

## **Scoping Analysis of Fuel Vapor Expansion Work Energy in KALIMER**

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### **Abstract**

An effort was made in this study to evaluate work energy arising from fuel vapor expansion during core disruptive accidents in KALIMER. A bounding approach was adopted to calculate the work potential assuming isentropic fuel vapor expansion to atmospheric pressure during super-prompt critical power excursions. Scoping calculations with a modified Bethe-Tait method were carried out to have available the initial thermodynamic conditions for this analysis, such as core temperature and pressure. It was shown that resulting value of the work potential for the design basis case of power excursion was less than the structural design criteria for the reactor system of KALIMER.

### **1. Introduction**

The work energy resulting from the high pressures generated in core disruptive accidents may cause structural damage of various parts of reactor system. Deformation of reactor internals is most likely to occur. However, a more severe spectrum of accidents may lead to the lifting of the reactor vessel head or rupture of the vessel. To preclude such unacceptable consequences in KALIMER, a conservative estimate of the work energy from the design basis excursion is made using a bounding approach, in which the maximum theoretical  $PdV$  work is computed assuming that the two-phase fuel expands isentropically down to a final pressure of one atmosphere. This work energy may then be compared to the design basis value of 500 MJ for the structural strength of the reactor system[1]. In reality, the fuel vapor is likely to lose a significant part of its energy to the surrounding medium by radiation and other heat transfer mechanisms. It is also known that pressure inside the reactor vessel would be considerably higher than one atmosphere at the time of the bubble expansion process is complete.

In this study, a simple method was established to determine the maximum theoretical work energy for an expanding mixture of two-phase fuel resulting from the super-prompt critical power excursion in a sodium-voided core of KALIMER. This study is part of the core disruptive accident(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].

## 2 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,  $T_i$ , at the completion of core disassembly. A simple expression can be derived in terms of the variables at the initial and final states of isentropic fuel expansion by making the following approximations: the fuel vapor acts as a perfect gas; fuel properties such as heat of vaporization,  $h_{fg}$ , and specific heat for liquid fuel,  $c_p$ , remain constant over the expansion process. The work energy generated in the process of fuel expansion is then

$$W = M_F [c_p (T_i - T_f) - h_{fg} (c_f - c_i) + R (c_f T_f - c_i T_i)] \quad (1)$$

where  $M_F$  is the fuel mass expanded and  $R$  is the gas constant for the fuel, and  $c$ 's are the qualities for the fuel [2,3].

The initial quality  $c_i$  can be expressed in terms of initial values of specific volume

$$c_i = \frac{\mathbf{u}_i - \mathbf{u}_{l,i}}{\mathbf{u}_{g,i} - \mathbf{u}_{l,i}} \quad (2)$$

where  $\mathbf{u}_i$  is the specific volume of the two-phase mixtures;  $\mathbf{u}_{g,i}$  and  $\mathbf{u}_{l,i}$  are the saturated vapor and liquid specific volume of the fuel, respectively at the initial stage of the expansion. The value of  $\mathbf{u}_i$  can be estimated by assuming that the total fuel mass  $M_F$  is uniformly dispersed over the core volume  $V_c$ :

$$\mathbf{u}_i = \frac{V_c}{M_F} \quad (3)$$

If coolant or structural material remain in the core, the volume of  $V_c$  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 from the relation

$$c_f = c_i \frac{T_f}{T_i} + \frac{c_p T_f}{h_{fg}} \ln \frac{T_i}{T_f} \quad (4)$$

The final temperature of the fuel mixture,  $T_f$ , can be determined from the equation of state for pressure and temperature, once the final pressure is known. A vapor pressure equation for uranium is given by Raugh and Thorn [4],

$$\log p = 5.702 - \left( \frac{23,300}{T} \right) \quad (5)$$

where pressure is in atmosphere and temperature in K.

### 3 Analysis Results

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[5]. A vapor pressure equation for uranium is given Eq.(5). 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/cm<sup>3</sup>, which is close to the density of the sodium-voided core of the KALIMER.

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. 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. The core dispersion would be then with the fuel of low energy density driven by relatively low pressure.

To calculate the work energy arising from expansion of the two-phase fuel mixture, we need to know its mass and 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

$$T_{avg} = T_b + \frac{1}{c_p} (Q_{avg} - Q_b) \quad (6)$$

where

$$Q_{avg} = Q_{max} \left[ 1 - 0.6 \left( 1 - \frac{Q_b}{Q_{max}} \right) \right] \quad (7)$$

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. Taking this as a initial core temperature for fuel expansion down to one atmosphere and applying Eq.(1), we get the work energy density of about 48 j/g.

Mass of the two-phase fuel mixture to expand is given by

$$M_f = M_c \left[ \frac{Q_0 - Q_b}{qQ_0} \right] \quad (6)$$

where

$M_c$  = the mass of total fuel loading in the core(9.2MTU),

$Q_0$  = energy density at the core center

$Q_b$  = fuel vaporization energy(0.8 kJ/g)

q = power shape factor

Table 2 lists the values of the mass fraction of expanding fuel vapor for a range of energy densities at the core center with the value of q set as 0.6 in Eq.(6).Mass fraction of the two-phase fuel mixture is 0.455 for the reference case. Since the amount of total core fuel loading is 9.2 MTU in KALIMER, the mass of the mixture is then about 4.2 MTU. This gives the work potential of 200 MJ.

Figure 1 shows the work energy released as a function of final pressures for the design-basis case, where the two-phase fuel is initially of average temperature at 5,300 K. It can be noted that a substantial part of the work energy is released after relatively low pressure is reached.

**Table 2. Fuel Vapor Mass Fraction**

<u>Qmax(j/g)</u>	<u>Mf/ Mc</u>
1000	0.333333
1100	0.454545
1200	0.555556
1300	0.641026
1400	0.714286
1500	0.777778

#### **4. Conclusion**

A conservative estimate of the work energy arising from the design basis power excursion in KALIMER was made using a bounding approach, in which the maximum theoretical  $PdV$  work is computed assuming that the two-phase fuel expands isentropically down to a final pressure of one atmosphere. The resulting value of the maximum work energy was about 200 MJ for the two-phase fuel initially at average temperature at 5,300 K. This work energy is lower than the design basis value of the structural strength of the reactor system, which is set to be 500 MJ.

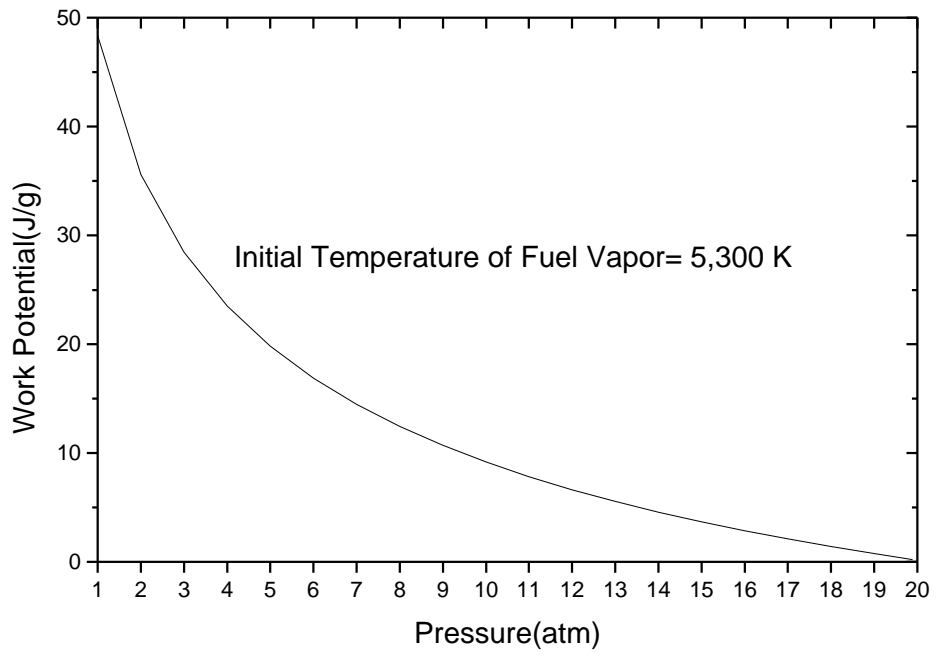
Fuel vapor is likely to lose a significant part of its energy to the surrounding medium by radiation and other heat transfer mechanisms. And pressure inside the reactor vessel would be considerably higher than one atmosphere when the bubble expansion process is completed. Therefore, the actual value of the work energy released would be far lower than the design value.

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**Figure 1. Work Potential by Expanding Fuel Vapor**