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# Investigation of Molten Fuel Relocation Dynamics with Applications to LMFBR Post-Accident Fuel Relocation

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**Abstract**

The process of solidification of a single-phase flowing hot fluid in a cylindrical tube has been investigated analytically and experimentally. A series of tests were performed, using paraffin wax and Wood's metal as flowing hot fluids. These data verified the existing quasistatic numerical analysis model of freezing process developed at Brookhaven National Laboratory. In addition, experimental results provided information regarding the effects of various parameters on the process of transient flowing and freezing through a vertical channel. The experimental apparatus and techniques are described. Comparison of experimental data with predictions of mathematical models for transient molten fluid displacement are presented in graphical form. In addition, the mathematical model is applied to LMFBR post-accident conditions.

**요 약**

원통형 관속을 흐르는 뜨거운 단상 유체의 응고 과정을 해석적인 방법과 실험적인 방법으로 연구하였다. 파라핀초와 Wood's Metal을 뜨거운 유체로 사용하여 일련의 실험을 하였다. 이 실험 데이터로 부룩헤븐 연구소에서 개발한 응고과정에 대한 기존 준정적 수리해석 모델을 증명하였다. 또한 이 실험결과, 수직관속을 순간적으로 흐르며 응고하는 과정에 미치는 여러가지 매개변수의 영향에 관한 자료를 얻게 되었다. 이 실험에 사용한 기구와 실험 방법도 아울러 기술하였다. 녹은 유체의 순간적으로 흘러내리는 양에 대한 수학적 모델의 예측 결과를 실험데이터와 비교하기 위해 도표로 제시하였다. 또한, 수학적 모델을 고속증식로(LMFBR)에 사고가 일어 났을 경우에 응용하여 보았다.

## 1. Introduction

Assessment of the dynamics of molten fuel relocation following hypothetical core-disruptive accidents in LMFBRs is of importance in studies of accident energetics and of post-accident heat removal (PAHR). The energetics of a molten core recriticality event is dependent upon the quantity of fuel remaining in the core and, hence, on the extent of material relocation by the streaming and freezing processes. The potential for safe containment of the core materials of an LMFBR following a hypothetical accident depends to a great extent on the post-accident distribution of fuel and other core materials, and on the time scale for material relocation.

Upward fuel relocation may be driven by sodium vapor pressure in a transient overpower accident (TOP), and by fuel or steel vapor pressure in a loss-of-flow (LOF) accident. Molten fuel relocation in the downward direction would be driven by static head pressure in addition to vapor pressure. In either case, if coolant channels are not plugged, ejection of the molten core debris can occur within a few seconds. However, deposition of the molten debris by freezing on cold structures could lead to plug development and the formation of a "bottled" core region. In such a case, fuel dispersal could only occur after melt-out of the plug and/or the lower assembly structure[1,2,3].

The rate and extent of core material relocation will depend upon the composition and phase distribution of the flowing fluid, and on the temperature and mass of the bounding steel walls of the flow structure. The relocation dynamics will also depend on the reactor power level. If the energy generation rate in the core is large, e.g., under conditions of the transition phase of the LOF accident, then the core material is likely to be boiled up and, perhaps, dispersed. On the other hand, under low power decay heat conditions, e.g., in PAHR circumstances, the rate of vapor generation may be small and the core material may be in a bubbly flow regime or, in the extreme, fully collapsed and single phase. Methods for predicting the flow regime and void distributions under accident conditions have not been adequately developed. An understanding of transient flow with solidification is needed over a broad spectrum of flow regimes[4].

This work is directed towards the processes involved in the flow of single-component, single-phase molten fuel through the cold lower structure of an LMFBR under relatively low driving pressures. The study of relocation of single-phase core material, in this case-fuel, is directed towards PAHR conditions and is particularly directed towards evaluation of the potential for rapid molten fluid flow through the shield block region of the Clinch River Breeder Reactor (CRBR) (as opposed to penetration of the shield block by a slow meltout process). In addition, this work serves as a baseline case for understanding of the more complex two-phase processes involved in the transition phase of the LOF accident[4].

The freezing of a flowing fluid falls into a general category of "Stefan"[5] type problems. These problems involve heat transfer between multiple regions with phase changes occurring at the moving region boundaries. Those works reviewed by the author could be grouped into a few broad categories: (a) the exact closed form solutions of Stefan[5], Carslaw and Jaeger[6], and Rosenthal[7], which exist for some special cases where conduction is the sole mode of heat transfer, (b) approximate analytical solutions to problems of freezing and melting, which take into consideration the effects of convective heating, such as the work done by Libby and Chen[8], and Lapadula and Mueller[9]. (c) those works offering finite-difference solutions, among which those by Landau[10], Bilenas and Jiji[11], and Beaubouef and Chapman[12] are outstanding, (d) a parametric study which results in an empirical correlation of the transient freezing data as the work done by Cheung and Baker[13], (e) several ad hoc models[14,15,16] that have been proposed for treatment of the fuel relocation problems. On the dynamics of the solidification process, in particular, two experimental results, those of Hirschberg[17] and the work done at Argonne National Laboratory[13,16] have been reported.

The previously reported analytical and experimental works do not enable one to estimate the transient rate of molten fluid flow through cold channels from a reservoir where the liquid is subjected to the constant driving pressure.

The objective of the present work was to study the process of freezing of a liquid in transient flow inside a cooled cylindrical tube. A simulation experiment was designed to evaluate a mathematical model developed at BNL[3] which describes the solidification of single-phase molten fuel flowing through cold channels with non-melting boundaries. The mathematical formulation is briefly outlined. The experimental apparatus and techniques are described and experimental results are described. Finally, results of application of the freezing process model to LMFBR post-accident conditions are presented.

## 2. Analytical Model

A two-dimensional transient freezing model in cylindrical geometry has been formulated[3,4] to study the phenomenon of solidification of flowing fluid inside a circular channel, the walls of which are cooled below the freezing temperature of the flowing fluid. The model is discussed in Refs. 3 and 4, and is not presented here in detail. Rather, the model is outlined as applied to the experimental test section. The test section shown schematically in Fig. 1, was in an annular co-axial counterflow heat exchanger configuration. The molten simulant fluid flowed downward through the inside tube. Cooling water flowed upward in the annular region. The model determines the thickness of the solidified shell on the inside wall of a vertical channel in terms of time and axial location. Since exact solutions are not feasible for the coupled nonlinear partial differential equations that describe the heat transfer and fluid dynamics of the solidification process, a number of simplifying assumptions and approximations were introduced which include[2]:

(a) A quasi-steady state radial temperature field exists in the frozen layer.

(b) A quasi-steady flow exists in the liquid region.

(c) Heat transfer from the flowing fluid to the solid-liquid interface is assumed to be a quasi-steady state process which is independent of the changing radius and solidification occurring at the interface.

(d) Axial heat conduction in the solidified shell and in any surrounding material is neglected.

(e) No melting of wall material occurs.

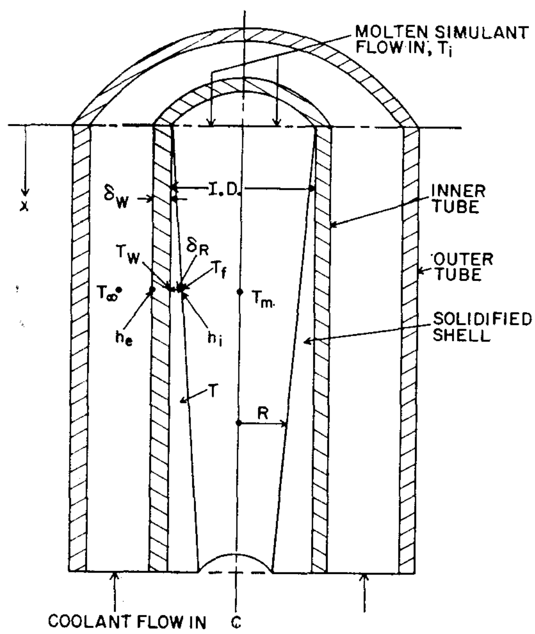


**Fig. 1. Physical Model of Countercurrent Flow Test Section**

(f) No heat generation in the simulant fluid.

(g) The temperature of the coolant flow in the test section annulus ($T_\infty$) is constant.

With the above assumption, the model is formulated by incorporation of steady conduction equation for the solidified shell and for the inner tube wall. The steay Bernoulli equation, which includes friction losses and the acceleration term due to channel area change, is applied to the molten fluid flow. The pressure drop across the test section length is assumed held constant. The molten fluid energy equation is written as

$$\rho C_p V \frac{dT_m}{dx} + \frac{2h_i}{R}(T_m - T_f) = 0 \qquad (1)$$

with inlet condition $T_m(x=0) = T_1$. The boundary condition at the moving interface is

$$-k\frac{\partial T}{\partial r}\bigg|_R = h_i(T_m - T_f) + \rho\lambda\frac{dR}{dt} \qquad (2)$$

In Eqs. (1) and (2), $\rho$ is the density, $C_p$ is the specific heat, V is the fluid velocity, $T_m$ is the fluid bulk temperature, $x$ is the axial coordinate, $h_i$ is the interior heat transfer coefficient betw een flowing fluid and solidified shell, $R$ is the radius of liquid-solid interface, $T_f$ is the fusion temperature, $T_1$ is the inlet fluid temprature, $k$ is the thermal conductivity, $T$ is the temperature field within the frozen layer, $r$ is the radial coordinate, $\lambda$ is the heat of fusion, and $t$ is the time.

Heat transfer from the inner tube to the coolant (at $T_\infty$) was assumed to occur across a film with conductance $h_e$. The model equations were nodalized by dividing the axial length into a number of equidistant nodes. The method of solution is discussed in detail in Ref. 3. The interior heat transfer coefficient ($h_i$) for the laminer regime is obtained from the Sieder-Tate equation[18], while those for the turbulent regime and the exterior heat transfer coefficient ($h_e$) are obtained from the Dittus-Boelter type equation. The interior heat transfer coefficient ($h_i$) used in the analysis of the Wood's metal case, however, is evaluated from the correlation developed for liquid metal by Seban and Shimazaki[19].

## 3. Experimental Method

### 3.1. Apparatus Description

Two series of experiments were designed; one using paraffin wax, the other Wood's metal as fuel simulants. The major components of the experimental system, shown in Figure 2, were; a reservoir tank, the test section, and a catch tank. The reservoir tank was a cylindrical vessel, where the molten fluid was stored at a controlled initial temperature and pressure. The two test sections (which differ only in their tube diameters) were single-pass countercurrent heat-exchangers. Both inner and outer tubes were made of brass. Molten fluid flowed through the inner tube, which was cooled by water flowing vertically upward through the cooling jacket formed by annulus between the inner and outer tubes. The catch tank received molten fluid leaving the vertical test section. The mass of fluid collected was monitored using a load-cell and associated recording equipment[4].

### 3.2. Test Parameters

The experiments were designed to measure, for each set of initial and boundary conditions, the time required for complete channel plugging, the mass of molten fluid displaced as a function of time, and the transient molten fluid exit temperature. These quantities were chosen in order to provide a direct comparison with the mathematical model. Plugging times were measured using an electrical timer. Fluid displacement and fluid exit temperature were measured by a load-cell and with an exposed thermocouple, respectively. Also measured were the molten fluid inlet temperature, reservoir pressure, water coolant flow rate and inlet and outlet temperatures.

The controllable test parameters were: (a) fluid type, (b) initial molten fluid temperature, (c) internal diameter of inner tube, (d) coolant water flow rate through test section annular space, and (e) the driving pressure behind the hot simulant fluid.

As stated above, two fluids (paraffin wax and Wood's metal) were chosen based primarily on their respective Prandtl numbers. The Prandtl number of $UO_2$ at 3000°C is about 0.86. For paraffin wax and Wood's metal, the Prandtl numbers are 43 and 0.018 respectively within the range of experimental conditions.

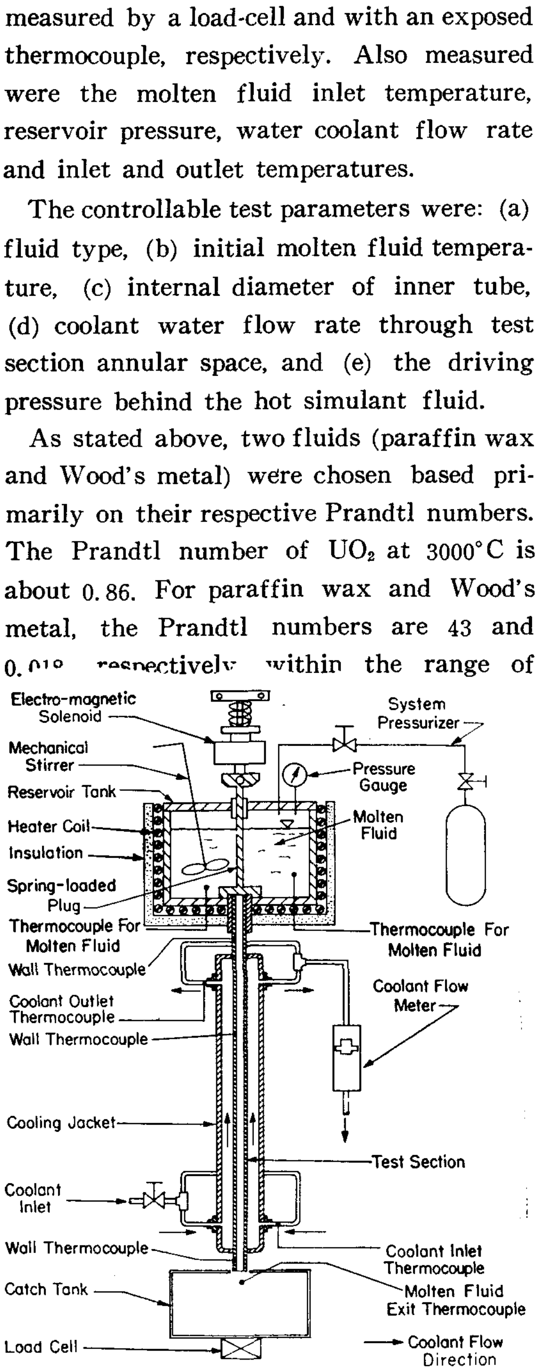


**Fig. 2. Schematic Diagram of Experimental Apparatus**

### 3.3 Test Procedure

The reservoir tank was charged with the molten fluid to be tested. Power was then applied to the heater coil surrounding the reservoir where a mechanical stirrer maintained a uniform fluid temperature distribution. At the same time, the coolant water flow rate and the pressure in the reservoir were set at the desired levels. When the temperature of the molten fluid reached the desired value, the heater power was turned off and a 4-way air-valve was opened by means of a push-button. This triggered on the recording systems and pulled the plug (Fig. 2) instantly upward; the molten fluid at this point began to flow into the test section. The displaced molten fluid was received inside the catch tank located immediately below the exit of the test channel. At the completion of the test, the monitoring and recording systems were terminated by means of a push-button as soon as the molten fluid stopped flowing as a result of either complete plugging or exhaustion of the entire initial mass of fluid in the reservoir. After all the appropriate quantities were measured, the inside surface of the test section was cleaned thoroughly with a long metal rod whose lower portion was covered with fine tissues, while the temperature of the test section was maintaind above the melting point of the simulant fluid by passing steam through the cooling jacket[4].

## 4. Comparison of Experimental Results with Analytical Models

### 4.1 Experimental Results and Comparison with Models

The data developed during this investigation can be classified chronologically into two parts, i.e., the early test data[1,2] and the new additional test data[4] obtained with upgraded instrumentation. Of these only the new experimental results of the transient mass displacements are shown in Figs. 3-6 along with comparison with the predictions of three analytical methods of the transient solidification process. In Figs. 3-6, $T_I$ is the fluid temperature at the inlet of the channel, $\Delta p$ is the driving pressure behind the fluid, $H_i$ is the initial molten fluid head in the reservoir, $T_c$ is the coolant temperature, and $D_i$ is the tube inside diameter.

Briefly, the three analytical methods are as follows:

Gasser and Kazimi[3] developed a model for the transient solidification process which accounts for the transient axial variation of solid-layer growth rate and the feedback of solid-layer growth on channel fluid flow behavir. This model neglects all heat capacity effects in both the solid layer and in the bulk liquid. The solid-layer growth rate, according to this model is given by[3,4]

$$\frac{dR}{dt} = \frac{h_i(T_n-T_f)\left(k_s+R_o h_{ov}\ln\frac{R_o}{R}\right)-\frac{R_o h_{ov} k_s}{R}(T_f-T_\infty)}{\rho_l\lambda\left(k_s+R_o h_{ov}\ln\frac{R_o}{R}\right)} \tag{3}$$

where $T_n$ is the temperature of any axial node, $k_s$ is the thermal conductivity of solid phase, $R_o$ is the initial channel radius, $h_{ov}$ is the overall heat transfer coefficient, $T_\infty$ is the sink temperature, and $\rho_l$ is the density of liquid phase.

On the other hand, it has been proposed[20] that a first-order approach to the effect of solid-layer heat capacity may be made by assuming that, in addition to removal of latent heat of fusion at the interface, energy

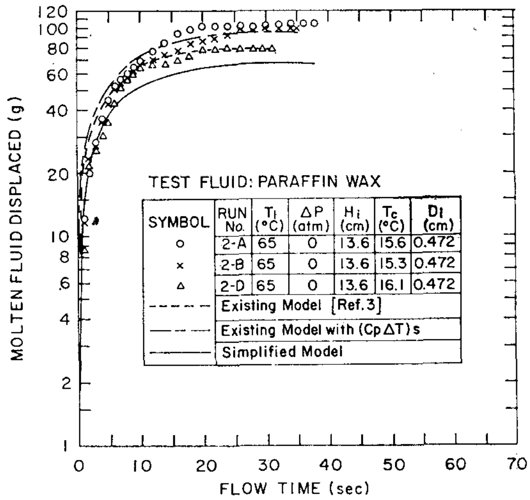


**Fig. 3.** **Reproducibility and Comparison with Theory for Paraffin Wax Inlet Temperature of 65°C**

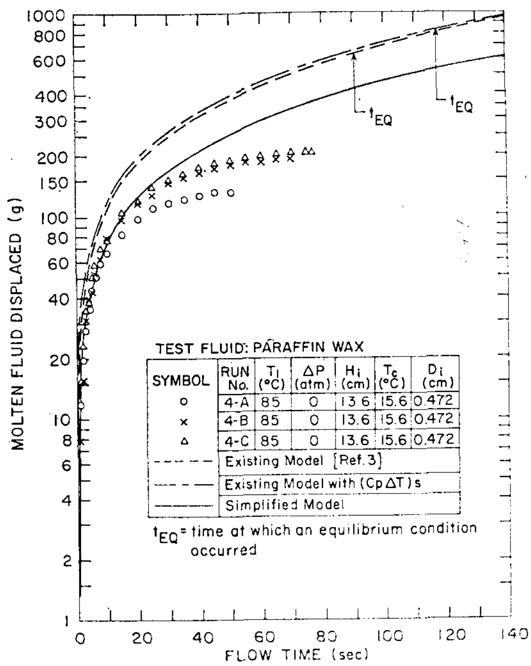


**Fig. 4.** **Reproducibility and Comparison with Theory for Paraffin Wax Inlet Temperature of 85°C**

is also removed to reduce the solidifying liquid to the average solid-layer temperature. With this modification, the solid-layer growth rate is

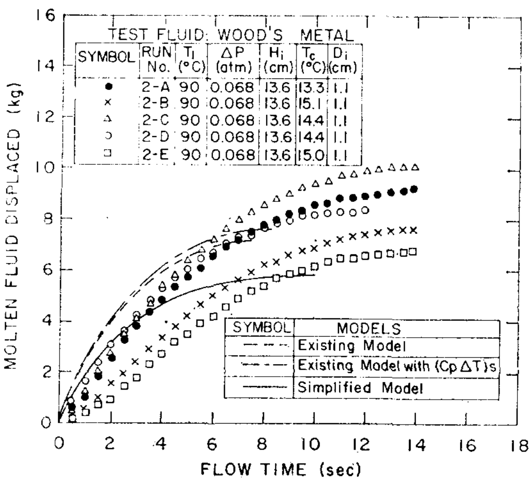


**Fig. 5. Reproducibility and Comparison with Theory for Wood's Metal Inlet Temperature of 90°C**

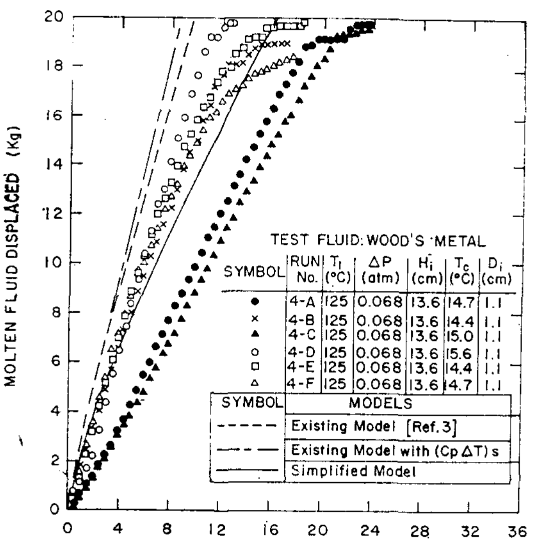


**Fig. 6. Reproducibility and Comparison with Theory for Wood's Metal Inlet Temperature of 125°C**

$$\frac{dR}{dt} = \frac{h_i(T_n - T_f)\left(k_s + R_o h_{ov} \ln\frac{R_o}{R}\right) - \frac{R_o h_{ov} k_s}{R}(T_f - T_\infty)}{\rho_l[\lambda + C_s(T_f - \bar{T}_s)]\left(k_s + R_o h_{ov} \ln\frac{R_o}{R}\right)} \tag{4}$$

where $C_s$ is the specific heat of solid phase.

The mean temperature of the solid-layer, $\bar{T}_s$, is defined by

$$\bar{T}_s = \frac{\int_{R_o}^{R} T_s r dr}{\int_{R_o}^{R} r dr} \tag{5}$$

More recently, Chun[21] has developed a simplified model in which the axial variation of the solid-layer growth is not considered. This model assumes that the liquid bulk temperature and velocity at the end of the channel are constant. The assumption of constant velocity is removed, however, in the computation of transient mass displacement. The solid-layer growth rate is given by

$$\frac{dR}{dt} = \frac{h_i(T_2 - T_f)\left(k_s + R_o h_{ov} \ln\frac{R_o}{R}\right) - \frac{R_o h_{ov} k_s}{R}(T_f - T_\infty)}{\rho_l \lambda \left(k_s + R_o h_{ov} \ln\frac{R_o}{R}\right)} \tag{6}$$

where $T_2$ is the fluid temperature at the exit of the channel.

Three independent calculations were performed. The first two used Gasser's and Kazimi's model[3] with Eq. (3) and Eq. (4), respectively, as the basic growth rate relations. These are here called the "existing model" and the "existing model with $(C_p \Delta T)_s$". The third calculation was performed using "simplified model" given basically by Eq. (6).

The agreement between the models and experimental data for the transient mass displacement is roughly within 5-60 per cent. The apparent discrepancy between all models and experimental data increases as the inlet temperature of the molten fluid increases. The main reason for this deviation seems to be the effect of the sensitivity of the heat balance at higher superheat levels.

### 4.2. Summary of Parametric Effects

The effects of various parameters observed on the freezing process may be briefly summarized as follows[4]:

(a) Effect of the Molten Fluid Inlet Temperature:

Results of the tests with paraffin wax and Wood's metal showed that the plugging time as well as the total mass displaced prior to plugging increased as the molten fluid inlet temperature level increased when other conditions were held constant. This result is in complete agreement with the theory.

(b) Effect of Cooling Rate:

The effect of the change in cooling rate (by changing the coolant flow rate from 18.93 liters/min to 11.35 liters/min, thereby reducing the exterior heat transfer coefficient, $h_e$, by 30%) on the paraffin wax transient freezing process was not appreciable. This was partly due to extremely low thermal conductivity of the paraffin wax which, in effect, acted as a thermal insulator when its frozen shell thickness was appreciably large. The ratios of thermal resistances of the solidified shell (when shell thickness is 0.1cm), to the tube wall, and to convective heat transfer (for 11.35 liters/min coolant flow rate) were 245:2:0.4, respectively. With respect to the Wood's metal, the present experimental data were inconclusive.

(c) Effect of Driving Pressure and the Channel Diameter:

The amount of fluid displaced is extremely sensitive to the driving pressure for the case of the molten paraffin wax whose density is very small. The effect of the driving pressure on the Wood's metal, however, was far smaller than that for the paraffin wax.

The effect of the channel diameter has been examined with paraffin wax only (by changing the test section inside diameter). The total displaced mass for smaller test section ($D_i=0.47$ cm) was between 31g and 162g (at $T_i=55-75°C$) for flowing time of 21-56 seconds, while for larger test sections it took between 24-31 seconds to displace all the initial mass charge ($\sim$1610g). Thus, there was an order of magnitiude difference in the total amount of displaced mass (for approximately the same flowing time) when the ratio of the cross-sectional area of the two test sections was only 5.6. This was mainly due to increase in average flow velocity for the larger test section[4].

## 5. Application to LMFBR Post-Accident Conditions

The mathematical model of the transient flow and freezing process[3], has been applied to the conditions which may occur in a nuclear reactor in the event of a hypothetical core disruptive accident. In the sequence of such an accident, it is predicted that molten fuel and/or stainless steel from the core will arrive at the top of the lower axial shield structure and begin to flow through the coolant channels in that structure. The shield structure is located below the blanket region in each fuel subassembly. It consists of a block of stainless steel hexagonal in cross section and containing a number of coolant flow channels. In the cases of the Clinch River Breeder Reactor which will be considered here, the shield block is approximately 50 centimeters in length and has seven one-inch diameter coolant channels arranged in a hexagonal pattern[3,4].

Some results of the analysis for fuel solidification are shown in Fig. 7. Here, a con-

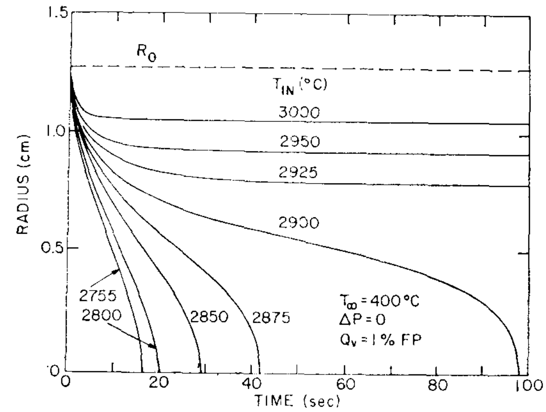


**Fig. 7. Channel Radius Versus Time for Various Molten Fuel Temperatures**

stant sink temperature of 400°C is maintained, a volumetric heat source of 1% (2.15 cal/cm$^3$-sec) of nominal CRBR full power is assumed, and flow is gravity-driven, with no static pressure difference across the flow channel. For fuel entering the channel at its freezing temperature, 2755°C, a freezing time of 16.5 seconds is predicted. Clearly,

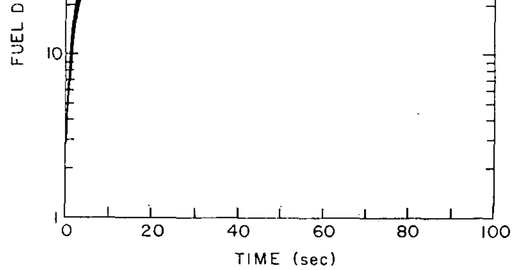


**Fig. 8. Mass of Fuel Displaced through a Single Channel as a Function of Time and Molten Fuel Temperature**

as the molten pool temperature increases, the time necessary to plug the channel increases unitl at 2900°C nearly 100 seconds are required to plug. Plugging will not occur, regradless of the length of flow time, for molten pool temperatures about 2900°C and an equilibrium solidified shell radius is reached. Increasing the initial fuel temperature results in increasing the asymptotic radius, but in addition, the results reveal that as the temperature increases, the time required to approach the asymptotic radius decreases sharply[3,4].

An estimate of the total amount of molten fuel which is displaced through a single channel in the shield structure is given in Fig. 8[3,4].

Inspection of Fig. 8 reveals that, if only one flow channel is open, at least 60% of the fuel in a single subassembly will flow through the shield. Assuming that two of the seven channels are open and fuel enters the channel at its freezing temperature, approximately 7-1/2 seconds would be required to empty the subassembly. Finally, with all seven channels clear, all the fuel in a subassembly will have exited through the shield block within less than 2 seconds regardless of the initial fuel temperature. These estimates are for the case of gravity flow. With nonzero pressure drop the quantity of displaced fuel will be considerably larger[3,4].

The potential for fuel relocation via the flowing mechanism depends to a large extent upon the condition of the shield block at the time that molten fuel arrives. If molten steel from the core contacts the shield structure prior to the time that molten fuel arrives, the shield may already be partialy or totally plugged[3,4].

## 6. Conclusions

The process of solidification of a single-phase flowing hot fluid in a cylindrical tube has been investigated analytically and experimentally to verify a model of the freezing process. Comparison of experimental data with mathematical models show that the simplified[21] as well as the existing model[3,30] for the solidification process are applicable to estimate the downward relocation rates of the molten fuel following a hypothetical core disruptive accident in an LMFBR for a wide range of conditions. The results of application of the existing model[3] to the conditions which may occur in a nuclear reactor in the event of a hypothetical core disruptive accident indicate that streaming of molten fuel through the axial shield below the pin structure in the assembly may be a very rapid mechanism for fuel downward relocation.

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