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**RADIOLOGICAL EVALUATION
OF A HYPOTHETICAL
CORE DISRUPTIVE ACCIDENT**

FEBRUARY 1971

**HANFORD ENGINEERING DEVELOPMENT LABORATORY
UNITED STATES ATOMIC ENERGY COMMISSION**

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RADIOLOGICAL EVALUATION
OF A
HYPOTHETICAL CORE DISRUPTIVE ACCIDENT

C. L. Fies

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TABLE OF CONTENTS

	<u>Page No.</u>
INTRODUCTION.	1
SUMMARY AND CONCLUSIONS	3
RADIONUCLIDE INVENTORY.	5
RADIONUCLIDE RELEASE FROM THE REACTOR VESSEL.	7
LEAK RATES FROM CONTAINMENT STRUCTURES.	12
AEROSOL BEHAVIOR WITHIN CONTAINMENT STRUCTURES.	15
RADIONUCLIDE DOSE - COMPUTATIONAL METHOD.	18
RESULTS	20
Plutonium Exposure.	20
Halogen Exposure.	20
Solid Fission Product Exposure.	23
Noble Gas Exposure.	24
Whole Body Exposure	24
Exposure Summary.	28
REFERENCES.	36

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Fuel Fragmentation Data from ANL Molten UO_2 - Sodium Drop Experiment	11
2	Hypothetical Core Disruptive Accident-Reactor Cavity Leak Rate Based on Peak Pressure of 25 psig	13
3	Hypothetical Core Disruptive Accident - Containment Building Leak Rate	14
4	Aerosol Fallout within Containment Structures	17
5	Potential Bone and Lung Dose as a Function of Distance resulting from 100 gram Plutonium Release to Reactor Cavity	21
6	Potential Thyroid and Whole Body Dose as a Function of Distance Resulting from a 2% Halogen Release to the Reactor Cavity	22
7	Potential Bone, Lung, Thyroid and Whole Body Dose vs Distance Resulting from a 1% Solid Fission Product Release - 2 Hour Exposure	25
8	Potential Bone, Lung, Thyroid and Whole Body Dose vs Distance Resulting from a 1% Solid Fission Product Release - 30 Day Exposure	26
9	Potential Whole Body Dose Rate as a Function of Distance Resulting from 100% Noble Gas Release to the Reactor Cavity	27
10	Components of Whole Body Dose versus Distance - 2 Hour Exposure	29
11	Components of Whole Body Dose versus Distance - 30 Day Exposure	30
12	Potential Dose Resulting from 2 Hour Exposure - Release of 100 grams of Pu, 100% Noble Gas, 2% Halogens, and 1% Solids to Reactor Cavity	31
13	Potential Dose Resulting from 30 Day Exposure - Release of 100 grams of Pu, 100% Noble Gases, 2% Halogens, and 1% Solids to Reactor Cavity	32

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Hypothetical Core Disruptive Accident Summary of Radiation Exposure	4
2	FFTF Fission Product Activity (400 MW for 200 days)	5
3	FFTF Plutonium Isotopic Content and Activities	6
4	Release from Reactor Vessel to Vessel Cavity	8
5	Aerosol Parameter Values	15
6	F Values for Plutonium Isotopes	18
7	F Values for Iodine Isotopes	19
8	Comparison of the Close Contribution from Volatile and Non-Volatile Fission Products	23
9	Potential 2 Hour Dose at 1 1/2 Miles Resulting from Various Release Categories	34
10	Potential 30 Day Dose at Site Boundary (4 1/2 Miles) Resulting from Various Release Categories	34
11	Comparison of Potential 30 Day Exposure with Exposure Guidelines	35

INTRODUCTION

It is believed that a realistic evaluation of a hypothetical core disruptive accident, without numerous conservative assumptions, would conclude that the radiological consequence of such an event is insignificant in respect to potential radiation exposure to members of the general public. A realistic evaluation based upon an anticipated sequence of events is as follows: Disruption of the reactor core involves failure of the cladding fission product barriers. A fraction of the fuel and fission products is released as an expanding "vapor bubble" to the surrounding sodium pool. Heat and pressures generated during the accident would cause these materials to expand outward, driving the uncontaminated sodium above the core upward toward the reactor vessel cover. Only the uppermost fraction of the sodium would be expelled through peripheral gaps into the reactor cavity, and the presence of the extensive sodium pool and structure above the core quenches the release. All solid fission products and plutonium would be combined and mixed with the sodium and none would escape from the top of the reactor vessel. The halogen gases released, because of their high affinity for sodium, would also be confined to the reactor vessel. Release of radioactive material would thus be limited to a small amount of primary sodium and a fraction of the non-condensable noble gas inventory. These radionuclides must then leak from the inerted reactor cavity region, to the containment vessel, and finally to the environment. The potential exposure at the site boundary under these conditions is insignificant; a whole body dose no larger than a small fraction of a rem.

It is realized, however, that the above statements describing a realistic evaluation are difficult to support with experimental data. With this in mind, this document evaluates the accident on the basis of a number of conservative assumptions which one can postulate to test the capability of the containment system to mitigate the consequences of such an accident. The following topics are discussed:

1. The radionuclide inventory, including plutonium, fission products, activation products, and sodium present in the reactor core.
2. The amount of the radioactive inventory released from the core to the primary sodium and from the reactor vessel into the reactor vessel cavity as a result of the hypothetical core disruptive accident.
3. The pressures and leak rates associated with the reactor cavity and the containment vessel.
4. The aerosol behavior within the reactor cavity and within the containment vessel, and
5. The potential exposure to an individual as a function of distance from the containment building, as a result of inhalation of the material leaking from the building, the dose resulting from the passage of the radioactive cloud, and the direct dose obtained from the fission products suspended within the containment building.

SUMMARY AND CONCLUSIONS

A mechanistic analysis of the radiological consequences of the hypothetical core disruptive accident indicate that the containment structures, together with the isolation characteristics of the site, are more than adequate to protect the general public from excessive radiation exposure.

The basic rationale used in the analysis can be summarized as follows:

1. Release of material from the reactor vessel to the vessel cavity was as follows:
 - 10,000 pounds of primary sodium
 - 100% of the noble gas inventory
 - 2% of the halogen inventory
 - 1% of the solid fission product inventory
 - 100 grams of PuO_2
2. The leak rate from the vessel cavity to the containment building was varied based on a value of 1000 %/day at 35 psig design pressure.
3. The leak rate from the containment building was held constant at 0.32 %/day, corresponding to an overpressure of 1 psig, and based on a value of 1 %/day at 10 psig design pressure.
4. Aerosol fallout within the containment volumes was based on the analytical techniques developed by Atomics International.

Table 1 presents a summary of the potential radiation exposure resulting from a hypothetical core disruptive accident.

Table 1 also compares the calculated exposures with the guidelines set forth in 10 CFR 100⁽¹⁾ which states: "For the purpose of establishing areas and distances under the conditions assumed in this guide, the whole body dose of 25 rem and the 300 rem dose to the thyroid are believed to be conservative values."

TABLE 1. Hypothetical Core Disruptive Accident
Summary of Radiation Exposure

<u>Organ</u>	<u>10 CFR 100 Guideline Values (Rem)</u>	<u>Potential Exposure (Rem)</u>	
		<u>2 hour at 1-1/2 Miles</u>	<u>30 day at 4-1/2 Miles</u>
Bone	150*	0.63	0.85
Lung	75*	0.28	0.36
Thyroid	300	0.45	0.40
Whole Body	25	0.028	0.17

*Not covered in 10 CFR 100. Used as guideline values
equivalent to 10 CFR 100.

With respect to bone and lung dose, from inhaled plutonium, not covered in 10 CFR 100, values of 150 rem to the bone and 75 rem to the lung are used as guidelines in evaluating the degree of protection afforded the public.

For evaluating potential exposure to the public at the present time, the nearest point of approach corresponds to the Hanford Reservation boundary, 4-1/2 miles to the east of the site. To allow for the possible future industrial development of the Hanford Reservation, Table 1 also summarizes the 2 hour exposure at a distance of 1-1/2 miles from the FFTF. It is evident from Table 1 that the potential exposures are well within the guidelines defined above.

The margin that exists between the computed exposure and the prescribed guidelines was also evaluated. If one compares the potential 2 hour dose at 1-1/2 miles with the guidelines it is shown that 100% of the core inventory of fission products released to the reactor cavity would not result in exposures to the general public exceeding the guidelines of 10 CFR 100. Independently, up to 30 kg of PuO₂ of aerosol size could be released to the reactor cavity without exceeding the 150 rem bone dose guideline value. Thus, a large margin of safety exists against even hypothetical events.

RADIONUCLIDE INVENTORY

Table 2 shows the FFTF fission product activity after 200 days of operation at full power of 400 MWt. The inventories were calculated by the Radio-Isotope Buildup and Decay (RIBD) computer code⁽²⁾. The RIBD code calculates the isotopic concentration resulting from fission, the normal downchain decay by beta emission, the isomeric transfers, and the interchain coupling resulting from n-gamma reactions. The FTR core, under these conditions, contains approximately 10^8 curies each of the noble gases, halogens and volatile solids, and approximately 10^9 curies of the remaining solid fission products. The noble gases, halogens and volatile solids decay by approximately a factor of 100 in 20 days, whereas the remaining solid fission products decay by a factor of 10 in 20 days.

TABLE 2. FFTF Fission Product Activity
(400 MW for 200 days)

<u>Fission Products</u>	<u>Activity, in Curies, at Selected Decay Times</u>			
	<u>0</u>	<u>1 hr</u>	<u>1 day</u>	<u>20 days</u>
Noble Gases(Kr,Xe)	1.4×10^8	5.5×10^7	2.5×10^7	1.7×10^6
Halogens(I,Br)	1.4×10^8	7.4×10^7	3.1×10^7	2.2×10^6
Volatile Solids(Cs,Se,Te)	1.5×10^8	4.3×10^7	1.5×10^7	1.0×10^7
All Remaining Fission Products	1.1×10^9	4.6×10^8	2.6×10^8	1.1×10^8

Table 3 shows the isotopic content and the activity of the plutonium in the FFTF core. The first core is expected to have a relatively clean plutonium loading with relatively small percentages of ^{238}Pu and the higher isotopes of plutonium ^{241}Pu and ^{242}Pu . Later cores may use recycled fuel from water reactors which would contain higher percentages of plutonium ^{238}Pu , ^{241}Pu and ^{242}Pu . Since the recycle composition with its greater activities gives higher potential doses in the event of the hypothetical accident. The results presented in this document are based on the recycle fuel mix. Calculations presented in the SSAR⁽³⁾ considered both first core and recycle plutonium and showed that the dose increases by approximately a factor of 3 when going from first core to recycle fuel. This increase is due mainly to the increased percentages of ^{238}Pu and ^{241}Pu isotopes.

TABLE 3. FFTF Plutonium Isotopic Content and Activities

<u>First Core Isotopic Content</u> (200-day irradiation)			<u>Water Reactor Recycle Fuel</u>	
<u>Pu</u> <u>Isotope</u>	<u>Percent</u>	<u>Activity,</u> <u>Curies</u>	<u>Percent</u>	<u>Activity,</u> <u>Curies</u>
238	0.14	1.6×10^4	1.0	1.4×10^5
239	83.7	3.2×10^4	54.0	2.7×10^4
240	14.0	2.0×10^4	30.0	5.5×10^4
241	2.03	1.4×10^6	12.0	1.1×10^7
242	0.05	1.1	3.0	94.0

The sodium 24 activity in the total primary coolant system is approximately 10^7 curies with a specific activity of .043 curies per gram. The sodium 22 total activity is approximately 100 curies with a specific activity of 3.3×10^{-7} curies per gram. When evaluating the hypothetical accident one can eliminate consideration of sodium because its effect is overridden by the large amount of noble gas which is postulated to be released in the course of the accident. It will be shown later that approximately 50 Kg of sodium becomes airborne in the reactor cavity after the hypothetical accident. The activity contained in this small amount of sodium is approximately 2,000 curies. This can be compared with a noble gas release of 10^8 curies.

Additional radionuclides such as tritium, neon, argon and structural activation products are present in the primary system. However, the activities associated with these radionuclides is small relative to the core fission product inventories and, consequently, these isotopes have been neglected in the analysis.

RADIONUCLIDE RELEASE FROM THE REACTOR VESSEL

This section describes the possible release of the fission product and fuel inventory from the reactor vessel to the reactor vessel cavity as a result of the hypothetical core disruptive accident. The first barrier, the fuel cladding, is expected to be violated during the course of the accident, allowing a fraction of the fission product and inventory to be released to the sodium coolant. The heated materials are pictured to transfer heat to the sodium, creating a sodium vapor bubble in the core region. The expansion of sodium vapor causes the sodium above it to impact the vessel head. At this time, only cover gas and sodium are postulated to escape to the vessel cavity.

Immediately after the accident all fission products, fuel, and core debris created by the accident remain covered by the large sodium pool between the active reactor core and the vessel head. The sodium vapor bubble will then tend to move upward through this large sodium pool propelled by buoyancy effects. As the bubble moves upward, however, it encounters the structure situated above the core. Instrument trees, control rod extensions, guide tubes, etc., would cause fragmentation of any coherent vapor bubble during its passage. Further, this structure is at the sodium outlet temperature at the time of the accident (approximately 1000 °F) and condensation of vaporized material on these surfaces would be extensive. Consideration of the limitations on fuel particle size, after a disruptive accident, provides an additional assurance that solids will not escape the reactor vessel as will be discussed later.

Based on the accident sequence described above the release would be limited to a small quantity of primary sodium and a fraction of the non-condensable gas inventory. Nevertheless, releases are assumed for various categories of fission products and fuel from the reactor vessel to the reactor vessel cavity to test the capability of the containment system against higher release fractions. A rationale is provided in this section to provide further assurance that any material releases will involve, in the limit, small quantities of fuel.

Table 4 shows the release which was assumed for the radiological evaluation. 4535 kgs (10,000 lbs) of sodium is released into the vessel cavity around the periphery of the head during the head lift shortly after the hypothetical accident occurs. This sodium is expected to be relatively clean sodium which is located in the pool over the reactor core at the time of the accident. Approximately 50 kg of sodium oxide is formed when this hot sodium reacts with the 1% oxygen content in the vessel cavity. The remaining sodium will fall to the floor of the cavity.

TABLE 4. Release from Reactor
Vessel to Vessel Cavity

<u>Material Released</u>	<u>Amount</u>	<u>Activity (Curies)</u>
Sodium	4535 kgs (50 kgs of Sodium Oxide formed)	2.2×10^3
Noble Gases	100% of Inventory	1.4×10^8
Halogens	2% of Inventory	2.8×10^6
Solid Fission Products	1% of Inventory	1.2×10^7
UO ₂	230 grams	---
PUO ₂	100 grams	1.8×10^3

In order to test the capability of the containment system it is postulated that the core inventory of noble gases, 1.4×10^8 curies, will be released to the cavity as a result of the hypothetical accident. The actual fraction will be limited to the amount released from the fuel.

The release of the halogen isotopes to the cavity will be a small fraction of the core inventory because of the affinity of the halogens for the sodium. Experimental data^(4,5,6,7) on the release of iodine under sodium shows that the fraction which escapes is a fraction of a percent of the amount released. For the calculations here we conservatively assume that 2% of the core halogen inventory, or 2.8×10^6 curies, is released to the reactor cavity. To arrive at the 2% release the following rationale was used:

- 1) 50% of the halogen inventory is released from the fuel.
- 2) The halogens are uniformly distributed in the primary sodium contained in the reactor vessel.
- 3) The quantity of sodium released from the reactor vessel to the cavity (3.3% of the vessel inventory) is assumed to transport a proportional quantity of the 50% halogen inventory released.
- 4) The iodine inventory released is then approximately 2%.

A similar argument was used to estimate the fraction of solid fission products released. The condensation, scrubbing, and mixing effect of the large sodium pool is expected to limit the release of these mixed fission products to a very small amount. The volatile and non-volatile components of the inventory have been combined since the volatile contribution to the exposure is not significant. We believe that the postulated release of 1% of the core solid fission product inventory is conservative.

As mentioned previously, it is difficult to visualize that any of the fuel or plutonium contained in the core will be released to the cavity since this fuel must travel through the large sodium pool before being released to this area. In addition, fuel particle sizes generated during the course of the accident have been shown to be rather large by experimental data and only a very small fraction of the fuel is of aerosol size. Consideration of the experimental data of fuel particle sizes leads one to conclude that the release of approximately 230 grams of UO_2 and 100 grams of PuO_2 would be the amount of aerosol size fuel that could be released into the reactor cavity.

The data used in this analysis in respect to fuel particle sizes after simulated accident conditions are from the molten fuel sodium drop experiments performed at ANL⁽⁸⁾. Some of this data is summarized on Figure 1. The percentage of UO_2 with particle sizes less than 44 microns was about 15%. Since this particle size is above the size considered in the aerosol model, (0.6 microns mass median diameter) we have extrapolated the ANL molten UO_2 sodium drop experiments to smaller particle sizes of interest around 1 micron. The fraction of fuel particles less than 1 micron in diameter is 3×10^{-4} . Data from experiments performed in TREAT⁽⁹⁾ and SPERT^(10,11) have indicated a similar distribution of fuel particle sizes.

The fuel particle data was combined with the amount of molten fuel expected in the core to arrive at the 330 grams as follows:

1. The core contains 3300 kg of UO_2 - PuO_2 at the time of the accident.
2. Approximately one-third of the fuel in the core contacts the sodium in a molten condition. Thus, 1100 kg of fuel can be expected to be in intimate contact with the sodium.
3. Based on the fuel particle size data the fraction of this fuel with particle sizes in the range of 1 micron is 3×10^{-4} or 330 grams.
4. A maximum of 100 grams of PuO_2 would be contained in the 330 grams of fuel material.

This is believed to be a strong argument in supporting the contention that the amount of fuel escaping the confines of the reactor vessel will be a number similar to or smaller than the one we have chosen here: 100 grams of plutonium oxide.

FIGURE 1. *Fuel Fragmentation Data from ANL Molten
UO₂ - Sodium Drop Experiment*

LEAK RATES FROM CONTAINMENT STRUCTURES

The leak rates and pressures assumed for the reactor vessel cavity and the containment building were based on those given in Reference (12). As shown in Figure 2, the initial reactor cavity pressure of 25 psig results in a leak rate of 850 %/day to the containment building based on the assumed value of 1000 %/day at 35 psig. This leakage decays to approximately 340 %/day in a few minutes due to heat transfer to the adjacent structures. The leakage assumes that the reactor cavity is a closed structure with no leakage to the surrounding volumes. In actuality, this is a conservative assumption since the cavity is assumed to leak at a rate of 1000 %/day and the pressure would drop off relatively fast due to this leakage phenomena. A further conservative factor in this evaluation is that the realistic pressures generated in the reactor cavity would be more nearly in the range of 5-10 psig.

Figure 3 shows the leak rate from the containment building as a function of time following the hypothetical disruptive accident. This curve assumes that leakage occurs from the reactor cavity at 1000 %/day and the pressure rises to approximately 0.6 psig in 40 hours after the accident. The heating of the containment atmosphere occurs by decay of the noble gas fission products which are estimated to contain 10% of the total core decay heat. After the pressure peaks at 40 hours it slowly drops during the remaining time as heat is transferred to the surrounding structures. Because of the long times involved and the possibility of changing atmospheric conditions outside the building, one could have an additional pressure differential imposed upon this curve. For the radiological analysis we have assumed a constant pressure of 1 psig (leak rate of 0.32 %/day) for the duration of the accident.

FIGURE 2. *Hypothetical Core Disruptive Accident - Reactor Cavity Leak Rate Based on Peak Pressure of 25 psig.*

FIGURE 3. *Hypothetical Core Disruptive Accident -
Containment Building Leak Rate*

AEROSOL BEHAVIOR WITHIN CONTAINMENT STRUCTURES

Figure 4 shows the predicted behavior of the particulate matter within the containment structures. This fallout is important in determining the amount of material which ultimately escapes to the environment. The plutonium, solid fission products, and sodium released to the reactor vessel cavity will be suspended in the cavity atmosphere as an aerosol. Experimental data have shown that the behavior of the halogens released will resemble an aerosol because of the high affinity of the halogens for sodium.⁽¹³⁾

The aerosol behavior within the containment spaces has been studied extensively by both Brookhaven National Laboratory^(14, 15, 16) and Atomics International.^(17, 18) Analytical methods have been developed to predict the behavior of suspended material as a function of time and the results have been verified by experimental data. For the analysis here the AI aerosol model and, in particular, the Heterogeneous Aerosol Agglomeration (HAA) codes^(19, 20) developed by AI were used in the analysis.

Table 5 shows the aerosol parameters which were employed for the calculation. The parameter values were selected based on the results of experimental data generated by AI.

TABLE 5. Aerosol Parameter Values

<u>Parameter</u>	<u>Inner Containment</u>	<u>Outer Containment</u>
Initial mass median radius (microns)	0.3	Variable
Initial sigma	2.0	Variable
Collision efficiency of gravitational agglomeration	1.0	1.0
Correction factor for Stoke's settling velocity	0.33	0.33

A similar particle size and distribution have been observed when sodium and fuel aerosols are generated under controlled conditions. The values for gravitational agglomeration efficiency and Stoke's settling velocity are modifications which give the best agreement between experiments and calculational methods.

The sensitivity of these parameters on the rate of fallout have been investigated and reported in Reference (21). A Stoke's correction factor change from 1.0 to 0.33 increases the long term mass leakage by a factor of 3.0. A gravitational agglomeration efficiency change from 1.0 to 0.5 results in a mass leakage increase of less than a factor of 2.0. These small changes in the rate of fallout would not effect the overall conclusion in this report.

Figure 4 shows the results of the calculation using the parameter values described above. The reactor cavity atmosphere contains 50 micrograms per cc of material comprised of 50 kilograms of sodium oxide, 230 grams of uranium oxide and 100 grams of plutonium oxide along with 100% of the core inventory of noble gases, 2% of the core inventory of halogens, and 1% of the core inventory of solid fission products. This concentration decreases rapidly due to agglomeration and fallout within the reactor cavity and the concentration is also depleted due to the large assumed leakage rate of 1000% per day to the containment structure. For the exposure calculations, the rate of fallout was set to zero for times greater than 10 hours. For these times, the cavity concentration is depleted mainly by the large leak rate. In the containment volume the concentration builds up over a period of 1 hour due to the leakage from the cavity and remains relatively constant for nearly 10 hours before fallout begins to occur for time periods beyond 10 hours. The fallout rate in the outer containment volume is relatively slow because of the low aerosol concentration of less than 0.1 micrograms per cc which does not allow for much agglomeration in the containment building atmosphere.

FIGURE 4. *Aerosol Fallout Within Containment Structures*

RADIONUCLIDE DOSE - COMPUTATIONAL METHOD

This section discusses the computational methods used for the radiological evaluation. The COMRADEX⁽²²⁾ code permits the use of multiple containment barriers including variable fallout and leakage from up to four volumes. The leakage and fallout rates discussed in previous sections were used as code input. Pasquill Type F conditions were used for the duration of the release. This assumption causes the results to be somewhat conservative since no account is taken of the effects of atmospheric conditions being variable over the 30 day release period. The breathing rate was assumed to be 3.47×10^{-4} cubic meters per second for the 2 hour release and 2.32×10^{-4} cubic meters per second for the 30 day release. Ground level release was assumed for all calculations with a 1 meter per second wind speed. The internal dose calculations for thyroid, bone, and lung were based on the report of ICRP committee II on permissible dose from internal radiation, 1959. Fallout was applied to all categories of fission products except the noble gases.

Table 6 presents the F values (rem/curie inhaled) used for bone and lung dose from the plutonium isotopes. It should be noted that the F values assume that the PuO_2 is insoluble for the lung dose and soluble for the bone dose.

TABLE 6. F Values for Plutonium Isotopes

<u>Isotope</u>	<u>Rem/Curie Inhaled</u>	
	<u>Bone</u>	<u>Lung</u>
^{238}Pu	5.23×10^9	1.80×10^8
^{239}Pu	5.57×10^9	1.80×10^8
^{240}Pu	5.57×10^9	1.80×10^8
^{241}Pu	1.24×10^8	1.80×10^5
^{242}Pu	5.57×10^9	1.80×10^8

Calculations in the SSAR⁽³⁾ show that the new lung model would increase the lung dose by approximately a factor of two. For the bone dose, however, the assumption of solubility for the PuO₂ is believed to be rather conservative.

Table 7 presents the F values used in the calculation of the thyroid dose due to the iodine isotopes. A complete listing of all fission product F values is contained in Reference (23).

TABLE 7. F Values for Iodine Isotopes

<u>Isotope</u>	<u>Rem to Thyroid/Curie Inhaled</u>
¹²⁹ I	6.7 x 10 ⁶
¹³¹ I	1.5 x 10 ⁶
¹³² I	5.3 x 10 ⁴
¹³³ I	3.9 x 10 ⁵
¹³⁴ I	2.5 x 10 ⁴
¹³⁵ I	1.2 x 10 ⁵

RESULTS

This section presents the results of the radiological calculations based on the previous sections of this report. Dose versus distance curves are presented for plutonium and for the categories of fission products (noble gases, halogens, and solids) in order to show the individual components of the total dose.

Plutonium Exposure

Figure 5 shows the potential bone and lung doses resulting from a 100 gram release of plutonium to the reactor cavity. Leak rates are taken into account in this calculation as discussed in previous sections. At distances beyond 2 miles the bone and lung doses fall below 2 rem for both 2 hour and 30 day exposure. It should be noted that the 30 day dose could be lowered to a position nearer the 2 hour dose by taking advantage of changing atmospheric conditions during the 30 day release period. The dose to the lung from plutonium is nearly a factor of 100 below the dose to the bone.

Halogen Exposure

Figure 6 shows the potential thyroid and whole body dose as a function of distance resulting from a 2% halogen release to the reactor cavity. Both the 30 day and 2 hour thyroid doses fall below 1 rem for distances from the containment greater than 2 miles. The whole body dose resulting from the release of halogens includes the direct dose from the building, the dose from the passing cloud, and the contribution from inhalations. The whole body dose falls to relatively insignificant levels: 10^{-3} rem at distances beyond 5 miles. The contribution at .1 mile is due mainly to the direct dose from halogens suspended in the containment building.

FIGURE 5. *Potential Bone and Lung Dose as a Function of Distance Resulting from 100 Gram Plutonium Release to Reactor Cavity*

FIGURE 6. *Potential Thyroid and Whole Body Dose as a Function of Distance Resulting from a 2% Halogen Release to the Reactor Cavity*

Solid Fission Product Exposure

The calculation of the potential exposure resulting from the release of solid fission products combines the volatile and non-volatile components into a single category. The volatile isotopes (cesium, selenium, and tellurium) do not make a significant contribution to the exposure. Table 8 compares the volatile and non-volatile contributions to the exposure categories for a 2 hour exposure at 1 1/2 miles and a 30 day exposure at 4 1/2 miles. The contribution made by the volatile solids can be seen to be a small fraction of that due to all solid fission products. The discussion which follows, therefore, combines the volatile and non-volatile solid fission products into a single solid fission product category.

TABLE 8
COMPARISON OF THE DOSE CONTRIBUTION FROM VOLATILE AND
NON-VOLATILE FISSION PRODUCTS

<u>Organ</u>	<u>2 Hour Exposure at 1 1/2 Miles (Rem)</u>		<u>30 Day Exposure at 4 1/2 Miles (Rem)</u>	
	<u>1% of all Solids</u>	<u>1% Cs, Te and Se</u>	<u>1% of all Solids</u>	<u>1% Cs Te and Se</u>
Bone	0.29	0.00083	0.38	0.00098
Lung	0.27	0.0082	0.35	0.0097
Thyroid	0.0067	0.0064	0.0097	0.0096
Whole Body	0.014	0.00052	0.019	0.00064

Figure 7 shows the potential bone, lung, thyroid and whole body 2 hour dose versus distance resulting from a 1% solid fission product release to the reactor cavity. Here the bone and lung doses are approximately equal. At distances greater than 1 mile the bone and lung dose falls below approximately .5 rem. The thyroid and whole body doses at distances greater than 1 mile fall below .02 rem.

Figure 8 shows the potential dose as a function of distance where 1% solid fission products are released and an individual is exposed for 30 days. Beyond 2 miles the potential dose to the bone and lung is below 1 rem. Thyroid and whole body doses again fall in the range of a fraction of a rem for distances beyond 1 mile.

Noble Gas Exposure

Figure 9 shows the whole body dose resulting from the release of 100% of the noble gases to the reactor vessel cavity. No fallout is applied to the noble gases in the vessel cavity or in the containment volume. The large difference between the 30 day and 2 hour exposure, that does not occur for the particulate release is a result of the absence of fallout within the containment structures. In this case the use of different atmospheric conditions in the time period between 2 hours and 30 days would cause a significant decrease in the 30 day dose. Even with Pasquill Type F conditions, the 30 day dose falls below 1 rem at distances beyond 1 mile.

Whole Body Dose

The contribution to the whole body dose includes three components:

- (1) The direct dose as a function of distance resulting from fission products suspended in the containment building. The source of material in the containment building results from the 1000%/day equivalent leakage from the reaction vessel cavity.

FIGURE 7. *Potential Bone, Lung, Thyroid and Whole Body Dose vs. Distance Resulting from a 1% Solid Fission Product Release - 2 Hour Exposure*

FIGURE 8. *Potential Bone, Lung, Thyroid and Whole Body Dose vs. Distance Resulting from a 1% Solid Fission Product Release - 30 Day Exposure*

FIGURE 9. *Potential Whole Body Dose as a Function of Distance Resulting from 100% Noble Gas Release to the Reactor Cavity*

- (2) The dose vs. distance from the fission products contained in the radioactive cloud presumed to be leaking from the building, and
- (3) The whole body dose resulting from the inhalation of fission products contained in the cloud.

Figure 10 shows these three contributions to the whole body dose for a two hour exposure resulting from the release of 100% noble gases, 2% halogens and 1% solids. The direct contribution falls to 10^{-3} rem in 1 1/2 miles. The internal and cloud contributions are insignificant compared to the direct dose for distances up to one mile, while for distances greater than one mile the cloud and internal doses are controlling. Figure 11 shows the contributions to whole body dose resulting from a 30 day exposure. Note that the cloud dose contribution is higher relative to the internal dose for the 30 day case since the solid fission products, which provide the contribution to the internal whole body dose, fall out within the containment building in relatively short time periods.

Exposure Summary

Figures 12 and 13 combine the release of 100 grams of plutonium, 100% of the noble gases, 2% of the halogens, and 1% of the solids. Figure 12 shows that the 2 hour dose to the organs of interest are below 1 rem at distances beyond 1 1/2 miles. Figure 13 shows that the 30 day dose to the organs of interest remain below 1 rem for distances beyond 4 1/2 miles

Table 9 summarizes the radiation exposure which would be received by an individual located 1-1/2 miles from the containment for the first two hours following the hypothetical core disruptive accident. The potential dose is shown by release category and by the organ exposed. The total potential dose to these organs (bone, lung, thyroid and whole body) falls below 1 rem in all cases.

FIGURE 10. *Components of Whole Body Dose vs. Distance - 2 Hour Exposure*

FIGURE 11. *Components of Whole Body Dose vs. Distance - 30 Day Exposure*

FIGURE 12. *Potential Dose Resulting from 2 Hour Exposure - Release of 100 GM of PU, 100% Noble Gas, 2% Halogens, and 1% Solids to Reactor Cavity*

FIGURE 13. *Potential Dose Resulting from 30 Day Exposure - Release of 100 Grams of PU, 100% Noble Gases, 2% Halogens, and 1% Solids to Reactor Cavity*

Table 10 shows the potential 30 day exposure at the Hanford site boundary 4-1/2 miles from the containment building. It should be noted that the lung dose is controlled by the release of solids, the thyroid dose by the release of halogens, and the whole body dose by the release of noble gases. It is instructive to compare these potential dose values with the 10 CFR 100 guideline values and the release fractions to see how much margin exists in the design. As a first approximation the dose will increase proportional to the activity released to the reactor cavity. This is actually a conservative approximation since a larger mass release will result in a more rapid rate of fallout. Increasing the halogen release from 2% to the maximum of 100% would increase the thyroid dose by a factor of 50 to a value of 20 rem at the site boundary. This value is still a factor of 15 below the 300 rem limit.

Table 11 ratios up the release fractions for the controlling categories of fission products for comparison with the 10 CFR 100 guideline values. We find that even with the conservative assumptions used for these calculations a release of 100% of the fission product activity would result in potential exposures below the 10 CFR 100 guidelines. With the plutonium bone dose guideline value of 150 rem, approximately 30 kg of plutonium oxide would have to be released to exceed this value.

TABLE 9 Potential 2 Hour Dose at 1-1/2 Miles Resulting from Various Release Categories

<u>Release</u>	<u>Potential Dose (Rem)</u>			
	<u>Bone</u>	<u>Lung</u>	<u>Thyroid</u>	<u>Whole Body</u>
100 grams PuO ₂	0.34	0.0055	- -	- -
2% halogens	- -	- -	0.44	0.0011
1% solids	0.29	0.27	0.0067	0.014
100% noble gases	- -	- -	- -	0.013
<hr/>				
Total	0.63	0.28	0.45	0.028

TABLE 10 Potential 30 Day Dose at Site Boundary (4-1/2 Miles) Resulting from Various Release Categories

<u>Release</u>	<u>Potential Dose (Rem)</u>			
	<u>Bone</u>	<u>Lung</u>	<u>Thyroid</u>	<u>Whole Body</u>
100 grams PuO ₂	0.47	0.0077	- -	- -
2% halogens	- -	- -	0.39	.0009
1% solids	0.38	0.35	0.0097	.019
100% noble gases	- -	- -	- -	0.15
<hr/>				
Total	0.85	0.36	0.40	0.17

TABLE 11 Comparison of Potential 30 Day Exposure
with Exposure Guidelines

<u>Organ</u>	<u>10 CFR 100 Guidelines (Rem)</u>	<u>Controlling Release</u>	<u>Amount Released to Obtain Guideline Values</u>
Bone	150*	PuO ₂	30 kg
Lung	75*	Solids	>100%
Thyroid	300	halogens	>100%
Whole body	25	noble gases	>100%

*Not covered in 10 CFR 100: Used as guideline values equivalent
to 10 CFR 100.

REFERENCES

1. Code of Federal Regulations, Title 10 - Atomic Energy, Part 100, Reactor Site Criteria, February 1961.
2. R. O. Gumprecht. "Mathematical Basis of Computer Code RIBD", DUN-4136, Douglas United Nuclear, Inc., Richland, Washington, May 1968.
3. J. P. Hale. "FFTF Site Safety Analysis Report", BNWL-1350, Pacific Northwest Laboratory, Richland, Washington, April 1, 1970.
4. R. S. Hart and C. T. Nelson, "Fission Product Retention Characteristics of Sodium at High Temperatures," NAA-SR-MEMO-8712, Atomics International, June 1, 1964.
5. W. P. Kunkel, et al, "High Temperature Experiments on Fission Product Retention in Sodium," NAA-SR-9287, Atomics International, February 1, 1965.
6. W. P. Kunkel, "Fission Product Retention in Sodium - A Summary of Analytical and Experimental Studies at Atomics International," NAA-SR-11766, Atomics International, August 8, 1966.
7. G. W. Keilholtz and G. C. Battle, Jr., "Fission Product Release and Transport in Liquid Metal Fast Breeder Reactor," ORNL-NSIC-37, Oak Ridge National Laboratory, March 1969.
8. D. R. Armstrong, et al, "Molten UO_2 -Sodium Dropping Experiments," ANS Transactions Winter Meeting, November 1970.
9. C. E. Dickerman, et al, "First TREAT Experiment on High-Energy Fuel Failure of an Unirradiated Oxide Fast Reactor Fuel Pin in Flowing Sodium," ANS Transactions, Volume 13, No. 1, June 1970.
10. Quarterly Technical Progress Report, SPERT Project, January-March 1968; IDO-17287, November 1968.
11. Z. R. Martinson, "Behavior of 5-Inch Long, 1/4-Inch O.D. Zircalloy-2 Clad Oxide Fuel Rods Subjected to High Energy Power Bursts," IN-ITR-107, August 1969.
12. D. D. Stepnewski, et al, "Mechanical Consequences of the Hypothetical Core Disruptive Accident," (to be published).
13. L. Baurmash, et al, "Behavior of Iodine in the Presence of Sodium Oxide," Proceedings of the 11th AEC Air Cleaning Conference, CONF 700816, Volume 1, December 1970.

14. F. L. Horn and A. W. Castleman, Jr. "PuO₂-UO₂-Na Aerosols Produced by Vaporization of Fast Reactor Core Materials", Symposium on Operating and Developmental Experiences in the Treatment of Airborne Radioactive Wastes, New York, August 26-30, 1968, BNL-12757.
15. A. W. Castleman, Jr. et al. "On the Behavior of Aerosols under Fast Reactor Accident Conditions, International Congress of the Diffusion of Fission Products", Saclay, France, November 4-6, 1969, BNL-14070.
16. A. W. Castleman, Jr. "A Summary of Recent Progress in Aerosol Research at Brookhaven National Laboratory", Specialist Meeting on the Behavior of Nuclear Aerosols in Closed Systems, Kernforschungszentrum Karlsruhe, 11-12 November 1969, Karlsruhe, Germany (BNL-14271).
17. R. L. Koontz, L. Baurmash. "Analysis of Aerosol Behavior for FFTF Hypothetical Accidents," AI-69-MEMO-95, October 28, 1969.
18. M. A. Greenfield, R. L. Koontz, D. F. Hausknecht. "Characteristics of Aerosols Produced by Sodium Fires, Vol. II: Comparisons of Experiment with a General Equation for the Coagulation of Heterogeneous Aerosols", AI-AEC-12878.
19. R. S. Hubner. "An Approximate Solution to the General Equation for the Coagulation of Heterogeneous Aerosols", AI-AEC-MEMO-12880, 1969.
20. R. S. Hubner. "Program HAA-3A; A Modification of the Computer Program HAA-3, TI-707-13-003, May 1970.
21. R. L. Koontz, et al, "Aerosol Modeling of Hypothetical LMFBR Accidents," AI-AEC-12977, August 31, 1970.
22. C. W. Willis, et al, "COMRADEX - A New Technique for Reactor Siting Dose Calculations," 13th Annual Health Physics Society Meeting, Denver, Colorado, June 16-20, 1968.
23. G. P. Kenfield, et al, "Curie-Dose-Thunderhead - A Digital Computer Program for External and Internal Radiation Dose Calculations," NAA-SR-8884, June 15, 1965.