

Analysis of Sodium Expansion Work Energy during Core Disruptive Accidents in KALIMER

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Abstract

An effort was made in this study to evaluate work energy arising from two-phase expansion of sodium during core disruptive accidents in KALIMER. Work potentials were calculated for sodium expansion using the simple thermodynamic models including the infinite heat transfer model during expansion(Hicks and Menzies method) and more realistic zero heat transfer model for a typical initial condition of core disruptive accident. 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. Scoping calculations with a modified Bethe-Tait method were carried out to have available 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 a bit higher than but close to 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. The reactor power is calculated using point kinetics with first-order perturbation theory to estimate the

reactivity feedback associated with the material motion. Modifications were made to the original method mainly in the use of a more realistic equation of state of the fuel. 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. A computer code SCHAMBETA was then developed in a form relevant to utilize the improved equations of state[3].

Analysis of the behavior of the sodium-voided core of the KALIMER during the super prompt-critical excursions was performed for various reactivity insertion rates up to 100 \$/s, using the SCHAMBETA code developed in this study. Calculations of the thermal energy generated during excursions in the sodium-voided core of the KALIMER were subsequently performed using the scoping code for various reactivity insertion rates up to 100 \$/s, which has been traditionally set as the upper limit of ramp rate. For the case of reactivity insertion rate of 100\$/s, the energy density at the peak location of the core goes over the boiling point and stays around 1.10 KJ/g , which corresponds to about 7,100 K. Central part of the core would boil, whereas 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 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[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 more efficient expansion fluid than the fuel. In this study, work potentials were 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[7], 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. Core Disassembly Analysis

2.1 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. The core consists of 48 driver fuel assemblies, 18 internal blankets, 6 control rods, 1 ultimate shutdown system(USS) assembly, 6 gas expansion modules (GEMs), and is surrounded by layers of radial blankets, reflectors, shield assemblies, and in-vessel storage 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 [1].

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 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. The fuel temperature (Doppler) coefficients are evaluated for sodium-flooded/voided cases. It is estimated to vary as $0.11 T^{-1.49}$ for the sodium-voided case, whereas it varies as $0.10 T^{-1.43}$ in the case of the sodium-flooded core. The Doppler coefficient does not show any substantial change with burnup[8].

2.2 Initial Conditions

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. 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, $p = \sum_{i=0}^4 B_i E^i$.

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/cm³, which is close to the density of the sodium-voided core of the KALIMER[4].

2.3 Analysis Results

The SCHAMBETA code predicts that the energy density at the peak location of the core goes over the boiling point and stays around 1.10 KJ/g for the design-base case of reactivity insertion rate of 100\$/s. The temperature reaches about 7,100 K at the peak location of the core. 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

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

where

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

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 1 lists the values of energy densities and temperatures of the two-phase mixtures averaged over the boiling regions of the core, for a set of given values of them at the core center.

Table 1. Initial Core Energy and Temperature

<u>Qmax(j/g)</u>	<u>Qavg(j/g)</u>	<u>Tmax(K)</u>	<u>Tavg(K)</u>
1000	880	6100	4900
1100	920	7100	5300
1200	960	8100	5700
1300	1000	9100	6100
1400	1040	10100	6500
1500	1080	11100	6900

We can see in the table that the average temperature of the fuel vapor mixture ranges from about 5,000 K to 7,000K for a range of values of energy density at the peak location of the core which may result at the time of the completion of core disruptive accidents. For the reference case, its value is about 5, 300 K.

3. Thermodynamic Analysis of Sodium Expansion Work

3.1. Analysis methods

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.

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

$$T_0 = \frac{c_f T_f + m c_{Na} T_{Na}}{c_f + m c_{Na}} \quad (3)$$

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. During the expansion, the sodium is the fluid that does work on the surroundings. 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 c of sodium vapor, and mass $m - c$ 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,

$$W = (c_f + m c_{Na})(T_0 - T) - c(h_{fg} - RT) \quad (4)$$

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.

For the work to be evaluated in Eq.(4), an auxiliary relationship for c must be derived. 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 adiabatic relation for the mixture can be written,

$$c = (c_f + m c_{Na}) \frac{T}{h_{fg}} \ln\left(\frac{T_0}{T}\right) \quad (5)$$

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

$$mR \ln\left[\frac{p(T_v)}{p}\right] = (c_f + m c_{p,g}) \ln\left(\frac{T_v}{T}\right) \quad (6)$$

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

$$W_v = (c_f + m c_{v,g})(T_v - T) \quad (7)$$

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

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 in the above, i.e., Eqs.(4),(5),(6), and (7) are omitted[6].

3.2 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. 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 in Eq.(3), we use a whole core average fuel temperature for T_f from preceding analysis of core disruptive accidents. The average sodium temperature of the pool is taken to be 1,150 K, which is used as the value of T_{Na} in this study. For the design-base case of reactivity insertion rate of 100 \$/s, the energy density at the peak location of the core goes over the boiling point and stays around 1.10 KJ/g. The temperature is about 7,100 K at the peak location of the core. Only the central part of the core would boil, whereas outer area of the core would be in the pre-boiling liquid state. Assuming that, at the final phase of super-prompt critical accidents, the core temperature remains just above the melting point (1,400 K and corresponding energy 0.25 J/kg) at around the core periphery, we can get the core average energy of 0.55 J/kg and corresponding temperature of about 3,000 K from Eqs. (1) and (2). It must be noted that, in these equations, the boiling temperature T_b of the core set at around 4,100 K and the corresponding energy Q_b of 0.8 KJ/g are replaced by the melting temperature and corresponding energy.

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]

$$\log p = 4,521 - \frac{5,220}{T} \quad (8)$$

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 3,100 K with sodium at 1,150 K). In accordance with Hicks and Menzies model, as the sodium mass fraction increases, the work done first increases to the maximum value (of about 160 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. With application of the modified approach, in the mean time, the work potential monotonically increases to about 72 J/g. The work potential is only 20 to 50 % that for the Hicks and Menzies method, depending on the sodium mass fractions.

Since the total mass of the reference breakeven core with the axial height 120 cm is about 8.4 MT, the total energy release amounts to the maximum of approximately 1,350 MJ with the use of Hicks and Menzies method. Using the modified method would result in the energy release of about 600 MJ at maximum. This value is slightly greater 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.

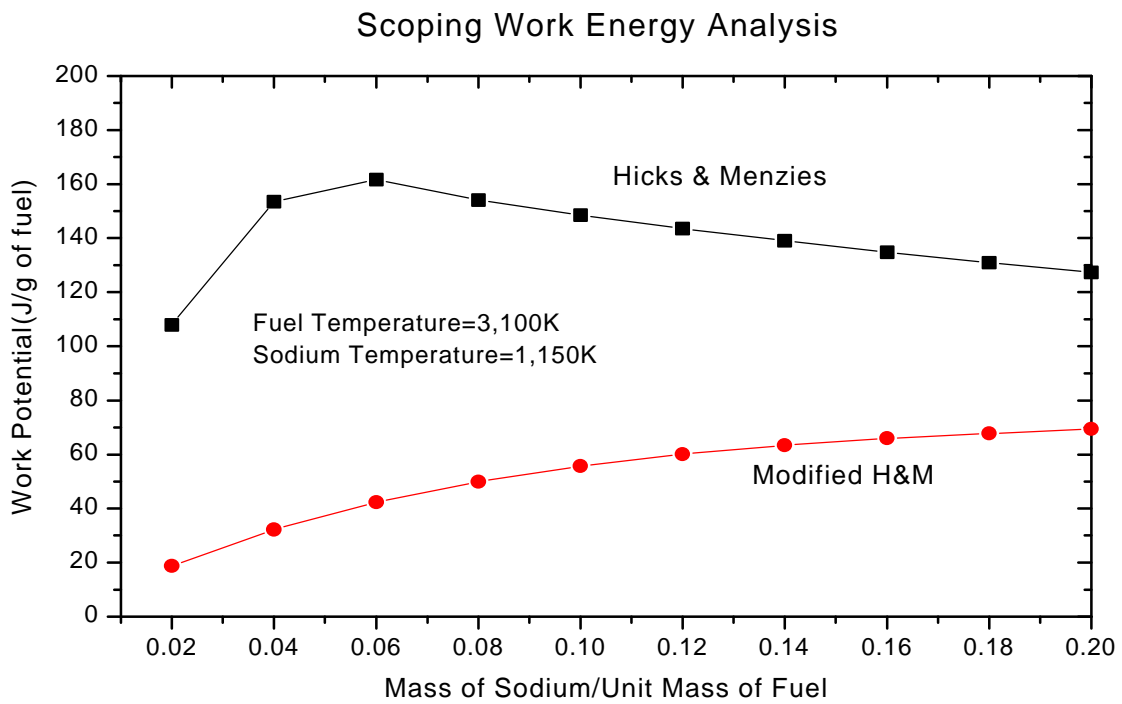


Figure 1. Comparison of Sodium-Expansion Work Potentials

4. SOCOOL-II analysis

4.1 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,

$$p(t) - p_0 = r_0 c_0 \frac{dZ}{dt} \quad (9)$$

where p is the system pressure, Z is the height of the mixing region, and p_0 , r_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,

$$p(t) - p_0 = r_0 L \frac{d^2 Z}{dt^2} \quad (10)$$

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''' ,

$$r c_p \frac{\partial T}{\partial t} = k \left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \right) + Q''' \quad (11)$$

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,

$$\frac{dp}{dt} = g_v \frac{dT}{dt} - \frac{1}{b_T V} \frac{dV}{dT} \quad (12)$$

where

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

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

The rate of temperature increase, dT/dt is calculated from the heat conduction equation in the above and the rate of volume increase, dV/dt is calculated from one-dimensional acoustic equation, Eq.(9).

4.2 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 dioxide fuel, mean particle diameter of the fragmented fuel in sodium is known to be in the order of 100 to 1,000 micrometers. 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 mm and 1.0 mm, respectively, as a function of sodium mass fraction during the thermal interaction of the liquid fuel at 3,100 K with sodium at 1,150 K. As the sodium mass fraction increases, the work potentials monotonically increase. It can be seen that the work energy gets large as the fuel diameter gets small. With the sodium mass fraction of around 10 %, which is the typical design value for the KALIMER core, work potentials are 53 J/g for the fuel diameter 1.0 mm and 85 J/g for the diameter 0.1 mm. These values of work energy are certainly less than 150 J/g, which is predicted by the Hicks and Menzies method. For the case of fuel diameter 1.0mm, SOCOOL-II code predicts approximately same value of the work energy as that calculated by the modified Hicks and Menzies method. It may be said that, for the fuel diameter 0.1 mm to 1.0 mm, the SOCOOL-II method predicts the work energy in the range between the Hicks and Menzies method (infinite heat transfer model) and the modified H & M method(finite heat transfer model) but more close to the latter one.

Since the total mass of the reference breakeven core with the axial height 120 cm is about 8.4 MT, the total energy release amounts to approximately 450 MJ for the case of fuel particle diameter 1.0 mm and 710 MJ for the diameter 0.1 mm, respectively. These

values are slightly smaller or greater than 500 MJ, which is the structural design criteria for the KALIMER reactor system.

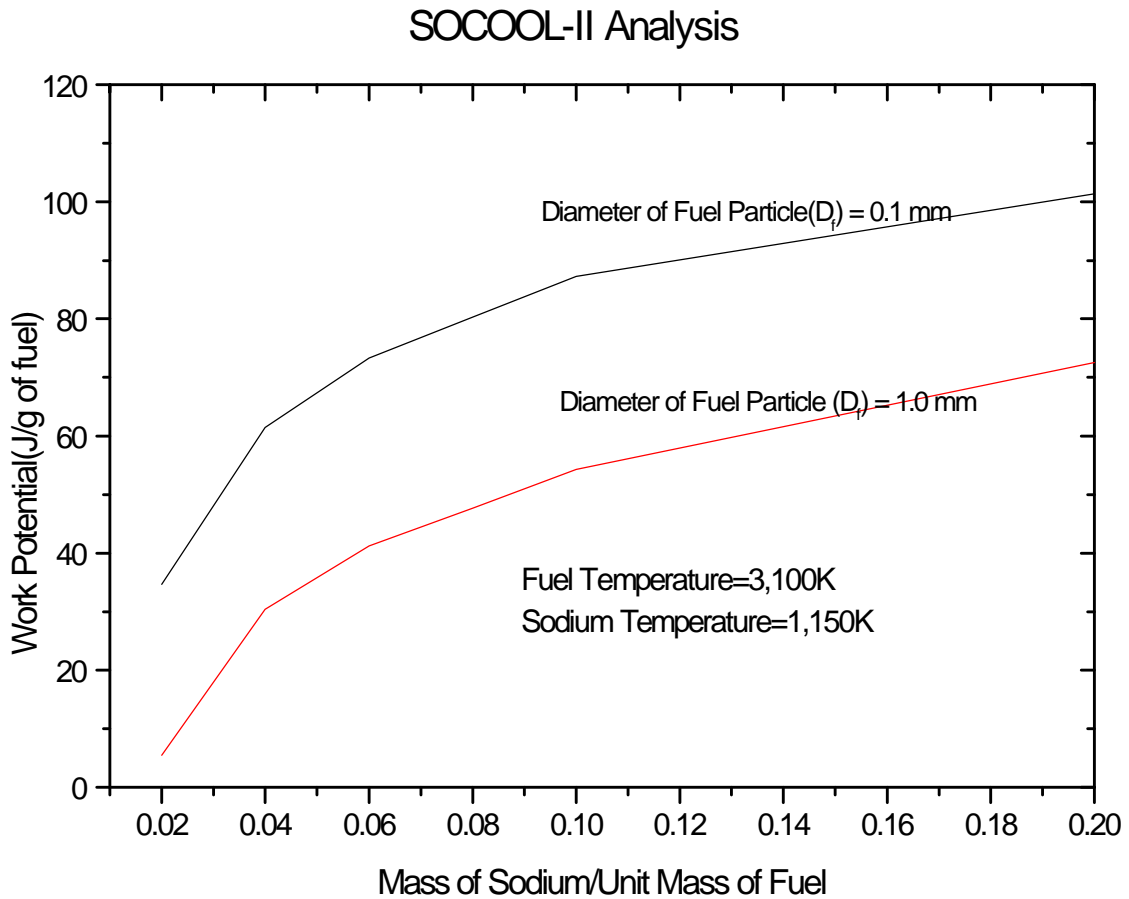


Figure 2. SOCOOL-II Analysis Results

5. Conclusion

Work potentials were calculated for sodium expansion using the Hicks and Menzies method (infinite heat transfer model) and more realistic zero heat transfer model for a typical initial condition of core disruptive accident. In accordance with the Hicks and Menzies method, work potential reaches the maximum value of about 160 J/g of fuel at the sodium mass fraction of around 0.06, for the thermal interaction of the liquid fuel at 3,100 K with sodium at 1,150 K and then decreases. In the mean time, the work potential monotonically increases to be saturated to about 72 J/g with the modified Hicks and Menzies method. The work potential is only 20 to 50 % that for the Hicks

and Menzies method, depending on the sodium mass fraction. The total energy release amounts to the maximum of approximately 1,350 MJ with the use of Hicks and Menzies method. Using the modified method would result in the energy release of about 600 MJ at maximum. This value is slightly greater than the structural design criteria for the KALIMER reactor system, which is set at 500 MJ.

Work energy arising from expanding sodium was also calculated using SOCOOL-II code, which deals with time-dependent finite heat transfer between the fuel particle and surrounding sodium. For the case of fuel diameter 1.0 mm, SOCOOL-II code predicts approximately same value of the work energy as that calculated by the modified Hicks and Menzies method. It may be said that, for the typical fuel diameter 0.1 mm to 1.0 mm, the SOCOOL-II method predicts the work energy in the range between the Hicks and Menzies method and the modified H & M method but more close to the latter one. The total energy release amounts to 450 MJ for the case of fuel particle diameter 1.0 mm and 710 MJ for the diameter 0.1 mm, respectively.. These values are rather close to 500 MJ, which is the structural design criteria for the KALIMER reactor system.

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