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ANALYSIS OF AEROSOL BEHAVIOR FOR FFTF
HYPOTHETICAL ACCIDENTS

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**ANALYSIS OF AEROSOL BEHAVIOR FOR FFTF
HYPOTHETICAL ACCIDENTS**

BY

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I. SUMMARY

A. OBJECTIVE

The objective of the study discussed in this report was to estimate the spatial and temporal distribution of the released mass of fuel, fission products, fuel cladding, and sodium coolant within the FFTF containment volumes following several postulated accidents. The objective was also to compute the mass leaking from the inner and outer vessels, assuming various leak rates from each compartment of the containment system.

B. PURPOSE

Knowledge of a physically realistic radiological source term is a primary need in reactor siting analysis. As shown in the present study, the quantities of material that could ultimately be released to the environment depends on the behavior of the airborne material within the containment as well as on the total quantities of material which might become airborne.

Over the past several years, Atomics International has developed an experimental program and analytical techniques for studying the transport of aerosols of the kinds produced in assumed accidents. These studies have demonstrated that airborne particles which are small in size initially, agglomerate and grow at rates that are proportional to mass concentrations. The larger the particles, the faster they are removed from the atmosphere because of the increase in settling velocities. With an initial high mass concentration, the removal rate is sufficiently great so that the concentration will be low in a very short time with little material left to leak out of the inner containment. In such circumstances, the source term for leakage to the outer containment is reduced, with a consequent reduction in the particulate leakage to the environs.

It is the purpose of this report to provide quantitative information concerning the source term for use in FFTF siting evaluation as a function of the relevant input parameters.

C. METHOD

A rigorous equation developed for the computation of the behavior of a heterogeneous distribution of aerosols was compared with data from experimental

studies of sodium and UO_2 aerosols in various sized vessels. Suitable confirmation of the applicability of this equation was followed by the development of a model which was used to calculate the leaked masses for postulated releases assuming various leak rates.

For these studies, Battelle-Northwest Laboratories (BNWL) specified two cases for the fraction of the total core fuel inventory released should be assumed as 3 and 19%. In addition, it was specified that 450 lb of sodium is expelled from the reactor cavity into an inner containment volume and allowed to react with the oxygen contained therein. Additional cases were also specified to exclude the sodium from the aerosol phase and to evaluate the effect of the addition of steel cladding to the released aerosol. For the latter cases, it was assumed that the released fraction of the cladding was the same as the fraction of fuel which was released. Calculations were also performed assuming no release of cladding. An assumed release in the outer containment was based on the vaporization of 1% of the fuel contained in one of 76 fuel pin assemblies which make up the core.

The fraction of the fission product inventory produced after 200 days at 400 Mw power, which was assumed to be released, is scavenged by the fuel and sodium, or by the fuel alone. The released fission products, except for the rare gases, are assumed to have mass distributions which are partitioned between the air, walls, and floors in the same proportion as the masses of fuel and sodium following agglomeration. The fraction of the total mass which leaks from the containment is thus representative of the fraction of any material present, and the amount of a given material which leaks is the product of the total leakage fraction and the released quantity of that material. These assumptions are based on experimental observations of multi-component aerosol systems discussed in the body of the report. In these studies, it was assumed that 7.5% of the mass of the fission products are released in a 3% fuel release and 38% of the mass in a 19% fuel release to take into account that some of the fission products have a higher volatility. However, the mass of fission products is a small fraction of the total released aerosol and has negligible effect on the behavior.

Leak rate calculations for the releases into the inner containment volume were performed by BNWL for three thermal models, and the results were used in the aerosol model calculations. One leak rate calculation was performed by

Atomics International using a different model. The leak rate calculation for the fuel release in the outer containment volume was made by BNWL.

D. CONCLUSIONS

The spatial and temporal behavior of the material released into the inner containment with subsequent leakage through the outer containment to the atmosphere has been estimated. The basis of these calculations is a model developed from an exact equation describing aerosol behavior and confirmed by comparison with experimental studies performed by Atomics International.

The fraction of the released mass which leaks to the atmosphere, $f'_L(\infty)$, following the postulated accidents increases exponentially with time to a limiting value and is an inverse function of the mass concentration released to the inner containment. See Table 7, Section IV. At $t = \infty$, the leakage fraction is given by:

$$f'_L(\infty) = \frac{K}{C_R} ,$$

where

$f'_L(\infty)$ = leakage fraction to atmosphere,

K = average leaked fraction based on three BNWL leak rates and its value is $6.9 \times 10^{-5} \pm 0.4 \times 10^{-5}$

C_R = initial mass concentration released to inner containment, expressed as $\mu\text{gm}/\text{cm}^3$.

If fallout were not present as a removal mechanism, all the material initially released in the inner containment would eventually leak to the atmosphere (corrected for radioactive decay). Thus, $f'_L(\infty)$ is the reduction factor attributable to agglomeration combined with fallout. For example, when 19% of the fuel is released into the inner containment vessel, and $C_R = 300 \mu\text{gm}/\text{cm}^3$, $f'_L(\infty)$ is 2.3×10^{-7} . Since 19% of the fuel is associated with 129 kgm of PuO_2 , the value of $f'_L(\infty)$ corresponds to a total release to the atmosphere of 0.03 gm of PuO_2 .

II. INTRODUCTION

Studies are currently being conducted at Atomics International* to characterize the release and transport of effluents which might be generated as a consequence of Liquid Metal Fast Breeder Reactor (LMFBR) accidents. The information developed under this program and others supports a realistic assessment of the radiological source term for hypothetical fast reactor accidents.

In this analysis, it is assumed that the fuel and sodium oxide aerosols spontaneously and continuously coagulate into larger particles. In the agglomeration process, the aerosols which come into contact stick together with almost 100% efficiency. This decreases the number of particles and increases the effective particle radius. As the aerodynamic radius of the aerosol becomes larger the particle settles faster. For high concentrations, large particles are produced and the settling rate is much faster than the rate of removal by leakage. Thus, after a very short time, the material available for leakage is considerably reduced.

The study described in this report represents the correlation and application of experimental and analytical modeling data to the evaluation of the fate of fuel, sodium, and radionuclides released as a result of the postulated releases for the FFTF.

In order to justify the hypothesis used in this analysis, a brief description of the state-of-the-art knowledge about aerosols, agglomeration, and fission product deposition on aerosols is presented. Correlation of laboratory experiments and modeling techniques is shown to be possible through the use of rigorous physical principles.

This analytical tool was then utilized for a study of the spatial and temporal distribution of the materials released to an inner containment which in turn leaked to and from the outer containment. Finally, the results of these computations are summarized and discussed in terms of their significance and application to safeguards evaluation.

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III. REVIEW OF MODEL DEVELOPMENT

A. THEORETICAL⁽¹⁾

Smoluchowski first formulated the physics of aerosols.⁽²⁾ He described the possibility of coagulation or agglomeration of particles colliding as a result of Brownian diffusion as well as shear flow. Müller⁽³⁾ formulated the integro-differential equation for a heterogeneous aerosol population. However, it was noted by Zebel⁽⁴⁾ that Müller neglected a factor inside one of the integrals of the basic equation. The first correct statement of the nonlinear integro-differential equation is credited to D. E. Goldman,⁽⁵⁾ who had worked on the problem during World War II. Attempts to obtain special solutions of the Goldman equation were made at that time by B. Friedman and M. Shiffman. Unfortunately, these early efforts have never been published in the open literature, although Friedman and Shiffman's work is available as an NDRC memo.⁽⁶⁾

Zebel⁽⁴⁾ is the first to have obtained solutions for heterogeneous particle populations, changing with time, by using a computer code programmed on an IBM 650. More recently Friedlander⁽⁷⁾ and Hidy⁽⁸⁾ have solved particular problems, aided by digital computer codes.

Spiegler⁽⁹⁾ and co-workers of this laboratory followed Zebel's lead and obtained solutions for a number of special cases designed to illuminate the general behavior of a sodium-oxide aerosol. They solved problems in which a source of particles was present for a finite period of time, with the particles subject to both agglomeration and settling in a closed volume. The source term was assumed to be a log-normal distribution of particle sizes released over a stated period of time. This has been verified experimentally in this laboratory.^(1,14)

The Müller-Goldman equation can be written in the form:

$$\begin{aligned} \frac{\partial n(r,t)}{\partial t} = & \frac{K_o}{2} \left[\int_0^{r/2^{1/3}} \varphi(R,R') n(R,t) n(R',t) \frac{r^2}{R'^2} dR \right. \\ & \left. - n(r,t) \int_0^\infty \varphi(r,R) n(R,t) dR \right] - \frac{v_s(r)}{h} n(r,t) + S(r,t) . \quad \dots (1) \end{aligned}$$

The quantity $K_o = 4/3 kT/\eta$ is known as the coagulation constant; $\varphi(R,R')$ is called the coagulation function and is given by:

$$\varphi(R,R') = \left\{ \frac{1}{R} [1 + C(R)] + \frac{1}{R'} [1 + C(R')] \right\} (R + R') . \quad \dots(2)$$

The expression $1 + C(X) = 1 + 1/X (0.084 + 0.0264 e^{-16.7X})$ is the Cunningham⁽⁹⁾ correction factor with constants suggested by Davies; $n(r,t)$ is the particle density function; and $n(r,t)dr$ gives the number of particles per cm^3 in suspension at time, t , with radii in the interval $(r, r + dr)$.

In the Smoluchowski-Müller formulation, the number of collisions per unit time and unit volume is given by:

$$\frac{K_o}{2} \varphi(R,R') n(R,t) n(R',t) dR dR' . \quad \dots(3)$$

With φ as defined above, the only collision mechanism implicitly included is that due to Brownian motion and diffusion.

Thus, the first integral in the general equation, Equation 1, represents the formation rate of particles in the radius interval $(r, r + dr)$ as a result of collisions between particles of radii R and R' such that

$$R^3 + (R')^3 = r^3 .$$

The second integral in Equation 1 is a "removal" term and represents the disappearance rate of particles in the size interval $(r, r + dr)$ as a consequence of collisions with all other particles.

The second removal term in the general equation $v_s(r)/h$ represents the loss of particles due to stirred settling with $v_s(r)$, the settling velocity, given by the Stokes expression:

$$v_s(r) = \frac{2}{9} \frac{r^2 \rho g}{\eta} [1 + C(r)] , \quad \dots(4)$$

where

ρ = density of the particle;

g = gravitational constant;

η = viscosity of air

$[1 + C(r)]$ = the Cunningham factor previously mentioned, and

$h = V/A_f$, the height of the settling chamber, V = the total volume,
and A_f = the floor area

The source term is assumed to be a log-normal distribution of particles:

$$S(r) = \frac{S_o}{\sqrt{2\pi \ln \sigma}} \cdot \exp \left[-\frac{\ln^2 \left(\frac{r}{r_g} \right)}{2 \ln^2 \sigma} \right] \quad \dots (5)$$

where

S_o = integrated number of particles per unit volume per unit time being released (Usually the source is kept constant for a period of time, τ , then stopped; this follows the experimental procedure employed in this laboratory.),

r_g = number median radius of distribution,

σ = geometrical standard deviation, and

$N_o = S_o \tau$ = the total number of particles released per unit volume.

One must consider the physical processes that may contribute to agglomeration. The Spiegler-Zebel^(9,4) formulation included only Brownian diffusion as a mechanism expressed analytically in the form of the function ϕ previously given in Expression (2).

Brownian motion of the aerosol particles arises from their collisions with air molecules which are in thermal motion. Assuming the aerosol is in thermal equilibrium with air, the collision rate between particles of radii R, R' is:^(3,4)

$$n(R)n(R') \left(\frac{2kT}{3\eta} \right) \frac{(R + R')^2}{RR'} dR dR',$$

where

$n(R) dR$ = the number of particles per unit volume in the radius interval $(R, R + dR)$, similarly for $n(R')$;

kT = thermal energy per degree of freedom of the system, and

η = viscosity of air.

Particles falling under the influence of gravity will distribute themselves over a range of speeds because of the dependence of the resistance of air on particle size. As a result, coarse particles will tend to sweep past finer ones, thereby causing collisions. The collision rate⁽¹⁰⁾ between particles of radii R and R' is

$$n(R)n(R')\frac{2\pi g\rho}{9\eta}\left(1 - \frac{\rho'}{\rho}\right)\left|R^2 - (R')^2\right|(R + R')^2 dR dR'.$$

ρ, ρ' = densities of particles and of air respectively. (Note the similarity to Stokes' velocity expression.)

A simple comparison of the effects of Brownian motion and gravity can be made by considering the relative collision rates for the two. By using the values for the constants, one obtains

$$\frac{\text{B.M.}}{G} = 0.175 \cdot \frac{1}{RR'} \cdot \frac{1}{\left|R^2 - (R')^2\right|}.$$

This expression shows that for small particles (say less than $1/2 \mu$), Brownian motion will dominate the agglomeration process. For larger particles, the gravity effect will be the prime mechanism.

B. AEROSOL MODEL DEVELOPMENT

The experimental data obtained at Atomics International show that approximately 10 to 30% of the total oxide mass plates on the walls, with the remaining 70 to 90% settling on the chamber floor. For this reason, the general equation was altered to include a wall-plating term. The data show that the mass concentration of the oxide particles at any moment (after burning is completed) is approximately uniform throughout the chamber volume. Thus, it is assumed that particles adjacent to wall surfaces diffuse and stick to the wall areas. At the surface, the particle density function n is zero. The plating per unit wall area will be at the rate:

$$D \frac{\partial n}{\partial x} \left(\frac{\text{Particles}}{\text{cm}^2} \frac{1}{\text{sec}} \right);$$

D is the diffusion constant for a particle of radius r .

Over the entire wall area available, A_w , the particle removal rate will be:

$$V \left(\frac{\partial n}{\partial t} \right)_w = - D A_w \frac{\partial n}{\partial x} .$$

If n is assumed to be constant spatially except for a "collision-distance" Δ over which the gradient exists, n/Δ replaces $\partial n/\partial x$ at the wall. Thus,

$$\left(\frac{\partial n}{\partial t} \right)_w = - \frac{D}{\Delta} \frac{A_w}{V} n .$$

But,

$$\frac{V}{A_w} \left(\frac{\partial n}{\partial t} \right)_w$$

is proportional to the rate of mass plating per unit wall area and is an observable parameter. Also, n is proportional to the mass concentration, and is also observable. Combining both observables with computed values of D as a known function of observed particle size, it was possible to estimate values for Δ in these experiments. On the basis of test data for experiments in which the mass concentration $C_R \approx 1$ to $4 \mu\text{gm}/\text{cm}^3$, Δ is of the order of 1μ for the duration of the test period.

The removal rate due to leakage is independent of particle size because it is assumed that the airborne particles act like a gas, thus the removal rate is proportional to the leak rate and airborne concentration. Thus,

$$V \left(\frac{\partial n}{\partial t} \right)_L = - L n ,$$

with L representing leakage in units of cm^3/sec . Then, $(\partial n/\partial t)_L = -(L/V)n$, and L/V (sec^{-1}) represents the fractional leakage per unit time usually designated as a stated requirement; e. g., $1\%/ \text{day} = 1.15 \times 10^{-7}/\text{sec}$.

It is clear from the structure of the terms that the temporal behavior of the processes of removal of particles from the atmosphere will be sensitive to the geometry, relative values of the wall and floor areas, and the absolute volume of the chamber. Furthermore, since two of the terms are functions of particle size, mean sizes affect the competition between removal processes

and affect the absolute values for "total" removal time constants. Since higher initial particle concentrations will lead to larger median particle sizes, that will be another factor in determining removal time constants. Obviously, higher concentrations will lead to larger particles (by agglomeration), producing larger values of $v_g(r)$, leading to shorter removal times, and will emphasize greater floor deposition at the expense of wall-plating. Laboratories using liter-sized vessels, cubic meter size vessels, or very large chambers should expect entirely different dynamic results in terms of removal times, median particles sizes, fraction settling, etc.

The complete equation is now written:

$$\begin{aligned} \frac{\partial n(r,t)}{\partial t} = & \int_0^{r/3\sqrt{2}} n(R,t)n(R',t) \left[B(R,R') + G(R,R') \right] \frac{r^2}{(R')^2} dR \\ & - n(r,t) \int_0^\infty n(R,t) \left[B(r,R) + G(r,R) \right] dR \\ & - n(r,t) \left[\frac{v_s(r)}{h} + \frac{D(r)}{\Delta} \cdot \frac{A_w}{V} + \frac{L}{V} \right] + S(r,t) . \end{aligned} \quad \dots (6)$$

A complete discussion of this equation and its application to aerosol behavior studies can be found in Reference 1.

Inclusion of the additional collision mechanisms in the agglomeration equation emphasizes the fact that it is a special form of the Boltzmann transport equation and that the kernels of the integrals are basically collision probabilities; hence, the form of the equation can be considered as general while the details of the physics contained in the kernels is specialized.

$$G(R,R') = \frac{2\pi g \rho}{9\eta} \left| R^2 - R'^2 + A(R - R') + B(e^{-\alpha R} - e^{-\alpha R'}) \right| (R + R')^2 . \quad \dots (7)$$

A, B, and α are the constants appearing in the Cunningham correction factor and are 0.084, 0.0264, and 16.7 respectively; R and R' are in μ .

$$B(R, R') = \frac{kT}{3\eta} \left\{ \frac{1}{R} \left[1 + \frac{1}{R} (A + B e^{-\alpha R}) \right] + \frac{1}{R'} \left[1 + \frac{1}{R'} (A + B e^{-\alpha R'}) \right] \right\} (R + R') \quad \dots (8)$$

$$v_s(r) = \frac{2g\rho}{9\eta} r^2 \left[1 + \frac{1}{r} (A + B e^{-\alpha r}) \right]. \quad \dots (9)$$

$$D(r) = \frac{kT}{6\pi\eta} \cdot \frac{1}{r} \left[1 + \frac{1}{r} (A + B e^{-\alpha r}) \right]. \quad \dots (10)$$

The integro-differential equation (6) has been evaluated by a numerical integration method and programmed for the IBM/360 as HAA-2. Equation 6 was also solved by a moments methods, where the log normality of the distribution is preserved, and programmed as HAA-3.⁽¹¹⁾

C. CODE COMPARISONS WITH EXPERIMENTS

1. Experimental Description

The solutions of the General Equation (6) were evaluated by comparisons with data obtained in tests conducted in a 40-ft³, 6-ft high Laboratory Test Chamber (LTC). Additional comparisons were made in a larger modeling facility referred to as the Phase II - Large Test Vessel. This chamber has a volume of 2200 ft³ and is 30-ft high. The comparisons are made with five independent measurements; suspended mass concentration, C; mass settled on floor, M_F; mass plated on walls, M_W; median radius by volume (or mass), r_v; and geometric standard deviation of the particle size distribution, σ; all five as a function of time.

Figure 1 shows the laboratory test chamber (LTC) in which the experiments were performed and Figure 2 shows the large test vessel (LTV). Sodium is heated up to temperatures of the order of 1000°F with the lid in place, after establishing the desired O₂ environment in the LTC. In the LTV, the sodium is heated externally and is allowed to drain into the burn pan.

After introduction or removal of the lid, the sodium reacts with oxygen and a fraction of the reaction products are released into the vessel. To provide a convective air current to produce a stirred aerosol environment, the sodium

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Figure 1. Laboratory Test Chamber

burn pan is heated throughout the duration of the experiment. A complete mass balance is obtained as a function of time, when account is taken of the sodium: in the burn pot, airborne, settled on the floor, and plated on walls.

The suspended mass concentration is measured by collecting samples (on millipore filter papers) with fixed flow rates. Mass deposition rates on the floor and on the chamber walls are measured by collecting samples on glass or stainless steel slides. A rotating turn table is programmed to permit collection on a series of slides each for a fixed time interval. Cumulative samples are collected on the floor and walls at various radial and vertical positions. All samples are analyzed for sodium content, with a flame photometer having a sensitivity of 0.5 ppm for sample volumes as low as 1 cm^3 . Particle size distributions by mass are measured with round jet cascade impactors; number distributions are determined by using samples collected in an electrostatic precipitator and analyzed via electron microscope photography. Thus, particle size distributions, mass deposition rates, and suspended mass concentration are all measured as a function of time.

When the chamber is opened at the conclusion of the test, the cumulative masses on the floor and walls are measured. The sum of these masses is defined as the released mass, M_R , for the fire. Addition of the mass remaining in the burn pot to the released mass provides a comparison with the total mass originally placed into the pot. A further check on mass conservation is made by comparing the released mass with the sum of the mass components suspended, on the floor, and on the walls, at all times. The burn time, τ , is characterized by the time that the suspended mass concentration reaches a maximum, C_{max} .

Air samples are collected at a number of radial and vertical positions in the chamber. In general, the mass concentration measured at any given height is within 10% of the average of all sampling stations. Similarly, cumulative fallout samples at various heights were within 10% of the average collected on the floor.

When UO_2 aerosols were studied, the aerosol was produced by arc vaporization. In early experiments, the resultant aerosol was a mixture of U_3O_8 ,

Figure 2. Phase II Test Vessel Before Assembly

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and metal oxides from the tungsten electrode and steel crucible which had also vaporized. In later experiments, the evaporation was performed with a carbon electrode and a carbon crucible. Similar measurements were made for the uranium oxide studies as for the sodium fires described above. Several experiments were performed in which sodium was burned at the same time that the UO_2 was vaporized.

2. HAA-2 Code Comparisons to Sodium Fires in LTC

Program HAA-2, the numerical integration of the Integro-Differential Equation (6) which describes the aerosol behavior, has been used for comparison of the computed results to experimental data.⁽¹⁾ For these comparisons, the following table lists the various constants which were used in the computer program.

Geometry

$$V = \text{LTC volume, } 1.13 \times 10^6 \text{ cm}^3 \text{ (40 ft}^3\text{)}$$

$$A_F = \text{floor area, } 6.26 \times 10^3 \text{ cm}^2$$

$$h = \text{LTC height, 180 cm}$$

$$A_w = \text{wall area, } 1.03 \times 10^5 \text{ cm}^2$$

Physical Constants

$$g = 980 \text{ cm/sec}^2$$

$$\eta = 1.82 \times 10^{-4} \text{ poise (gm/cm-sec), at } 20^\circ\text{C}$$

$$\rho = 2.27 \text{ gm/cm}^3, \text{ density of sodium monoxide}$$

$$k = 1.38 \times 10^{-16} \text{ ergs/}^\circ\text{K}$$

$$T = 293^\circ\text{K}$$

$$K_o = 2.96 \times 10^{-10} \text{ cm}^3/\text{sec, initial agglomeration constant}$$

Three additional input parameters which are adjustable are needed for solutions of the general equation. These are: the initial number median radius, $\bar{r}(0)$; the initial geometric standard deviation of the log-normal distribution, σ ; and Δ , the collision distance in the wall removal term.

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Figure 3. Airborne Mass Concentration vs Time for LTC Test

The initial particle size distribution was determined experimentally in each test, and the initial mass median radius $\overline{r}_V(0)$ was found to be 0.5 to 0.6 microns with a standard deviation of 2.0. The number median radius is therefore, 0.118 to 0.142 μm . The collision distance, Δ , was obtained from experimental data. Values of Δ are computed and shown in Section III-B of this report.

A typical example, from Reference 11, of an experiment for which a computer solution was attempted is described below. Table 1 summarizes the input data. Figures 3 through 5 give the detailed test results for all observables as a function of time.

TABLE 1
CODE INPUT PARAMETER VALUES FOR
Na POOL FIRES IN LTC

Selected Input Parameter to Simulate	Test
	B
M_R (gm)	4.5
C_R ($\mu\text{gm}/\text{cm}^3$)	4.0
τ (sec)	1000
$Q((\mu^3/\text{cm}^3) = C_R/\rho^*$	1.76×10^6
$\overline{r}_V(t = 0)$ (μ)	0.6
σ	2.0
$N_o((\text{particles}/\text{cm}^3) = \frac{3}{4} \frac{Q \exp\left(\frac{9}{2} \ln^2 \sigma\right)}{\overline{r}_V(0)^3}$	1.69×10^7
$S_o(\text{particles}/\text{cm}^3\text{-sec}) = N_o/\tau$	1.69×10^4
$\Delta(\mu)$ (wall plating parameter)	1.5

*The quantity $Q = C_R/\rho$ is the fraction of space occupied by the sodium oxide and is expressed in units of (μ^3/cm^3), with $\rho = 2.27$ (gm/cm^3). The constancy of this quantity, computed as the sum of suspended, floor, and wall masses, is used as a check on the accuracy of the computer solutions.

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Figure 4. Median Particle Radius by Volume vs Time for LTC Test

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Figure 5. Percentages of Total Released Mass Settled and Plated vs Time for LTC Test

In general, it can be stated that the HAA-2 computed results agree well with those of experiments when the initial concentrations are less than $5 \mu\text{gm}/\text{cm}^3$. The log normal approximation solution, HAA-3 gives identical results to that of HAA-2 for the low concentration cases.

3. Comparison of HAA-3 Code with Data on Vaporized UO_2 Aerosols in LTC

The UO_2 aerosols were also generated in the LTC. The geometrical constants for the HAA-3 code are thus identical to those used for sodium aerosol comparisons.

The initial distribution for the aerosol created by vaporizing and oxidizing UO_2 , stainless steel, and tungsten was found to have a $\overline{r}_v(0)$ of $0.4 \mu\text{m}$ and σ equal to about 2. The mass median radius was estimated to be $0.4 \mu\text{m}$ by assuming that the effective density of the mixture of U_3O_8 , Fe_3O_4 , and WO_3 which was formed was about $4 \text{ gm}/\text{cm}^3$.

Input test data correlated, are shown in Table 2.

TABLE 2
CODE INPUT PARAMETER VALUES FOR
 UO_2 VAPORIZATION IN THE LTC

Selected Simulated Input Parameters	
$M_R(\text{gm})$	13.9
$C_R(\mu\text{gm}/\text{cm}^3)$	12.3
$\tau(\text{sec})$	60.0
$Q(\mu^3/\text{cm}^3) = C_R/\rho^*$	3.08×10^6
$\overline{r}_v(t=0)(\mu)$	0.7
σ	2.0
$N_o(\text{particles}/\text{cm}^3)^\dagger$	8.64×10^7
$S_o(\text{particles}/\text{cm}^3\text{-sec})$	1.44×10^6
$\Delta(\mu)$ (wall plating parameter)	0.7

*The quantity $Q = C_R/\rho$ is the fraction of space occupied by the metal oxide and is expressed in units of μ^3/cm^3 , with $\rho = 4.00 \text{ gm}/\text{cm}^3$. The constancy of this quantity, computed as the sum of suspended, floor, and wall masses, is used as a check on the accuracy of the computer solutions.

$^\dagger N_o$ is defined in Table 1.

Figure 6. Airborne Mass Concentrations and Settled Mass vs Time for LTC- UO_2 No. 6

Figure 6 shows the detailed comparison of experimental and computed results as a function of time. Figure 7 shows typical experimental confirmation that the different chemical species do indeed coagulate into single aggregates and settle as one material. Reasonable agreement is obtained for the mass distribution, in the air and on the floor and walls. Computed results obtained for low concentrations ($<4 \mu\text{gm}/\text{cm}^3$) are identical when either HAA-3 or HAA-2 is used.

4. Comparisons of HAA-3 Code with Experiments on Sodium Fires in the Large Test Vessel

The experimental data obtained from sodium pool fires performed in the 30-ft high, large test vessel have been compared to the computed results obtained from the HAA-3 program.

In the Phase II studies, the released mass, M_R , and the released concentrations are approaching those expected in the hypothetical reactor accident (see Table 3). The height of this vessel, 30-ft, is almost the same as the height of the inner containment. As previously mentioned, the general aerosol equation predicts a strong dependence between geometry and the aerosol behavior. The initial oxide particle distributions observed in these tests were identical to those observed in the LTC experiments. Because of the increased temperature and the decrease in the wall surface-to-volume ratio the observed values of Δ were significantly different from values observed in the LTC. The value of Δ used in the code was $0.05 \mu\text{m}$.

The following table lists the geometrical and physical parameters used in the modeling the Phase II fires.

Geometry

$$\begin{aligned} V &= \text{Phase II, volume, } 6.01 \times 10^7 \text{ cm}^3, \\ A_F &= \text{floor area, } 6.63 \times 10^4 \text{ cm}^2, \\ h &= V/A_F = \text{Phase II, height, } 906 \text{ cm (30 ft)}, \\ A_w &= \text{wall area, } 7.71 \times 10^5 \text{ cm}^2. \end{aligned}$$

Figure 7. LTC- UO_2 Test No. 4, Airborne Concentration vs Time for Components of Aerosol Mixture

Physical Constants

$$g = 980 \text{ cm/sec}^2$$

$$\eta = 2.27 \times 10^{-4} \text{ poise (gm/cm-sec), at } 120^\circ\text{C}$$

$$\rho = 2.27 \text{ gm/cm}^3 \text{ (for sodium oxide)}$$

$$k = 1.38 \times 10^{-16} \text{ erg/}^\circ\text{K}$$

$$T = 394^\circ\text{K}$$

$$K_o = 2.96 \times 10^{-10} \text{ cm}^3/\text{sec}$$

TABLE 3
CODE INPUT PARAMETERS VALUES FOR PHASE II
Na POOL FIRES IN THE LTV

Selected Simulated Input Parameters	Test No.	
	2	3
M_R (gm)	2360	7718
C_R ($\mu\text{gm/cm}^3$)	53.0	174.0
τ (sec)	1000	3600
Q (μ^3/cm^3) = C_R/ρ^*	2.33×10^7	7.66×10^7
$\bar{r}_v$ ($t = 0$) (μ)	0.5	0.5
σ	2.0	2.0
N_o (particles/ cm^3) [†]	3.86×10^8	1.27×10^9
S_o (particles/ cm^3 -sec)	Variable	Variable
$\Delta(\mu)$ (wall plating parameter)	0.05	0.05

* The quantity $Q = C_R/\rho$ is the fraction of space occupied by the sodium oxide and is expressed in units of μ^3/cm^3 , with $\rho = 2.27 \text{ gm/cm}^3$. The constancy of this quantity, computed as the sum of suspended, floor, and wall masses, is used as a check on the accuracy of the computer solutions.

[†] N_o is defined in Table 1.

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Figure 8. Comparison of Density Effects on Phase II Test 2 Model Results

Figures 8 through 10 show the comparison of the computed and experimental data as a function of time. It should be noted that if the ideal density of sodium oxide ($\rho = 2.27 \text{ gm/cm}^3$) is used to compute the settling velocity of the coagulated and effectively larger particle, that the results do not agree with the experimental data. As shown in Figures 9 and 10, an effective density change, which changes the settling velocity, can be used to adjust the fit of the computation to the experiment. The settling velocity equation used in the models should be modified when used to compute the settling velocity of nonspherical particles which reduce the settling velocity. This is shown by Fuks⁽¹⁵⁾ and others. A spherical particle has a greater mobility than any other shape so that nonspherical particles will have smaller settling velocities than spheres of the same volume.

All models assume that the environment is stirred, i.e., the air is not tranquil. When HAA-3 is used to compute the airborne concentration at levels below which agglomeration occurs, it fails, because the log normality approximation no longer holds. The computed data shown in Figures 9 and 10 were obtained by switching from HAA-3 to HAA-2 when the particle number density decreased to a value such that HAA-3 was not computing correctly. In some instances, when the wall plating has ended, it is possible to use a simpler method for determining the decrease in concentration after agglomeration has decreased to a very slow rate. This technique involves the computation of the settling rate of an initial log normal distribution in which no agglomeration occurs.⁽¹²⁾ The equations used are programmed as a stirred settling model; the code name is SSM.⁽¹²⁾ The computed data of Figures 9 and 10 are identical when either HAA-2 or SSM are used to evaluate the rate of decrease of very low aerosol concentrations.

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Figure 9. Model Computations Compared to Phase II Test 2

IV. APPLICATION OF AEROSOL BEHAVIOR MODEL TO FFTF

A. SELECTION OF CODES

The models used to compute the aerosol behavior following the postulated FFTF release is identical to those described previously. The detailed procedure involved and the choice of the model used in the calculations is somewhat complicated because of several reasons. First, the high concentration produced as a result of the postulated release necessitates the use of HAA-3 for calculation of the initial growth, settling, and leakage in the inner containment vessel. Second, as the particles became larger and the number concentration decreases, the log normal approximation of HAA-3 fails and HAA-2 or SSM must be used to compute the aerosol behavior. The growth rate is negligible at these times and either of these codes is satisfactory. The particle size distribution of the computed leaked mass which enters the secondary vessel changes because of growth and settling in the inner containment. The distribution of particles within the outer containment changes because of the varying input and because settling and leakage occurs in this volume also. Since the mass which leaks from the inner barrier is reduced due to fallout, and because the outer vessel volume is large, the resultant concentration and agglomeration rate is low. This necessitates the use of the HAA-2 code for computing the behavior. When the leakage from the outer containment is occurring over a long time period and the airborne concentration is changing relatively slowly, the HAA-2 code, as programmed, is time-consuming. Thus, in order to economize, the SSM code was used to determine the mass leaking from the outer vessel for times greater than one day.

B. RELEASED MASS SOURCE TERMS

As shown in Section III, an important input parameter for computing the aerosol behavior is $Q = C_R / \bar{\rho}$, the fraction of space occupied by the released oxides; $\bar{\rho}$ is computed from the relation:

$$\bar{\rho} = \frac{\sum M_{Ri}}{\frac{\sum C_{Ri}}{\rho}}$$

TABLE 4
DESCRIPTION FOR COMPUTER CASES

(Code Input Initial mass median radius = 0.28, Initial geometric standard deviation = 2.0)

Case No	Fuel Vaporized		Released Mass (kg)				$M_R/V = (C_R)$ ($\mu\text{gm/cc}$)	Leak Rate Calculated By
	(%)	(kg)	Cladding Vaporized	Fission Products Vaporized	Na Oxide	Total, M_R		
1C	3	89	68	6.5	256	419.5	92	BNWL No. 1
2C	19	564	434	33	256	1287	282	BNWL No. 1
3C	19	564	434	33	0	1031	226	BNWL No. 1
1D	3	89	0	6.5	256	419.5	75	BNWL No. 1
2D	19	564	0	33	256	853	187	BNWL No. 1
1E	3	89	68	6.5	256	419.5	75	BNWL No. 1
2E	19	564	434	33	256	1287	230	BNWL No. 1
3E	19	564	434	33	0	1031	185	BNWL No. 1
1H	3	89	0	6.5	256	351.5	92	BNWL No. 1
2H	19	564	0	33	256	853	153	BNWL No. 1
1F	3	89	68	6.5	256	419.5	92	AI
2F	19	564	434	33	256	1287	282	AI
3F	19	564	434	33	0	1031	226	AI
1G	3	89	0	6.5	256	351.5	77	AI
2G	19	564	0	33	256	853	187	AI
1J	3	89	68	6.5	256	419.5	75	AI
2J	19	564	434	33	256	1287	230	AI
3J	19	564	434	33	0	1031	185	AI
1K	3	89	0	6.5	256	351.5	63	AI
2K	19	564	0	33	256	853	153	AI
4C	3	89	68	6.5	256	419.5	92	BNWL No. 2
5C	19	564	434	33	256	1287	282	BNWL No. 2
6C	19	564	434	33	0	1031	226	BNWL No. 2
4D	3	89	0	6.5	256	351.5	77	BNWL No. 2
5D	19	564	0	33	256	853	187	BNWL No. 2
7C	3	89	68	6.5	256	419.5	92	BNWL No. 3
8C	19	564	434	33	256	1287	282	BNWL No. 3
9C	19	564	434	33	0	1031	226	BNWL No. 3
7D	3	89	0	6.5	256	351.5	77	BNWL No. 3
8D	19	564	0	33	256	853	187	BNWL No. 3

Assumed 38% released when 19% fuel is vaporized, 7.5% when 3% fuel vaporized

where M_{Ri} and C_{Ri} are the released mass and concentration of the material designated by i . In the present example, i is the PuO_2 , UO_2 , NaO_2 , Fe_2O_3 , and the mass of fission products.

One should note that in Tables 1, 2, and 3; that $\bar{\rho}$, the effective density of the source term is used to compute Q and N_0 , the total number of particles which are available to agglomerate. After agglomeration occurs and the particles begin to settle more rapidly the density which is used in Stokes equation is designated as 1.0 gm/cm^3 . Thus, the effective settling velocity is decreased by ratios which vary according to the mixture under consideration. The data in Table 4 which describe the mass released and the released concentrations can be used together with the ideal density of each material to compute $\bar{\rho}$. The effective density, $\bar{\rho}$, computed from the equation above is 2.9 gm/cm^3 for Cases No. 1, 4, and 7; 5.0 gm/cm^3 for Cases No. 2, 5, and 8; and 6.0 gm/cm^3 for Cases No. 3, 6, and 9. Thus, all particulates will take longer to settle out of the air by a factor of $\bar{\rho}$, a conservative assumption. The additional geometry and source input parameters which were used in the FFTF calculations are shown in Table 5.

The released mass for the fuel handling accident was based on the release of 1% of one driver assembly and 40% of the 500 lb of sodium originally contained in the fuel handling machine. The FHA resulted in a release of $1.22 \times 10^5 \text{ gm}$ and $\bar{\rho}$ for this mixture was 2.3 gm/cm^3 .

C. LEAK RATES

The leak term L/V of Equation 6 is estimated from the computed pressure-temperature histories in the primary vaults following the DBA. The pressure-temperature calculations are strong functions of the heat transfer models which are used. There were 3 different estimates made of the "pressure-time-leak-rate" by BNWL for the inner and outer containment vessel, and these are shown in Table 6. Reference leak rates of 10 vol %/day at 30 psig and 1 vol %/day at 15 psig for the inner and outer containment respectively, were used to extrapolate to the leak rate at different pressures. A thermal model developed at AI was also used to determine the leak rate from the inner and outer containment. These calculations are also presented in Table 6. The AI model was based on the heat capacity of the gas at constant pressure. When the calculations were

TABLE 5
FIXED INPUT PARAMETERS FOR FFTF RELEASES

Parameter	Inner Containment	Outer Containment
Volume (ft ³)	161,000 and 197,000	2.7 x 10 ⁶ and 3.34 x 10 ⁶
A _F (ft ²)	5,700 and 7,000	30,200 and 38,400
H (ft)	28	90 and 86
A _W (ft ²)	32,000 and 39,000	69,000 and 87,000
g (cm/sec ²)	980	980
η (Poise)	3.70 x 10 ⁻⁴	2.27 x 10 ⁻⁴
ρ (gm/cm ³) (used for settling calc.)	1.0	2.9, 5.0, 6.0
T (°K)	800.0	400.0
$\Delta(\mu)$ (wall plating parameter)	1.0	1.0
$\bar{r}_v(t=0) \mu$	0.3	Variable
σ	2.0	Variable
τ (sec)	0	Variable

where M_{Ri} and C_{Ri} are the released mass and concentration of the material designated by i . In the present example, i is the PuO_2 , UO_2 , NaO_2 , Fe_2O_3 , and the mass of fission products.

One should note that in Tables 1, 2, and 3; that $\bar{\rho}$, the effective density of the source term is used to compute Q and N_o , the total number of particles which are available to agglomerate. After agglomeration occurs and the particles begin to settle more rapidly the density which is used in Stokes equation is designated as 1.0 gm/cm^3 . Thus, the effective settling velocity is decreased by ratios which vary according to the mixture under consideration. The data in Table 4 which describe the mass released and the released concentrations can be used together with the ideal density of each material to compute $\bar{\rho}$. The effective density, $\bar{\rho}$, computed from the equation above is 2.9 gm/cm^3 for Cases No. 1, 4, and 7; 5.0 gm/cm^3 for Cases No. 2, 5, and 8; and 6.0 gm/cm^3 for Cases No. 3, 6, and 9. Thus, all particulates will take longer to settle out of the air by a factor of $\bar{\rho}$, a conservative assumption. The additional geometry and source input parameters which were used in the FFTF calculations are shown in Table 5.

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A _F (ft ²)	5,700 and 7,000	30,200 and 38,400
H (ft)	28	90 and 86
A _W (ft ²)	32,000 and 39,000	69,000 and 87,000
g (cm/sec ²)	980	980
η (Poise)	3.70 x 10 ⁻⁴	2.27 x 10 ⁻⁴
ρ (gm/cm ³) (used for settling calc.)	1.0	2.9, 5.0, 6.0
T (°K)	800.0	400.0
Δ (μ) (wall plating parameter)	1.0	1.0
$\bar{r}_v(t=0)$ μ	0.3	Variable
σ	2.0	Variable
τ (sec)	0	Variable

TABLE 6
LEAK RATE CALCULATIONS USED IN FFTF ANALYSIS
(Sheet 1 of 2)

Source of Leak Calculation	Time (sec)	Inner Leak Rate (ft ³ /hr)	Time (sec)	Outer Leak Rate (ft ³ /hr)
BNWL No. 1	0.0	870	0.0	250
	100	730	1.08×10^5	250
	200	580	1.08×10^6	700
	300	450	1.8×10^6	400
	7.2×10^4	450		
BNWL No. 2	0.0	0.0	0.0	0
	0.144	1190	36.7	0
	0.216	1270	360	110
	0.36	1260	1.08×10^3	140
	1.44	1260	1.8×10^3	170
	36.7	1200	3.6×10^3	220
	360	875	7.2×10^3	290
	1.08×10^3	815	1.8×10^4	400
	1.8×10^3	990	3.6×10^4	460
	3.6×10^3	1080	5.4×10^4	490
	7.2×10^4	967	7.2×10^4	520
	1.8×10^4	957	1.08×10^5	540
	3.6×10^4	975	1.44×10^5	560
	5.4×10^4	914	1.8×10^5	580
	7.24×10^4	915	2.08×10^5	590
	1.08×10^5	790	2.88×10^5	635
	1.44×10^5	760	3.6×10^5	651
	1.8×10^5	790	5.4×10^5	655
	2.08×10^5	802	7.2×10^5	630
	2.88×10^5	838	9.0×10^5	605
	3.6×10^5	774	1.08×10^6	544
	5.4×10^5	557	1.44×10^6	455
	7.2×10^5	249	1.8×10^6	345
	9.0×10^5	0	2.16×10^6	241
BNWL No. 3	0.0	0	0.0	0
	0.144	1190	108	0
	0.216	1270	360	90
	0.36	1260	1.8×10^3	140
	108	1120	3.6×10^3	190
	360	874	7.2×10^3	280
	1.8×10^3	775	1.44×10^4	360
	3.6×10^3	857	2.16×10^4	400
	7.2×10^3	785	3.6×10^4	430
	1.44×10^4	747	7.2×10^4	450
	2.16×10^4	719	2.16×10^5	450
	3.6×10^4	680	7.2×10^5	450
	7.2×10^4	614	4.32×10^5	449

TABLE 6
LEAK RATE CALCULATIONS USED IN FFTF ANALYSIS
(Sheet 2 of 2)

Source of Leak Calculation	Time (sec)	Inner Leak Rate (ft ³ /hr)	Time (sec)	Outer Leak Rate (ft ³ /hr)
BNWL No. 3 (Continued)	2.16×10^5	502	5.4×10^5	430
	7.2×10^5	428	7.2×10^5	400
	4.32×10^5	410	9.0×10^5	378
	5.4×10^5	388	1.08×10^6	356
	7.2×10^5	353	1.44×10^6	270
	9.0×10^5	306	1.80×10^6	136
	1.08×10^6	238		
	1.44×10^6	0		
AI (Inner Volume = 197,000 ft ³)	0.0	402	0.0	250
	180	272	1.8×10^6	250
	400	278		
	540	280		
	970	295		
	1260	306		
	1.55×10^3	316		
	2.0×10^3	330		
	2.55×10^3	348		
	3.7×10^3	376		
	5.4×10^3	410		
	7.3×10^3	442		
	9.0×10^3	464		
	1.1×10^4	477		
	1.26×10^4	490		
	1.44×10^4	500		
	2.13×10^4	530		
	3.28×10^4	535		
	4.66×10^4	526		
	5.58×10^4	517		
	7.42×10^4	496		
	1.57×10^5	406		
	2.68×10^5	300		
	3.78×10^5	206		
	5.44×10^5	27		
	9.00×10^5	0		
FHA-BNWL	-	-	0.0	528
			3.6×10^3	350
			9.0×10^4	340
			3.6×10^5	340
			5.4×10^5	268
			7.20×10^5	212
			9.0×10^5	0

rerun using constant volume heat capacity, the computed leak rates were even lower. Therefore, the higher leak rate was used in these calculations.

Use of the AI model yielded such a small buildup of pressure in the outer vessel that hardly any leakage occurs (thus no particulate mass will escape). For this reason, a fixed pressure differential of 0.5 psig (constant leak rate) was arbitrarily assigned between the outer containment vessel and the atmosphere. The fixed leak is shown in Table 6. In the Atomics International leak calculations, the leak rate at any pressure other than the reference leak rate pressure was computed as follows:

$$L_{\Delta P} = \frac{\Delta P_{\text{new}}}{\Delta P_{\text{design}}} \times L_{\Delta P_{\text{design}}}, \quad \Delta P_{\text{new}} > \Delta P_{\text{design}}$$
$$L_{\Delta P} = \left(\frac{\Delta P_{\text{new}}}{\Delta P_{\text{design}}} \right)^{1/2} \times L_{\Delta P_{\text{design}}}, \quad \Delta P_{\text{new}} < \Delta P_{\text{design}}$$

where

L = leak rate in scfh at the stated pressure differential, and

ΔP = pressure differential between inner and outer containment or between the later and atmosphere.

The leak rates from the Atomics International model were so low that more conservative results are obtained with the use of the BNWL leak rate calculations.

The leak rate calculations for the fuel release to the outer containment volume were also performed by BNWL.

D. UNCERTAINTIES IN MODEL

The development of the model expressed by Equation 6 is based on the following physical assumptions which creates an uncertainty factor in the computed leak mass.

- 1) Particles are always spherical and have the theoretical density of the materials forming the particles for the source term calculations. Large particle formed from the collision of several smaller ones have a theoretical shape, density, and settling velocity which may

differ from the Stokes' Law assumptions; and all agglomerated particles have been assigned a density of 1 gm/cm^3 for the settling velocity determinations.

- 2) All particles which collide do not rebound so that the collision efficiency is unity.
- 3) All collisions result in the formation of a particle whose volume is the sum of the volumes of the colliding particles.
- 4) Only binary collisions are counted.
- 5) The aerosol particles are not electrically charged. If they are bipolarly charged the agglomeration rates are even higher than those used in the code. This assumption would make the estimated leaked masses conservative.
- 6) All particles are large compared with the mean free path of the suspending medium, so that a continuum hydrodynamic model can be assumed. For air at STP, the mean free path is $\sim 0.1\mu$. This assumption is somewhat ameliorated by inclusion of a correction factor due to Cunningham; however, even at $r = 0.05\mu$, the Brownian coagulation rate is a factor of 2 greater than it should be. However, the mass concentration of particles with this size is negligible.
- 7) The collision-causing mechanisms are uncorrelated; i. e., each rate was derived by assuming that particle motion was due to a single mechanism, rather than by considering the resultant particle motion under the influence of all forces.
- 8) The wall plating rate is governed by an empirical process constant collision distance, Δ .
- 9) The system is stirred so that the settling removal rates can be described by stirred settling equations. If a stagnant or nonuniform environment exist, the model is even more conservative in the estimation of the time for a given particle to settle.
- 10) It is assumed that the particulates which are formed will leak through the containment leak paths in the same fraction as the gas.

- 11) If the initial distribution used for the FFTF analyses is larger than that described in Section IV-B, less material will leak than was calculated. If the initial distribution is smaller, more material would be expected to leak. The effect of varying the initial median radius of the distribution from 0.28 to 0.10 microns was studied, and it was found that the mass and particle distribution which leaked to the outer containment increased less than 3%.

V. DISCUSSION OF RESULTS OF COMPUTATIONS

In Tables 7 and 8, various estimates of the total leaked mass vs time from the inner and outer containment are shown. In addition, several other computed parameters are tabulated. The primary grouping had to do with the fuel fraction released and the choice of the leak calculation (4 choices). The estimates of leaked mass also varied when the volumes of the inner and outer barriers were changed (2 choices for both) and when the released fuel was accompanied by sodium and or cladding. Table 8 lists the total mass leaked vs time from the inner containment for those cases for which the leakage to the atmosphere was not computed. Table 9 lists the atmospheric leakage for the fuel handling accident.

The computed data is tabulated as a function of time so that BNWL can use the leaked mass for calculating the radiological dose downwind from the FFTF site. Figures 11 and 12 show graphically what is tabulated for a typical case.

In studying the leaked mass to the outer vessel, it is convenient to compare the leaked mass fraction, $f_L(\infty)$ to the released mass concentration, C_R . Figure 13 shows a graph of $f_L(\infty)$ vs C_R for the 3 and 19% fuel release studies and for the various BNWL leak rate estimates. The curves in Figure 13 show that as the released concentration increases, the leaked fraction to the secondary vessel decreases for a given fuel release. Also, it can be seen that a six fold increase in the released fuel fraction (3 to 19%) only causes the leaked fraction to increase by a factor of 1.7. Both facts demonstrate the dependence of the leak fraction on the released mass concentration. The total leaked fraction from either compartment represents the leaked fraction of any constituent of the total. Thus, the computed value, $f_L(\infty)$, can be multiplied by the released mass of Pu, or fission products to obtain the leaked mass of either material into the secondary containment.

Figure 14 shows the fraction of the total released material, $f'_L(\infty)$, which leaks from the outer containment vessel as a function of the released concentration, C_R , in the inner containment vessel. The various BNWL leak estimates, the 3 and 19% fuel released, and the combinations of volumes and leak rates were used to prepare the graphs in Figure 14. Again, the fraction leaking is inversely proportional to released mass concentration.

The relationship of $f'_L(\infty)$ to C_R , for the BNWL leak estimate 1, 2, and 3 can be formulated as

$$f'_L(\infty) = \frac{6.9 \times 10^{-5}}{C_R},$$

where the constant is an average for the three leak rate calculations and C_R is expressed as $\mu\text{gm}/\text{cm}^3$. The mass of Pu which leaks from the outer containment vessel is:

$$M_{L(\infty)}(\text{Pu}) = M_{R(\text{Pu})} f'_L(\infty) = \frac{M_{R(\text{Pu})} \times 6.9 \times 10^{-5}}{C_R} \text{ (gm)}$$

If $M_{R(\text{Pu})}$ is fixed, and C_R is increased by the addition of cladding and sodium, then $M_{L(\text{Pu})}$ will decrease. M_R is expressed in grams.

The mass fraction which leaks from the outer vessel after 2 hr, is also a function of the initial concentration released to the inner containment, C_R . The dependence is also reflected in the time for 50% of the total mass to leak from the outer vessel. The following relationships were observed for values of C_R in the range of 15 to 150 $\mu\text{gm}/\text{cm}^3$.

BNWL No. 1 Leak Rate Estimate:

$$f'_L(2 \text{ hr}) = \frac{6.0 \times 10^{-7}}{C_R^{0.46}} \quad \parallel \quad T_{50} = \frac{235}{C_R^{0.45}} \text{ (hr)}$$

BNWL No. 2 Leak Rate Estimate:

$$f'_L(2 \text{ hr}) = \frac{1.70 \times 10^{-6}}{C_R^{0.59}} \quad \parallel \quad T_{50} = \frac{64}{C_R^{0.43}} \text{ (hr)}$$

BNWL No. 3 Leak Rate Estimate:

$$f'_L(2 \text{ hr}) = \frac{7.6 \times 10^{-7}}{C_R^{0.49}} \quad \parallel \quad T_{50} = \frac{76}{C_R^{0.43}} \text{ (hr)}$$

TABLE 7
MASS LEAKAGE RESULTS FROM FFTF MODEL CALCULATIONS
FOR INNER AND OUTER CONTAINMENT
(Sheet 1 of 5)

Case 1C - 3% Release									
Time (hr)	Inner Containment Vol = 161,000 ft ³				Outer Containment Vol = 2.7 x 10 ⁶ ft ³				
	HAA-3				HAA-2			SSM	
	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma	Total Mass Airborne (gm)	Mass Leaked to Atmo- sphere (gm)	PuO ₂ Leaked to Atmo- sphere (gm)	Mass Leaked to Atmo- sphere (gm)	PuO ₂ Leaked to Atmo- sphere (gm)
0.0	4.190 x 10 ⁵	0.0	0.3	2.00	0.0	0.0	0.0		
0.1	4.148 x 10 ⁵	161.7	1.8	1.60	161.1	9.00 x 10 ⁻⁴	4.32 x 10 ⁻⁵		
0.25	9.758 x 10 ⁴	278.8	14.5	1.98	210.4	3.70 x 10 ⁻³	1.78 x 10 ⁻⁴		
0.5	1.674 x 10 ⁴	301.0	10.9	1.98	192.4	8.85 x 10 ⁻³	4.24 x 10 ⁻⁴		
1.0	5.006 x 10 ³	307.8	8.1	1.98	160.4	1.70 x 10 ⁻²	8.16 x 10 ⁻⁴		
1.5	2.512 x 10 ³	310.0			138.8	2.42 x 10 ⁻²	1.16 x 10 ⁻³		
2.0	1.514 x 10 ³	311.0			123.1	3.07 x 10 ⁻²	1.47 x 10 ⁻³		
3.0	752	312.0			98.5	4.15 x 10 ⁻²	1.99 x 10 ⁻³		
4.0	423	312.3			79.0	5.07 x 10 ⁻²	2.43 x 10 ⁻³		
12.0	36.8	312.6			36.8	8.25 x 10 ⁻²	3.96 x 10 ⁻³		
1 day	5.6	312.6			25.4			0.137	6.58 x 10 ⁻³
2 day					10.1			0.212	1.02 x 10 ⁻²
4 day					2.61			0.279	1.34 x 10 ⁻²
10 day					0.22			0.312	1.50 x 10 ⁻²
30 day					0.02			0.315	1.51 x 10 ⁻²
Case 2C - 19% Release									
0.0	1.280 x 10 ⁶	0.0	0.3	2.00	0.0	0.0	0.0		
0.1	8.256 x 10 ⁵	482.2	15.0	2.42	420.2	2.36 x 10 ⁻³	2.36 x 10 ⁻⁴		
0.25	1.088 x 10 ⁵	557.0	16.6	2.08	408.7	9.00 x 10 ⁻³	9.00 x 10 ⁻⁴		
0.5	2.376 x 10 ³	565.2	11.7	2.08	350.6	1.72 x 10 ⁻²	1.72 x 10 ⁻³		
1.0	7.332 x 10 ³	568.5	8.9	2.08	275.0	3.35 x 10 ⁻²	3.35 x 10 ⁻³		
1.5	3.657 x 10 ³	569.5			226.9	4.60 x 10 ⁻²	4.60 x 10 ⁻³		
2.0	2.270 x 10 ³	570.0			192.5	5.54 x 10 ⁻²	5.54 x 10 ⁻³		
3.0	1.099 x 10 ³	570.0			145.2	7.20 x 10 ⁻²	7.20 x 10 ⁻³		
4.0	611	570.0			118.4	8.20 x 10 ⁻²	8.20 x 10 ⁻³		
12.0	49.8				58.8	0.126	1.26 x 10 ⁻²		
1 day	10.0				11.8			0.183	1.83 x 10 ⁻²
2 day					6.56			0.259	2.59 x 10 ⁻²
4 day					1.36			0.297	2.97 x 10 ⁻²
10 day					0.086			0.313	3.13 x 10 ⁻²
30 day					0.006			0.313	3.13 x 10 ⁻²
Case 3C - 19% Release									
0.0	1.029 x 10 ⁶	0.0	0.3	2.00	0.0	0.0	0.0		
0.1	1.016 x 10 ⁶	397.0	2.5	1.81	390.2	1.70 x 10 ⁻³	2.12 x 10 ⁻⁴		
0.25	1.968 x 10 ⁵	608.1	16.0	2.00	534.8	9.00 x 10 ⁻³	1.12 x 10 ⁻³		
0.5	5.408 x 10 ⁴	637.2	11.1	2.00	479.8	2.16 x 10 ⁻²	2.70 x 10 ⁻³		
1.0	1.034 x 10 ⁴	647.4	8.2	2.00	407.2	4.30 x 10 ⁻²	5.38 x 10 ⁻³		
1.5	5.125 x 10 ³	650.4			351.4	6.40 x 10 ⁻²	8.00 x 10 ⁻³		
2.0	3.064 x 10 ³	652.2			313.2	7.73 x 10 ⁻²	9.66 x 10 ⁻³		

TABLE 7
MASS LEAKAGE RESULTS FROM FFTF MODEL CALCULATIONS
FOR INNER AND OUTER CONTAINMENT
(Sheet 2 of 5)

Case 3C - 19% Release (Continued)									
Inner Containment Vol = 161,000 ft ³					Outer Containment Vol = 2.7 x 10 ⁶ ft ³				
Time (hr)	HAA-3				HAA-2			SSM	
	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma	Total Mass Airborne (gm)	Mass Leaked to Atmo- sphere (gm)	PuO ₂ Leaked to Atmo- sphere (gm)	Mass Leaked to Atmo- sphere	PuO ₂ Leaked to Atmo- sphere (gm)
3.0	1.486 x 10 ³	652.8			258.9	0.106	1.32 x 10 ⁻²		
4.0	825	653.4			198.6	0.123	1.54 x 10 ⁻²		
12.0	68.0	654.0			48.1	0.198	2.48 x 10 ⁻²		
1 day	10.8	654.0			11.2	0.221		0.221	2.76 x 10 ⁻²
2 day					1.46			0.249	3.11 x 10 ⁻²
4 day					0.104			0.255	3.18 x 10 ⁻²
10 day					3.86 x 10 ⁻²			0.256	3.20 x 10 ⁻²
30 day					8.70 x 10 ⁻⁶			0.256	3.20 x 10 ⁻²

Case 1J - 3% Release									
Inner Containment Vol = 197,000 ft ³					Outer Containment Vol = 3.34 x 10 ⁶ ft ³				
0.0	4.224 x 10 ⁵	0.0	0.3	2.00	0.0	0.0	0.0		
0.1	4.184 x 10 ⁵	66.3	1.5	1.52	59.2	5.44 x 10 ⁻⁴	2.61 x 10 ⁻⁵		
0.25	1.807 x 10 ⁵	140.2	11.6	2.17	112.8	1.36 x 10 ⁻³	6.52 x 10 ⁻⁵		
0.50	4.437 x 10 ⁴	165.7	10.8	1.92	116.6	3.50 x 10 ⁻³	1.68 x 10 ⁻⁴		
1.0	6.684 x 10 ³	174.0	7.8	1.92	92.0	7.24 x 10 ⁻³	3.48 x 10 ⁻⁴		
1.5	3.426 x 10 ³	176.8			76.8	1.08 x 10 ⁻²	5.18 x 10 ⁻⁴		
2.0	2.008 x 10 ³	178.2			66.0	1.38 x 10 ⁻²	6.62 x 10 ⁻⁴		
3.0	943	179.6			51.4	1.79 x 10 ⁻²	8.59 x 10 ⁻⁴		
4.0	537	180.3			41.5	2.15 x 10 ⁻²	1.03 x 10 ⁻³		
12.0	50.0	181.2			11.0	3.27 x 10 ⁻²	1.57 x 10 ⁻³		
1 day	8.1	181.2			2.6	4.00 x 10 ⁻²	1.92 x 10 ⁻³	3.97 x 10 ⁻²	1.90 x 10 ⁻³
2 day					1.0			4.29 x 10 ⁻²	2.06 x 10 ⁻³
4 day					0.26			4.48 x 10 ⁻²	2.15 x 10 ⁻³
10 day					0.020			4.58 x 10 ⁻²	2.20 x 10 ⁻³
30 day					0.0014			4.59 x 10 ⁻²	2.20 x 10 ⁻³

Case 2J - 19% Release									
0.0	1.310 x 10 ⁶	0.0	0.3	2.00	0.0	0.0	0.0		
0.1	1.158 x 10 ⁶	202.6	9.3	2.60	176.3	1.15 x 10 ⁻³	1.15 x 10 ⁻⁴		
0.25	9.109 x 10 ⁴	276.8	16.4	2.04	219.9	3.15 x 10 ⁻³	3.15 x 10 ⁻⁴		
0.50	2.780 x 10 ⁴	285.6	11.4	2.04	178.2	7.50 x 10 ⁻³	7.50 x 10 ⁻⁴		
1.0	9.112 x 10 ³	289.5	8.5	2.04	133.6	1.23 x 10 ⁻²	1.23 x 10 ⁻³		
1.5	4.569 x 10 ³	290.7			115.6	1.74 x 10 ⁻²	1.74 x 10 ⁻³		
2.0	2.868 x 10 ³	291.2			106.2	2.18 x 10 ⁻²	2.18 x 10 ⁻³		
3.0	1.362 x 10 ³	291.8			86.7	2.90 x 10 ⁻²	2.90 x 10 ⁻³		
4.0	758	291.9			68.5	3.50 x 10 ⁻²	3.50 x 10 ⁻³		
12.0	65.3	292.0			19.1	5.91 x 10 ⁻²	5.91 x 10 ⁻³		
1 day	8.8	292.0			10.9	6.71 x 10 ⁻²	6.71 x 10 ⁻³	7.54 x 10 ⁻²	7.54 x 10 ⁻³
2 day					3.49			8.69 x 10 ⁻²	8.69 x 10 ⁻³

TABLE 7
MASS LEAKAGE RESULTS FROM FFTF MODEL CALCULATIONS
FOR INNER AND OUTER CONTAINMENT
(Sheet 3 of 5)

Case 2J - 19% Release (Continued)									
Inner Containment Vol = 197,000 ft ³					Outer Containment Vol = 3.34 x 10 ⁶ ft ³				
Time (hr)	HAA-3				HAA-2			SSM	
	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma	Total Mass Airborne (gm)	Mass Leaked to Atmo- sphere (gm)	PuO ₂ Leaked to Atmo- sphere (gm)	Mass Leaked to Atmo- sphere (gm)	PuO ₂ Leaked to Atmo- sphere (gm)
4 day					0.76			9.31 x 10 ⁻²	9.31 x 10 ⁻³
10 day					0.049			9.56 x 10 ⁻²	9.56 x 10 ⁻³
30 day					3.28 x 10 ⁻³			9.59 x 10 ⁻²	9.59 x 10 ⁻³
Case 3J - 19% Release									
0.0	1.031 x 10 ⁶	0.0	0.3	2.00	0.0	0.0			
0.1	1.021 x 10 ⁶	158.2	1.8	1.59	130.8	1.15 x 10 ⁻³	1.43 x 10 ⁻⁴		
0.25	2.523 x 10 ⁵	309.6	14.2	2.01	243.6	3.15 x 10 ⁻³	3.94 x 10 ⁻⁴		
0.50	8.588 x 10 ⁴	343.9	11.0	1.96	186.8	7.50 x 10 ⁻³	9.38 x 10 ⁻⁴		
1.0	1.404 x 10 ⁴	356.0	7.9	1.96	141.2	1.28 x 10 ⁻²	1.60 x 10 ⁻³		
1.5	7.042 x 10 ³	360.1			123.2	1.80 x 10 ⁻²	2.25 x 10 ⁻³		
2.0	4.185 x 10 ³	362.2			108.0	2.30 x 10 ⁻²	2.88 x 10 ⁻³		
3.0	2.031 x 10 ³	364.1			90.0	3.06 x 10 ⁻²	3.82 x 10 ⁻³		
4.0	1.149 x 10 ³	365.0			74.9	3.76 x 10 ⁻²	4.70 x 10 ⁻³		
12.0	104	366.0			20.8	6.45 x 10 ⁻²	8.06 x 10 ⁻³		
1 day	17.6	366.1			6.09	7.26 x 10 ⁻²	9.08 x 10 ⁻³	7.39 x 10 ⁻²	9.24 x 10 ⁻³
2 day					1.36			7.93 x 10 ⁻²	9.91 x 10 ⁻³
4 day					0.22			8.15 x 10 ⁻²	1.02 x 10 ⁻²
10 day					8.66 x 10 ⁻³			8.21 x 10 ⁻²	1.03 x 10 ⁻²
30 day					3.74 x 10 ⁻⁴			8.21 x 10 ⁻²	1.03 x 10 ⁻²
Case 4C - 3% Release									
Inner Containment Vol = 161,000 ft ³					Outer Containment Vol = 2.7 x 10 ⁶ ft ³				
0.0	4.190 x 10 ⁵	0.0	0.3	2.00	0.0	0.0			
0.1	4.146 x 10 ⁵	275.0	1.8	1.61	269.4	7.10 x 10 ⁻⁴	3.40 x 10 ⁻⁵		
0.25	9.261 x 10 ⁴	491.0	14.5	2.00	411.8	2.86 x 10 ⁻³	1.37 x 10 ⁻⁴		
0.50	1.684 x 10 ⁴	534.8	11.0	2.00	365.2	8.55 x 10 ⁻³	4.10 x 10 ⁻⁴		
1.0	5.043 x 10 ³	550.7	8.0	2.00	305.6	2.34 x 10 ⁻²	1.12 x 10 ⁻³		
1.5	2.530 x 10 ³	555.6			259.8	3.88 x 10 ⁻²	1.86 x 10 ⁻³		
2.0	1.523 x 10 ³	557.8			236.8	5.10 x 10 ⁻²	2.44 x 10 ⁻³		
3.0	757	559.7			183.4	8.80 x 10 ⁻²	4.22 x 10 ⁻³		
4.0	425	560.6			150.5	0.110	5.28 x 10 ⁻³		
12.0	35.8	561.4			39.6	0.200	9.60 x 10 ⁻³		
1 day	19.8	561.4			18.6	0.242	1.16 x 10 ⁻²	0.251	1.20 x 10 ⁻²
2 day					5.22			0.300	1.44 x 10 ⁻²
4 day					0.88			0.324	1.55 x 10 ⁻²
10 day					0.030			0.332	1.59 x 10 ⁻²
30 day					8.92 x 10 ⁻⁴			0.332	1.59 x 10 ⁻²

TABLE 7
MASS LEAKAGE RESULTS FROM FFTF MODEL CALCULATIONS
FOR INNER AND OUTER CONTAINMENT
(Sheet 4 of 5)

Case 5C - 19% Release									
Inner Containment Vol = 161,000 ft ³					Outer Containment Vol = 2.7 x 10 ⁶ ft ³				
Time (hr)	HAA-3				HAA-2			SSM	
	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma	Total Mass Airborne (gm)	Mass Leaked to Atmo- sphere (gm)	PuO ₂ Leaked to Atmo- sphere (gm)	Mass Leaked to Atmo- sphere (gm)	PuO ₂ Leaked to Atmo- sphere (gm)
0.0	1.280 x 10 ⁶	0.0	0.3	2.00	0.0	0.0	0.0		
0.1	8.018 x 10 ⁵	805.5	15.0	2.42	764.0	1.60 x 10 ⁻³	1.60 x 10 ⁻⁴		
0.25	1.819 x 10 ⁵	949.0	16.5	2.08	832.7	7.50 x 10 ⁻³	7.50 x 10 ⁻⁴		
0.50	2.376 x 10 ⁴	965.5	11.7	2.08	676.1	2.35 x 10 ⁻²	2.35 x 10 ⁻³		
1.0	7.323 x 10 ³	972.5	9.0	2.08	515.7	4.64 x 10 ⁻²	4.64 x 10 ⁻³		
1.5	3.648 x 10 ³	974.5			420.2	6.60 x 10 ⁻²	6.60 x 10 ⁻³		
2.0	2.261 x 10 ³	975.5			355.2	8.18 x 10 ⁻²	8.18 x 10 ⁻³		
3.0	1.094 x 10 ³	976.0			267.4	1.09 x 10 ⁻¹	1.09 x 10 ⁻²		
4.0	602	976.0			209.3	0.133	1.33 x 10 ⁻²		
12.0	48.5	976.0			27.5	0.250	2.50 x 10 ⁻²		
1 day	20.5	976.0			9.6	0.278	2.78 x 10 ⁻²	0.287	2.87 x 10 ⁻²
2 day					1.45			0.306	3.06 x 10 ⁻²
4 day					0.12			0.312	3.12 x 10 ⁻²
10 day					1.93 x 10 ⁻³			0.313	3.13 x 10 ⁻²
30 day					3.30 x 10 ⁻⁵			0.313	3.13 x 10 ⁻²

Case 6C - 19% Release									
0.0	1.029 x 10 ⁶	0.0	0.3	2.00	0.0	0.0	0.0		
0.1	1.016 x 10 ⁶	664.2	2.4	1.78	664.2	1.70 x 10 ⁻³	2.12 x 10 ⁻⁴		
0.25	2.099 x 10 ⁵	1062.6	16.0	2.00	916.8	9.30 x 10 ⁻³	1.16 x 10 ⁻³		
0.50	1.076 x 10 ⁵	1116.6	11.2	2.00	817.4	2.10 x 10 ⁻²	2.62 x 10 ⁻³		
1.0	1.238 x 10 ⁴	1134.9	8.2	2.00	683.8	5.40 x 10 ⁻²	6.75 x 10 ⁻³		
1.5	5.677 x 10 ³	1140.3			580.6	8.60 x 10 ⁻²	1.08 x 10 ⁻²		
2.0	3.301 x 10 ³	1142.4			500.4	0.123	1.54 x 10 ⁻²		
3.0	1.514 x 10 ³	1144.8			383.5	0.166	2.08 x 10 ⁻²		
4.0	848	1145.4			301.8	0.223	2.78 x 10 ⁻²		
12.0	74.4	1146.0			63.0	0.400	5.00 x 10 ⁻²		
1 day	28.7	1146.0			10.9	0.450	5.62 x 10 ⁻²	0.450	5.62 x 10 ⁻²
2 day					1.30			0.470	5.88 x 10 ⁻²
4 day					8.22 x 10 ⁻²			0.474	5.92 x 10 ⁻²
10 day					6.42 x 10 ⁻⁴			0.475	5.94 x 10 ⁻²
30 day					5.14 x 10 ⁻⁶			0.475	5.94 x 10 ⁻²

Case 7C - 3% Release									
0.0	4.190 x 10 ⁵	0.0	0.3	2.00	0.0	0.0	0.0		
0.1	4.145 x 10 ⁵	273.8	1.9	1.60	198.6	4.40 x 10 ⁻⁴	2.11 x 10 ⁻⁵		
0.25	9.446 x 10 ⁴	488.0	14.5	2.00	409.5	2.95 x 10 ⁻³	1.42 x 10 ⁻⁴		
0.50	1.684 x 10 ⁴	531.2	11.0	1.96	361.4	8.40 x 10 ⁻³	4.03 x 10 ⁻⁴		
1.0	5.043 x 10 ³	544.0	8.0	1.96	293.4	1.83 x 10 ⁻²	8.78 x 10 ⁻⁴		
1.5	2.530 x 10 ³	548.1			249.8	2.69 x 10 ⁻²	1.29 x 10 ⁻³		
2.0	1.523 x 10 ³	549.7			216.2	3.67 x 10 ⁻²	1.76 x 10 ⁻³		

TABLE 7
MASS LEAKAGE RESULTS FROM FFTF MODEL CALCULATIONS
FOR INNER AND OUTER CONTAINMENT
(Sheet 5 of 5)

Case 7C - 3% Release (Continued)									
Inner Containment Vol = 161,000 ft ³					Outer Containment Vol = 2.7 x 10 ⁶ ft ³				
Time (hr)	HAA-3				HAA-2			SSM	
	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma	Total Mass Airborne (gm)	Mass Leaked to Atmo- sphere (gm)	PuO ₂ Leaked to Atmo- sphere (gm)	Mass Leaked to Atmo- sphere (gm)	PuO ₂ Leaked to Atmo- sphere (gm)
3.0	757	551.3			168.8	6.18 x 10 ⁻²	2.96 x 10 ⁻³		
4.0	425	551.8			136.0	9.80 x 10 ⁻²	4.70 x 10 ⁻³		
12.0	36.4	552.4			29.6	0.174	8.35 x 10 ⁻³		
1 day	5.7	552.4			18.3	0.201	9.64 x 10 ⁻³	0.232	1.11 x 10 ⁻²
2 day					4.84			0.279	1.34 x 10 ⁻²
4 day					0.75			0.301	1.44 x 10 ⁻²
10 day					2.24 x 10 ⁻²			0.307	1.47 x 10 ⁻²
30 day					5.98 x 10 ⁻⁴			0.308	1.48 x 10 ⁻²
Case 8C - 19% Release									
Inner Containment Vol = 161,000 ft ³					Outer Containment Vol = 2.7 x 10 ⁶ ft ³				
0.0	1.280 x 10 ⁶	0.0	0.3	2.00	0.0	0.0	0.0		
0.1	8.018 x 10 ⁵	803.5	1.4	2.42	802.2	9.60 x 10 ⁻⁴	9.60 x 10 ⁻⁵		
0.25	1.819 x 10 ⁵	945.0	16.6	2.07	725.8	1.03 x 10 ⁻²	1.03 x 10 ⁻³		
0.50	2.376 x 10 ⁴	960.2	11.7	2.07	607.4	3.05 x 10 ⁻²	3.05 x 10 ⁻³		
1.0	7.323 x 10 ³	966.4	8.9	2.07	450.0	5.05 x 10 ⁻²	5.05 x 10 ⁻³		
1.5	3.648 x 10 ³	968.0			344.5	6.90 x 10 ⁻²	6.90 x 10 ⁻³		
2.0	2.180 x 10 ³	968.5			270.4	8.50 x 10 ⁻²	8.50 x 10 ⁻³		
3.0	1.094 x 10 ³	969.0			187.9	0.122	1.12 x 10 ⁻²		
4.0	602	969.0			139.8	0.131	1.31 x 10 ⁻²		
12.0	48.5	969.0			20.9	0.145	1.45 x 10 ⁻²		
1 day	20.5	969.0			6.74	0.207	2.07 x 10 ⁻²	0.232	2.32 x 10 ⁻²
2 day					1.14			0.246	2.46 x 10 ⁻²
4 day					0.12			0.250	2.50 x 10 ⁻²
10 day					2.64 x 10 ⁻²			0.251	2.51 x 10 ⁻²
30 day					6.74 x 10 ⁻⁵			0.251	2.51 x 10 ⁻²
Case 9C - 19% Release									
0.0	1.029 x 10 ⁶	0.0	0.3	2.00	0.0	0.0			
0.1	1.016 x 10 ⁶	664.2	2.4	1.78	664.0	1.40 x 10 ⁻³	1.75 x 10 ⁻⁴		
0.25	2.093 x 10 ⁵	1002.6	16.0	2.00	901.5	6.25 x 10 ⁻³	7.81 x 10 ⁻⁴		
0.50	1.067 x 10 ⁵	1116.6	11.2	2.00	821.3	1.60 x 10 ⁻²	2.00 x 10 ⁻³		
1.0	1.238 x 10 ⁴	1134.9	8.2	2.00	665.4	4.20 x 10 ⁻²	5.25 x 10 ⁻³		
1.5	5.677 x 10 ³	1140.3			580.6	8.40 x 10 ⁻²	1.05 x 10 ⁻²		
2.0	3.301 x 10 ³	1142.4			500.4	0.116	1.45 x 10 ⁻²		
3.0	1.514 x 10 ³	1144.8			383.5	0.169	2.11 x 10 ⁻²		
4.0	848	1145.4			301.8	0.208	2.60 x 10 ⁻²		
12.0	74.4	1146.0			62.6	0.398	4.98 x 10 ⁻²		
1 day	24.6	1146.0			13.2	0.440	5.50 x 10 ⁻²	0.436	5.45 x 10 ⁻²
2 day					1.68			0.462	5.78 x 10 ⁻²
4 day					0.11			0.467	5.84 x 10 ⁻²
10 day					8.97 x 10 ⁻⁴			0.468	5.85 x 10 ⁻²
30 day					2.79 x 10 ⁻⁴			0.468	5.85 x 10 ⁻²

TABLE 8
MASS LEAKAGE RESULTS FROM FFTF MODEL CALCULATIONS
FOR INNER CONTAINMENT
(Sheet 1 of 5)
(All cases computed by use of HAA-3)

Case 1D - 3% Release					Case 2D - 19% Release				
Inner Containment Vol = 161,000 ft ³					Inner Containment Vol = 161,000 ft ³				
Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma	Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma
0.0	3.519 x 10 ⁵	0.0	0.30	2.00	0.0	8,304 x 10 ⁵	0.0	0.3	2.00
0.1	3.514 x 10 ⁵	135.0	1.52	1.52	0.1	8,206 x 10 ⁵	323.8	2.4	1.75
0.25	1.444 x 10 ⁵	257.7	12.05	2.14	0.25	1,658 x 10 ⁵	502.0	15.8	1.99
0.50	3.862 x 10 ⁴	293.2	11.8	1.93	0.50	8,643 x 10 ⁴	528.5	11.2	1.99
1.0	5.73 x 10 ³	303.0	7.8	1.93	1.0	9,704 x 10 ³	538.0	8.2	1.99
1.5	2,946 x 10 ³	306.2			1.5	4,569 x 10 ³	540.2		
2.0	1,724 x 10 ³	308.0			2.0	2,663 x 10 ³	541.8		
3.0	812	309.4			3.0	1,218 x 10 ³	543.0		
4.0	465	310.0			4.0	684	543.5		
12.0	43.8	310.6			12.0	59.2	543.5		
1 day	8.36	310.6			1 day	9.8	543.5		
2 day		310.6			2 day		543.5		
4 day		310.6			4 day		543.5		
10 day		310.6			10 day		543.5		
30 day		310.6			30 day		543.5		

Case 4D - 3% Release					Case 5D - 19% Release				
Inner Containment Vol = 161,000 ft ³					Inner Containment Vol = 161,000 ft ³				
Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma	Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma
0.0	3.505 x 10 ⁵	0.0	0.3	2.00	0.0	8,304 x 10 ⁵	0.0	0.3	2.00
0.1	3.474 x 10 ⁵	225.8	1.52	1.52	0.1	8,201 x 10 ⁵	549.0	2.4	1.78
0.25	1.449 x 10 ⁵	453.2	11.8	2.15	0.25	1,084 x 10 ⁵	883.5	15.7	1.85
0.50	3.670 x 10 ⁴	523.7	10.9	1.94	0.50	2,772 x 10 ⁴	933.0	11.2	1.85
1.0	5,791 x 10 ³	547.8	7.8	1.94	1.0	8,755 x 10 ³	953.5	8.2	1.85
1.5	2,973 x 10 ³	555.4			1.5	4,309 x 10 ³	960.5		
2.0	1,742 x 10 ³	558.2			2.0	2,571 x 10 ³	963.0		
3.0	820	561.1			3.0	1,252 x 10 ³	965.0		
4.0	470	562.6			4.0	766	966.0		
12.0	40.8	564.0			12.0	67.4	966.5		
1 day	7.8	564.0			1 day	14.1	966.5		
2 day		564.0			2 day		966.5		
4 day		564.0			4 day		966.5		
10 day		564.0			10 day		966.5		
30 day		564.0			30 day		966.5		

TABLE 8
MASS LEAKAGE RESULTS FROM FFTF MODEL CALCULATIONS
FOR INNER CONTAINMENT
(Sheet 2 of 5)

Case 7D - 3% Release					Case 8D - 19% Release				
Inner Containment Vol = 161,000 ft ³					Inner Containment Vol = 161,000 ft ³				
Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma	Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma
0.0	3.518 x 10 ⁵	0.0	0.3	2.00	0.0	8.304 x 10 ⁵	0.0	0.3	2.00
0.1	3.485 x 10 ⁵	226.6	1.5	1.52	0.1	8.208 x 10 ⁵	549.0	2.4	1.78
0.25	1.378 x 10 ⁵	457.0	12.0	2.14	0.25	1.498 x 10 ⁵	878.0	15.8	1.99
0.50	3.704 x 10 ⁴	519.6	10.9	1.90	0.50	2.795 x 10 ⁴	928.0	11.1	1.99
1.0	5.736 x 10 ³	538.8	7.8	1.90	1.0	8.755 x 10 ³	944.0	8.1	1.99
1.5	2.946 x 10 ³	544.6			1.5	4.309 x 10 ³	948.5		
2.0	1.724 x 10 ³	547.2			2.0	2.572 x 10 ³	951.5		
3.0	812	549.5			3.0	1.258 x 10 ³	953.2		
4.0	460	550.4			4.0	702	954.0		
12.0	42.8	551.6			12.0	69.8	954.5		
1 day	9.6	551.6			1 day	13.6	954.5		
2 day		551.6			2 day		954.5		
4 day		551.6			4 day		954.5		
10 day		551.6			10 day		954.5		
30 day		551.6			30 day		954.5		

Case 1E - 3% Release					Case 2E - 19% Release				
Inner Containment Vol = 197,000 ft ³					Inner Containment Vol = 197,000 ft ³				
Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma	Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma
0.0	4.236 x 10 ⁵	0.0	0.3	2.00	0.0	1.309 x 10 ⁶	0.0	0.3	2.00
0.1	4.197 x 10 ⁵	163.0	1.5	1.52	0.1	1.158 x 10 ⁶	508.5	9.3	2.60
0.25	1.866 x 10 ⁵	309.7	11.6	2.18	0.25	9.118 x 10 ⁴	655.0	16.7	2.04
0.50	5.803 x 10 ⁴	357.8	10.8	1.92	0.50	2.782 x 10 ⁴	671.5	11.6	2.04
1.0	6.623 x 10 ³	370.6	7.8	1.92	1.0	9.118 x 10 ³	677.5	8.5	2.04
1.5	3.850 x 10 ³	374.6			1.5	4.592 x 10 ³	679.2		
2.0	2.109 x 10 ³	376.5			2.0	2.756 x 10 ³	680.0		
3.0	926	378.4			3.0	1.362 x 10 ³	680.5		
4.0	538	379.0			4.0	758	681.0		
12.0	48.3	379.9			12.0	72.5	681.5		
1 day	9.5	379.9			1 day	14.0	681.5		
2 day		379.9			2 day		681.5		
4 day		379.9			4 day		681.5		
10 day		379.9			10 day		681.5		
30 day		379.9			30 day		681.5		

TABLE 8
MASS LEAKAGE RESULTS FROM FFTF MODEL CALCULATIONS
FOR INNER CONTAINMENT
(Sheet 3 of 5)

Case 3E - 19% Release					Case 1F - 3% Release				
Inner Containment Vol = 197,000 ft ³					Inner Containment Vol = 161,000 ft ³				
Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma	Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma
0.0	1.031×10^6	0.0	0.3	2.00	0.0	4.190×10^5	0.0	0.3	2.00
0.1	1.021×10^6	398.0	1.8	1.59	0.1	4.150×10^5	64.3	1.8	1.60
0.25	2.524×10^5	695.4	14.2	2.02	0.25	9.000×10^4	123.5	14.5	1.98
0.50	8.593×10^4	758.4	11.2	2.02	0.50	3.256×10^4	135.9	11.0	1.96
1.0	1.405×10^4	777.6	7.9	2.02	1.0	5.290×10^3	140.4	8.0	1.96
1.5	7.538×10^3	783.6			1.5	2.836×10^3	141.8		
2.0	4.175×10^3	786.3			2.0	1.628×10^3	142.6		
3.0	2.031×10^3	788.4			3.0	752	143.4		
4.0	1.149×10^3	789.6			4.0	424	143.6		
12.0	99.2	790.8			12.0	37.3	144.0		
1 day	22.0	790.8			1 day	5.6	144.1		
2 day		790.8			2 day		144.1		
4 day		790.8			4 day		144.1		
10 day		790.8			10 day		144.1		
30 day		790.8			30 day		144.1		

Case 2F - 19% Release					Case 3F - 19% Release				
Inner Containment Vol = 161,000 ft ³					Inner Containment Vol = 161,000 ft ³				
Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma	Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma
0.0	1.280×10^6	0.0	0.3	2.00	0.0	1.029×10^6	0.0	0.3	2.00
0.1	8.021×10^5	190.6	15.0	2.42	0.1	1.017×10^6	157.9	2.4	1.78
0.25	1.875×10^5	228.2	16.6	2.08	0.25	2.040×10^5	265.2	15.9	2.00
0.50	2.374×10^4	232.9	11.6	2.08	0.50	1.044×10^5	281.2	11.0	2.00
1.0	7.332×10^3	235.0	8.8	2.08	1.0	1.141×10^4	287.2	8.3	2.00
1.5	3.657×10^3	235.6			1.5	5.426×10^3	289.3		
2.0	2.389×10^3	235.8			2.0	3.150×10^3	290.4		
3.0	1.104×10^3	236.0			3.0	1.436×10^3	291.3		
4.0	611	236.2			4.0	802	291.7		
12.0	50.6	236.2			12.0	71.3	292.0		
1 day	36.2	236.2			1 day	12.8	292.1		
2 day		236.2			2 day		292.1		
4 day		236.2			4 day		292.1		
10 day		236.2			10 day		292.1		
30 day		236.2			30 day		292.1		

TABLE 8
MASS LEAKAGE RESULTS FROM FFTF MODEL CALCULATIONS
FOR INNER CONTAINMENT
(Sheet 4 of 5)

Case 1G - 3% Release					Case 2G - 19% Release				
Inner Containment Vol = 161,000 ft ³					Inner Containment Vol = 161,000 ft ³				
Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma	Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma
0.0	3.506 x 10 ⁵	0.0	0.3	2.00	0.0	8.304 x 10 ⁵	0.0	0.3	2.00
0.1	3.474 x 10 ⁵	50.8	1.6	1.53	0.1	8.208 x 10 ⁵	129.1	2.4	1.76
0.25	1.472 x 10 ⁵	115.0	11.8	2.16	0.25	1.611 x 10 ⁵	219.8	15.8	1.99
0.50	5.485 x 10 ⁴	135.7	10.8	1.94	0.50	4.854 x 10 ⁴	234.2	11.1	1.99
1.0	2.446 x 10 ⁴	142.0	7.8	1.94	1.0	8.764 x 10 ³	239.8	8.1	
1.5	3.214 x 10 ³	144.3			1.5	4.368 x 10 ³	241.8		
2.0	2.134 x 10 ³	145.4			2.0	2.590 x 10 ³	242.6		
3.0	998	146.5			3.0	1.263 x 10 ³	243.5		
4.0	538	147.0			4.0	684	243.8		
12.0	44.0	147.7			12.0	59.1	244.2		
1 day	7.5	147.8			1 day	10.2	244.2		
2 day		147.8			2 day		244.2		
4 day		147.8			4 day		244.2		
10 day		147.8			10 day		244.2		
30 day		147.8			30 day		244.2		

Case 1H - 3% Release					Case 2H - 19% Release				
Inner Containment Vol = 197,000 ft ³					Inner Containment Vol = 197,000 ft ³				
Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma	Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma
0.0	3.502 x 10 ⁵	0.0	0.3	2.00	0.0	8.529 x 10 ⁵	0.0	0.3	2.00
0.1	3.470 x 10 ⁵	134.8	1.3	1.46	0.1	8.430 x 10 ⁵	329.1	1.7	1.58
0.25	2.427 x 10 ⁵	275.8	8.7	2.32	0.25	2.164 x 10 ⁵	580.0	14.1	2.00
0.50	5.189 x 10 ⁴	345.6	10.4	1.89	0.50	7.136 x 10 ⁴	631.0	11.0	1.96
1.0	1.433 x 10 ⁴	365.4	7.5	1.89	1.0	1.148 x 10 ⁴	647.5	8.0	1.96
1.5	4.475 x 10 ³	370.3			1.5	6.115 x 10 ³	652.5		
2.0	2.254 x 10 ³	373.5			2.0	3.526 x 10 ³	655.0		
3.0	1.082 x 10 ³	376.1			3.0	1.640 x 10 ³	656.8		
4.0	703	377.0			4.0	926	675.5		
12.0	57.7	378.7			12.0	79.0	658.5		
1 day	10.6	378.7			1 day	13.3	658.5		
2 day		378.7			2 day		658.5		
4 day		378.7			4 day		658.5		
10 day		378.7			10 day		658.5		
30 day		378.7			30 day		658.5		

TABLE 8
 MASS LEAKAGE RESULTS FROM FFTF MODEL CALCULATIONS
 FOR INNER CONTAINMENT
 (Sheet 5 of 5)

Case 1K - 3% Release					Case 2K - 19% Release				
Inner Containment Vol = 197,000 ft ³					Inner Containment Vol = 197,000 ft ³				
Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma	Time (hr)	Total Mass Airborne (gm)	Total Mass Leaked (gm)	Mass Median Radius (μ)	Sigma
0.0	3.502 x 10 ⁵	0.0	0.3	2.00	0.0	8.526 x 10 ⁵	0.0	0.3	2.0
0.1	3.470 x 10 ⁵	57.7	1.4	1.48	0.1	8.448 x 10 ⁵	131.0	1.75	1.58
0.25	2.460 x 10 ⁵	124.7	8.6	2.33	0.25	2.202 x 10 ⁵	256.8	14.0	2.03
0.50	4.566 x 10 ⁴	163.4	10.5	1.80	0.50	3.520 x 10 ⁴	287.1	10.9	2.03
1.0	2.662 x 10 ⁴	176.1	7.6	1.80	1.0	1.072 x 10 ⁴	297.0	7.9	2.03
1.5	4.028 x 10 ³	180.0			1.5	5.859 x 10 ³	300.4		
2.0	2.790 x 10 ³	182.0			2.0	3.526 x 10 ³	302.0		
3.0	1.228 x 10 ³	184.3			3.0	1.640 x 10 ³	303.7		
4.0	675	185.4			4.0	926	304.5		
12.0	62.6	186.9			12.0	82.8	305.4		
1 day	12.6	187.0			1 day	17.4	305.4		
2 day		187.0			2 day		305.4		
4 day		187.0			4 day		305.4		
10 day		187.0			10 day		305.4		
30 day		187.0			30 day		305.4		

TABLE 9
MASS LEAKAGE RESULTS FROM FFTF MODEL CALCULATIONS
FOR OUTER CONTAINMENT ACCIDENT

Outer Containment Vol = $2.7 \times 10^6 \text{ ft}^3$					
Time (hr)	HAA-2			SSM	
	Total Mass Airborne (gm)	Mass Leaked to Atmo- sphere (gm)	PuO ₂ Leaked to Atmo- sphere (gm)	Mass Leaked to Atmo- sphere (gm)	PuO ₂ Leaked to Atmo- sphere (gm)
0.0	1.233×10^5	0.0	0.0		
0.1	1.225×10^5	2.01	1.57×10^{-3}		
0.25	1.214×10^5	4.96	3.88×10^{-3}		
0.5	1.190×10^5	8.95	7.00×10^{-3}		
1.0	1.136×10^5	16.94	1.32×10^{-2}		
1.5	1.034×10^5	27.78	2.17×10^{-2}		
2.0	9.025×10^4	40.35	3.15×10^{-2}		
3.0	6.566×10^4	65.06	5.08×10^{-2}		
4.0	4.464×10^4	85.07	6.64×10^{-2}		
12.0	1.047×10^4	108.61	8.26×10^{-2}	98.61	7.70×10^{-2}
1 day	7.459×10^3			107.2	8.36×10^{-2}
2 day	2.749×10^3			114.2	8.92×10^{-2}
4 day	79.4			118.9	9.28×10^{-2}
10 day	96.4			120.3	9.39×10^{-2}
30 day	3.41			120.6	9.42×10^{-2}

Figure 11. Computed Airborne Mass and Leakage for Inner Containment, Case 2C

Figure 12. Computed Airborne Mass and Leakage for Outer Containment, Case 2C

VI. CONCLUSIONS

The present evaluation is based on computer solutions of a general equation which describes the spatial and temporal behavior of a heterogeneous distribution of aerosols. The model is justified on the basis of its comparison and agreement to experimental data.

In these accident studies, either 3 or 19% of the fuel is vaporized along with 450 lb of sodium and a fraction of the cladding and fission products. All of the material which becomes airborne (other than gases) is assumed to have an initial log normal distribution which changes as agglomeration, settling, plating, and leakage occurs. The effective size of the distribution which is airborne increases with time and increases in proportion to the total mass of all of the released material.

The most significant result of the study is shown in Figure 14 where the fraction of the total material released to the inner volume which leaks from the outer containment vs the released mass concentration in the inner containment volume is shown. The relation obtained from these studies may be stated algebraically as:

$$f'_L(\infty) = 6.9 \times 10^{-5} / C_R .$$

One can see that as the released concentration increases, that the leaked fraction decreases. One may also infer that for the cases studied, that the product of the leaked mass fraction and the released mass concentration is constant. The above equation can also be written in terms of the leaked mass of Pu, $M'_{L(Pu)}$:

$$M'_{L(Pu)} = \frac{M_{R(Pu)} \times 6.9 \times 10^{-5}}{C_R} .$$

Thus, if $M_{R(Pu)} / C_R$ is constant, then M'_{LPu} , the leaked mass of Pu is independent of C_R . If $M_{R(Pu)}$ is fixed and C_R is increased by the addition of relatively nontoxic materials such as sodium and cladding, then M'_{LPu} is decreased to a safer level.

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Figure 13. Computed Mass Fraction Leaked at Time = ∞ , to Outer Containment Vessel vs Released Mass Concentration in Inner Vessel

7702-40207

Figure 14. Computed Mass Fraction Leaking to Atmosphere, at $T = \infty$ vs Concentration Released to Inner Containment

The computed mass of material leaking to the atmosphere as a result of the release occurring in the outer volume is greater than that computed for any of the releases occurring in the inner volume. The initial particle size distribution of the released aerosol after the outer containment release is the same as that assumed in the inner containment releases. However, because of the difference in initial concentration, the particles which are airborne as a result of the releases in the outer volume remain smaller than the sizes which leak to the outer containment after the releases in the inner volume. Even though the cumulative mass of material airborne in the outer containment is about the same as that released as a result of the outer containment accident, the settling velocities are much less for the aerosols resulting from a release in the outer volume. As a result, the material remains airborne for longer times which results in larger mass leakage.

The leaked mass calculations are believed to represent an overestimate of the actual situation because it has been assumed that the aerosol leaks through the containment barrier pores and cracks without attenuation due to settling, impingement, or diffusion to surfaces. The effective settling velocity of the aerosol was arbitrarily set to values of about $1/3$ to $1/6$ that which might be expected, because a reduced density was suggested by the attempts to model experiment performed in the LTV.

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