysis

The core is assumed to be initially at prompt critical in molten state. Initial energy content of the core, Q_0, is therefore taken to be 0.25 KJ/g, the internal energy to heat uranium from room temperature to the melting point(1,400 K). The boiling temperature of the core is set at around 4,500 K and the corresponding energy Q_b 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[4].

Another initial condition to specify is $k_{\max}$, amount of step reactivity equivalent to the total reactivity inserted by the ramp during the excursion. In addition to what are given in the above, we need the power at the prompt critical state, $\dot{Q}(0)$. A simple formula for $\dot{Q}(0)$, brought by introducing the 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 without reactivity feedback[12] ;

$$\dot{Q}(0) = \dot{Q}_{ss} \left(\frac{\pi\beta}{2a\ell}\right)^{1/2}. \quad (1)$$

where β is the delayed neutron fraction, ℓ is the prompt neutron lifetime. In this study, β is taken to be 0.0035, ℓ is 2.0E-07, and $\dot{Q}_{ss}$ is assumed 60 W/g for the reference core of the medium-sized KALIMER.

The fuel temperature (Doppler) coefficients were evaluated for the sodium-flooded cases. It is estimated to vary as $-0.005T^{-0.90}$ for the BOEC case, whereas it varies as $0.0046T^{-0.90}$ in the case of EOEC core. The Doppler coefficient does not show any substantial change with burnup. Taking into account some uncertainty with the correlation for the Doppler coefficients, –0.005 is taken as the best-estimate value of the Doppler constant for the subsequent analyses for the sake of conservatism.

A vapor pressure equation for uranium is given as,

$$\log p = 5.702 - \left(\frac{23{,}300}{\mathrm{T}}\right). \quad (2)$$

where pressure is in atmosphere and temperature in K. This equation has been shown to provide the vapor pressure in reasonable accuracy from the melting point to the critical point. We need an expression relating pressure to energy rather than to temperature. Assuming 0.1J/g-K as a reference value of the specific heat of the vaporized uranium core, the pressure-temperature relation was converted to that of pressure and energy density, which was then curve-fitted to a fourth-order polynomial ,

$$p = \sum_{i=0}^{4} B_i E^i \quad (3)$$

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

$B_3 = -8.182 \times 10^3$, $B_4 = 2.416 \times 10^3$ (4)

where the pressure is measured in MPa and the liquid energy in KJ/g.

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 9.92g/cm^3, which is close to the density of the sodium-voided core of the KALIMER. The result of our fitting is

$$p = 11{,}000(E - 1.10) \quad (5)$$

where the pressure is measured in MPa and the liquid energy in kJ/g[4].

3.2. Thermodynamic Analysis Method for Sodium Expansion Work

The thermodynamic models are characterized by the assumption that the rate of heat transfer is either infinite (Hicks and Menzies model)[5] or zero (modified Hicks and Menzies method) [6] during the sodium expansion. Consequently the expansion of the sodium is independent of the system geometry and can be calculated from thermodynamic principles. The Hicks & Menzies model is a two-step process. First, fuel and sodium are mixed and heat is instantaneously transferred from molten fuel to liquid sodium until thermal equilibrium is reached. In the second step, the sodium vaporizes and expands doing *pdV* works on surroundings. Throughout the expanding process, heat transfer from the fuel to the sodium is assumed to continue so that the mixture of the two remains in thermal equilibrium. This assumption results in a bounding estimate of the thermal efficiency of the process of converting heat to work by sodium vaporization.

The assumption made in the above that the rate of heat transfer from molten fuel to sodium is infinite becomes less valid in the later stages of the sodium expansion, when the sodium vapor generated would significantly reduce the rate of heat transfer. It is assumed in the modified Hicks and Menzies method that the rate of heat transfer is negligible after the initial thermal equilibrium between the fuel and sodium. For this approach, the terms corresponding to the fuel in the expansion phase are omitted[6].

Assuming that the liquid phase of the sodium is incompressible and of negligible specific volume compared with the vapor phase, and that sodium vapor is an ideal gas, the work done per unit mass of fuel during the adiabatic expansion is given by,

$$W = mc_{Na}(T_0 - T) - \chi(h_{fg} - RT) \quad (6)$$

where m is the mass of sodium interacting with the fuel, c_{Na} the specific heats of liquid sodium, T_0 the initial equilibrium temperature of the mixture, χ mass of sodium vapor, h_{fg} the latent heat of vaporization of sodium, and R is the gas constant per unit mass of sodium. The specific and latent heats are assumed to be constant. The initial equilibrium temperature of the mixture is given by

$$T_0 = \frac{c_f T_f + mc_{Na} T_{Na}}{c_f + mc_{Na}} \quad (7)$$

where C_f is the specific heats of fuel. A mass m of sodium at absolute temperature T_{Na} is assumed to mix intimately with unit mass of fuel at temperature T_f and that

thermodynamic equilibrium is established instantaneously.

The results in the above are not valid once all the sodium is vaporized. That is, they hold up until χ reaches sodium mass fraction *m* during the expansion. During the further adiabatic expansion of the mixture, the appropriate adiabatic relation is given by

$$mR\ln[\frac{p(T_v)}{p}] = mc_{p,g}\ln(\frac{T_v}{T}) \quad (8)$$

where $c_{p,g}$ is the constant-pressure specific heat of sodium vapor and T_v is the temperature of sodium vapor when χ reaches sodium mass fraction *m*. The additional work done is

$$W_v = mc_{v,g}(T_v - T) \quad (9)$$

where $c_{v,g}$ is the constant volume specific heat of sodium.

Thermodynamic properties of the fuel and sodium are assumed to be constant over the expansion process. Parametric values used in the calculations are as follows: c_f = 0.2 J/g.K, c_{Na} =1.2 J/g.K, $c_{p,g}$ = 0.9 J/g.K, h_{fg} = 40 kJ,*R* = 0.33 J/g.K. A vapor pressure equation for sodium is given by [5]

$$\log p = 4,521 - \frac{5,220}{T} \quad (10)$$

where pressure is in atmosphere and temperature in K.

3.3 Analysis approach and results

To calculate the work energy during the expansion of the fuel-sodium mixture, we need to know the initial temperatures of the fuel and sodium as well as the thermodynamic properties of them. It is assumed 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 from the surrounding pool, and come to temperature equilibrium without heat loss from the fuel-sodium mixture.

To determine the initial temperature of the mixture using Equation (7), we use a whole core average fuel temperature for T_f, which is determined from preceding analysis of core disruptive accidents. The average sodium temperature of the pool is taken to be 800 K, which is used as the value of T_{Na} in this study. The SCHAMBETA code predicts that the energy density and temperature at the peak location of the core for the reactivity insertion rate specified as an input to it. To calculate the work energy arising from expansion of the two-phase fuel mixture, we need to know its average temperature. 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

$$T_{avg} = T_b + \frac{1}{c_p}(Q_{avg} - Q_b) \quad (11)$$

where

$$Q_{avg} = Q_{\max}[1 - 0.6(1 - \frac{Q_b}{Q_{\max}})] \quad (12)$$

Here

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

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

Q_b = fuel vaporization energy(0.8 kJ/g)

T_b = fuel boiling temperature(4,100 K)

Table 2 lists the values of average temperatures of the reference core at the completion of the core disassembly and subsequent sodium expansion work energies for a set of given values of the reactivity insertion rates with different values of Doppler constants.

Table 2. Core average temperature and Work energy densities

Doppler Constant / Ramp Rate($/s)	-0.002	-0.003	-0.005
50	2,710 K 33.5 J/g	2,120 K 13.7 J/g	1,710 K 3.9 J/g
100	3,720 K 80.4 J/g	2,690 K 32.3 J/g	**2,000 K** **10.6 J/g**

We can see in the table that the average temperature of the fuel in the core decreases with the increase of magnitude of Doppler constants and so does the value of sodium-expansion work energy density. In case of the reference ramp rate and Doppler constant, that is 100 $/s ramp rate with Doppler constant -0.005, the average fuel temperature is estimated to be around 2,000 K. When this fuel interacts with the sodium in the pool above the core, 10.6 J of work energy per gram of fuel can be generated at maximum. Since the total mass of the reference breakeven core is about 36 MT, the total energy release amounts to the maximum of approximately 380 MJ. This value is less than the structural design criteria for the KALIMER reactor system, which is set at 500 MJ. It must be noted that these values are based on the assumption that the mixture of fuel and sodium expands down to the final pressure of 1 atm. Under realistic accident conditions, the final pressure would be expected to be greater than 1 atm

Figure 1 compares work potentials per unit mass of fuel as a function of sodium mass fraction for the thermal interaction of the liquid fuel at 2,000 K with sodium at 800 K, for two different values of Doppler constant. In the reference case of Doppler constant (-0.005), the work done first increases to the maximum value of about 10.6 J/g of fuel at the sodium mass fraction of around 0.06 and then decreases, as the sodium mass

fraction increases. We can see in the figure the similar trend with the case of lower magnitude of Doppler constant. The initial increase is due to the formation of an increasing volume of sodium vapor. The later decrease is due to the quenching effect of the sodium; the loss of energy in heating liquid sodium.

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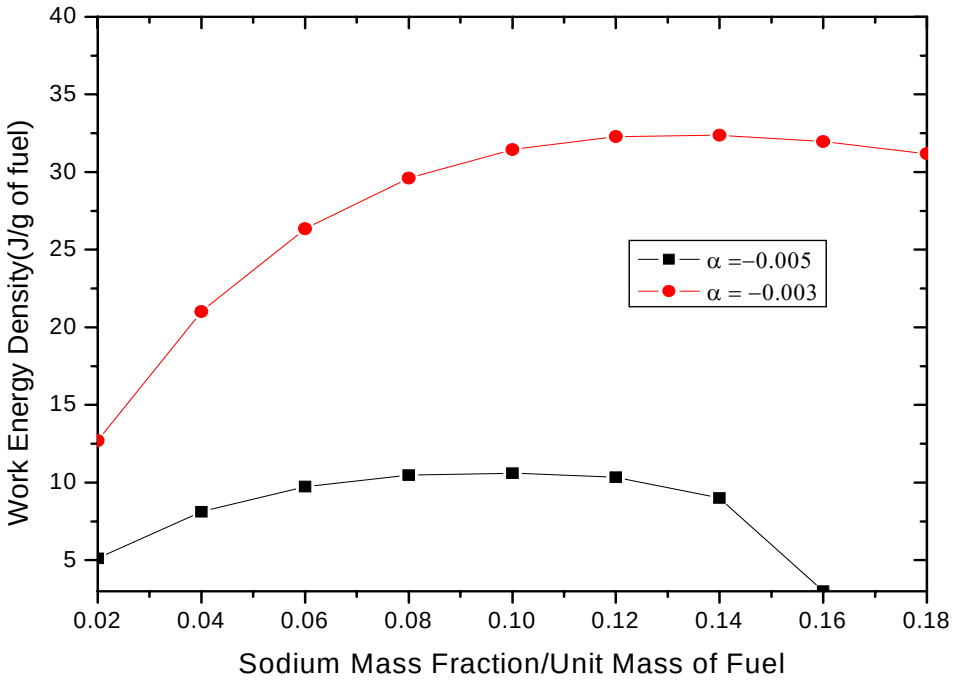

Figure 1. Work energy densities as function of sodium mass fraction for two different values of Doppler constants (Ramp rate=100 $/s, Sodium temperature= 800 K)

5. Conclusion

Mechanical work energy arising from sodium expansion was calculated for a typical initial condition of core disruptive accident using the SWEEP code, in which a modified Bethe-Tait model and the zero heat transfer thermodynamic model are employed. Results show that, work potential reaches the maximum value of about 10.6 J/g of fuel at the sodium mass fraction of around 0.06, for the thermal interaction of the liquid fuel at 2,000 K with sodium at 800 K. The total energy release amounts to the maximum of approximately 380 MJ. This value is less than the structural design criteria for the KALIMER reactor system, which is set at 500 MJ.

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