THERMALLY INDUCED DISPERSION MECHANISMS FOR ALUMINUM-BASED PLATE-TYPE FUELS UNDER RAPID TRANSIENT ENERGY DEPOSITION

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Thermally Induced Dispersion Mechanisms for Aluminum-Based Plate-Type Fuels
Under Rapid Transient Energy Deposition

by

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Abstract

A thermally induced dispersion model was developed to analyze for dispersive potential and determine the onset of fuel plate dispersion for aluminum-based research and test reactor fuels. The effect of rapid energy deposition in a fuel plate was simulated. Several data types for aluminum-based fuels tested in the Nuclear Safety Research Reactor (NSRR) facility in Japan and in the Transient Reactor Test (TREAT) facility in Idaho, U.S.A., were reviewed. Analyses of experiments show that the onset of fuel dispersion is clearly linked to a sharp rise in the predicted strain rate, which further coincides with the onset of aluminum vaporization. Analysis also shows that aluminum oxidation and exothermal chemical reaction between the fuel and aluminum can significantly affect the energy deposition characteristics, and therefore dispersion onset connected with aluminum vaporization, and affect the onset of vaporization.

Introduction

Containment loads during hypothetical severe accidents of research and test reactor systems using uranium-aluminum (U-Al) based fuel can be significantly impacted by energetic fuel coolant interaction (FCI) events. To analyze energetics of FCI events the molten material breakup or dispersion characteristics need to be evaluated. Material type plays an important role in determining the phenomenological process that will disperse the fuel. Under rapid heating, aluminum-based fuels disperse at temperatures that are significantly above the melting temperature of the fuel plate. Dispersion of aluminum-based fuel is proposed to be a function of volumetric strain rate. The concept of using strain rate as the measure of dispersive potential originates from the requirement that the fuel has to be accelerated to a certain velocity in order for it to fragment into smaller pieces. The strain rate concept is used extensively in determining the spallation characteristics for high strain rate high deformation problems. Velocity difference is usually necessary for hydrodynamic break up. Therefore, it was postulated that hydrodynamic breakup causes dispersion or fragmentation of aluminum-based fuels.

To determine the mechanism by which acceleration occurs, several separate mechanisms for strain rate were implemented in the model. These mechanisms include the strain rates caused by thermal expansion in solid state, expansion due to melting-induced phase change, thermal expansion in liquid state, expansion due to the presence of gases in the plate (present at fabrication or caused by fission product gases), and expansion due to vaporization-induced phase change. Since material strength properties are not well characterized, the modeling procedure used to determine the strain rates consists of using the concept of predicting the potential for generating strain rates. To illustrate the concept of using the potential for generating strain rates, the analogy of the conversion of potential to kinetic energy can be applied. If an object is elevated to a certain height, the potential energy from the gravitational force will be converted to a certain kinetic energy. Maximum velocity will correspond to the entire conversion of potential into kinetic energy. Since an object moving through air is retarded by drag, the velocity will not be as high as velocity achieved without drag. However, for a range of conditions, the potential for reaching that velocity relates to the height to which the object is raised. This range of acceptable conditions is limited by maximum velocity, which is terminal velocity of the object. Therefore, using the potential energy analogy, by determining the potential for achieving a certain strain rate, the model can then be used to predict the onset of dispersion as long as material properties do not interfere with the evaluation in the range of interest. As analysis shows the assumption is justified.

Numerical models that predict strain rates under different energy depositions were developed.
Evaluations of strain rates for different fuel thicknesses, clad thicknesses, energy depositions and deposition rates were conducted. Dispersion data from several types of aluminum-based fuels were compared with variational trends of peak strain rate to arrive at a criterion for onset of dispersion for different U-Al fuel types.

**Strain Rate Model**

The hypothesis that hydrodynamic breakup causes fuel-plate dispersion is illustrated in Fig. 1. To evaluate the dispersion potential, the maximum possible velocity or strain rate must be determined during the transient. To understand and rank the primary mechanisms leading to the onset of fuel-aluminum mixture dispersion, a one-dimensional (1-D) modeling framework centered on the prediction of material strain rates was developed. Strain is defined as

\[ \varepsilon = \frac{\Delta L}{L}, \]  

(1)

where \( \varepsilon \) is the strain, \( \Delta L \) is the change in length, and \( L \) is the original length. A dimensionless approach was taken to eliminate the effect of fuel-plate thickness on the results. Differentiation with respect to time results in the strain rate given by Eq. (2).

\[ \dot{\varepsilon} = \frac{d}{dt} \left( \frac{\Delta L}{L} \right) \]

(2)

Strain rate for the physical process described earlier can be expressed by

\[ \dot{\varepsilon}(z, t) = (1 - f)(\dot{\varepsilon}_m(z, t) + \dot{\varepsilon}_v(z, t) + \dot{\varepsilon}_{other}(z, t) + f \dot{\varepsilon}_{f.p.}(z, t)), \]

(3)

where \( f \) is the fraction of original volume composed of vapor or gas, \( \varepsilon_{th} \) is the thermally induced strain rate, \( \varepsilon_m \) is the melting-induced strain rate, \( \varepsilon_v \) is the vaporizing induced strain rate, \( \varepsilon_{f.p.} \) is the strain rate induced by expansion of fission product gases and \( \varepsilon_{other} \) could accommodate additional phenomena. The volumetric change rate due to the thermal expansion of material at a particular location is given by

\[ \dot{\varepsilon}_m(z, t) = \frac{d}{dt} \left( \frac{\Delta L}{L} \right) = \frac{d}{dt} \left( \beta(T(z, t) - T_0) \right) = \beta \frac{dT(z, t)}{dt} \]

(4)

where \( \beta \) is the thermal expansion coefficient, \( T(z, t) \) is the temperature, and \( T_0 \) is the initial temperature. When a material such as aluminum is undergoing a phase change, the density change will cause a change in volume. If material is melting at a certain rate, then the strain rate is

\[ \dot{\varepsilon}_m(z, t) = \frac{\rho_s - \rho_f}{\rho_f} \frac{dx_m(z, t)}{dt}, \]

(5)

where \( x_m \) is the melt quality (fraction) and \( \rho_s \) and \( \rho_f \) are the solid and liquid densities, respectively. Similarly, for vaporization phase change the strain rate is
where $x_v$ is vapor quality (fraction) and $\rho_v$ is the vapor density. As gases and fission products heat up, they expand. The strain rate (the rate of change of volume) due to the gas expansion (assuming ideal gas behavior) is given by

$$\dot{\varepsilon}_{v, p} (z, t) = \frac{1}{T(z, t)} \frac{dT(z, t)}{dt} .$$

From Eqs. (5) through (7) the strain rate can be seen to depend on the change of temperature. To determine the rate of change of temperature as a function of time, position, and energy deposition rate, thermal energy transfer under various regimes needs to be resolved.

**Thermal Energy Transfer Model**

The conservation of energy equation that determines the 1-D transient temperature profile in a fuel plate is given by

$$k \frac{d^2 T(z, t)}{dz^2} + q''' = \rho c_p \frac{dT(z, t)}{dt} ,$$

where $T(z, t)$ is the position and time-dependent temperature, $c_p$ is the specific heat capacity, $q'''$ is the volumetric heat generation source, and $k$ is the material thermal conductivity. In a finite difference approximation the conservation equation for the $i^{th}$ node is given by:

$$\frac{T_i - \frac{2}{dz^2} \frac{dT(z, t)}{dt} + \alpha_i \frac{T_i}{dz^2}}{k} = -\alpha_i \frac{dT(z, t)}{dt} ,$$

where $\alpha$ is the thermal diffusivity, $T_i$ is the temperature for node $i$ during the current time step, $T_i^{*}$ is the temperature for node $i$ during a previous time step, $dz$ is the mesh size, and $dt$ is time step. If any node is undergoing a phase change from solid to liquid, Eq. (10) determines the extent of change:

$$k \frac{d^2 T(z, t)}{dz^2} + q''' = \frac{dx_s}{dt} ,$$

where $x_s$ is the melting quality of the solid, and $h_{sf}$ is the latent heat of fusion. In a finite difference form Eq. (10) is given by

$$x_s = x_s + \frac{dt}{\rho h_{sf}} \left[ k \left( \frac{T_{i+1} + T_{i-1} - 2T_i}{dz^2} + q''' \right) \right] .$$

Equation (12) is the conservation equation involving a material vaporization process, and Eq. (13) is its
finite difference approximation.

\[ \frac{d^2 T}{dz^2} + q'' = \rho h_{fg} \frac{dx_f}{dt}, \]  

(12)

where \( x_f \) is the mass quality of the liquid, and \( h_{fg} \) is the latent heat of vaporization.

\[ x_n = x_{fi} + \frac{dt}{\rho h_{fg}} \left( \frac{1}{k} \left( T_{i+1}^* + T_{i-1}^* - 2T_i^* \right) + q'' \right) \]  

(13)

The qualities \( x_s \) and \( x_f \) are defined over a range from zero to one. When the value of \( x_s \) is zero, the node is fully solid, and when \( x_s \) is equal to one, the node is liquid. Similarly, when material changes phases from liquid to vapor, \( x_f \) tracks the quality in an analogous manner.

An implicit method determines the transient temperature solution to Eq. (8). When melting or vaporization temperature is reached, the temperature in the main matrix for node \( i \) is set to a constant melting temperature until the node fully melts or vaporizes. During the phase change process, energy equation for \( i \)th node is given by Eq. (10) or (12). These equations consider the energy deposited in the node and energy flowing into or out of the node to determine the new quality. To solve the conservation equations, fuel plate boundary conditions have to be defined. The left boundary corresponds to the center line of the fuel (symmetry boundary condition) and the right boundary corresponds to the edge (convective/radiative boundary condition). The boundary conditions are given by Eqs. (14) and (15), respectively:

\[ \frac{dT}{dz} = 0, \]  

(14)

\[ k \frac{dT(L, t)}{dz} = h(T(L, t) - T_{\text{inf}}), \]  

(15)

where \( h \) is the heat transfer coefficient for the plate surface and \( T_{\text{inf}} \) is the bulk coolant temperature. The heat transfer coefficient at the boundary is assumed to be a steady-state heat transfer coefficient. For large energy depositions the film boiling condition is reached rapidly. Therefore, the heat transfer coefficient is not significantly affected by the transient nature of heat transfer as for the lower energy deposition case.²

The described numerical model that evaluates transient temperature distribution with phase change processes was compared with an analytical closed form solution of a sample problem. A sample problem consisted of a semi-infinite solid block (at its melting temperature) whose boundary was instantaneously elevated to a new temperature. This sample problem has a closed form solution. The solution as a function of time and space is given by³

\[ \frac{T(z, t) - T_o}{T_m - T_o} = \frac{\text{erf} \left[ \frac{z}{2(\alpha t)^{1/2}} \right]}{\text{erf}[\lambda]}, \]  

(16)

where \( T(z, t) \) is the temperature at location \( z \) and time \( t \), \( T_o \) is the surface temperature, \( T_m \) is the melting
temperature, $\alpha$ is the material thermal diffusivity, and $\lambda$ is the root of the transcendental equation given by

$$\lambda e^{\lambda^2} \text{erf}[\lambda] = \frac{c_p(T_m - T_0)}{h \sqrt{\pi}}$$  \hspace{1cm} (17)

The melt front position $s(t)$ at any time $t$ is given by

$$s(t) = \lambda (\alpha t)^{1/2}$$  \hspace{1cm} (18)

and the rate at which the slab is melting is given by

$$\frac{ds}{dt} = \frac{\lambda \alpha^{1/2}}{2t^{1/2}}$$  \hspace{1cm} (19)

Comparisons were made using the arbitrarily chosen properties given by the following: thermal conductivity = 100; initial temperature = 100; density = 1000; boundary temperature = 200; specific heat = 10; melting temperature = 100; and $hsf = 100$. Figure 2 shows the comparison of ideal with numerical solution, and results compare well.

**Strain Rate Modeling and Analysis Framework**

Two key assumptions of the present work are noteworthy. These assumptions are as follows:

1. The as-developed model represents the potential for acceleration and not the actual acceleration. The dynamic interaction between expansion and retention forces through material strength properties was not explicitly modeled.
2. Because of the insufficient knowledge base, the rate characteristics of the secondary sources of energy were not taken into account. The secondary sources of energy are aluminum oxidation and exothermal reaction between the fuel particles and aluminum.

**The effect of neglecting material strength properties**

In general, the material cohesive forces will reduce the strain rate and cumulative strain caused by the deposition of energy into a plate. The consequences of not taking into account the effect of material strength properties should therefore be quantified. During a heating transient four separate stages can be identified where material properties change and could influence the retention forces. The four stages are (1) solid, (2) slurry; (3) liquid, and (4) vapor. Restraining force depends on the state of the material.

When energy is deposited into the plate, the fuel changes from solid into liquid. Restraint in the solid is governed by elasticity of the material. The transition from solid to liquid is fuzzy because of eutectic formation. The melting point is not a single temperature but a range of temperatures. The cermet fuels seem to form a viscous slurry. During the slurry stage, it is not known whether the fuel will behave according to Newtonian or Bingham flow manner. When fluid properties exhibit non-Newtonian behavior, the mixture may have solidlike properties for a range of imposed shear stresses and exhibit linear Newtonian behavior past a critical shear stress. Some experimental evidence suggests that the cermet fuel in the plate/tube geometry remains stiff (solidlike) up to very high temperatures that are significantly beyond the melt temperatures of the pure aluminum. Further deposition of energy causes full melting of the fuel plate. When in liquid form, the restraint is caused by the viscosity of the liquid. This restraint is significantly lower then the elasticity-based restraint. Further energy deposition leads to
vaporization. Vapor states generally do not display any significant restraint.

The liquid and vapor stages provide very little resistance to flow when compared with the solid and slurry stages. Therefore, the only two stages where material strength effects have to be considered are solid and slurry. As will be shown in the examination of experimental data, dispersion is observed at very high temperatures. Material of the fuel exists only in liquid and vapor stages before dispersion. This means that neglecting material strength may not significantly affect the predicted strain rates during the important stages where dispersion is likely to occur.

The effect of not including chemical oxidation

The chemical oxidation phenomenon between aluminum and steam is very complex. The energy from its reaction was not included in the temperature predictions. Energy associated with this reaction is approximately 18 MJ/kg. To estimate the error associated with neglect of the reactions, some physical examination of the phenomenological events occurring during the reaction needs to be performed. Two mechanisms by which aluminum oxidizes are vapor phase burning and steam diffusion through the solid/liquid aluminum oxide layer. Figure 3 illustrates the two effects.

When aluminum is at temperatures where aluminum vapor pressure is appreciable, evaporated aluminum chemically reacts with steam and burns away from the aluminum surface. For this reaction to sustain itself, there has to be steady supply of aluminum vapor and steam that feeds into the reaction. For that process to occur, energy from the reaction needs to be transferred to the aluminum surface. Part of this energy is then used for changing the phase of the aluminum from liquid to vapor. The energy from the oxidation reaction is close to 18 MJ/kg; however, the latent heat of vaporization of aluminum is 10.8 MJ/kg. To sustain the reaction, 60% of the energy needs to be transferred to the aluminum surface. If an aluminum oxide layer is present on the surface, significant evaporation of aluminum will not occur until the aluminum oxide allows the aluminum vapor to pass though the oxide. This occurs when the temperature of the aluminum oxide reaches 2330 K (the melting temperature of the aluminum oxide).

The second phenomenon is the diffusive oxidation. When aluminum is in a cold solid state, a thin oxide film builds up rapidly. This oxide forms a protective layer that prevents further diffusion of steam or oxygen, and the reaction ends. The diffusion process is governed by the diffusivity of steam in the oxide layer. As the temperature increases, the diffusivity increases, allowing more steam to penetrate through the oxide layer. As the temperature is increased to the melting temperature of the oxide layer, the diffusion coefficient increases rapidly and allows steam to penetrate at a significantly higher rate than when the oxide layer is in the solid state. When aluminum oxide melts, significant chemical oxidation can take place. This oxidation continues until all the aluminum oxidizes or when the temperature of the aluminum oxide falls below solidification temperature. Solidification occurs when heat transfer from the surface exceeds the heat generation rate.

Under certain conditions aluminum ignition was postulated to occur at subcooled aluminum oxide temperatures. This phenomenon seems to occur when the oxide layer is in a subcooled metastable liquid state and the aluminum surface-area-to-volume ratio is large. Due to the finite time associated with the growth of the aluminum oxide crystal, sufficient steam can diffuse and oxidize a large fraction of aluminum because of the large surface-area-to-volume ration. When the surface-area-to-volume ratio is small, the fraction of oxidized aluminum is small. The condition that determines whether vapor phase burning or the diffusive oxidation process governs the reaction is not clear. It seems that the vapor phase burning will occur when significant aluminum vapor pressure is exerted. The diffusion-governed oxidation occurs when aluminum oxide is barely molten and diffusion of steam through the aluminum oxide layer is more likely than evaporation of aluminum. Both of these reactions clearly can become predominant at temperatures that are near or above the melting temperature of the aluminum oxide layer. Therefore, oxidation energy clearly becomes an important source when the 2330 K is exceeded. As the
following section shows, the available data confirm this effect. The uncertainty in the energy release rate is the main reason for not including the oxidation as the energy source in the analysis. To predict the energy release rate detailed phenomenological models need to be implemented. The models of fundamental processes are not currently available. As shown later by the predictions, most of the deviation in data originates when temperatures are around 2300 K.

The effect of not including the energy from fuel-Al reaction

Several research reactors use cermet-type fuels like U$_3$O$_8$-Al or U$_3$Si$_2$-Al mixtures. Such mixtures undergo a thermitic reaction once the aluminum melts. The reaction rate varies proportionally with the temperature of the mixture.\cite{4,5} The reaction of U$_3$Si$_2$ fuels with aluminum in the mixture is exothermic and releases anywhere between 0.3 and 0.35 MJ/kg of U$_3$Si$_2$, depending on the volume fraction of the fuel in the mixture. The energy associated with this reaction is significantly smaller than the energy associated with aluminum oxidation. The reaction begins at a very slow rate when aluminum reaches melting temperature at 900 K and increases rapidly as the temperature increases. When fuel particles melt, the reaction rate is the fastest. The main problem is that the rate of these reactions is not well known and implementation of the energy deposition over a wrong time scale could significantly affect the predicted results.

Analysis of Experimental Results

The experimental data for aluminum-based fuels were obtained from the TREAT facility in Idaho. The types of plates tested were those from the High Flux Isotope Reactor (HFIR) and SL-1 reactor. Advanced Neutron Source (ANS) fuel plates are being tested in Japan Atomic Energy Research Institute's (JEARI) NSRR facility in Japan. The NSRR results are not included as part of this work due to an incomplete data base. Some differences exist between the two facilities, producing variations in experimental conditions. One dominant difference is the duration of the neutron exposure. The TREAT facility pulse width varies between 0.3 and 1 second whereas the pulse width of the NSRR facility varies between 25 and 100 milliseconds. The amount of energy that can be deposited into a plate is a function of the neutron flux density and the duration of exposure.

TREAT tests with SL-1 fuel plates

SL-1 fuel plates were tested in the TREAT facility.\cite{10} SL-1 plate samples were U-Al alloy fuel without cladding. The dimensions of test sample were 0.005 m x 0.0127 m x 0.0127 m. The fuel sample was an Al-U-Ni alloy that was composed of 81% Al, 17% U, and 2% Ni. For energies deposited into the plate during the experiments, peak computed strain rate vs energy per unit mass of the plate was determined and plotted in Fig. 4. Comparison with the observed dispersion was also presented in the same plot. The results indicate that the location where the slope of the strain rate curves changes is the location where the dispersion is likely to occur.

Experiments show that for all cases in which energy deposition was greater than 2.3 MJ/kg, the plate dispersed. It was hoped that the prediction for dispersion would be represented by the point of inflection where the curve of peak strain rate as a function of energy begins to increase. The point of inflection where the strain rate begins to increase is 2.7 MJ/kg. This represents a discrepancy between the point of inflection and the observed data point where dispersion was observed. The test number CEN 115 was not in line with the predictions. To explain the discrepancy, aluminum oxidation phenomenon was investigated. Figure 5 shows the peak computed surface temperature and the fraction of aluminum oxidation that took place as a function of the energy deposited. The test CEN 115 peak temperature reached by nuclear heating alone was computed to be 2300 K, which was sufficient to melt the oxide layer and allow oxidation to begin. Using a diffusion law, a separate calculation to determine the
maximum oxidation over a ten-second period was performed. When aluminum temperature is below oxide melting temperature, the oxidized fraction should not exceed 7%. This is roughly the oxidized fraction measured for the CEN 122 test.

For the CEN 115 test, the oxide melting temperature was reached during the period when nuclear heating was still taking place. Additional energy from oxidation was sufficient to raise the temperature of the fuel to the vaporization state and cause dispersion. This seems to indicate that energy from nuclear heating was supplemented by chemical oxidation to provide sufficient energy for the onset of vaporization. The chemical reaction phenomenon was not modeled; therefore, the strain rate is not representative of vaporization process.

TREAT Tests with HFIR Fuel

HFIR fuel plates are made with U_3O_8 particles dispersed in an aluminum matrix. HFIR fuel sample dimensions were 0.0254 m x 0.0127 m x 0.00127 m. Composition by mass of the HFIR fuel is 59% Al and 41% U_3O_8. Similar to SL-1 tests, HFIR plates were subjected to neutron bursts in the TREAT facility. Figure 6a shows strain rate vs energy deposited per gram for the two initial temperatures, and Fig. 6b shows the strain rate compared with the fragmented fraction for one of the initial temperatures. Results show that HFIR and SL-1 fuel test exhibit reasonable similarity in response to energy deposition. Just as in test CEN 115 with the SL-1 plates, CEN 211H and CEN 204 data fall into the category of dispersing without reaching vaporization temperature by nuclear heating alone. Figure 7 shows the peak computed temperature and measured oxidized fraction plotted against the deposited energy. Both test points in question have significantly oxidized. The computed peak clad temperature from nuclear heating alone for both tests is above the oxide melting temperature. Therefore, just as observed with SL-1 fuel tests these two points are expected to use some of the oxidation energy to aid in reaching the vaporization state. The initial fuel temperatures for the SL-1 tests were 303 K, 393 K, and 558 K. Since only two data points were tested with the initial temperature of 558 K, they were not plotted in Figs. 6a and 6b but were included in Fig. 7. Sensitivity to initial temperatures is shown in Fig. 6a where strain rate was compared for the two initial temperatures. Comparison of the fragmented fraction with the strain rate for different energies appears in Fig. 6b.

Predictions of ANS fuel dispersion

ANS fuel plates are composed of a fuel meat section sandwiched by aluminum cladding. The fuel meat is 0.00076 m thick, and the cladding is 0.000254 m thick. Fuel meat is composed of uranium silicide particles dispersed in an aluminum matrix. The density of uranium silicide in the meat is 1400 kg/m^3. Based on a criteria deduced from comparison of the dispersion model with the TREAT experimental data, the model was used to predict the behavior of ANS fuel. The criteria for dispersion is the location on the peak strain rate plot where the curve changes slope. Two types of plots resulted from the model. One plot shows the variation of strain rate with deposited energy in the plate over a 25-ms period per unit mass of the plate. This plot is given by Fig. 8. The second plot, Fig. 9, shows the variation of strain rate with a the varying period for fixed cumulative energy deposited in the plate. Both Figs. 8 and 9 show a change in the slope of the strain rate curve.

When Fig. 8 is examined the expected dispersion energy is ~ 2.7 MJ/kg. This conclusion is valid as long as a chemical reaction does not occur. If a chemical reaction occurs, then the threshold will be lower. If it is assumed that oxidation aids dispersion, for a constant 25 ms energy deposition period, the onset of oxidation will be achieved when energy deposition of 2.4 MJ/kg is exceeded.

For the second case a fixed cumulative energy of 2.15 MJ/kg was used. For very short energy depositions, most of the deposited energy is used in raising the temperature of the fuel meat, and
vaporization of the meat was achieved. For longer durations, the energy spreads, and cumulative energy cannot raise the temperature of the entire plate to the vaporization temperatures, so the plate does not disperse. In other words, as the energy deposition duration is increased, the energy has time to diffuse, which results in a lower peak temperature of the meat. If dispersion criteria deduced earlier is applied, one can conclude that for 2.15 MJ/kg to disperse the plate the pulse width has to be shorter than 5 milliseconds. If oxidation is assumed to occur when clad temperatures exceed 2300 K, the pulse width has to be anywhere between 12 and 27 milliseconds.

Experiments conducted with ANS plates in the NSRR facility in Japan have not been irradiated with a neutron flux that is sufficient to cause dispersion. All of the data gathered with the ANS fuel have been in the low energy range where dispersion did not occur. The energies deposited in the ANS fuel varied between approximately 0.5 to 1.1 MJ/kg. The nature of the tests required varying durations of exposure to neutrons. The period varied from 20 to 60 milliseconds. It should be noted that higher energies were sufficient to melt the fuel plates, but were significantly below the predicted threshold for dispersion of 2.4 MJ/kg for a 25 milliseconds exposure.

General Observations and Discussion

Transient behavior of fuel and the effects of the fuel components can be difficult to visualize without the performance of a series of parametric evaluations. Parametric evaluations performed on the fuel plate showed that some parameters significantly affect the fuel heat-up behavior. Since heat-up behavior affects the expansion characteristics and dispersion, it is worthwhile to discuss some effects. Parameters that are controllable by design are plate thickness, fuel meat thickness, clad thickness, and meat composition. Meat composition is the fraction of fuel combined with the aluminum. The parameter that affects the fuel behavior is the energy deposition transient. For a given energy deposition, the outcome varies significantly, depending on the input duration, as shown by ANS fuel predictions.

The manufacturing method produces a small volume of gases in the meat section of the fuel plate. During heat-up, the gas expands, potentially causing swelling. Meat composition affects the plate behavior by changing the meat thermal conductivity, heat capacity, and void fraction. The secondary effects are (1) the chemical reaction between the fuel and the aluminum that is, the extent of eutectic formed from the reaction under elevated temperatures; and (2) the melting temperature of the meat with the new eutectic. Thermal conductivity affects the transient performance of the fuel plate. Increasing the fuel loading reduces thermal conductivity in the fuel meat. Also, increasing the fuel loading reduces the specific heat capacity of the meat. The combination of these two parameters causes a more pronounced increase in temperature for a given constant volumetric energy deposition rate. The effect of meat and clad thickness on the transient behavior of the plate tends to affect the temperature distribution. For thinner meat and thicker cladding, the energy from the meat tends to diffuse out to the clad and cause the cladding to heat up. Since the specific heat of the cladding is higher than the specific heat of the meat, more energy is absorbed by the clad, thereby lowering the overall temperature. This is true if the energy is deposited over a longer period of time. If the energy deposition period is reduced, the effect can be reversed. For such cases, the fuel meat does not have sufficient time to transfer energy to the cladding. Therefore, the meat heats up faster to higher temperatures, reaching vaporization temperatures with less energy.

Results show that reducing the thermal conductivity of the meat section seems to increase the strain rate. The strain rate is caused by a reduced transfer of thermal energy from the meat to the cladding; thus, the temperature increases faster than it would if the thermal conductivity was higher. The buildup of temperature causes other effects to become significant, such as: the expansion of gases, or the increase in melt or vaporization rate. Lower thermal conductivity of the meat can occur if fuel is not fabricated up to specifications where significant inhomogeneities exist. Fuel (U3Si2) particles not only have lower thermal conductivity but also have lower specific heat capacity. Thus, increasing the concentration of fuel particles decreases both thermal conductivity and heat capacity of the meat. This causes the temperature
of the meat during a transient to increase and possible strain rates to be higher than for the lower concentration case. This means that homogeneity of the fuel plates is very important and flawed production could cause premature failure of the plate.

**Summary and Conclusion**

To summarize, a mathematical modeling framework was developed to predict the threshold to dispersion during heat-up transients for U-Al plate-type reactor fuels. The model centers on the determination of thermally induced strain rates which considers several physical phenomena. Exact closed form solution compared with a numerical model for an arbitrary simplified problem shows good agreement. Data from TREAT facility tests with SL-1 and HFIR fuel plate samples were analyzed for determining dispersion and rapid Al-H₂O reaction thresholds. Comparison of model predictions with the TREAT experiments produced a good verification for the onset of dispersion. The study shows that the strain rate parameter displays a sharp increase coincident with the onset of material vaporization. Model predictions against the NSRR data taken with ANS reactor test samples indicate no onset of dispersion for the energies that were deposited. The NSRR data obtained so far with ANS miniplate samples corroborate this.

Overall, this work shows that the rate of energy deposition is just as important as the cumulative energy deposited in the fuel when one is trying to determine the dispersion potential during rapid transients. Strain rate as a method of determining the fragmentation characteristics predicts correct overall trends. To improve the model, a chemical energy deposition model needs to be implemented. Upon the melting of aluminum oxide, exothermic energy from an aluminum-steam chemical reaction is added to the fuel plate. For evaluating the criteria that should be used to determine the onset of dispersion, the energy deposition history needs to be taken into account. For slower transients, the temperature gradient in the fuel tends to be small. For such cases, when surface temperature of the clad exceeds the aluminum oxide melting temperature, dispersion should be assumed to follow. For rapid heat-up rates, the temperature gradients are large. The meat vaporizes before the clad surface temperature reaches the melting temperature of the oxide layer. For this case, the vaporization of the meat triggers the onset of dispersion.

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**References**

Fig. 1. Illustration of the dispersion process.

Fig. 2. Comparison of closed form with the numerical approximation solutions.
Fig. 3. Illustration of diffusive oxidation and vapor phase burning.

Fig. 4. Strain rate and fragmented fraction as a function of cumulative deposited energy.
Computed surface temperatures for SL-1 tests performed in the TREAT facility

Note: The label next to the test number refers to the percentage of fuel that oxidized.

Fig. 5. Peak computed temperatures for different energy depositions.
Fig. 6a. Comparison of computed strain rate with energy for different initial fuel temperatures applied to HFIR fuel.

Fig. 6b. Comparison of strain rate with fragmented fraction for different energies applied to HFIR fuel.

Fig. 7. Fraction of aluminum oxidation and peak computed temperatures for HFIR tests as a function of energy deposition.
Strain rate as a function of energy deposited in the ANS fuel plate with 1.4 g/cc loading under 25 ms pulse duration.

- Peak center line fuel temperature (K)
- Peak clad surface temperature (K)
- Strain rate

Fig. 8. Strain rate and temperature variation for ANS fuel as a function of deposited energy for a fixed pulse width.
Peak strain rate and peak centerline temperatures as a function of pulse width for ANS fuel plates for a 2.15 MJ/kg energy deposition.

Fig. 9. Strain rate variation as a function of pulse width for a fixed total energy deposition.

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