

## **Analysis of Fuel/Sodium Expansion Work Energy during Core Disruptive Accidents in KALIMER**

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### **Abstract**

Scoping analyses were carried out in this study to evaluate work energy arising from the two-phase expansion of fuel or sodium during core disruptive accidents in KALIMER, a 150 MWe pool-type sodium cooled prototype fast reactor that uses U-TRU-Zr metallic fuel. A bounding approach was adopted to calculate the work potential assuming isentropic fuel vapor expansion to atmospheric pressure during super-prompt critical power excursions. Work potentials for sodium expansion were also calculated for theoretically possible thermal interaction of molten fuel with the sodium remaining in the core or present in the pool above, using the finite heat transfer rate model as well as the simple thermodynamic models for a typical initial condition of a core disruptive accident. Scoping calculations with a modified Bethe-Tait method were carried out to give rise to the initial thermodynamic conditions for this analysis. It was shown that the resulting values of the work potential for the design basis case of power excursion were comparable to or 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], where spherical core is treated as a homogeneous fluid so that the material motion during disassembly can be calculated using a hydrodynamic approach. Calculations of the

thermal energy generated during excursions in the sodium-voided core of the KALIMER were subsequently performed for various reactivity insertion rates up to a few hundred dollars per second. The case of reactivity insertion rate of 100\$/s, which has been traditionally set as the upper limit of ramp rate, was taken as the reference case in this study[3,4].

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 a more efficient expansion fluid than the fuel. In this study, the work done by the expanding fuel vapor was first estimated using a bounding approach, in which the maximum theoretical  $PdV$  work is computed assuming that the two-phase fuel mixture of the initial core isentropically expands down to a final pressure of one atmosphere.

Work potentials were also calculated for sodium expansion using the simple thermodynamic models including the Hicks and Menzies method[5] and more realistic zero heat transfer model for a typical initial condition of core disruptive accident[6]. Sodium expansion analysis was also carried out using the SOCOOL-II code, 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. 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 temperature equilibrium without heat loss from the fuel-sodium mixture.

## 2. Core Disassembly Analysis

### 2.1 Reactor Model

It is assumed that the power excursion begins with the reactor at 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 ,

$$\frac{d^2Q(t)}{dt^2} = \frac{k(t)-1-\beta}{l} \frac{dQ}{dt} \quad (1)$$

where  $Q(t)$  is the time dependence of the energy generation density. The other quantities in Eq. (1) are expressed in standard notation;  $k$  for multiplication constant,  $l$  for prompt neutron lifetime, and  $\beta$  delayed neutron fraction.

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

$$k(t) = k_0 + k_I(t) + k_d(t) + k_D(t) \quad (2)$$

where  $k_0$  is the initial multiplication constant,  $k_I(t)$  is the reactivity insertion responsible for initiating the excursion,  $k_d(t)$  is the reactivity feedback resulting from

material displacement during the disassembly process, and  $k_D(t)$  is the feedback from Doppler effect[4].

The rate of reactivity insertion initiating the excursion is assumed constant and  $k_I(t)$  may be written as;  $k_I(t) = [dk/dt]t = \alpha t$ . It is assumed that the step reactivity, equivalent to the total reactivity inserted by the ramp during the excursion, is initially introduced beyond prompt critical. The initial multiplication constant is then defined as  $k(0) = k_0 + k_I(t_1) = 1 + \beta + \alpha t_1$  (3)

It is assumed that  $t_1$  comes when the fuel boiling occurs at the peak power location of the core.

The time rate of change of reactivity due to the Doppler effect can be expressed as 
$$\frac{dk_D}{dt} = -\left(\frac{dk_D}{dT}\right)_{T_0} \left(\frac{T_0}{T}\right)^n \frac{dT}{dt}$$
 (4)

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  $n^{\text{th}}$  power of the temperature  $T$ , measured from absolute zero.

Applying the first-order perturbation theory to the one group diffusion equation for a spherical reactor, the second derivative in time of the reactivity feedback due to material displacement is given in a form,

$$\frac{d^2 k_d}{dt^2} = F(q) \int p dV$$
 (5)

where  $F$  is function of power shape factor  $q$  and other reactor parameters. It is assumed that the density in the hydrodynamic equations is constant in time, and that the flux can be approximated by a parabola in the core ;  $\Phi = 1 - q(r^2/b^2)$ , where  $b$  is the core radius.

We can see that  $\ddot{k}_d$  is proportional to the pressure integrated over the volume of the core. The pressure-energy relations for the core during the power excursion are among the key parameters to be provided for the core disassembly process. At the initiation of the super-prompt critical excursion, liquid uranium is assumed 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 begins to rise rapidly thereupon. In this context, therefore, the equations of state of pressure-energy density relationship are derived in this study for the saturated-vapor as well as the single-phase liquid of metallic uranium fuel.

A vapor pressure equation for uranium is given by Raugh and Thorn [4] as,

$$\log p = 5.702 - \left(\frac{23,300}{T}\right).$$
 (6)

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. Assuming 0.2J/g-K as a reference value of the specific heat of the molten 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. 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  $9.92\text{g/cm}^3$ , which is close to the density of the sodium-voided core of the KALIMER. The equations of state developed in the above can be plugged in to Eq.(5) to obtain the expressions for the disassembly reactivity.

Initial energy content  $Q(0)$ , initial power level  $\dot{Q}(0)$ , and  $k(0)$  are the initial conditions to be specified for a set of the coupled equations in the above to have a unique solution. The core is assumed to be initially at prompt critical in the molten state. Initial energy content of the core is therefore taken to be 0.25 KJ/g, the internal energy to heat uranium from room temperature to the melting point(1,450 K). The boiling temperature of the core is set at around 4,200 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 that. The initial multiplication constant is defined in Eq.(3). 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 about by introducing the reactivity at the constant rate of dollars per second to an initially delayed critical reactor of the power level may be derived by solving the one-group point kinetics equations without reactivity feedback.

## 2.2 Analysis Results

Analysis results of core disassembly accidents are listed in Table 1, including the peak values of energy generation density, temperature and pressure for various reactivity insertion rates. 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 reactor would shutdown without any significant pressure rise or energy release.

Table 1. Results of Energy, Temperature and Pressure at the center of KALIMER core

Ramp Rate (\$/s)	Peak Values at Core Center		
	Energy Density (KJ/g)	Temperature (K)	Gauge Pressure (Kbar)
10	0.48	2,600	0.0
20	0.58	3,100	0.0
50	0.80	4,200	0.0
100	1.10	5,700	0.36
150	1.40	7,200	2.80
200	1.64	8,400	11.9

In case of reactivity insertion rate of 100 $\$/s$ , which has been traditionally set as the upper limit of 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. When reactivity insertion rate is increased further beyond 100 \$/s, the core peak pressure, temperature and energy builds up very rapidly[4].

### 3. Fuel Expansion Work Energy

#### 3.1 Analysis Methods

To estimate the work done by the expanding fuel vapor, it is assumed that the coolant has been expelled from the reactor core, and two-phase fuel mixture of droplets and vapor are in thermal equilibrium with one another. The destructive work is then produced by the isentropic(i.e., adiabatic and reversible) expansion of this two-phase mixture to a lower pressure. The expansion would cease after the sodium above the core impacted the closure head of the reactor vessel and the fuel bubble filled all the space left by the rising sodium and strained vessel.

An approximate calculation can be made by assuming that the entire core is at the core average temperature at the completion of core disassembly. A simple expression can be derived in terms of the variables(temperature and quality) at the initial and final states of isentropic fuel expansion by making the following approximation ; the fuel vapor acts as a perfect gas, and fuel properties such as heat of vaporization and specific heat for liquid fuel remain constant over the expansion process.

The initial quality can be expressed in terms of initial values of specific volume for the two-phase mixtures, the saturated vapor and liquid. The value of specific volume for the two-phase mixture can be estimated by assuming that the total fuel mass is uniformly dispersed over the core volume. If coolant or structural material remains in the core, the volume of the core is reduced to include only the fuel volume plus any free volume within the core not occupied by the other materials. The quality at the completion of fuel expansion can be determined once the initial and final temperatures of the fuel mixture are known. The final temperature of the fuel mixture can be determined from Eq.(6), once the final pressure is known.

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 by the core disassembly analysis performed in Section 3.3, we can find out the average temperature of the mixture  $T_{avg}$  , using the relationship

$$T_{avg} = T_0 + \frac{1}{c_p} [Q_{max} (1 - 0.6q) - Q_0] \quad (7)$$

Here

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

$Q_0$  = fuel melting energy(0.25 kJ/g)

$T_0$  = fuel melting temperature(1,450 K)

$C_p$  = 0.2 J/g.K

### 3.2 Analysis Results

Table 2 lists the values of peak energy densities, temperatures of the two-phase mixtures averaged over the core, for a set of ramp rates. Also included in the table are fuel expansion work energy densities and total work energy..

Table 2. Initial Core Temperature and Work Energy

Ramp Rate (\$/s)	Peak Energy (KJ/g)	Average Temperature(K)	Work Energy (J/g)	Total Work (MJ)
50	0.80	2,760	0	0
100	1.10	3,720	22	57
150	1.40	5.100	37	310
200	1.64	6,700	158	1,350

We can see in the table that, for the reference case of reactivity insertion rate at 100 \$/s, the core average temperature remains at 3,720 K, which is below the fuel boiling point( 0.8 KJ/g or 4,150 K). Only the central 30 % of the core is estimated to boil, whereas the rest of the core is in the pre-boiling liquid state. Consequently the total amount of work energy generated remains insignificant for the reference case. It may be noted in the table that for the reactivity insertion rate of more than 150 \$/s is required to release work energy corresponding to the structural design criteria for the reactor system of the KALIMER, which is set at 500 MJ.

In the above, the work potential was evaluated using a single temperature, which is averaged over the whole core or the boiling part of it. The actual condition during disassembly and subsequent expansion of fuel is a distribution of temperatures with the hottest temperature at the core center. If each mesh cell of fuel volume is independently expanded to the final as in “multipacket method” , the work potential may be significantly greater than if the entire core were completely mixed to obtain a uniform temperature prior to expansion as assumed in this paper. The extent of significance would depend on the degree of fuel mixing expected to occur prior to or during fuel vapor expansion, which is not well known.

The most conservative approach to the evaluation of work potential would be to use the peak temperature of the fuel in the core. For the reference case of reactivity insertion rate at 100 \$/s, the peak temperature of the core is about 5, 700 K, as can be seen in Table 1. If this peak temperature is used as the representative fuel temperature of the core, the work potential would be about 630 MJ for the reference case, which is a bit greater than the structural design criteria of the reactor system of the KALIMER.

In reality, however, fuel vapor is likely to lose a significant part of its energy to the surrounding medium by radiation and other heat transfer mechanisms during expansion. The actual value of the work energy released would be far lower than the values computed in the above

## 4. SODIUM EXPANSION WORK ENERGY

At the end of the nuclear disassembly phase, the fuel expands and may come into contact with the sodium coolant remaining in the core or that present in the pool above the core. If a substantial amount of energy can be rapidly transferred from the molten fuel to the sodium, much higher mechanical work energies can be obtained because the sodium is a 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 (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. In the finite heat transfer rate models as used in SOCOOL-II code[7], the rate of heat transfer is determined by conduction in the fuel and sodium and geometrical constraints are utilized to determine the time available for heat transfer.

### 4.1 Thermodynamic Model Analyses

#### 4.1.1 Analysis Methods

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 the 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.

Suppose that a mass  $m$  of sodium at absolute temperature  $T_{Na}$  mixes intimately with unit mass of fuel at temperature  $T_f$  and that thermodynamic equilibrium is established instantaneously. Assuming no phase change during the initial mixing process and constant specific heats, the initial equilibrium temperature of the mixture is given by

$$T_0 = \frac{c_f T_f + m c_{Na} T_{Na}}{c_f + m c_{Na}} \quad (8)$$

where  $C_f$  and  $C_{Na}$  are the specific heats of fuel and liquid sodium, respectively. It is supposed then that the mixture begins to expand adiabatically, remaining in thermodynamic equilibrium throughout the expansion. The fuel transfers its heat to the sodium and is always at the same temperature as the sodium. The mixture is assumed to be made up of unit mass of fuel, mass  $\chi$  of sodium vapor, and mass  $m - \chi$  of liquid sodium.

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,

$$W = (c_f + mc_{Na})(T_0 - T) - \chi(h_{fg} - RT) \quad (9)$$

where  $h_{fg}$  is the latent heat of vaporization of sodium,  $R$  is the gas constant per unit mass of sodium, and the specific and latent heats are assumed to be constant. An auxiliary relationship for  $\chi$  can be derived in a simple form, 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 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 approach 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 in the above are omitted[6].

#### 4.1.2 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. To determine the initial temperature  $T_f$  of the mixture in Eq.(8), we use a whole core average fuel temperature from preceding analyses of core disruptive accidents. For the design-base case of reactivity insertion rate of 100 \$/s, the average temperature is about 3,700 K. The average sodium temperature,  $T_{Na}$ , is taken to be 800 K, which is close to the hot pool temperature of KALIMER.

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

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

where pressure is in atmosphere and temperature in K.

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 3,700 K with sodium at 800 K. Hicks and Menzies model predicts that, as the sodium mass fraction increases, the work done sharply increases to the maximum value of about 220 J/g of fuel at the sodium mass fraction of around 0.06 and then decreases. 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. In the mean time, the application of more realistic finite heat transfer model results in gradual increase to the maximum work potential of about 80 J/g at the sodium mass fraction of 0.16, which corresponds to the total amount of energy release of about 670 MJ. This value is somewhat larger than the structural design criteria for the KALIMER reactor system.



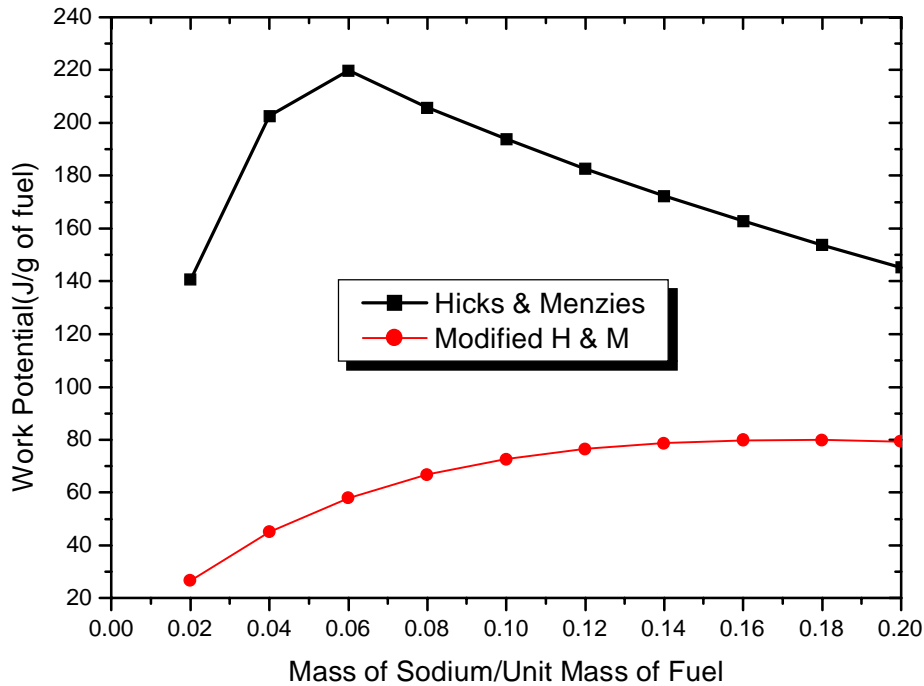


Figure 1. Sodium-Expansion Work Potentials(Fuel Temperature=3,700K, Sodium Temperature=800K)

## 4.2. Finite Heat Transfer Rate Model

### 4.2.1 Analysis Methods

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 [6,7].

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,

$$p(t) - p_0 = \rho_0 c_0 \frac{dZ}{dt} \quad (11)$$

where  $p$  is the system pressure,  $Z$  is the height of the mixing region, and  $p_0$ ,  $\rho_0$ , 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,

$$p(t) - p_0 = \rho_0 L \frac{d^2 Z}{dt^2} \quad (12)$$

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 is solved in spherical coordinate with internal heat generation, 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,

$$\frac{dp}{dt} = \gamma_v \frac{dT}{dt} - \frac{1}{\beta_T V} \frac{dV}{dT} \quad (13)$$

where

$$\gamma_v = \left( \frac{\partial p}{\partial T} \right) = \text{thermal pressure constant}$$

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

The rate of temperature increase,  $dT/dt$  is calculated from the heat conduction equation and the rate of volume increase,  $dV/dt$  is calculated from one-dimensional acoustic equation, Eq.(11).

#### 4.2..2 Analysis approach and results

In the SOCOOL-II code, the acoustic work is first calculated by integrating under 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 10  $\mu$ m, whereas it is in the range of 0.1 to 1 mm for oxide fuel. The

thermal equilibrium case like Hicks and Menzies model corresponds to a droplet size of zero.

Figure 2 shows the work potential per unit mass of fuel for the fuel particle diameters of 0.1 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 go down and are saturated with less amount of sodium per unit mass of fuel. In case of fuel particle diameter 1.0 cm, work energy reaches its maximum to 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 500 MJ, which is the structural design criteria for the KALIMER reactor system.

It may be noted that, for the case of fuel diameter 0.1cm, SOCOOL-II code predicts approximately same value of the work energy as that calculated by the zero-heat-transfer thermodynamic model (i.e., modified Hicks and Menzies method).

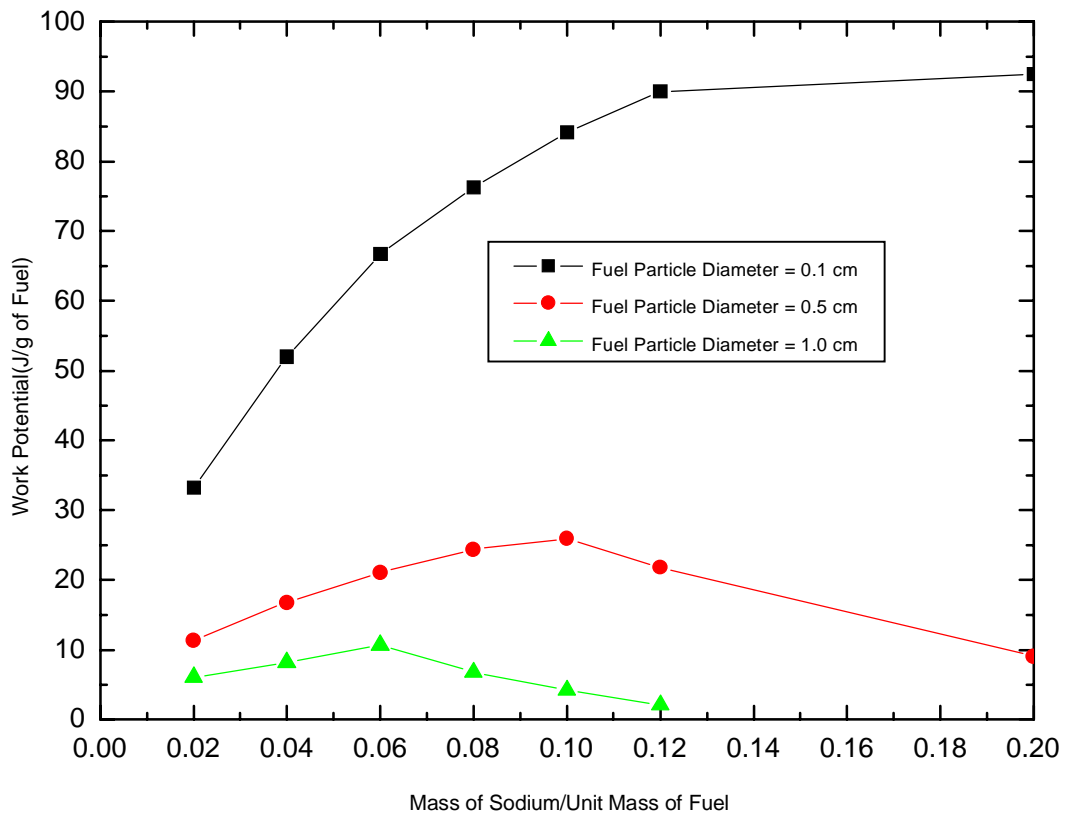


Figure 2. Sodium-Expansion Work Potentials (Fuel temperature=3,700K, Sodium Temperature=800K)

## 5. Conclusion

Scoping studies to estimate of the work energy arising from the expansion of two-phase fuel or sodium during the design basis power excursion in KALIMER was made using a set of simple methods. The work done by the expanding fuel vapor was estimated using a bounding approach, in which the maximum theoretical  $PdV$  work is computed assuming that the two-phase fuel which is thermally mixed expands isentropically down to a final pressure of one atmosphere. For the reference case of reactivity insertion rate at 100 \$/s, the core average temperature remains below the fuel boiling point( 0.8 KJ/g or 4,150 K)and consequently work energy generated remains insignificant. It was estimated that reactivity insertion rate of more than 150 \$/s is required to release work energy equivalent to the structural design criteria of the reactor system of KALIMER(500 MJ).

Work potentials were also calculated for sodium expansion in this study, using the finite heat transfer rate model as well as the simple thermodynamic models including the Hicks and Menzies method and more realistic zero heat transfer model for a typical initial condition of core disruptive accident.. The finite heat transfer model predicted work energy far less than the structural design criteria, for a representative fuel particle sizes. In the mean time, the thermodynamic models predict the peak energy releases somewhat higher than the structural design criteria. For instance, the modified Hicks and Menzies method (zero heat transfer model ) predicts the work potential of about 670 MJ at maximum. The actual values of the total energy release would be less than these values, since the amount of fuel dispersed above the core, which depends on the design detail of the reactor structure, would be quite limited. Also the mixture of fuel and sodium vapor is likely to lose a significant part of its energy to the surrounding medium by radiation and other heat transfer mechanisms during expansion

## 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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