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FAST REACTOR FUEL INTERACTION
WITH A CONCRETE FLOOR
AFTER A HYPOTHETICAL CORE MELTDOWN

G. Jansen

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PACIFIC NORTHWEST LABORATORY

RICHLAND, WASHINGTON

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BATTELLE MEMORIAL INSTITUTE

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UNITED STATES ATOMIC ENERGY COMMISSION UNDER CONTRACT AT(45-1)-1830

FAST REACTOR FUEL INTERACTION
WITH A CONCRETE FLOOR
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INTRODUCTION

As part of the effort to assure the safety of sodium-cooled fast reactors, hypothetical situations are assumed to occur during reactor operation. One of these situations is the postulated fuel core meltdown during an accidental loss of coolant. Although the meltdown is extremely unlikely, elaborate precautions have been suggested to assure that the safety of the environment is in no way jeopardized.

In a core meltdown the heat generated by fission product decay, instead of being removed by coolant, creates temperatures as high as 3550°C in the fuel.⁽¹⁾ A molten mass of fuel and structural material may then deposit on the floor of the core cavity. If the rate of heat generation by radioactive decay is greater than the loss by conduction through the floor and by upward radiation and convection to the reactor containment cavity, the fuel core may melt a hole through the floor and penetrate the reactor containment shell, releasing radioactive fission products to the external environment. In previous analyses of the problem,^(2,3,4) the solubilities of fuel components in the concrete floor material have not been considered.

The purpose of this report is to present the results of preliminary calculations of the penetration by core material from the Fast Flux Test Facility (FFTF) into a concrete floor made with basalt aggregates.

SUMMARY AND CONCLUSIONS

Spalling of the concrete will probably be confined to the first few inches of floor thickness. Vertical cracks may penetrate the concrete to the containment shell but they are expected to be very narrow and not a source of local fuel penetration. The evaporation rate of water from the concrete was estimated to be $0.7 \text{ lb}(\text{hr})(\text{ft}^2 \text{ of floor area})$ after one hour and $0.1 \text{ lb}(\text{hr})(\text{ft}^2 \text{ of floor area})$ after 100 hr. The steam passes through the fissures in the concrete and provides local agitation of the molten material.

The primary interactions between the core material and the concrete floor involve heat transfer, melting and dissolution. The hot fuel dissolves in the molten concrete, eventually making a pool that has a temperature near 1100°C . The rate of dissolution is assumed to be rapid enough so that solubility controls the UO_2 content of the pool and the fuel always remains in solution as the pool enlarges. The initial heat content of the fuel and cladding at 3550°C dissolves enough concrete to dilute the fuel by a volumetric factor of 5 and lower the temperature to 1720°C . The steel cladding sinks to the bottom of the pool at 2550°C and a fuel volumetric dilution of 1.5, and it freezes at 1600°C at a fuel dilution of 8. The steel remains as a separate phase throughout the pool formation. The estimated solubility of UO_2 in the molten concrete is 7.5 wt. % at 1100°C and 38 wt. % at 1600°C .

A thin multiphase melt front composed of SiO_2 , $\text{CaO}\cdot\text{SiO}_2$, $\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot 2\text{SiO}_2$ and UO_2 is probably formed at the pool boundaries and the temperature drops to 1100°C at the side of the front next to undisturbed concrete. PuO_2 and heat generating fission products are expected to remain in solution even if some UO_2 precipitates out.

The formation of a crust over the melt pool is crucial in determining how far the melt will penetrate the concrete. If no crust is formed, an initial 125 ft^2 disc-shaped pool about 6 inches deep will freeze in about 10 minutes, primarily because of radiation to the reactor cavity. With the formation of a crust, the disc-shaped pool would grow and gradually become hemispherical. A hemispherical pool would have an initial radius of 3.2 ft. if the heat content of the fuel and cladding are assumed to melt enough concrete instantaneously to produce a UO_2 saturated melt. If localized deposits of UO_2 are formed, they will become hotter than the bulk of the melt, which will increase the local solubility of UO_2 and cause the UO_2 to redissolve. The hemispherical pool would reach a maximum radius of 4.5 ft. in 30 minutes if no crust were formed. With crust formation the hemispherical pool would reach a radius of 10 ft. in 10 hours, and it would reach a maximum radius of about 23 ft. after 100 days. The crust would be 11 inches thick after 10 hours and it would eventually freeze the pool solid after 240 days. Shrinkage of the melt pool after 100 days would have formed a 6 inch thick layer of silicate glass along its bottom before complete solidification. This glass would act as a container for the fission products.

Numerous assumptions that should be verified were made in the calculations. The uncertainties in UO_2 , PuO_2 and fission product solubilities can be removed by phase diagram experiments. The stability and extent of the melt front can be determined from induction-heated melt front experiments. The potential for crust formation should be verified experimentally. The rate of solution of UO_2 in the melt is assumed to be rapid. Kinetics of dissolution of UO_2 in the melt should be determined as a function of particle size, temperature and mixing. The removal of mathematically simplifying assumptions such as a stationary melt front for transient heat conduction, linear temperature gradients across the crust, and a constant reactor cavity temperature could be removed by more precise finite difference calculations using high speed computers. The removal of these assumptions might result in a smaller estimated maximum pool volumes.

A volume of concrete large enough to accomodate the fission product heat might be included beneath the reactor cavity and within the containment shell. This could be a cheaper and more reliable method for insuring that meltthrough does not occur than building cooling pipes or high temperature ceramic barriers into the floor.

DISCUSSION

The following treatment deals first with the fission product heat generation rate and the basic assumptions used in the chemical and heat transfer calculations. The mechanical integrity of the concrete and the behavior of the moisture in the concrete are then discussed. The melting ranges of molten concrete components and the available data on the solubility of fuel compounds in the molten concrete are evaluated prior to the consideration of fuel-concrete interactions during pool formation. The size of the molten pool is then estimated as a function of heat transfer rates, pool shape, and whether upward heat transfer is impeded by crust formation. An experimental program to provide missing information and more rigorous calculational techniques are recommended for improvement of the model.

FISSION PRODUCT HEAT GENERATION RATE

The total heat generated by decay of fission products in the core of the FFTF after being operated at 470 mW for 200 days is estimated to be 9.5×10^9 Btu. About 0.24% of this heat is released during the first hour, 2.3% during the first day, 20% during the first month, 62% during the first year and 97% during the first 10 years. Figure 1 shows the rate of heat generation and the accumulated

FIGURE 1. HEAT GENERATED BY FISSION PRODUCTS FROM A 470 mW CORE

total heat produced by fission products. (5)

ASSUMPTIONS IN MOLTEN POOL CALCULATIONS

The basic assumptions in the model for establishing the initial melt pool and for subsequent heat transfer calculations are:

1. The molten fuel and cladding are initially at 3550°C (6400°F), the boiling point of the cladding.
2. The UO_2 in the fuel does not freeze at its melting point of 2800°C but dissolves in the concrete which melts at 1100°C to form a molten mass at an intermediate temperature.
3. The rate of dissolution of any precipitated UO_2 is rapid enough to keep it dissolved because of locally higher temperatures caused by internal heating of solid fuel that increase the solubility of UO_2 in the melt.
4. As more concrete is melted, it dilutes the molten solution which remains saturated in UO_2 , in equilibrium with an infinitesimal amount of UO_2 in a negligibly thin frozen wall, or melt front, at the advancing edge of the pool.
5. PuO_2 and fission products do not precipitate or volatilize.
6. The steel cladding and structural material remain in thermal equilibrium with the pool but do not dissolve.
7. The pool is well-mixed chemically and is at constant temperature.
8. There is no heat loss from the fuel to the reactor cavity while the initial pool is being established by the initial heat content of the fuel.
9. No fission product heat is generated during the formation of the initial pool.
10. The temperature at the cold side of the advancing melt front is 1100°C .
11. Conduction into the concrete can be approximated by stationary front calculations.
12. The temperature of the top of the pool is 1100°C , determined by the freezing point of the concrete that forms the crust.

SPALLING AND SPLITTING OF CONCRETE

A large body of information exists on spalling of concrete due to high temperature fires. This information is in the Journal of the American Concrete Institute and is usually for standardized tests performed for the National Board of Fire Underwriters. It deals with safety assurance of structures

containing concrete walls and beams when exposed to oil fires. Most of the information is qualitative and does not apply precisely to the situation of a very hot solid falling on a concrete floor; however, some approximate guide lines are given in the article, "Fire Resistance of Prestressed Concrete." (6) The following general statements from this article appear to be pertinent to our problem:

1. Explosive spalling can be observed occasionally within the first 30 minutes after the beginning of a fire.
2. Spalling seldom occurs with thick slabs or with large prestressed beams.
3. In the United States, no spalling has been observed with beams of normal concrete containing limestone, dolomite or quartz aggregates.
4. One possible reason for spalling is a high moisture content of concrete in conjunction with a relatively high resistance to diffusion so that steam cannot escape quickly enough.
5. Certain aggregates are transformed at high temperatures with a sudden release of water and simultaneous increase of volume. Both effects together can cause spalling. Limestone, dolomite, or quartz aggregates do not generally exhibit this characteristic.

The above statements refer to initially much lower temperature shocks to the concrete than those produced by contact with molten fuel. Because concrete has a low thermal conductivity and because the basalt aggregate does not release water suddenly, it is reasonable to conclude that only a little surface spalling will occur during the initial period of contact of fuel and concrete. This will occur in the top inch or two of the floor during the first hour when the temperature gradients are steepest and before the main body of the concrete has had a chance to heat up. At the worst, minor spalling of the concrete could result in some redistribution of molten fuel on the floor through steam ejection. The spalled concrete would melt or dissolve at an increased rate, which would lower the temperature of the fuel-concrete fluid mass more rapidly.

The possible splitting of the concrete mass to allow molten fuel to penetrate crevices toward the steel liner is potentially more serious. The thermal stress in the floor after a core meltdown closely resembles the thermal stress near hot spots in the reinforced concrete underground radioactive waste storage tanks operated at Hanford by the Atlantic Richfield Hanford Company. (7) Vertical cracks in the domes of these underground tanks due to internal heating also appear similar to the present situation. (8) The thick concrete floor will almost certainly split clear through to the containment shell because of expansion of the hot side of the slab since the concrete will readily fail in tension.

Enlargement of any cracks is resisted by the presence of reinforcing steel in the concrete. If enough steel is present in the body of the concrete, the width of any cracks could be held below a tenth of an inch, particularly at the hot surface where compression will occur. It is highly unlikely that molten fuel or slag could penetrate a significant distance into a crack this small because the fluid material would quickly freeze due to the large surface area for heat dissipation at the sides of the crack. Freezing would occur even though the fuel is generating heat at a high rate because the heat capacity of the first few millimeters of wall thickness of the crack is sufficient to cool the fuel to its freezing point before it has passed more than a few crack widths into the floor. In addition, dilution of the fuel with melted crack wall would also slow it down appreciably. Quantitative definition of this effect requires experimental verification with heated fluids and cracks of known width because the fluid properties of molten fuel and slag are not known sufficiently well to predict the rate of flow. The existence of appreciable flow rates of water vapor upward through the cracks would also tend to retard any local penetration by the melt.

LIBERATION OF WATER FROM THE CONCRETE

Preliminary data for typical samples of crushed concrete to be used in construction of the FFTF indicate that the total bound and free water content is in the range 5.5 to 6.0 weight percent. ⁽⁹⁾ The water content, of course, will vary significantly with the age, thermal history and humidification history of the concrete. For 180 day old concrete kept in plastic bags to prevent drying out, the accumulative water evolution with temperature was 63% at 150°C, 77% at 300°C, 94% at 450°C and 100% at 900°C.

Our differential thermal analysis of crushed concrete samples shows that heat absorption (usually due to water evaporation) is significant only at or below 100°C and at 490°C, at which a definite endothermic chemical decomposition of an undefined nature occurs. About half of the water is bound chemically and comes off at elevated temperatures and about half of the water comes off near its boiling point.

With the probable existence of vertical cracks in the concrete, steam can readily escape from the body of the concrete into the cracks and can bubble out through the molten pool at localized spots. This would also keep the pool stirred so that it can be regarded as a homogeneous liquid.

Quantitative estimates of water evolution can be made from the basic assumption that heat is conducted from an 1100°C stationary melt front into a semi-infinite body of the concrete, and that all the water is liberated at an advancing 100°C isotherm. This treatment can be partially justified by assuming that the water all diffuses laterally into cracks after which there is no further heat transfer between the water and the concrete.

Calculations of the water evolution rate were made with the transient one-dimensional conduction computer program THERM. An assumed linear heatup of the melt front from 0 to 1100°C during the first 12 min. of contact was used to simulate an instantaneous contact with hot material followed by melting. The results are shown in Figure 2 as maximum and minimum rates of water evolution. The minimum rate was estimated by assuming that all heat flux crossing at the 100°C isotherm was used to evaporate water and that the temperature gradient in the dry concrete and the advance of the evaporating front were not affected by the sink at the 100° isotherm. The maximum water rate was estimated by assuming that the rate of advance of the 100°C isotherm was not affected by the evaporation of water and that this rate of advance determined the rate of evaporation of water. The last approximation is clearly too high a value since the latent heat of vaporization cannot be supplied to the 100°C isotherm this rapidly by conduction. The minimum rate (probably the right order of magnitude for the water evaporation rate) is $0.7 \text{ lb}/(\text{hr})(\text{ft}^2 \text{ of floor area})$ at 1 hour and $0.1 \text{ lb}/(\text{hr})(\text{ft}^2 \text{ of floor area})$ at 100 hr. At 1 hour the 100°C isotherm has advanced 4 inches ahead of the melt front and at 100 hr it is 3 ft. ahead of the melt front. Because the water from the concrete that has melted is not included in the estimates, the water evaporation rate is biased low. Also, the forward movement of the melt front tends to move the 100°C boundary forward, which also makes the stationary front calculation too low. More accurate estimates could be made if necessary by finite difference techniques and a moving phase boundary but the work seems unwarranted for heat transfer in the molten pool. The absorption of heat by water evaporation is insignificant, and it occurs well ahead of the advancing melt front.

If sodium is present above the molten pool, heat can be generated by reaction of the steam with sodium. Assuming a heat of reaction of 90,000 BTU/lb per mole water, the heat generated for a 125 ft^2 area would be about $4.4 \times 10^5 \text{ Btu/hr}$ at 1 hr. and $6.3 \times 10^4 \text{ Btu/hr}$ at 100 hr.

FIGURE 2
WATER EVAPORATION RATE FROM CONCRETE
IN CONTACT WITH AN 1100°C PLANAR HEAT SOURCE

This is about 2% of the heat generated by fission product decay. The corresponding hydrogen production rates would be 5.4 lb/hr at 1 hour and 0.7 lb/hr at 100 hr., which appear to be insignificant from an explosion hazards standpoint.

CONCRETE MELTING

After the water has been evaporated, the dry concrete heats up until sintering and melting begins. Concrete is a heterogeneous physical mixture of several aggregates with chemically-reacted cement and water as binder. Most naturally the actual overall composition of the concrete is a strong function of the type of aggregate available locally. A chemical composition of a typical local concrete sample with basaltic aggregates that might be used for the FFTF was compiled by E. V. Werry ⁽⁹⁾ and is given in Table 1.

Table 1

Local Concrete Analysis (Preliminary)

	<u>weight percent</u>	<u>mole percent</u>
H ₂ O	5.6	7.9
CO ₂	0.6	0.8
Na ₂ O	0.2	0.2
SiO ₂	50.3	48.2
CaO	19.8	20.3
Fe ₂ O ₃	9.7	3.5
MgO	1.8	2.6
Al ₂ O ₃	11.6	6.5
K ₂ O	0.1	0.1
<u>Total</u>	<u>99.7</u>	<u>100.1</u>

The average molecular weight is 57.5 for wet concrete and 65.9 for dry concrete. The chief components of dry concrete are then SiO₂, CaO, Al₂O₃, and Fe₂O₃, present in a mole ratio of 1/0.42/0.13/0.07. The acidic oxide of silicon can be expected to control the chemical properties of homogenized concrete since it is present in excess. Major solid phase interactions will be between basic oxides and silica with the pairs CaO-SiO₂, Al₂O₃-SiO₂, and Fe₂O₃-SiO₂ being of prime interest. Inspection of the binary and ternary phase diagrams of these systems reveals the formation of CaO-SiO₂ (pseudowollastonite) with a melting point of 1544°C, 3Al₂O₃·2SiO₂ (mullite) with a melting point of

1850°C, $\text{CaO} \cdot \text{SiO}_2 \cdot \text{Al}_2\text{O}_3$ (anorthite) with a melting point of 1553°C and SiO_2 (cristobalite above 1470°C and tridymite below 1470°C).⁽¹⁰⁾ Interactions between Fe_2O_3 and $\text{CaO} \cdot \text{SiO}_2$ and $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ are not significant, although with a deficiency of silica, calcium ferrites would be formed. Most naturally occurring soils and rocks out of which concrete could be made melt in the range 1000 - 1500°C.⁽¹¹⁾

The behavior of a concrete melt on cooling can be explained in terms of the ternary phase diagram $\text{CaO} \cdot \text{SiO}_2 \cdot \text{Al}_2\text{O}_3$ shown in Figure 3. With the composition of concrete given above, cooling of the melt results in the precipitation of tridymite (SiO_2) at 1380°C. At 1320°C a mixture of SiO_2 and $\text{CaO} \cdot \text{SiO}_2$ begins to precipitate. Approximately 40 mole percent of the melt solidifies before the minimum temperature of 1170°C is reached. At 1170°C the ternary eutectic of SiO_2 , $\text{CaO} \cdot \text{SiO}_2$, and $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ freezes at constant composition.

The quantity of Fe_2O_3 present in the concrete would probably produce a quaternary eutectic and lower this freezing point by less than 30°C because of the dilution effect. Other impurities would lower it a few degrees more. The formation of additional compounds between concrete constituents would tend to increase the melting temperature, while solid solubilities, such as the demonstrated solubility of Fe_2O_3 in $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$ would tend to lower the freezing point.⁽¹⁰⁾

The detailed behavior of concrete upon melting cannot be determined because of its heterogeneity. The cement contains a mole ratio of CaO/SiO_2 that may be as high as 2:1⁽¹²⁾ while the ratio in basalt is only 1:5⁽¹³⁾. In general, the basalt aggregates have lower melting points than the cement that binds them. Because of this, one would not expect melting of the interstitial material with large blocks of unmelted aggregate, but rather a holding in place of the melted material until the interstitial material was dissolved by the aggregate or reached its own higher melting point. Such behavior would retard the development of local fingers of interstitial material. This is in contrast to chemically-formed heterogeneous systems for which the interstices are lower melting.

Differential thermal analyses were made on powdered concrete samples obtained from E. V. Werry.⁽⁹⁾ Heating runs showed a melting range from 1100°C to 1250°C. At 1300°C the melt appeared to have a fluidity comparable to that of water. This fact is consistent with general knowledge that the high viscosity

(10)

of silica is lowered by dilution with lime and alumina, and it leads to the conclusion that molten concrete pools are easily mixed. The cooling curves showed no definite phase transition with the formation of a homogeneous glass that wetted platinum even after cooling. The formation of this glass on cooling of a melt could result in an impervious barrier to prevent movement of fission products through the concrete.

SOLUBILITY OF FUEL AND CLADDING IN THE CONCRETE

The fuel material is composed largely of UO_2 with up to 25% PuO_2 and less than 1% fission products.

The ratio of stainless steel to fuel is variable and it adds substantially to the total heat content of the molten material. Examination of the free energies of formation of the various oxides ⁽¹⁴⁾ shows that the iron and nickel will remain in their metallic states in contact with the oxides in the concrete. The only possible exception is the reaction of iron with steam, for which the free energies are too close together to draw a conclusion without experimental verification.

The binary phase diagrams of UO_2 with the constituents of concrete (CaO , Al_2O_3 , and SiO_2) are given in Figure 4. ^(10, 15) Fortunately for the purposes of extrapolation UO_2 forms single eutectics with these materials; that is, there are no compound formations or mutual solubilities of solid phases. With the assumption of ideal liquid solutions, the liquidus lines of these binary systems can be extrapolated to give an approximate liquidus line at lower temperatures for the multicomponent system by the simple Van't Hoff relationship and the assumption of constant entropy of fusion. ⁽¹⁶⁾

$$\ln x_{\text{UO}_2} = N_{\text{UC}_2} \left(1 - \frac{T_{\text{UO}_2}}{T} \right) = 3 \left(1 - \frac{3153}{T} \right)$$

where x_{UO_2} is the mole fraction of UO_2 dissolved in the melt, T_{UO_2} the melting point of UO_2 , N_{UC_2} is the number of atoms in a molecule of UO_2 , and T is the absolute temperature in $^\circ\text{K}$. The solid solubility of PuO_2 in UO_2 is ignored in this treatment. These extrapolations should be confirmed by experiment since other investigators indicate significant effects due to the oxidation of UO_2 to U_3O_8 ^(17,18) and the presence of sodium. ⁽¹⁹⁾ In Figure 5 the composition for precipitation of UO_2 from the UO_2 - SiO_2 system is extrapolated from the UO_2 - SiO_2 eutectic at 1650°C to its intersection with the SiO_2 precipitation line in concrete.

FIGURE 4
BINARY PHASE DIAGRAMS OF UO_2 AND CONCRETE COMPONENTS (10)

$\text{SiO}_2\text{-UO}_2$

FIG. 360.—System $\text{SiO}_2\text{-UO}_2$.

S. M. Lang, F. P. Knudsen, C. L. Fillmore, and R. S. Roth, *Natl. Bur. Standards Circ.*, No. 568, p. 17 (Feb. 20, 1956).

$\text{Al}_2\text{O}_3\text{-UO}_2$

FIG. 317.—System $\text{Al}_2\text{O}_3\text{-UO}_2$.

S. M. Lang, F. P. Knudsen, C. L. Fillmore, and R. S. Roth, *Natl. Bur. Standards Circ.*, No. 568, p. 14 (Feb. 20, 1956).

FIG. 100.—System MgO-UO_2 ; idealized.

P. P. Budnikov, S. G. Tresvyatskiĭ, and V. I. Kushakovskii, *Proc. U. N. Intern. Conf. Peaceful Uses At. Energy*, 2nd, Geneva, 6, 130 (1958).

CaO-UO_2

FIG. 241.—System CaO-UO_2 .

K. B. Alberman, R. C. Blakey, and J. A. Anderson, *J. Chem. Soc.*, 26, 1354 (1951).

FIGURE 5
ESTIMATED SOLUBILITY OF UO_2 IN MOLTEN CONCRETE

UO_2 is the phase in equilibrium with the liquid melt down to 1355°C ; SiO_2 also begins to precipitate at this temperature.

As concrete is melted, part of the UO_2 may precipitate but most of it will remain dissolved in the melt. As more concrete dissolves and is mixed into the melt, the temperature of the melt gradually decreases until it reaches the melting range of concrete (1100°C to 1300°C). From this point, dilution of the melt with more and more concrete proceeds until the melt becomes unsaturated in UO_2 . The detailed history of the amount of UO_2 dissolved in the melt and the amount in the precipitate during the period of initial mixing when the heat content of the UO_2 is being used to melt the concrete is not known. This is true because the rate of heat transfer from the hot, freezing and dissolving UO_2 to the cold, melting concrete depends on convective mass transfer that can be determined only by experimentation. The quantity of concrete that will dissolve a given amount of UO_2 and the temperature at which saturation occurs is readily evaluated and is shown in Figure 6. The path assumed in the following treatment of fuel-concrete interaction is that above 1100°C the melt is always saturated in UO_2 but that a negligible fraction of the UO_2 is precipitated.

The solubility of PuO_2 in the melt is less well known than that of UO_2 . The best estimates are given in Figure 7. Only one set of data exists for the $\text{PuO}_2\text{-SiO}_2$ system. D. F. Carroll ⁽²⁰⁾ found that metallographic analyses of a $\text{PuO}_2\text{-SiO}_2$ glass produced by arc melting revealed little solid solubility between PuO_2 and SiO_2 . Nevertheless, x-ray diffraction showed the existence of the compound $\text{PuO}_2\cdot\text{SiO}_2$. The results in Figure 7 ignore the existence of the compound $\text{PuO}_2\cdot\text{SiO}_2$ which could lower the solubility an order of magnitude, and are based on the equation

$$\ln x_{\text{PuO}_2} = N_{\text{PuO}_2} \left(1 - \frac{T_{\text{PuO}_2}}{T} \right) = 3 \left(1 - \frac{2553}{T} \right)$$

A larger fraction of the PuO_2 should be in solution because PuO_2 is twice as soluble as UO_2 and exists in the fuel only 1/4 as concentrated as UO_2 . The solubility of UO_2 is limiting in the phase equilibrium between concrete and fuel. This treatment disregards the known solid solutions of PuO_2 in UO_2 and possible $\text{PuO}_2\text{-Al}_2\text{O}_3$ and $\text{PuO}_2\text{-CaO}$ interactions, which could also lower the PuO_2 solubility.

FIGURE 6
TEMPERATURE OF THE MELT AS A FUNCTION OF COMPOSITION

FIGURE 7

COMPARATIVE SOLUBILITIES OF UO_2 , PuO_2 , AND La_2O_3 IN MOLTEN SILICATES

SOLUBILITY OF OXIDE IN MOLTEN SILICATES, mole fraction

The concentrations of fission products in the melt control the distribution of the heat generation in the system. If the UO_2 and PuO_2 are first molten, then precipitated and finally redissolved, the fission products should have ample time to be leached from any solids that are formed if their solubilities are high in the molten silicates. Little data is available on fission product silicate solubilities, and an appreciable fraction of them may volatilize during the melting process. Reduction in heat generation by volatilization should be considered in further studies,

The rare earths will be among the least volatile fission products and among the greatest heat generators. As an example, consider lanthanum, for which some data are available. ⁽²¹⁾ Although La_2O_3 has a melting point of only 2315°C , it forms a series of compounds with silica, the most siliceous of which is $\text{La}_2\text{O}_3 \cdot 2\text{SiO}_2$ with a melting point of 1750°C . The equation for extrapolating the solubility of La_2O_3 based on this compound is given below.

$$\ln x_{\text{La}_2\text{O}_3 \cdot 2\text{SiO}_2} = N_{\text{La}_2\text{O}_3 \cdot 2\text{SiO}_2} \left(1 - \frac{T_{\text{La}_2\text{O}_3 \cdot 2\text{SiO}_2}}{T} \right) = 11 \left(1 - \frac{2023}{T} \right)$$

The results shown in Figure 7 indicate a solubility of La_2O_3 in silicate ranging from 10% of the solubility of UO_2 at 1000°C to 100% at 1350°C . Because any rare earth is present at less than 1% of that of UO_2 in irradiated fuel, the rare earths would probably be soluble even when the UO_2 was precipitating. Leaching of rare earth from solid UO_2 and maintenance of them in the liquid phase is highly probable. Any solid UO_2 resting on the pool bottom will pass countercurrent to fresh molten concrete. One can regard the molten pool in a first approximation as a uniformly heat generating liquid rather than a pool heated from below by hot UO_2 or PuO_2 . This factor strongly promotes the non-formation of localized fingers of fuel penetrating the concrete. With a well-mixed liquid, localized UO_2 precipitates would even tend to retard penetration of the melt and promote a uniform rate of advance of the melt front.

Chemical Interaction Between Fuel, Cladding and Concrete

Loss of coolant in the reactor might result in a rapid meltdown of the fuel. It must then penetrate structural elements and a steel floor liner before contacting the floor. As the molten fuel-cladding mixture lands on the floor, it is usually assumed to be at the boiling point of the cladding (3550°C , or 6400°F). If deposited in a localized heap, the mixture is expected to flow out over the floor in a thin layer before solidification takes place. One assumption that has been made is that the fuel will cover a 125 ft^2 area about 1 inch deep before heat

losses to the reactor cavity and the concrete cause it to solidify. (1) As the molten fuel contacts the colder concrete, the concrete will begin to melt at $1100-1300^{\circ}\text{C}$, a temperature 2400°C below the fuel temperature and 1800°C below the fuel melting point. Part of the initial heat in the fuel and cladding and the decay heat generated by the fission products are absorbed by this melting. Even without dissolution by the molten concrete, the dense fuel and cladding could sink into any molten concrete formed. Lateral movement of the fuel might then be impeded more than that estimated from hydraulic considerations. On the other hand, explosive rupture of the fuel system could spread the core material uniformly over the entire floor or even concentrate it at the edges of the cavity if substantial quantities of it spread down the walls. With such a situation, the best assumption that can be made is to assume a uniform floor loading of fuel and core and vary the floor surface area covered by the core.

An energy balance on an elemental area of the floor would show whether the rates of heat loss upward by radiation and convection, downward by conduction and rate of absorption of latent heat by melting are greater than the sum of initial heat content of the fuel and the rate of heat generation by the fission products. The chief difficulty in such an analysis is that the initial heat content of the fuel and cladding is not a rate term. The mechanism of heat transfer at the interface between a hot liquid initially above its freezing point and a cold solid initially below its melting point cannot even be described qualitatively, particularly when the hot liquid is soluble in the melt formed from the solid. Such information must be obtained by experiment because the rate of convective mass transfer of the interface is probably the controlling factor in the heat transfer.

The calculational approach taken here is to assume that all of the initial heat content of the fuel is used to melt concrete before any heat is transferred upward by radiation and convection or any heat is transferred downward by conduction. The initial conditions are then a well-mixed molten pool with partially dissolved fuel and fission products. The melt is in equilibrium with a trace quantity of precipitated solid phase consisting of UO_2 and whatever concrete components are still unmelted at the equilibrium temperature of the pool. This analysis is probably incorrect because heat will be transferred

upward by radiation before the fuel and concrete temperatures are equalized, but it is conservative because a maximum rate of downward penetration is predicted.

The multiphase region of the melt front is established at the same time as the initial pool. Within the multiphase region, the temperature drops from the pool temperature to 1100°C . The melt front is assumed to contain negligible quantities of materials and it is a heterogeneous mixture of liquid and solids with a layered structure and a steep temperature gradient. The composition of the melt front depends on the temperature and volume of the pool. In its early stages the melt front consists of liquid plus the following solid constituents in descending layers: UO_2 above 1355°C ; UO_2 and SiO_2 between 1355°C and 1320°C ; UO_2 , SiO_2 and $\text{CaO}\cdot\text{SiO}_2$ from 1320°C to 1170°C ; and UO_2 , SiO_2 , $\text{CaO}\cdot\text{SiO}_2$ and $\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot 2\text{SiO}_2$ below 1170°C . The temperature at which the liquid ceases to exist at the advancing side of the melt front is taken to be 1100°C , consistent with melting experiments on concrete powder. As the pool becomes larger and lower in temperature, the higher temperature regions of the melt front disappear. Concrete flux, melted at the bottom of the multiphase wall flows upward countercurrent to the descending solids that are not yet dissolved, leaching out the most soluble materials and entering the pool with them. A quantitative description of the melt front is not attempted here, but the thickness and temperature of each layer of the melt front can be estimated as a function of initial conditions and a fixed melt temperature by the technique described by Wiener. (22)

The cladding is an immiscible material at the temperature of the melt. Calculations based on room temperature densities show that the cladding will remain atop the melt until its dissolved UO_2 content reaches 70 vol. %. This corresponds to a uniform melt temperature of 2550°C , which is far above the melting point of 1600°C for the cladding. Thus, the cladding will sink before it freezes and will be an inert material on the bottom of the pool around which melting concrete will flow. Few fission products will be dissolved in the iron; it will tend to be a cold spot retarding local penetration, rather than a hot spot that promotes melting.

The amount of concrete that is melted at the initial conditions is determined from (1) an energy balance on the fuel and concrete before either heat generation or heat transfer is considered and (2) the solubility of UO_2 in the molten pool. The calculations are given in Appendix A.

With these assumptions, the volume and temperature of the initial pool are determined by the solubility of UO_2 in the melt as a function of temperature and an energy balance between the initial heat contents of the molten fuel and cladding and the solid concrete at room temperature and the final heat content of the molten solution of calcium aluminum silicates containing dissolved fuel and in contact with molten or frozen cladding.

The temperature and volume of this initial pool are given in Figure 8 as a function of the steel to fuel ratio. A ratio of steel to fuel of 0.6 kg steel/kg fuel is arbitrarily taken for further calculations. This ratio results in a pool volume (excluding the steel) of 5.6 times the initial volume of fuel. For an initial fuel volume of 10.5 ft^3 , this gives a pool volume of 58 ft^3 before heat transfer to the surroundings begins. The temperature of the pool is then 1720°C . If the path of pool formation up to this point is assumed to have been along the UO_2 saturation curve, the pool has previously become less dense than the steel at a temperature of 2550°C and a pool volume of 15 ft^3 . At the beginning of heat transfer to the surroundings, the steel is still molten at 1720°C which is still above its melting point of 1600°C , but it has sunk to the bottom of the pool.

HEAT TRANSFER FROM THE MOLTEN POOL

Once the pool is formed, time begins to move forward and heat generation, heat transfer to the reactor cavity and heat transfer to the concrete begin. The calculations for these conditions are given in Appendix A.

Two pool geometries are considered here. One is a disc-shaped pool covering 125 ft^2 (6.5 ft radius). The depth of this pool is 5.6 inches after the heat content of the fuel and cladding melts sufficient concrete to reach thermal equilibrium for a UO_2 saturated pool. Unimpeded radiation to the cavity at 450°C from a surface of 1100°C and transient conduction into the concrete from an 1100°C stationary melt front were assumed to occur for one set of calculations. These effects transferred more heat away from the pool than was generated by decay heat and the pool froze in approximately 10 minutes. The time for pool growth to stop is shown as the ordinate in Figure 9 for other pool radii. A disc-shaped pool rapidly becomes hemispherical as the initial pool radius is increased. The disc pool model breaks down at a pool radius of about 4 ft. with maximum penetration depths of about 4 ft in 1.5 hr.

FIGURE 8

CONDITIONS AFTER ADIABATIC MIXING OF CORE AND MELTED CONCRETE

FIGURE 9
CONDITIONS FOR A DISC-SHAPED POOL WITH NO CRUST
TO STOP PENETRATING THE CONCRETE

If all the heat lost by radiation was assumed to come from freezing of a crust (described later) the pool grew to about a 6 ft. depth in 2 hours. Because the shape of the pool was then nearly hemispherical, further treatment of the disc geometry was abandoned in favor of calculations with a hemispherical pool. The formation of a crust is decisive in determining whether the fuel freezes quickly by radiation to the reactor cavity or continues to melt downward. Crust formation always causes significant downward penetration by insulating the melt from the reactor cavity which is the most effective heat sink in the system.

A hemispherical pool is the most severe geometry for greatest concrete penetration because the surface area to volume ratio is a minimum. The hemispherical pool has an initial radius of 3.16 ft, a temperature of 1720°C and an initial volume of 66.7 ft^3 .

In the first set of calculations for a hemispherical pool without crust formation, the heat generated was dissipated by direct radiation from the melt surface at 1100°C , by transient conduction into solid concrete from a stationary melt front at 1100°C and by melting of concrete initially at 25°C . The first two assumptions are conservative because (1) the melt surface is initially appreciably above 1100°C and (2) when the melt front is advancing the temperature gradient is steeper than for a stationary front. The third assumption is not conservative because the concrete that melts has been warmed up before the melt front reaches it. The results for these conditions are given in Figure 10. The pool reaches a maximum size of 4.5 ft. after 30 minutes. When the heat generation rate becomes less than the rate at which heat can be transferred by radiation and conduction, the pool begins to shrink. Greater than 80% of the heat is lost by radiation. The pool does not shrink rapidly because the available surface area for heat dissipation decreases as the pool volume decreases.

The possibility of formation of a frozen crust on the surface of the pool cannot be ruled out because most of the heat was lost upward by radiation. Factors that could lead to crust formation are the presence of frozen iron in the system and poor mixing in the pool. Steam bubbles would tend to prevent crust formation by stirring the melt and the higher density of solids would tend to cause them to precipitate downward. In the million gallon underground waste storage tanks operated by the Atlantic Richfield Hanford Company a 3-inch thick crust of NaNO_3 , which is denser than the mother liquor, is often found on the surface of nonboiling solutions that are not stirred.

FIGURE 10
THICKNESS OF CRUST ON MOLTEN POOL

A natural convection coefficient of about $15 \text{ Btu}/(\text{hr})(^{\circ}\text{F})(\text{ft}^2)$ was estimated from a correlation in McAdams ⁽²³⁾ for molten pools deeper than 1 ft. This could result in a surface temperature of the pool as much as $150\text{-}200^{\circ}\text{C}$ lower than the bulk pool temperature. Such a situation would promote localized freezing at the surface.

With the assumption that all the heat lost by radiation goes to produce crust at 1100°C , and with a cavity temperature of 450°C , the crust thickness increases as shown in Figure 10. A linear temperature gradient across the crust was assumed. This assumption is good only for thin crusts. ⁽²⁴⁾ The crust soon becomes the main resistance to heat flow in the upward direction, with the temperature of the upper surface of the crust approaching the reactor cavity temperature.

Relieved of the upward heat losses, the pool begins to enlarge as shown in Figure 11, because the downward conductive heat transfer is initially much smaller than the heat generation rate.

An upper limit on the size of the pool can be obtained without integrating the heat generation and heat losses. The rate of generation can be balanced against the transient conductive losses from a stationary melt front at 1100°C initially in contact with cold concrete. The hemispherical surface area is allowed to vary to make the two rates match. This envelope is also shown in Figure 11. The maximum pool radius is 31.5 ft. at 200 hours. This treatment ignores the heat used to melt the concrete in changing the pool size but it is useful as a check on the more complex calculation described below.

When the heat required to melt the concrete in the pool is included in the calculations, the pool advances more slowly than the above balance indicates. As shown in Figure 11, the radius is 6.3 ft. at 1 hour, 10 ft. at 10 hours, 16.4 ft at 100 hrs, and 22.5 ft at 1000 hr. It finally reaches a maximum of 23 ft. in 100 days. Simultaneously the crust is growing thicker and the last bit of the pool finally freezes solid at 22.4 ft. and 240 days. The time of final freezing would be somewhat longer than 240 days because the assumed linear gradient does not exist in the crust, ^{and} allowances were not made for the decrease in surface area of the melt front from crust formation. Also, the fission products will become concentrated in the last remaining melt, increasing the local heat generation rate and lowering the melting point. During the pool shrinking period, one would expect a layer of glass several inches thick to form at the pool bottom which would encase the radioactive materials.

FIGURE 11
SIZE OF HEMISPHERICAL POOL

A recapitulation of ^{the} development of the pool throughout its lifetime is given in Figure 12. The qualitative behavior of the pool seems to be well determined, although the assumptions made to obtain numerical answers may significantly alter the maximum pool depth.

RECOMMENDATIONS FOR FURTHER WORK

In this preliminary analysis of the meltdown problem for the Fast Flux Test Facility project, an insight into the factors involved in the process of fuel-concrete interaction has been developed. The simplifications in chemical behavior, geometry of the components, and mathematical treatment may significantly alter the maximum calculated pool depth.

The major uncertainties are in the nature of the melt-solid interaction at the bottom of the molten region and the possibility of a crust formation at the top of the pool to retard upward heat flow. It is necessary to do the experimental work described below to confirm the crucial assumptions of the heat transfer at the melt boundaries.

Solubility measurements, solution kinetics experiments, and melt front experiments are needed. Computerized calculations with the mathematical simplifications removed are required to accurately describe the pool growth. Lastly, the nature of the fuel dissolution and pool growth suggests potential improvements in containment systems design that should be considered.

(1) Computer Calculations

Once the assumptions have been confirmed, a relatively straightforward (though quite time consuming) calculation of the rate of melt front movement can be made for various operating conditions. A moving phase boundary with changing properties presents special mathematical difficulties even for high speed computers. This calculation is complicated by the changing shapes and temperature of the molten pool and by the necessary assumptions of complete mixing within the pool. The restrictions of a negligibly thin melt front boundary layer, a stationary melt front for conductive heat loss calculations and a linear temperature gradient across the crust should be removed to give more realistic estimates of the pool growth. The result could be a model that would predict pool behavior over a wide range of initial conditions and material surroundings.

FIGURE 12
HEMISPHERICAL MOLTEN POOL HISTORY

Floating Steel

Initial fuel
volume
 10.5 ft^3
 $T=3550^\circ\text{C}$

Steel sinks
to bottom
Pool volume =
 15 ft^3
 $T=2550^\circ\text{C}$

Thermal Equilibrium
Established in Pool.
Clock Begins.
Pool volume = 67 ft^3
 $T=1720^\circ\text{C}$
Pool Radius =
3.17 ft.

Steel Freezes
Time < 10 min.
Pool Volume =
 85 ft^3
 $T=1600^\circ\text{C}$
Pool Radius =
3.45 ft.

Crust = 0.28 ft.

Frozen
Steel

Time = 1 hr
 $T=1100^\circ\text{C}$
Pool Radius = 6.3 ft.

Crust = 0.92 ft.

Time = 10 hr
Pool Radius = 10 ft.
 $T=1100^\circ\text{C}$

Crust = 2.8 ft.

Time = 100 hr
Pool Radius = 16.4 ft.
 $T=1100^\circ\text{C}$

Crust = 9.2 ft.

Time = 2400 hr.
Pool Radius = MAXIMUM = 23.1 ft.
 $T=1100^\circ\text{C}$

Crust = 21 ft.

0.5 ft. glass wall

Time = 5000 hr.
Pool Radius = 22.6 ft.

(2) Solubility Measurements

The solubilities of uranium and fission products in molten calcium and aluminum silicates were extrapolated from data for known binary oxide systems. For PuO_2 they were obtained from a single experiment performed several years ago under poorly characterized conditions. All information used in estimates of phases present is based on large extrapolations which may affect the validity of stated conclusions.

Data on phase equilibria are needed for these systems. Certain mixtures of silicates have lower melting points than others; it may be

advantageous to (a) control the composition of aggregates in concrete, (b) use a premixed glass that does not contain water, (c) add low melting fluxes to the aggregate in the concrete, or (d) include UO_2 solubility promoters such as Na_2O .

(3) Solution Kinetics Experiments

In the extreme case of very poor mixing, a ball of fuel could be chilled to a surface temperature in the range 1100°C to 1500°C by melting concrete. If the rate of dissolution of the UO_2 in the molten concrete is low, even though the solubility of UO_2 is high, the fuel could still remain segregated from the molten concrete and penetrate a significant distance locally. Measurements of the rate of dissolution of UO_2 , fission products, and PuO_2 in molten silicates are needed as a function of particle size, temperature, and agitation of the melt to establish the importance of this effect. Viscosity measurements on the molten material would also be useful in helping to estimate the degree of mixing. Internal heating of the solid fuel materials will raise the temperature of the solid above the melt temperature, increasing the local solubility and the rate of solution of fuel oxides in the melt. Estimates of solid-to-melt heat transfer coefficients are needed to determine the importance of localized heating effects of the rate of solution.

(4) Melt Front Experiments

The nature of the solid-liquid interaction at the melting front is probably the most important single factor that influences the localization of penetration. Although deep narrow cracks will probably form in the concrete, local penetration by melt should be minimal. Any local overheating will tend to be self limiting because long intrusions of melt will have an opportunity to lose heat more readily and because a frozen wall of

multiple phase changes will tend to form at any melt front. The concept of a high-density, heat generating fuel material melting its way through a low density floor appears to be invalid because the high solubility of the fuel oxides and the fission products in the silicate melt will almost certainly disperse the heat generating fission products in the fuel throughout the silicate melt.

To study the development of the melt front between the fuel-containing slag and the solid concrete, an induction-heated system with a metallic core surrounded by oxide mixtures and concrete with radial heat transfer is suggested. It is also possible to introduce sodium oxides and moisture into this matrix. This technique comes as close as any one can to the actual conditions involved in the contact of a high melting fuel oxide with a low melting slag without actually using heat-generating fuel materials. Because the fuel materials are not generating heat in the experiments, such experiments put a lower limit on the rate of solubilization of UO_2 and fission products and probably an upper limit on the degree of localization of penetration. The width and composition of the multiphase region between the melt and solid oxide greatly influence the heat transfer and the rate of penetration of the floor material by the melt. Generally, in attempts at mathematical modelling, the details of heat transfer through such multiphase regions have been ignored completely.

The available free energy data indicate that there will not be any significant chemical interaction between the cladding and any oxide flux. The melt front experiments would reveal the extent of any such interactions, if any.

During receding of the pool after the maximum penetration into the floor has been achieved a relatively impermeable glassy frozen wall may be formed which will further protect the containment shell and itself provide supplementary containment ability. This should be experimentally confirmed.

The possibility of crust formation should be investigated experimentally. Without a crust there will be little penetration of the floor and with a crust a large pool can be formed. Immersion heaters would probably be needed in an investigation of this kind.

(5) New Methods for Containment of the Molten Pool

An innovative search is needed for special low melting materials to be incorporated in a core "catcher" or in the floor material. The establishment of design basis criteria for such materials concerning their physical, chemical properties and the geometry of such arrangements is needed. In particular, a variation of chemical composition of aggregate with position to increase the melting point of the pool as the containment shell is approached may result in a safer system. The volume of low melting material needed for containment is also a prime consideration. Too large a volume might require distortions of the volume enclosed by the containment shell. The containment shell would probably hold up quite well in contact with molten concrete at 1100°C , although corrosion might increase rapidly as the 1600°C melting point of steel was approached. The possibility of melting all the concrete and using the shell as a crucible should not be overlooked. Such innovative efforts should be integrated with the experimental and modelling work since this phase of the work cannot rationally be done without a reasonable understanding of the physicochemical and heat transfer provided by the experimental program.

The results could provide a cheaper, more nearly foolproof passive system for preventing contamination of the environment during reactor core meltdowns.

CALCULATIONAL TECHNIQUES1. Estimation of Initial Pool Volume

Determination of the initial pool volume involves a simultaneous solution of the UO_2 solubility expression as a function of temperature and the adiabatic energy balance between the initial heat content of the fuel and cladding and the cold concrete that is melted and dissolves the fuel.

(a) The solubility expression is: (16)

$$\ln x_U = N_{\text{UO}_2} \left(1 - \frac{T_{\text{UO}_2}}{T} \right) = 3 \left(1 - \frac{3153}{T} \right)$$

where x_U = mole fraction of UO_2 dissolved in the melt at saturation

N_{UO_2} = number of atoms per molecule of UO_2

T_{UO_2} = melting point of UO_2 , $^{\circ}\text{K}$

T = temperature of melt, $^{\circ}\text{K}$.

(b) The energy balance is

$$x_u C_u (T_u - T) + x_u R_s C_s (T_u - T) + R_s L_s = (1 - x_u) C_c (T - T_c) + L_c$$

Where

C_u = the specific heat capacity of UO_2 , taken to be 22 Btu/lb mole $^{\circ}\text{F}$.

T_u = the initial temperature of the cladding, 3550°C

R_s = the ratio of steel to fuel,

C_s = the specific heat capacity of steel, 7.7 Btu/lb mole $^{\circ}\text{F}$.

L_s = the heat of fusion of steel, 6950 Btu/lb mole. This term is non-zero only for temperatures below 1600°C .

C_c = the specific heat of concrete (including vaporization of water), 25 cal/g mole $^{\circ}\text{C}$.

T_c = initial temperature of the concrete, 100°C

L_c = the heat of fusion of concrete, 11,000 Btu/lb. mole.

Densities of fuel, cladding, and concrete were assumed to be room temperature values, and no volume change on mixing was allowed. The results presented in Figures 6 and 8 are solutions of these equations.

2. Conduction into the Concrete

A stationary front was assumed since no useful analytical solutions exist for moving boundaries between a well-mixed liquid with an arbitrarily variable heat generation rate and a melting solid. (22, 24, 25, 26, 27, 28)

A step function increase in temperature was imposed at the interface. This gives the usual error function transient temperature profile in the concrete for slab geometry,

$$T - T_a = (T_o - T_a) \operatorname{erfc} \left(\frac{x}{\sqrt{\alpha \theta}} \right)$$

The heat flux at the melt front is given by

$$q/A = -K \left(\frac{dT}{dx} \right)_{x=0} = \frac{K(T_o - T_a)}{\sqrt{\pi \alpha}} \frac{1}{\theta^{1/2}}$$

and the total heat transferred across the front is found by integration over time.

where

$A = 2\pi r^2$ is the surface area of the pool bottom

K is the thermal conductivity of concrete, 1 Btu/(hr)(ft²)(°F/ft)

x = distance from melt front, ft.

T_a is the initial concrete temperature, taken as 0°C

T_o is the melt front temperature, 1100°C

α is the thermal diffusivity of concrete, 0.015 ft²/hr

θ is the time since contact, hr.

For conduction from a hemispherical pool calculations show that the area of concrete heated above 100°C is within a 10% increase of radius so that slab geometry is applicable. Corrections for a decrease in pool surface area as the crust catches up with the melt front were not made.

3. Heat Loss by Radiation - No Crust

$$q/S = 0.1713 \epsilon \left(\left(\frac{T}{100} \right)^4 - \left(\frac{T_r}{100} \right)^4 \right)$$

where

S is the pool free surface area, πr^2

ϵ is the pool surface emissivity, 1.0

T is the pool temperature in degrees Rankine corresponding to 1100°C (2472°C)

T_r is the reactor cavity temperature assumed to be 800°F (1260°R).

4. Melting of the Concrete

The heat necessary to heat the concrete from 0°C and to melt it was taken to be $48,500 \text{ Btu/ft}^3$.

5. Crust Formation by Radiation Heat Loss

Assuming a linear gradient in the crust

$$q/A = L_c \rho_c dx + h_{\text{eff}} (T_m - T_c) dt = \frac{K_c}{x} (T_c - T_s) d\theta = \sigma \epsilon (T_s^4 - T_r^4) d\theta$$

Where

K_c = thermal conductivity of crust, $1 \text{ Btu}/(\text{hr})(\text{ft}^2)(^{\circ}\text{F}/\text{ft})$

T_c = temperature of inside of crust

T_s = outer surface of crust

T_r = sink temperature

The heat transferred from the melt to the crust is

$$h_{\text{eff}} (T_m - T_c) \approx 1200 \frac{\text{Btu}}{\text{hr ft}^2}$$

although this is significant it will be ignored

then

$$x = \frac{K_c (T_c - T_s)}{\sigma \epsilon (T_s^4 - T_r^4)}$$

$$\frac{dx}{d\theta} = \frac{K_c}{L_c \rho_c x} (T_c - T_s) = h_{\text{eff}} (T_m - T_c) \approx \frac{K}{L_c \rho_c x} (T_c - T_s)$$

Solve simultaneously by picking a small value of x at a short time θ .

This is first done numerically, but as the crust becomes thicker $T_s \rightarrow T_r$ and

$$x^2 - x_0^2 = \frac{2 K_c}{L_c \rho} (T_c - T_r) (\theta - \theta_0)$$

Eventually $x^2 \sim \theta$

6. Energy Balance on Pool

With all the radiation heat losses coming from the process of freezing the crust, a balance is made as follows:

Heat generated - Heat conducted = Heat to melt concrete - Heat from pool cooling

$$\Delta \int q_{\text{gen}} d\theta = \Delta \int \frac{(q)}{A_{\text{cond}}} A_{\text{avg}} d\theta = \frac{\Delta V_{\text{pool}}}{\Delta q_{\text{heat+melt}}} - V_{\text{pool}} C_p (\Delta T_{\text{pool}})$$

This is numerically integrated in tabular form with time increments approximately doubling for each successive time increment. Several trials are needed to establish the average surface area for each time interval. For pools without crusts a loss term $[\Delta \int (q/s)_{\text{rad}} S_{\text{av}} d\theta]$ is subtracted from the right side.

Example

Time, hr.	$\Delta \int q_{\text{gen}} d\theta, \text{Btu}$	$V_{\text{pool}}, \text{ft}^3$	$r_{\text{pool}}, \text{ft}$	$\Delta \int q_{\text{cond}} d\theta$	$V_{\text{pool}} \rho C_p (\Delta T_{\text{pool}})$
0		66.7	3.17		
1	22.3×10^6	532	6.31	0.995×10^6	1.407×10^6
2	14.6×10^6	794	7.25	1.84×10^6	~0
5	34.4×10^6	1303	7.90	4.48×10^6	-
10	46.9×10^6	2105	10.0	8.0×10^6	-
24	103.8×10^6	3795	12.2	21.8×10^6	-
48	140×10^6	5935	14.15	36.4×10^6	-
120	305×10^6	10,015	16.9	106.5×10^6	-
240	357×10^6	14,275	19.0	151×10^6	-
480	506×10^6	19,085	20.9	274×10^6	-
1176	942×10^6	23,930	23.3	709×10^6	-
2352	975×10^6	25,800	23.1	882×10^6	-
4872	1287×10^6	21,600	22.9	1500×10^6	-

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