THE RATE OF DISSOLUTION
OF FUEL PARTICLES
IN MOLTEN FLOOR MATERIAL
AFTER A FAST REACTOR
CORE MELTDOWN

Battelle

Pacific Northwest Laboratories
Richland, Washington 99352

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AFTER A FAST REACTOR CORE MELTDOWN

M. J. Herbst*
NORCUS Appointee

and

G. Jansen
Chemical Technology Department*

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RICHLAND, WASHINGTON 99352

*The major portion of this work was done during the month of January 1973. M. J. Herbst is now a graduate student doing fusion research at UCLA. G. Jansen is now in the Nuclear Waste Technology Department.

TABLE OF CONTENTS

	<u>Page No.</u>
ABSTRACT	i
INTRODUCTION	1
THEORY	2
Free Convection Model	2
The Forced Convection Model	3
Model for Penetration of Fuel Particles Resting on the Pool Floor	4
RESULTS	4
Free Convection Model	4
The Forced Convection Model	8
Model for Penetration Depth of Particle Resting on Floor of Pool	13
CONCLUSIONS	19
APPENDIX I: RELEVANT MATERIAL PROPERTIES	21
APPENDIX II: DERIVATION OF EQUATIONS	22
APPENDIX III: <u>BASIC</u> LANGUAGE COMPUTER PROGRAM	26
REFERENCES	34

Errata in BNWL-B-348

On page 17, the last line in the third paragraph, which read:

"at 1100°C into the solid floor before dissolving"

should be augmented to read:

"at 1100°C into the solid floor before dissolving according to the simplified subterranean equation, but the penetration depth is limited to only 90 cm by the energy balance."

ABSTRACT

Models have been developed to predict the rate of dissolution of self-heating fast reactor fuel particles in large pools of molten floor materials. Calculations were made with simultaneous heat, mass and momentum transfer for free convection around a stationary particle, forced convection around a particle settling at its terminal velocity, and for particles which penetrate the floor of the molten pool.

The results do not support an unconditional assumption of quick dissolution of UO_2 in molten basalt, but if the particles are of sufficiently small size, and the viscosity is low enough, and the pool temperature is high enough the assumption is approached. Appreciable depths of penetration of the pool floor by resting particles were predicted.

The numerical results are completely dependent on an arbitrarily guessed value of the diffusion coefficient for UO_2 in molten basalt. There is a need for data on fuel solubility, melt viscosity, diffusion coefficient, and rate of dissolution in molten ceramics. The solubility and rate of dissolution of UO_2 in molten floor materials would be significantly increased by lowering the melt viscosity and introducing additives.

INTRODUCTION

In the event of a coolant failure in a fast reactor, one of the hypothetical situations that might be assumed to occur for the purposes of accident analysis is that the core will melt down through the reactor pressure vessel and find its way to the reactor building floor. If the core is not cooled in place, the most probable occurrence would be that the fuel would disperse into particles that would be cooled sufficiently by sodium in the case of a liquid metal cooled reactor as they lay on the core support structure or on the containment floor without further downward movement.⁽¹⁾ The work in this report is directed toward the hypothetical situation in which fuel particles are not cooled sufficiently and melt significant quantities of floor material. No attempt is made here to investigate how large molten pools might be formed or how a self-heating fuel particle might come to be suspended in a molten pool. The analysis is for a single particle in an infinite medium.

Some have claimed that the molten core would proceed to melt its way into the earth in an uncontrolled fashion,⁽²⁾ which has been called the China syndrome. A recent analysis by G. Jansen and D. D. Stepnewski⁽³⁾ indicates that the fuel might instead form a homogeneous molten pool by dissolving in the melted floor material. A critical assumption in that analysis, however, is that the core dissolves rapidly in the molten floor material; otherwise the heat-generating fission products in the fuel might be contained in a UO_2 precipitate at the bottom of the pool, increasing the penetration of the fuel into the floor.

As a test of the quick-dissolution assumption, a calculational model for the dissolution of self-heating UO_2 particles in an infinite medium of molten floor was developed. For a particle in an infinite molten pool, the true behavior would be bounded by a free convection model, which would yield longer dissolution times and by a combined free and forced convection model, which would give shorter dissolution times.

In this context a free convection model is one in which the particle is stationary, but the heat transfer and rate of dissolution are controlled by natural convection induced by density differences in the surrounding fluid. Forced convection results from the particles falling through the molten floor.

material at their terminal velocities, with the convection being caused only by the motion of the particle relative to the fluid. Combined free and forced convection includes both of these effects, although they are not necessarily additive.

Only the free convection model is developed in detail here, although sufficient calculations were made with the forced convection model to estimate the settling depth at complete dissolution. Additional calculations were made to determine dissolution times and penetration depths with the particles resting on the pool floor.

THEORY

Free Convection Model

The particles in this analysis are assumed to be stationary and to have spherical symmetry, and the transfer coefficients as developed in Appendix II are mean values applicable over the entire particle surface. The fission products are assumed to be distributed uniformly throughout the particles, and as dissolution proceeds the heat generation rate within the particles varies both due to fission product decay with time and loss of particle mass with accompanying fission products. No allowance is made for diffusion of fission products out of or away from the fuel particle except through dissolution of the fuel itself. The surrounding pool is assumed to be at constant temperature during dissolution, and gross convection patterns not due to the particle itself are omitted. Neither of these conditions exist during a meltdown.

At any given time, then, a steady-state temperature profile is deduced from the condition that any heat being generated within the particle is being transported away. The temperature of the fluid film at the particle surface is assumed to be an arithmetic mean of the particle surface temperature and the ambient molten floor temperature, and fluid properties relevant to transport are calculated for the film temperature. Both mass density and thermal conductivity of the molten floor are assumed constant, as are the corresponding properties for the fuel particle.

To calculate mass transfer rates, it is assumed that the concentration of fuel at the particle surface is the saturation concentration of the fuel in molten floor at the particle surface temperature, and that the ambient concentration is zero. Since the mass transfer rate also depends on the

time history of the surface concentration, it is assumed at each point in time that the surface concentration calculated for that time has been the surface concentration for all previous time. As the surface temperature and surface concentration decrease with time, this serves to decrease calculated mass transfer rates, or increase dissolution times.

No reliable data could be found for the diffusion coefficient of fuel in molten basalt, though for sodium diffusion in solid SiO_2 glass near its melting point one of $10^{-5} \text{ cm}^2/\text{sec}$ had been measured.⁽⁴⁾ To be more consistent with other existing data on diffusion coefficients in high viscosity fluids, and to obtain an estimate of dissolution times, a diffusion coefficient of 10^{-6} to $10^{-8} \text{ cm}^2/\text{sec}$ is assumed to vary inversely with molten floor viscosities in the range 10 to 10^3 poise. This range of diffusion coefficients gives dissolution times of the same order as McCormack's experiments.⁽⁹⁾

For purposes of initializing the heat generation rate, the fuel is assumed to contact the floor 5 hours after cessation of fission in a 3000-kg core, after goal exposure of 100,000 MWd/MT at 400 MW(th).

The Forced Convection Model

The forced convection model uses the same assumptions as the free convection model except that the particle is a single sphere settling through the molten pool at a terminal velocity estimated from its current size. This pool might be formed by melting of an entire core, with the assumptions of Reference 3. The correlations for heat transfer, mass transfer, and sphere motion (given in Appendix II) were all taken from Bird, Stewart and Lightfoot⁽⁵⁾ and are suitable for simultaneous heat and mass transfer with constant surface temperature and concentration and small mass transfer rates. The total distance the particles settled was found by integrating the current terminal velocity over the particle dissolution time. No allowance was made for gross convection patterns in the pool or interparticle hindrance.

Investigations of simultaneous heat and mass transfer have shown that under some conditions both free convection and forced convection must be considered. Indeed, it has been shown that their interaction is quite complex and that they are by no means additive.⁽⁶⁾

Model for Penetration of Fuel Particles Resting on Pool Floor

A device called the subterrene has been developed at Los Alamos Scientific Laboratory for melting holes in rock.⁽⁷⁾ It consists of a heater that moves downward under hydraulic pressure as it melts the rock. The rate of penetration is dependent only on the power of the heater per unit cross-sectional area of the hole and the rock properties.⁽⁸⁾ The hole is usually somewhat larger than the particles because of a peripheral melt zone. The conduction heat losses are significant, even though the surrounding rock is an excellent insulator, and are taken into account by loss factors. Self-heating fuel particles penetrating basalt are like subterrines with the penetration rate directly proportional to the particle size. To estimate the penetration depth at total dissolution of the particle, the rate of dissolution from the free convection model was combined with the rate of penetration taken from subterrene theory (see Appendix II). Because the subterrene equation assumes the heat supply is always sufficient to keep the particle surface at the melting point of basalt, an energy balance was also performed on the particle to put an additional restriction on the maximum *depth*.

RESULTS

Free Convection Model

In Figures 1 and 2, the times of dissolution of UO_2 in molten basalt are plotted as functions of the initial particle radius and ambient molten floor temperature. The simple variation with a power of the radius below 0.1 cm is easily explained by the fact that the steady-state temperature profiles for these small particles is flat, as shown later in Table I. Thus, the surface temperatures are all the same, and the mass transfer rates vary with the transfer area, which is proportional to R^2 , while the masses to be transferred vary as R^3 . For larger radii, the times increase less rapidly, showing that the effect of self-heating is to increase the temperature of the fluid film at the particle surface and thereby increase mass transfer rates. Particles larger than 3 to 5 cm may have steady-state center temperatures above the boiling point of UO_2 (3750°C) and may break up into smaller particles. This size limit is indicated to the upper right in Figure 1. Since the exponential variation of viscosity with reciprocal temperature is the dominating temperature dependence, it is not surprising that in Figure 2 the dissolution times also vary exponentially with reciprocal temperature.

FIGURE 1 TIME OF DISSOLUTION AS A FUNCTION OF INITIAL PARTICLE RADIUS AT CONSTANT AMBIENT BASALT TEMPERATURE

FIGURE 2 TIME OF DISSOLUTION AS A FUNCTION OF AMBIENT BASALT TEMPERATURE AT CONSTANT INITIAL PARTICLE RADIUS

TABLE I.

COMPARISON OF FREE CONVECTION MODEL WITH
FORCED CONVECTION MODEL FOR HEAT AND MASS TRANSFER
FROM UO_2 PARTICLES

Initial Particle Radius, cm	Ambient Pool Tempera- ture, °C	Free Convection Around Stationary Particle			Convection Caused Only By Particle Settling At Its Terminal Velocity		
		Initial Temperature at Particle Surface, °C	at Center of Particle, °C	Time to Dissolve Particle, hr	Initial Temperature at Particle Surface, °C	Time to Dissolve Particle, hr	Depth of Settling of Particle, cm
0.001	1100	1100	1100	0.0024	1100	1.4	0.00353
0.01	1100	1100	1100	0.23	1100	137.	33.
0.1	1100	1100	1100	23.3	1100	6880.	1.4×10^5
1.0	1100	1218	1290	1390.	1174	32,700.	7.2×10^7
3.95	1100	1739	2880*	6870.	1265	43,500.	2.0×10^9
5.0	1100	1874	3700*	8030.	1299	48,000.	3.6×10^9
5.06	1100	1880	3750*	----	1300	----	----
0.001	2300	2300	2300	1.1×10^{-6}	2300	6.6×10^{-6}	1.6×10^{-4}
0.01	2300	2300	2300	1.0×10^{-4}	2300	3.3×10^{-4}	0.78
0.1	2300	2300	2300	7.3×10^{-3}	2300	3.5×10^{-3}	240
1.0	2300	2336	2409	0.25	2303	0.044	2×10^4
2.54	2300	2410	2880*	----	2315	0.16	1.1×10^5
4.16	2300	2486	3750*	----	2325	0.35	2.9×10^5

* The melting point of UO_2 is about 2880°C and the boiling point is about 3750°C. The particle center temperature was calculated assuming conduction through solid UO_2 .

One point on which experimental data is sparse and inconsistent is the solubility of the fuel in molten basalt. To determine the effect of solubility variation, runs made with the calculated solubility data used by Jansen and Stepnewski, which were supported by limited experiments by McCormack at the Hanford Engineering Development Laboratory,⁽⁹⁾ were compared with runs made using experimental solubility data measured by Fischer, Mrazek, and Chasanov of Argonne National Laboratory which indicated much lower solubility.⁽¹⁰⁾ The solubility data of the two groups are compared in Figure 3, and in Figure 4 are the results of the two computer runs. The high sensitivity of the results to solubility variation can be explained by the assumed mass transfer boundary condition, which makes the mass transfer rate directly proportional to the solubility. Although the Argonne data represent a greater experimental effort, they were not used in developing the remainder of the results. They would have given longer dissolution times in all cases.

A last point of interest was the effect on dissolution times of varying the floor material. Substituted into the model were viscosity relations for olivine-basalt and synthetic fayalite as well as for a sodium silicate glass with 44.6 weight percent SiO_2 . All other material properties were assumed to remain the same, except that for the sodium silicate runs were made down to ambient temperatures of 1000°C , the melting point of that substance. Results of these runs are plotted in Figure 5, again illustrating the strong dependence of dissolution times on viscosity. The effect of changing the diffusion coefficient, but not the viscosity, is shown in Figure 6. Further comparisons between these materials were not made because the difference in solubility of UO_2 in the various solvents is unknown.

The Forced Convection Model

The results of calculations using the forced convection model with particles at terminal settling velocity are compared with the free convection model results for stationary particle in Table I. The dissolution times are much longer for the moving particle in an 1100°C ambient pool at the melting point of basalt, although they are somewhat shorter at 2300°C . Particles greater than 0.01 cm radius at 1100°C and 0.03 cm radius at 2200°C settle farther than 30 cm before dissolving.

FIGURE 3 SOLUBILITY OF UO_2 IN BASALT

FIGURE 4 TIME OF DISSOLUTION AS A FUNCTION OF AMBIENT BASALT TEMPERATURE-EFFECT OF ASSUMED SOLUBILITIES

FIGURE 5 TIME OF DISSOLUTION AS A FUNCTION OF AMBIENT TEMPERATURE-COMPARISON OF VARYING VISCOSITY MATERIALS FOR $R=1\text{cm}$

FIGURE 6 TIME OF DISSOLUTION AS A FUNCTION OF AMBIENT TEMPERATURE - EFFECT OF UO_2 DIFFUSION COEFFICIENT BASALT, $R = 1 \text{ cm}$

Self-heating begins to raise the initial temperature of the particle significantly above the ambient pool temperature in the particle radius range 0.1 to 1.0 cm for both forced and free convection, but the rise is less for forced convection. This is somewhat puzzling because it seems to indicate that forced convection is more effective in promoting heat transfer than free convection but it is less effective in promoting mass transfer.

Since the free convection field appears far more important at basalt melting temperatures than the convection generated by the particle settling at its terminal velocity, a combination of free convection heat and mass transfer with settling velocities was used for further calculation.

Model for Penetration Depth of Particle Resting on Floor of Pool

In the analysis of pool formation,⁽³⁾ depth of molten basalt up to 500 cm were predicted. In the absence of gross convection patterns in the pool, particles larger than about 0.03 cm to 0.3 cm radius would then fall to the floor of the molten pool before dissolving completely and rest on it as shown in Figure 7. The dissolution times are estimated by the free convection models.

The depth of penetration of a dissolving particle into the floor was estimated by the subterrene equation in Appendix II,⁽⁸⁾ which assumes that a heat supply is always available to keep the UO_2 particle surface at the melting point of basalt. In reality, an energy balance on the particle is required to determine whether it is frozen into the basalt.⁽¹⁹⁾ An advancing temperature profile exists below the molten pool as shown in Figure 8. The maximum penetration given by the energy balance is typical of a heat generating particle riding along the advancing profile. As the local ambient temperature increases, the particle melts the basalt and descends to a region where the local ambient temperature is lower. The equations for this phenomenon are developed in Appendix II, and the maximum depth is shown for various times after the core hits the floor in Figure 9. For large particles there is no maximum depth without dissolution because the temperature rise around the self-heating particle is sufficient to raise the particle temperature from 100°C ambient to the melting point. Because heat generation rate decreases with time because of radioactive decay, the particle size for which there is no maximum depth increases with time.

FIGURE 7. SETTLING DEPTH OF UO_2 PARTICLES INTO MOLTEN BASALT

FIGURE 8 TEMPERATURE PROFILES IN BASALT BENEATH MOLTEN POOL

FIGURE 9 MAXIMUM DEPTH ATTAINABLE FROM ENERGY BALANCE ON PARTICLE

In Figure 10, the estimated penetration depth of particles resting on the pool floor from the time of the incident (starting 5 hours after meltdown) estimated by the subterrene equation are presented. The maximum depth attainable (for 1000 hr from Figure 9) is also shown. The dissolution times for both cases are estimated by the free convection model. With the melted basalt around the particle at 1100°C , particles with radii of 1.5 cm will penetrate 500 cm into the floor according to the simplified subterrene equation, but the energy balance limits its maximum penetration to only 12 cm. Because of the shorter dissolution times at 2300°C , particles with radii as great as 7 cm will only penetrate 500 cm into the floor according to the simplified subterrene equation but with no limitation imposed by the energy balance. What the temperature really is at the surface of a dissolving particle penetrating a solid floor and what concentration driving force should be used to the bulk fluid around the particle is not clear without a more complete model. A more accurate analysis could be obtained by using more detailed computer programs developed for the subterrene.⁽²⁰⁾

Settling depths and dissolution times up to a particle size for which the surface of particle reaches the melting point of UO_2 have been estimated. Particles with radii larger than this (20 cm at 1100°C and 15 cm at 2300°C) would surely not survive because molten UO_2 is miscible with basalt in all proportions at the melting point of UO_2 . (Actually the molten basalt would boil locally at the particle surface at about 2300°C , and the resultant rapid heat removal would prevent further surface temperature rise.) Particles with radii larger than 2.5 cm at 2300°C or 4.0 cm at 1100°C would have a molten core due to self-heating above the 2880°C melting point of UO_2 . At this melting threshold, particles would penetrate 2.7 cm at 2300°C and 12,900 cm at 1100°C into a solid floor before dissolving.

If no internal convection takes place in the molten core, the center of particles with a greater radius than 5.06 cm at 1100°C and 4.16 cm at 2300°C would exceed the boiling point of UO_2 (3750°C). If the internal pressure were not relieved in any other way (such as by flow-through pores) larger UO_2 particles than this would crack apart. An additional factor that should be considered in this particle size range is nuclear criticality, i.e., a 5.0 cm radius particle would have a mass of 4.6 kg of which about 20% is PuO_2 .

FIGURE 10 PENETRATION DEPTH OF UO_2 PARTICLES INTO SOLID BASALT

CONCLUSIONS

Methods for estimating the dissolution times and penetration depths of self-heating UO_2 in molten basalt have been developed for free convection around stationary particles, forced convection around particles in free fall, and particles resting on the floor of a molten pool.

The numerical results presented here should be regarded only as indicating trends because they are based on a value of the UO_2 diffusion coefficient in molten ceramics that was an order of magnitude guess.

This report investigates the assumption of quick dissolution as utilized by Jansen and Stepnewski.⁽³⁾ What is shown is that if the core comes down in particles of sufficiently small size and if the pool temperature and/or floor material are such that the pool viscosity does not restrict transport coefficients, then such an assumption may be justified. The model used in this analysis gives conservatively long dissolution times, and a combined free and forced convection analysis merits further attention so that the real case for a single particle in an infinite medium may be bounded.

Particles of sufficient size can penetrate considerable distances into a solid floor. It is doubtful whether such large particles can be formed without the center of the particle reaching the boiling point of UO_2 and pressurizing the particle, causing it to crack apart.

Although many inaccuracies are present in the model as constructed, the most serious defect is the lack of data. Solubility data for UO_2 in floor material disagree by an order of magnitude. The viscosity of candidate melts is unknown over most of the region of interest, especially above 1400°C . Diffusion coefficients for UO_2 cannot reliably be estimated within several orders of magnitude. Except for McCormack's crude estimates, we know of no data on the rate of dissolution of UO_2 in any molten ceramics at any temperature. We know of no data on the rate of settling of UO_2 particles in molten ceramics. The rate of leaching of heat-generating fission products from UO_2 particles in ceramics is unknown. Heat and mass transfer correlations must be used far outside the range of the data upon which they are based.

Of course, theoretical simulations are limited in value and it is hoped that an experimental analysis of the dissolution of core in various sacrificial materials will eventually be performed.

There appears to be appreciable incentive for lowering the viscosity of candidate floor materials and to introduce specific chemical additives to reduce the UO_2 particle dissolution time.

APPENDIX I: RELEVANT MATERIAL PROPERTIES

Solid UO_2 :

mass density:⁽¹³⁾ 8.8 g/cm³

thermal conductivity:⁽¹³⁾ 8.25×10^{-3} cal/sec-cm-°C

Molten Basalt:

melting point:⁽³⁾ 1100°C

mass density:⁽¹⁴⁾ 2.4 g/cm³

thermal conductivity:⁽¹⁴⁾ 4×10^{-3} cal/sec-cm-°C

heat capacity:⁽¹⁴⁾ 0.30 cal/g-°C

thermal expansion coefficient:⁽³⁾ 3.2×10^{-5} °C⁻¹

concentration expansion coefficient:⁽³⁾ $3.1 \times UO_2$

viscosity:⁽¹⁵⁾ $(8.327 \times 10^{-6})\exp(26084/T)$, T in °K, poise

Synthetic Fayalite:

viscosity:⁽³⁾ $(2.692 \times 10^{-3})\exp(12359.8/T)$, T in °K, poise

Olivine-Basalt:

viscosity:⁽³⁾ $(4.2658 \times 10^{-17})\exp(63912.3/T)$, T in °K, poise

Sodium Silicate Glass:

viscosity:⁽¹¹⁾ $(5.37 \times 10^{-4})\exp(12000/T)$, T in °K, poise

Diffusion coefficient of UO_2 : UNKNOWN. Assumed to be 10^{-6} cm²/sec

at a viscosity of 10 poise and to vary inversely with the viscosity of the melt. The sensitivity of the results to diffusion coefficient

is shown indirectly by showing the sensitivity of the results to viscosity, to which it is tied by an assumed arbitrary constant factor.

APPENDIX II: DERIVATION OF EQUATIONS

Free Convection Model

From the given properties in Appendix I and the assumed diffusion coefficient, one can readily verify that the Prandtl and Schmidt numbers will be in the following range:

$$\text{Pr: } 7 \times 10^2 \text{ to } 7 \times 10^4$$

$$\text{Sc: } 4 \times 10^6 \text{ to } 4 \times 10^{10}$$

In a NASA STAR abstract,⁽¹⁶⁾ a free convection heat transfer correlation is suggested for small particles with Prandtl numbers ranging from 0.7 to 10^5 :

$$\text{Nu}_H = \text{Nu}_H^0 + 0.45(\text{PrGr})^{1/4}$$

where Nu_H^0 is the limiting Nusselt number. A similar correlation for simultaneous heat and mass transfer in free convection, but from flat plates, is given by Lightfoot, Massot, and Irani⁽¹⁷⁾ as:

$$\text{Nu}_H \propto (\text{Gr}_H + (\text{Pr}/\text{Sc})^{1/2} \text{Gr}_D)^{1/4} \text{Pr}^{1/4} / (1 + (0.95/\text{Pr}))^{1/4}$$

$$\text{Nu}_D = (\text{Sc}/\text{Pr})^{1/2} \text{Nu}_H$$

for Pr large and $\text{Pr} \ll \text{Sc}$ (heat transfer controlled). From these two can be inferred a simultaneous heat and mass transfer correlation from spheres in the form:

$$\text{Nu}_H = \text{Nu}_H^0 + \text{const.} (\text{Gr}_H + (\text{Pr}/\text{Sc})^{1/2} \text{Gr}_D)^{1/4} \text{Pr}^{1/4} / (1 + (0.95/\text{Pr}))^{1/4}$$

$$\text{Nu}_D = (\text{Sc}/\text{Pr})^{1/2} \text{Nu}_H$$

For this case, the term $0.95/\text{Pr}$ is essentially zero because of the magnitude of the Prandtl numbers, and the constant was chosen after inspection of

many of these correlations to be 0.5. In addition, if the diameter of the sphere is used in the Nusselt number, the limiting Nusselt number is 2. So:

$$\begin{aligned} Nu_H &= 2 + 0.5(Gr_H + (Pr/Sc)^{1/2} Gr_D)^{1/4} Pr^{1/4} \\ Nu_D &= (Sc/Pr)^{1/2} Nu_H \end{aligned}$$

The free fall settling times used with the free convection models are estimated using the equations for terminal settling velocities given in the forced convection model below.

Forced Convection Model

The friction factor correlations for steady flow around a sphere given by Bird, Stewart and Lightfoot⁽⁵⁾ for the different flow regimes (BSL p. 182, p. 192) are solved for the terminal settling velocities (BSL nomenclature).

$$v_\infty = \frac{1}{18} \frac{gd^2}{\mu_f} (\rho_s - \rho) \quad Re < 1$$

$$v_\infty = 0.153 \left[\frac{gd^5}{\mu^3} \frac{(\rho_s - \rho)}{\rho^2} \right]^{1/4} \quad 1 \leq Re < 10^3$$

$$v_\infty = \left[6.06gR \left(\frac{\rho_s - \rho}{\rho} \right) \right]^{1/2} \quad Re \geq 10^3$$

The forced convection heat transfer coefficient for a single sphere is

$$\frac{h_\infty d}{k_f} = 2.0 + 0.60 \left(\frac{dv_\infty \rho_f}{\mu_f} \right)^{1/2} \left(\frac{C_p \mu}{k} \right)_f^{1/3} \quad (\text{BSL p. 409})$$

The mass transfer coefficient is:

$$\frac{k_{xm} d}{\rho_f D_{AB} f} = 2.0 + 0.60 \left(\frac{dv_\infty \rho_f}{\mu_f} \right)^{1/2} \left(\frac{\mu}{\rho D_{AB}} \right)_f^{1/3} \quad (\text{BSL p. 647})$$

This is good for simultaneous heat and mass transfer with constant surface temperature and concentration at small mass transfer rates. (BSL p. 648)

Model for Penetration of Fuel Particles
Resting on Pool Floor

The theory of the subterranean penetration rate is given by Gido. (8)

$$V = \frac{\dot{E}_H}{\rho_m \Delta H_m A_m} \left(\frac{1}{1 + \eta_C + \eta_R} \right)$$

where V is the velocity of penetration, $\dot{E}_H$ is the heater power, ρ_m is the basalt density, ΔH_m is the enthalpy change of basalt from ambient to superheated melt, A_m is the cross-sectional area of the melted basalt, η_C is the inefficiency factor due to heat losses to the subterranean coolant and η_R is the inefficiency factor due to losses to ambient rock. Gido correlated the experimental results for a 51 mm-diameter subterranean melting a 76 mm-diameter hole by

$$V = 3.64 \times 10^{-5} \dot{E}_H$$

where

V is the penetration velocity in cm/sec and

$\dot{E}_H$ is the power in cal/sec and the inefficiency η_C averaged 1.0 and $\eta_R = 0.4$.

Since the power per unit cross-sectional area in a fuel particle is directly proportional to the diameter of the particle, the particle penetration rate is also directly proportional to the particle diameter. The above equation was used directly although it can be argued that the melt left behind the particle should have an inefficiency much less than the value of η_C for the subterranean. A more detailed treatment of heat losses from subterraneans as a function of size has been given by Murphy and Gido. (18)

Implicit in the simplified subterranean equation is the assumption that enough heat is supplied to keep the basalt at the surface of the penetration and its melting point. This is not necessarily true for smaller particles because heat generation decreases inversely with the cube of the radius and the area for heat conduction varies inversely with the square of the radius. Eventually the particle gets so small that it freezes in place.

For a particle surrounded by basalt of temperature T_0 , the particle radius, or at which freezing would occur is defined by

$$T_M = \frac{S(t)a^2}{3K} + T_0$$

where T_M is the melting point of basalt, $S(t)$ is the time varying volumetric heat generation rate within the UO_2 particles and K is the thermal conductivity of basalt. The ambient temperature of the basalt is not T_0 because a temperature profile moves downward ahead of the molten pool. An approximate expression using the stationary spherical front model from Reference (3) is given by

$$T_M = \frac{S(t)a^2}{3K} + (T_M - T_0) \operatorname{erfc} \frac{X}{2\sqrt{\alpha(t-t_0)}}$$

Where X is the depth beneath the pool bottom at which the particle is located, α is the thermal diffusivity of basalt, t is the time since the UO_2 core has contacted the floor, and t_0 is the time the stationary front model becomes applicable (at about $t = 40$ hr). Solving for the radius a allows the maximum penetration depth to move along with the temperature profile.

$$a = \sqrt{\frac{3K}{S(t)} (T_M - T_0) \operatorname{erf} \left(\frac{X}{2\sqrt{\alpha(t-t_0)}} \right)}$$

A more accurate analysis could be obtained by using more detailed computer programs developed for the subterranean.⁽²⁰⁾

APPENDIX III. BASIC LANGUAGE COMPUTER PROGRAMS

CONV3 - Program for the free convection model

Sample output from CONV3

FALL1 - Statements to merge into CONV3 to estimate settling depth during dissolution by the free convection model

REST1 - Statement to merge into CONV3 + FALL1 to estimate penetration depth into solid floor

FORC1 - Program for forced convection model

Sample output from FORC1

CONV3

```

10 DIM X(100)
20 DIM Y(100)
30 DATA .1,.2,.3,.4,.5,.6,.7,.8,.9,1,1.2,1.4,1.6,1.8,2,3,4,5,6,7,8
40 DATA 9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,30,36,42
50 DATA 48,72,96,120,144,168,192,216,240,264,288,312,336,360,384,408
60 DATA 432,456,480,504,528,552,576,600,624,648,672,696,720,744,768,792,816,840,864,888,912,936,960,984,1008,1032,1056,1080,1104,1128,1152,1176,1200,1224,1248,1272,1296,1320,1344,1368,1392,1416,1440,1464,1488,1512,1536,1560,1584,1608,1632,1656,1680,1704,1728,1752,1776,1800,1824,1848,1872,1896,1920,1944,1968,1992,2016,2040,2064,2088,2112,2136,2160,2184,2208,2232,2256,2280,2304,2328,2352,2376,2400,2424,2448,2472,2496,2520,2544,2568,2592,2616,2640,2664,2688,2712,2736,2760,2784,2808,2832,2856,2880,2904,2928,2952,2976,3000,3024,3048,3072,3096,3120,3144,3168,3192,3216,3240,3264,3288,3312,3336,3360,3384,3408,3432,3456,3480,3504,3528,3552,3576,3600,3624,3648,3672,3696,3720,3744,3768,3792,3816,3840,3864,3888,3912,3936,3960,3984,4008,4032,4056,4080,4104,4128,4152,4176,4200,4224,4248,4272,4296,4320,4344,4368,4392,4416,4440,4464,4488,4512,4536,4560,4584,4608,4632,4656,4680,4704,4728,4752,4776,4800,4824,4848,4872,4896,4920,4944,4968,4992,5016,5040,5064,5088,5112,5136,5160,5184,5208,5232,5256,5280,5304,5328,5352,5376,5400,5424,5448,5472,5496,5520,5544,5568,5592,5616,5640,5664,5688,5712,5736,5760,5784,5808,5832,5856,5880,5904,5928,5952,5976,6000,6024,6048,6072,6096,6120,6144,6168,6192,6216,6240,6264,6288,6312,6336,6360,6384,6408,6432,6456,6480,6504,6528,6552,6576,6600,6624,6648,6672,6696,6720,6744,6768,6792,6816,6840,6864,6888,6912,6936,6960,6984,7008,7032,7056,7080,7104,7128,7152,7176,7200,7224,7248,7272,7296,7320,7344,7368,7392,7416,7440,7464,7488,7512,7536,7560,7584,7608,7632,7656,7680,7704,7728,7752,7776,7800,7824,7848,7872,7896,7920,7944,7968,7992,8016,8040,8064,8088,8112,8136,8160,8184,8208,8232,8256,8280,8304,8328,8352,8376,8400,8424,8448,8472,8496,8520,8544,8568,8592,8616,8640,8664,8688,8712,8736,8760,8784,8808,8832,8856,8880,8904,8928,8952,8976,9000,9024,9048,9072,9096,9120,9144,9168,9192,9216,9240,9264,9288,9312,9336,9360,9384,9408,9432,9456,9480,9504,9528,9552,9576,9600,9624,9648,9672,9696,9720,9744,9768,9792,9816,9840,9864,9888,9912,9936,9960,9984,10000
82 DATA 5555,8333,11111,13889,16667,19444,22222,25000,27778
90 FOR I=1 TO 96
100 READ X(I)
110 NEXT I
120 DATA 25.619,21.867,19.959,18.313,17.131,16.221,15.490,14.884
130 DATA 14.367,13.919,13.177,12.580,12.085,11.665,11.302,10.039
140 DATA 9.326,8.808,8.406,8.080,7.808,7.553,7.320,7.116,6.935,6.772
150 DATA 6.625,6.491,6.367,6.254,6.149,6.051,5.960,5.874,5.793,5.718
160 DATA 5.646,5.253,4.908,4.635,4.410,3.791,3.358,3.023,2.774,2.579
170 DATA 2.421,2.291,2.179,2.084,1.995,1.911,1.837,1.770,1.709,1.655
180 DATA 1.605,1.559,1.516,1.477,1.266,1.122,.9958,.9003,.8251,.7369
190 DATA .7131,.6700,.6330,.6007,.5723,.5471,.5245,.5001,.4740,.4505
200 DATA .4293,.4101,.3926,.3765,.3618,.3481,.3356,.3239,.3130,.3028
210 DATA .2934
211 DATA .270,.176,.129,.100,.077,.061,.050,.043,.040
220 FOR I=1 TO 96
230 READ Y(I)
240 NEXT I
242 PRINT USING 243
243: FUEL HITS FLOOR FIVE HOURS AFTER MELTDOWN
245 T3=1375
246 V3=8.327E-6*AE+(26084/T3)
247 PRINT USING 248, T3,V3
248: AMBIENT BASALT TEMP=#### DEG K AND VISCOSITY=###!!!! POISE
250 READ P,PI,G,C,K,K1,R
260 DATA 2.4,8.8,980,0.30,4E-3,8.25E-3,3.24E-5
270 DIM R(10)
280 FOR I=1 TO 4
290 READ R(I)
300 DATA 0.05,3.5,5.0,7.5
301 NEXT I
302 I=1
310 R=R(I)
315 M=4*PI*PI*(R13)/3
320 PRINT USING 330,R
330: R=###.### CM
331 PRINT USING 332
332: T(HR)      R(CM)      M(G)      TO(K)      TI(K)      Q(CAL/S)      DMASS(G/S)
333 IF R>=1.00 GO TO 636
334 D2=M/10
340 T=5
350 D=0.1
360 GO TO 640
370 Q=Q0*M
380 TI=1375
390 S=50
395 T4=(TI+1375)/2
400 V=8.327E-6*AE+(26084/T4)
410 D2=D2+V
420 X=AE*(2*(1-(3153/TI)))
430 A=0.5*(Q0*(K13)*(PI2)/R)+(0.25)
440 LI=B*(TI-1375)

```

```

450 L2=P*(C*P*3.09*(X12)/K
455 IF L1+L2<0 GO TO 631
460 F=(L1+L2)*(0.25)
470 Y=V*(0.25)
480 H=(A*F/(2*Y))+(K/R)
490 Q1=H*4*PI*(R12)*(T1-1375)
500 IF Q1<Q GO TO 631
510 IF S>2 GO TO 633
520 T0=T1+(Q-Q1*PI*(R12))/(3*K1)
530 A1=((P*P)/(Y*C))*(0.5)
540 K2=A1*K
550 M=K2*4*PI*(R12)*X
551 PRINT USING 552, T, P, M, T0, T1, Q, M1
552:###.## #.##### #.##### #.##### #.#####
560 IF M1*D<3600<M2 GO TO 615
570 T=T+D
580 M=M-M1*D<3600
590 IF M<0 GO TO 617
600 R=((0.75*M)/(&PI*P1))*(1/3)
610 GO TO 640
615 D=D+5
616 GO TO 570
617 T5=T-5+M/(M1*3600)
618 PRINT USING 619, T5
619: TIME OF DISSOLUTION IS ###.#### HOURS AFTER FUEL HITS FLOOR
620 IF I=4 GO TO 630
621 I=I+1
622 GO TO 310
630 END
631 T1=T1+S
632 GO TO 395
633 S=S/2
634 T1=T1-S
635 GO TO 395
636 P2=M/5
637 GO TO 340
640 IF T>X(1) GO TO 670
650 Q0=Y(1)*2.33E-2
660 GO TO 370
670 FOR N=2 TO 96
680 IF T>X(N) GO TO 720
690 Q0=Y(N-1)+(T-X(N-1))*(Y(N)-Y(N-1))/(X(N)-X(N-1))
700 Q0=Q0*2.33E-2
710 GO TO 370
720 NEXT N
725 PRINT USING 726
726: TIME OF DISSOLUTION IS GREATER THAN 27778 HOURS
727 IF I=4 GO TO 730
728 I=I+1
729 GO TO 310
730 END
READY

```

SAMPLE OUTPUT FROM CONV3

CONV3

FUEL HITS FLOOR FIVE HOURS AFTER MELTDOWN

AMBIENT BASALT TEMP=1375 DEG K AND VISCOSITY=1.44E+03 POISE

R= .050 CM

T(HR)	R(CM)	M(G)	TO(K)	TI(K)	Q(CAL/S)	DMASS(G/S)
5.00	5.0E-02	4.6E-03	1377	1377	9.5E-04	2.8E-07
5.50	4.8E-02	4.1E-03	1377	1377	8.2E-04	2.7E-07
6.00	4.6E-02	3.6E-03	1377	1377	7.1E-04	2.6E-07
6.50	4.4E-02	3.2E-03	1377	1377	6.1E-04	2.5E-07
9.00	2.9E-02	9.4E-04	1377	1377	1.7E-04	1.6E-07

TIME OF DISSOLUTION IS 5.59E+00 HOURS AFTER FUEL HITS FLOOR

R= 3.500 CM

T(HR)	R(CM)	M(G)	TO(K)	TI(K)	Q(CAL/S)	DMASS(G/S)
5.00	3.5E+00	1.6E+03	2842	1948	3.2E+02	2.4E-03
5.50	3.5E+00	1.6E+03	2813	1941	3.2E+02	2.3E-03
8.00	3.5E+00	1.6E+03	2689	1905	2.8E+02	1.8E-03
20.50	3.4E+00	1.5E+03	2384	1811	2.0E+02	9.7E-04
83.00	3.2E+00	1.3E+03	1978	1666	1.0E+02	3.2E-04
395.50	2.9E+00	8.9E+02	1630	1514	3.5E+01	8.2E-05
1958.00	2.3E+00	4.3E+02	1445	1417	6.4E+00	2.4E-05

TIME OF DISSOLUTION IS 6.81E+03 HOURS AFTER FUEL HITS FLOOR

R= 5.000 CM

T(HR)	R(CM)	M(G)	TO(K)	TI(K)	Q(CAL/S)	DMASS(G/S)
5.00	5.0E+00	4.6E+03	3971	2147	9.5E+02	1.3E-02
5.50	5.0E+00	4.6E+03	3913	2136	9.2E+02	1.2E-02
8.00	5.0E+00	4.5E+03	3679	2092	8.1E+02	9.3E-03
20.50	4.8E+00	4.1E+03	3096	1970	5.6E+02	4.4E-03
83.00	4.4E+00	3.1E+03	2342	1775	2.6E+02	1.1E-03
395.50	3.7E+00	1.8E+03	1754	1566	7.2E+01	1.8E-04
1958.00	2.8E+00	8.4E+02	1477	1434	1.3E+01	3.8E-05

TIME OF DISSOLUTION IS 8.03E+03 HOURS AFTER FUEL HITS FLOOR

R= 7.500 CM

T(HR)	R(CM)	M(G)	TO(K)	TI(K)	Q(CAL/S)	DMASS(G/S)
5.00	7.5E+00	1.6E+04	6505	2400	3.2E+03	8.4E-02
5.50	7.5E+00	1.5E+04	6371	2386	3.1E+03	7.9E-02
8.00	7.4E+00	1.5E+04	5833	2330	2.7E+03	5.9E-02
20.50	6.9E+00	1.2E+04	4490	2166	1.7E+03	2.3E-02
83.00	5.7E+00	6.8E+03	2848	1888	5.7E+02	3.5E-03
395.50	4.3E+00	2.9E+03	1859	1605	1.1E+02	3.0E-04
1958.00	3.2E+00	1.2E+03	1499	1445	1.8E+01	4.9E-05

TIME OF DISSOLUTION IS 8.61E+03 HOURS AFTER FUEL HITS FLOOR

NOW AT 630

READY

FALL1

```

300 DATA .001,.01,.1,1
332: T(HR)      R(CM)      M(G)      TO(K) TI(K) Q(CAL/S) DMASS(G/S) X(CM)
350 D=.1*R(I)
412 VO=2*G*(R+2)*(P1-P)/(9*V)
413 IF 2*R*VO+P/V<1 GO TO 417
414 VO=3.37E-1*((G+5)*(R+2)*((P1-P)+5)/((V+3)*(P+2)))+(1/7)
415 IF 2*R*VO+P/V<1000 GO TO 417
416 VO=(6.06*G*(P1-P)/P)+(0.5)
417 CONTINUE
545 X1=X1+ VO*D*3600
551 PRINT USING 552, T,R,M,TO,TI,Q,M1,X1
552: ###.## #.#####.#####.#####.#####.#####.#####
620 X1=X1+((3600*D)+(M/M1))*VO
621 PRINT USING 622,X1
622: PENETRATION DEPTH IS #.##### CM
623 IF I=4 GO TO 630
624 I=I+1
625 GO TO 310
READY

```

REST1

```

417 VO=.0870*Q/238.9/10
READY

```

FORC1

```

10 DIM X(100)
20 DIM Y(100)
30 DATA .1,.2,.3,.4,.5,.6,.7,.8,.9,1,1.2,1.4,1.6,1.8,2,3,4,5,6,7,8
40 DATA 9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,30,36,42
50 DATA 48,72,96,120,144,168,192,216,240,264,288,312,336,360,384,408
60 DATA 432,456,480,504,528,552,576,600,624,648,672,696,720,744,768,792,816,840,864,888,912,936,960,984,1008,1032,1056,1080,1104,1128,1152,1176,1200,1224,1248,1272,1296,1320,1344,1368,1392,1416,1440,1464,1488,1512,1536,1560,1584,1608,1632,1656,1680,1704,1728,1752,1776,1800,1824,1848,1872,1896,1920,1944,1968,1992,2016,2040,2064,2088,2112,2136,2160,2184,2208,2232,2256,2280,2304,2328,2352,2376,2400,2424,2448,2472,2496,2520,2544,2568,2592,2616,2640,2664,2688,2712,2736,2760,2784,2808,2832,2856,2880,2904,2928,2952,2976,3000,3024,3048,3072,3096,3120,3144,3168,3192,3216,3240,3264,3288,3312,3336,3360,3384,3408,3432,3456,3480,3504,3528,3552,3576,3600,3624,3648,3672,3696,3720,3744,3768,3792,3816,3840,3864,3888,3912,3936,3960,3984,4008,4032,4056,4080,4104,4128,4152,4176,4200,4224,4248,4272,4296,4320,4344,4368,4392,4416,4440,4464,4488,4512,4536,4560,4584,4608,4632,4656,4680,4704,4728,4752,4776,4800,4824,4848,4872,4896,4920,4944,4968,4992,5016,5040,5064,5088,5112,5136,5160,5184,5208,5232,5256,5280,5304,5328,5352,5376,5400,5424,5448,5472,5496,5520,5544,5568,5592,5616,5640,5664,5688,5712,5736,5760,5784,5808,5832,5856,5880,5904,5928,5952,5976,6000,6024,6048,6072,6096,6120,6144,6168,6192,6216,6240,6264,6288,6312,6336,6360,6384,6408,6432,6456,6480,6504,6528,6552,6576,6600,6624,6648,6672,6696,6720,6744,6768,6792,6816,6840,6864,6888,6912,6936,6960,6984,7008,7032,7056,7080,7104,7128,7152,7176,7200,7224,7248,7272,7296,7320,7344,7368,7392,7416,7440,7464,7488,7512,7536,7560,7584,7608,7632,7656,7680,7704,7728,7752,7776,7800,7824,7848,7872,7896,7920,7944,7968,7992,8016,8040,8064,8088,8112,8136,8160,8184,8208,8232,8256,8280,8304,8328,8352,8376,8400,8424,8448,8472,8496,8520,8544,8568,8592,8616,8640,8664,8688,8712,8736,8760,8784,8808,8832,8856,8880,8904,8928,8952,8976,9000,9024,9048,9072,9096,9120,9144,9168,9192,9216,9240,9264,9288,9312,9336,9360,9384,9408,9432,9456,9480,9504,9528,9552,9576,9600,9624,9648,9672,9696,9720,9744,9768,9792,9816,9840,9864,9888,9912,9936,9960,9984,10000,10024,10048,10072,10096,10120,10144,10168,10192,10216,10240,10264,10288,10312,10336,10360,10384,10408,10432,10456,10480,10504,10528,10552,10576,10600,10624,10648,10672,10696,10720,10744,10768,10792,10816,10840,10864,10888,10912,10936,10960,10984,11008,11032,11056,11080,11104,11128,11152,11176,11200,11224,11248,11272,11296,11320,11344,11368,11392,11416,11440,11464,11488,11512,11536,11560,11584,11608,11632,11656,11680,11704,11728,11752,11776,11800,11824,11848,11872,11896,11920,11944,11968,11992,12016,12040,12064,12088,12112,12136,12160,12184,12208,12232,12256,12280,12304,12328,12352,12376,12400,12424,12448,12472,12496,12520,12544,12568,12592,12616,12640,12664,12688,12712,12736,12760,12784,12808,12832,12856,12880,12904,12928,12952,12976,13000,13024,13048,13072,13096,13120,13144,13168,13192,13216,13240,13264,13288,13312,13336,13360,13384,13408,13432,13456,13480,13504,13528,13552,13576,13600,13624,13648,13672,13696,13720,13744,13768,13792,13816,13840,13864,13888,13912,13936,13960,13984,14008,14032,14056,14080,14104,14128,14152,14176,14200,14224,14248,14272,14296,14320,14344,14368,14392,14416,14440,14464,14488,14512,14536,14560,14584,14608,14632,14656,14680,14704,14728,14752,14776,14800,14824,14848,14872,14896,14920,14944,14968,14992,15016,15040,15064,15088,15112,15136,15160,15184,15208,15232,15256,15280,15304,15328,15352,15376,15400,15424,15448,15472,15496,15520,15544,15568,15592,15616,15640,15664,15688,15712,15736,15760,15784,15808,15832,15856,15880,15904,15928,15952,15976,16000,16024,16048,16072,16096,16120,16144,16168,16192,16216,16240,16264,16288,16312,16336,16360,16384,16408,16432,16456,16480,16504,16528,16552,16576,16600,16624,16648,16672,16696,16720,16744,16768,16792,16816,16840,16864,16888,16912,16936,16960,16984,17008,17032,17056,17080,17104,17128,17152,17176,17200,17224,17248,17272,17296,17320,17344,17368,17392,17416,17440,17464,17488,17512,17536,17560,17584,17608,17632,17656,17680,17704,17728,17752,17776,17800,17824,17848,17872,17896,17920,17944,17968,17992,18016,18040,18064,18088,18112,18136,18160,18184,18208,18232,18256,18280,18304,18328,18352,18376,18400,18424,18448,18472,18496,18520,18544,18568,18592,18616,18640,18664,18688,18712,18736,18760,18784,18808,18832,18856,18880,18904,18928,18952,18976,19000,19024,19048,19072,19096,19120,19144,19168,19192,19216,19240,19264,19288,19312,19336,19360,19384,19408,19432,19456,19480,19504,19528,19552,19576,19600,19624,19648,19672,19696,19720,19744,19768,19792,19816,19840,19864,19888,19912,19936,19960,19984,20000,20024,20048,20072,20096,20120,20144,20168,20192,20216,20240,20264,20288,20312,20336,20360,20384,20408,20432,20456,20480,20504,20528,20552,20576,20600,20624,20648,20672,20696,20720,20744,20768,20792,20816,20840,20864,20888,20912,20936,20960,20984,21008,21032,21056,21080,21104,21128,21152,21176,21200,21224,21248,21272,21296,21320,21344,21368,21392,21416,21440,21464,21488,21512,21536,21560,21584,21608,21632,21656,21680,21704,21728,21752,21776,21800,21824,21848,21872,21896,21920,21944,21968,21992,22016,22040,22064,22088,22112,22136,22160,22184,22208,22232,22256,22280,22304,22328,22352,22376,22400,22424,22448,22472,22496,22520,22544,22568,22592,22616,22640,22664,22688,22712,22736,22760,22784,22808,22832,22856,22880,22904,22928,22952,22976,23000,23024,23048,23072,23096,23120,23144,23168,23192,23216,23240,23264,23288,23312,23336,23360,23384,23408,23432,23456,23480,23504,23528,23552,23576,23600,23624,23648,23672,23696,23720,23744,23768,23792,23816,23840,23864,23888,23912,23936,23960,23984,24000,24024,24048,24072,24096,24120,24144,24168,24192,24216,24240,24264,24288,24312,24336,24360,24384,24408,24432,24456,24480,24504,24528,24552,24576,24600,24624,24648,24672,24696,24720,24744,24768,24792,24816,24840,24864,24888,24912,24936,24960,24984,25000,25024,25048,25072,25096,25120,25144,25168,25192,25216,25240,25264,25288,25312,25336,25360,25384,25408,25432,25456,25480,25504,25528,25552,25576,25600,25624,25648,25672,25696,25720,25744,25768,25792,25816,25840,25864,25888,25912,25936,25960,25984,26000,26024,26048,26072,26096,26120,26144,26168,26192,26216,26240,26264,26288,26312,26336,26360,26384,26408,26432,26456,26480,26504,26528,26552,26576,26600,26624,26648,26672,26696,26720,26744,26768,26792,26816,26840,26864,26888,26912,26936,26960,26984,27000,27024,27048,27072,27096,27120,27144,27168,27192,27216,27240,27264,27288,27312,27336,27360,27384,27408,27432,27456,27480,27504,27528,27552,27576,27600,27624,27648,27672,27696,27720,27744,27768,27792,27816,27840,27864,27888,27912,27936,27960,27984,28000,28024,28048,28072,28096,28120,28144,28168,28192,28216,28240,28264,28288,28312,28336,28360,28384,28408,28432,28456,28480,28504,28528,28552,28576,28600,28624,28648,28672,28696,28720,28744,28768,28792,28816,28840,28864,28888,28912,28936,28960,28984,29000,29024,29048,29072,29096,29120,29144,29168,29192,29216,29240,29264,29288,29312,29336,29360,29384,29408,29432,29456,29480,29504,29528,29552,29576,29600,29624,29648,29672,29696,29720,29744,29768,29792,29816,29840,29864,29888,29912,29936,29960,29984,30000,30024,30048,30072,30096,30120,30144,30168,30192,30216,30240,30264,30288,30312,30336,30360,30384,30408,30432,30456,30480,30504,30528,30552,30576,30600,30624,30648,30672,30696,30720,30744,30768,30792,30816,30840,30864,30888,30912,30936,30960,30984,31000,31024,31048,31072,31096,31120,31144,31168,31192,31216,31240,31264,31288,31312,31336,31360,31384,31408,31432,31456,31480,31504,31528,31552,31576,31600,31624,31648,31672,31696,31720,31744,31768,31792,31816,31840,31864,31888,31912,31936,31960,31984,32000,32024,32048,32072,32096,32120,32144,32168,32192,32216,32240,32264,32288,32312,32336,32360,32384,32408,32432,32456,32480,32504,32528,32552,32576,32600,32624,32648,32672,32696,32720,32744,32768,32792,32816,32840,32864,32888,32912,32936,32960,32984,33000,33024,33048,33072,33096,33120,33144,33168,33192,33216,33240,33264,33288,33312,33336,33360,33384,33408,33432,33456,33480,33504,33528,33552,33576,33600,33624,33648,33672,33696,33720,33744,33768,33792,33816,33840,33864,33888,33912,33936,33960,33984,34000,34024,34048,34072,34096,34120,34144,34168,34192,34216,34240,34264,34288,34312,34336,34360,34384,34408,34432,34456,34480,34504,34528,34552,34576,34600,34624,34648,34672,34696,34720,34744,34768,34792,34816,34840,34864,34888,34912,34936,34960,34984,35000,35024,35048,35072,35096,35120,35144,35168,35192,35216,35240,35264,35288,35312,35336,35360,35384,35408,35432,35456,35480,35504,35528,35552,35576,35600,35624,35648,35672,35696,35720,35744,35768,35792,35816,35840,35864,35888,35912,35936,35960,35984,36000,36024,36048,36072,36096,36120,36144,36168,36192,36216,36240,36264,36288,36312,36336,36360,36384,36408,36432,36456,36480,36504,36528,36552,36576,36600,36624,36648,36672,36696,36720,36744,36768,36792,36816,36840,36864,36888,36912,36936,36960,36984,37000,37024,37048,37072,37096,37120,37144,37168,37192,37216,37240,37264,37288,37312,37336,37360,37384,37408,37432,37456,37480,37504,37528,37552,37576,37600,37624,37648,37672,37696,37720,37744,37768,37792,37816,37840,37864,37888,37912,37936,37960,37984,38000,38024,38048,38072,38096,38120,38144,38168,38192,38216,38240,38264,38288,38312,38336,38360,38384,38408,38432,38456,38480,38504,38528,38552,38576,38600,38624,38648,38672,38696,38720,38744,38768,38792,38816,38840,38864,38888,38912,38936,38960,38984,39000,39024,39048,39072,39096,39120,39144,39168,39192,39216,39240,39264,39288,39312,39336,39360,39384,39408,39432,39456,39480,39504,39528,39552,39576,39600,39624,39648,39672,39696,39720,39744,39768,39792,39816,39840,39864,39888,39912,39936,39960,39984,40000,40024,40048,40072,40096,40120,40144,40168,40192,40216,40240,40264,40288,40312,40336,40360,40384,40408,40432,40456,40480,40504,40528,40552,40576,40600,40624,40648,40672,40696,40720,40744,40768,40792,40816,40840,40864,40888,40912,40936,40960,40984,41000,41024,41048,41072,41096,41120,41144,41168,41192,41216,41240,41264,41288,41312,41336,41360,41384,41408,41432,41456,41480,41504,41528,41552,41576,41600,41624,41648,41672,41696,41720,41744,41768,41792,41816,41840,41864,41888,41912,41936,41960,41984,42000,42024,42048,42072,42096,42120,42144,42168,42192,42216,42240,42264,42288,42312,42336,42360,42384,42408,42432,42456,42480,42504,42528,42552,42576,42600,42624,42648,42672,42696,42720,42744,42768,42792,42816,42840,42864,42888,42912,42936,42960,42984,43000,43024,43048,43072,43096,43120,43144,43168,43192,43216,43240,43264,43288,43312,43336,43360,43384,43408,43432,43456,43480,43504,43528,43552,43576,43600,43624,43648,43672,43696,43720,43744,43768,43792,43816,43840,43864,43888,43912,43936,43960,43984,44000,44024,44048,44072,44096,44120,44144,44168,44192,44216,44240,44264,44288,44312,44336,44360,44384,44408,44432,44456,44480,44504,44528,44552,44576,44600,44624,44648,44672,44696,44720,44744,44768,44792,44816,44840,44864,44888,44912,44936,44960,44984,45000,45024,45048,45072,45096,45120,45144,45168,45192,45216,45240,45264,45288,45312,45336,45360,45384,45408,45432,45456,45480,45504,45528,45552,45576,45600,45624,45648,45672,45696,45720,45744,45768,45792,45816,45840,45864,45888,45912,45936,45960,45984,46000,46024,46048,46072,46096,46120,46144,46168,46192,46216,46240,46264,46288,46312,46336,46360,46384,46408,46432,46456,46480,46504,46528,46552,46576,46600,46624,46648,46672,46696,46720,46744,46768,46792,46816,46840,46864,46888,46912,46936,46960,46984,47000,47024,47048,47072,47096,47120,47144,47168,47192,47216,47240,47264,47288,47312,47336,47360,47384,47408,47432,47456,47480,47504,47528,47552,47576,47600,47624,47648,47672,47696,47720,47744,47768,47792,47816,47840,47864,47888,47912,47936,47960,47984,48000,48024,48048,48072,48096,48120,48144,48168,48192,48216,48240,48264,48288,48312,48336,48360,48384,48408,48432,48456,48480,48504,48528,48552,48576,48600,48624,48648,48672,48696,48720,48744,48768,48792,48816,48840,48864,48888,48912,48936,48960,48984,49000,49024,49048,49072,49096,49120,49144,49168,49192,49216,49240,49264,49288,49312,49336,49360,49384,49408,49432,49456,49480,49504,49528,49552,49576,49600,49624,49648,49672,49696,49720,49744,49768,49792,49816,49840,49864,49888,49912,49936,49960,49984,50000,50024,50048,500
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400 V=3.37E-6*(P1-P)/(S*V)
410 V0=2*(P1-P)/(S*V)
415 IF 2*R*V0*P/V<1 GO TO 435
420 V0=3.37E-1*((G15)*(R18)*((P1-P)15)/((V13)*(P12)))1(1/7)
425 IF 2*R*V0*P/V<1000 GO TO 435
430 V0=(6.06*(R*(P1-P)/P)1(0.5)
435 H=(K/R)+0.42*(((V0*P)/(V*R))1(0.5))*((C*(K12)*V)1(1/3))
490 Q1=H*4*PI*(R12)*(T1-1375)
500 IF Q1<Q GO TO 631
510 IF S>2 GO TO 633
520 T0=T1+(Q0*P1*R12)/(3*K1)
530 D2=2E-5/V
540 K2=(P*D2/R)+0.42*(((V0*P)/(V*R))1(0.5))*((V*(D212)*(P12))1(1/3))
545 X1=X1+A*D*3600
546 X=X1*(3*(1-(3153/T1)))
550 M1=K2*4*PI*(R12)*X
551 PRINT USING 552, T,R,M,T0,T1,Q,M1,X1
552:####.## #.##### #.##### #.##### #.#####
553 A=V0
560 IF M1*D*3600<MP GO TO 615
570 T=T+D
580 M=M-M1*D*3600
590 IF M<0 GO TO 617
600 R=((0.75*M)/(PI*P1))1(1/3)
610 GO TO 640
615 D=D*5
616 GO TO 570
617 T5=T-5+M/(M1*3600)
618 PRINT USING 619, T5
619: TIME OF DISSOLUTION IS ####.## HOURS AFTER FUEL HITS FLOOR
620 X1=X1+((3600*D)+(M/M1))*V0
621 PRINT USING 622, X1
622: PENETRATION DEPTH IS ####.## CM
623 IF I=5 GO TO 630
624 I=I+1
625 GO TO 310
630 END
631 T1=T1+S
632 GO TO 395
633 S=S/2
634 T1=T1-S
635 GO TO 395
636 M2=M/5
637 GO TO 340
640 IF T>X(1) GO TO 670
650 Q0=Y(1)*2.33E-2
660 GO TO 370
670 FOR N=2 TO 96
680 IF T>X(N) GO TO 720
690 Q0=Y(N-1)+(T-X(N-1))*(Y(N)-Y(N-1))/(X(N)-X(N-1))
700 Q0=Q0*2.33E-2
710 GO TO 370
720 NEXT N
725 PRINT USING 726
726: TIME OF DISSOLUTION IS GREATER THAN 2.7778 HOURS
727 IF I=5 GO TO 730
728 I=I+1
729 GO TO 310
730 END
READY

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SAMPLE OUTPUT FROM FORC1

FORC1

FUEL HITS FLOOR FIVE HOURS AFTER MELTDOWN

AMBIENT BASALT TEMP=1375 DEG K AND VISCOSITY=1.44E+03 POISE

R= .001 CM

T(HR)	R(CM)	M(G)	T0(K)	T1(K)	Q(CAL/S)	DMASS(G/S)	X(CM)
5.00	1.0E-03	3.7E-08	1377	1377	7.6E-09	8.8E-12	.0E+00
5.50	8.3E-04	2.1E-08	1377	1377	4.2E-09	7.3E-12	1.8E-03
6.00	6.0E-04	7.8E-09	1377	1377	1.5E-09	5.3E-12	3.0E-03

TIME OF DISSOLUTION IS 1.41E+00 HOURS AFTER FUEL HITS FLOOR

PENETRATION DEPTH IS 3.5E-03 CM

R= .010 CM

T(HR)	R(CM)	M(G)	T0(K)	T1(K)	Q(CAL/S)	DMASS(G/S)	X(CM)
5.00	1.0E-02	3.7E-05	1377	1377	7.6E-06	9.3E-11	.0E+00
5.50	1.0E-02	3.7E-05	1377	1377	7.4E-06	9.3E-11	1.8E-01
8.00	9.9E-03	3.6E-05	1377	1377	6.5E-06	9.2E-11	1.1E+00
20.50	9.5E-03	3.2E-05	1377	1377	4.4E-06	8.8E-11	5.4E+00
33.00	9.1E-03	2.8E-05	1377	1377	3.3E-06	8.4E-11	9.3E+00
45.50	8.7E-03	2.4E-05	1377	1377	2.5E-06	8.0E-11	1.3E+01
108.00	5.4E-03	6.0E-06	1377	1377	4.4E-07	4.9E-11	2.9E+01

TIME OF DISSOLUTION IS 1.37E+02 HOURS AFTER FUEL HITS FLOOR

PENETRATION DEPTH IS 3.3E+01 CM

R= .100 CM

T(HR)	R(CM)	M(G)	T0(K)	T1(K)	Q(CAL/S)	DMASS(G/S)	X(CM)
5.00	1.0E-01	3.7E-02	1377	1377	7.6E-03	2.5E-09	.0E+00
5.50	1.0E-01	3.7E-02	1377	1377	7.4E-03	2.5E-09	1.8E+01
8.00	1.0E-01	3.7E-02	1377	1377	6.7E-03	2.5E-09	1.1E+02
20.50	1.0E-01	3.7E-02	1377	1377	5.1E-03	2.5E-09	5.4E+02
83.00	9.9E-02	3.6E-02	1377	1377	3.0E-03	2.5E-09	2.7E+03
395.50	9.7E-02	3.3E-02	1377	1377	1.3E-03	2.4E-09	1.4E+04
1958.00	8.2E-02	2.0E-02	1377	1377	3.0E-04	1.7E-09	6.5E+04
3520.50	6.6E-02	1.0E-02	1377	1377	9.9E-05	1.2E-09	1.0E+05
5083.00	4.7E-02	3.9E-03	1377	1377	2.6E-05	6.7E-10	1.3E+05
6645.50	1.5E-02	1.3E-04	1377	1377	6.9E-07	1.5E-10	1.4E+05

TIME OF DISSOLUTION IS 6.88E+03 HOURS AFTER FUEL HITS FLOOR

PENETRATION DEPTH IS 1.4E+05 CM

R= 1.000 CM

T(HR)	R(CM)	M(G)	T0(K)	T1(K)	Q(CAL/S)	DMASS(G/S)	X(CM)
5.00	1.0E+00	3.7E+01	1520	1447	7.6E+00	1.4E-06	.0E+00
5.50	1.0E+00	3.7E+01	1517	1445	7.4E+00	1.4E-06	2.8E+03
8.00	1.0E+00	3.7E+01	1505	1441	6.7E+00	1.3E-06	1.7E+04
20.50	1.0E+00	3.7E+01	1476	1427	5.1E+00	1.1E-06	8.4E+04
83.00	1.0E+00	3.7E+01	1437	1408	3.1E+00	8.2E-07	3.9E+05
395.50	9.9E-01	3.6E+01	1404	1391	1.4E+00	6.3E-07	1.7E+06
1958.00	9.5E-01	3.2E+01	1386	1381	4.8E-01	5.1E-07	7.7E+06
9770.50	7.8E-01	1.8E+01	1377	1377	6.3E-02	2.9E-07	3.4E+07
*****	6.4E-01	9.6E+00	1377	1377	1.6E-02	1.8E-07	5.0E+07

TIME OF DISSOLUTION IS 3.27E+04 HOURS AFTER FUEL HITS FLOOR

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USAEC 9800 South Cass Ave.
Argonne, Illinois 60439

AA Churm, Chief

Technical Information Center (3)

Battelle-Columbus
505 King Avenue
Columbus, Ohio 43201

RL Ritzman

Oak Ridge National Laboratory

P.O. Box X
Oak Ridge, Tennessee 37830

MH Fontana

Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87544

RJ Hanold
MJ Herbst (3)

ON-SITEAEC/RL Patent Attorney

RM Poteat

AEC Richland Operations Office

GR Gallagher
BJ Melton

Hanford Engineering Development
Laboratory

JD McCormack
DL Simpson
DD Stepnewski (2)

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DL Condotta
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