

# **HYPOTHETICAL CORE DISRUPTIVE ACCIDENT CONSIDERATIONS IN CRBRP**

## **VOLUME 2:**

### **ASSESSMENT OF THERMAL MARGIN BEYOND THE DESIGN BASE**

**CLINCH RIVER BREEDER REACTOR PLANT**

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#### 4.0 ASSESSMENT OF RADIOLOGICAL CONSEQUENCES

This section addresses the radiological consequences associated with an HCDA. These radiological analyses are based on the design described in Section 2 and the thermal and structural analyses presented in Section 3. Section 4.1 discusses the development of the radiological source terms considered in the cases analyzed. A wide range of assumptions on materials initially released to the RCB is used. Section 4.2 provides the results of radiological calculations for atmospheric releases. Section 4.3 considers potential releases to the groundwater. The overall conclusions on radiological consequences are provided in Section 4.5. The radiological calculations and results are based on the heterogeneous core design.

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##### 4.1 HCDA RADIOLOGICAL SOURCE TERM

The radiological consequences associated with the TMBDB scenario are based on a complete core meltdown. The release of radioactive material from the reactor cavity to the RCB is considered in two parts: an initial release phase, and a sodium boil-up phase. The types and amounts of radioactivity released from the RC depend on how much damage occurs to the head as a result of the HCDA, which in turn, depends on how much energy is assumed to be released as a result of the HCDA. Four cases, representing varying degrees of immediate leakage through the head, were evaluated. The first case represents the best estimate consequence of a hypothetical core disruptive accident. Subsequent cases assume greater initial releases through the reactor vessel head.

#### 4.1.1 Non-Energetic Core Meltdown

##### Initial Release Phase

The initial release phase includes materials that, because of their physical state or high volatility, are not expected to be retained to an appreciable extent in the liquid sodium. For a non-energetic meltdown, 100% of the noble gases (Kr, Xe) and 100% of the more volatile elements (Cs, Rb) are assumed to be released immediately from the molten fuel. Although no appreciable release of these nuclides to the RCB would be expected until after the penetration of the reactor vessel and guard vessel and subsequent release through the RC to RCB vent (beyond 1000 seconds), the radiological analyses conservatively are based on the release at time zero.

##### Boil-Up Phase

During the sodium boil-up phase the non-gaseous radioactivity trapped in the sodium pool enters the RCB atmosphere as the sodium pool boils.

One hundred percent of the halogens (principally I) and the remaining volatile elements (Se, Sb, Te) are assumed to have been released from the molten fuel, uniformly distributed in the sodium pool, and then released to the RCB atmosphere in proportion to the sodium vaporization (i.e., no credit for partitioning).

The term volatile, as used here, refers to the elements Cesium (Cs), Rubidium (Rb), Tellurium (Te), Selenium (Se), and Antimony (Sb). In addition to these five, Reference 4-1 includes Xenon (Xe), Krypton (Kr), Iodine (I), and Bromine (Br) in the category of volatile fission products. This report refers to these four additional elements as noble gases (Xe and Kr) and halogens (I and Br), but it does recognize the volatility of these four additional elements as they are also considered to be 100% released from the molten fuel. References 4-2 and 4-3 present the results of a study of existing experimental and theoretical data on the volatility of elements in molten fuel. This study generated a list of volatility factors

for fission products. These factors represent conservative estimates of the percent release of elements from molten fuel. The volatility of Xe, Kr, I, and Br are given as 100%. The volatility of Cs, Rb, Te, Se, and Sb are given as 90%. The next largest volatility factor given is 4% which is significantly lower than the 90 to 100% values. Elements with factors of 4% and lower are considered in the class of non-volatiles.

It was assumed that after release from the sodium pool 100% of the volatiles will co-agglomerate with sodium based particulates. That assumption is based on two premises. First, the volatiles are in a non-gaseous state (i.e., they are either a liquid or solid aerosol) and as such are capable of agglomerating. Second, an aerosol composed of different chemical species will coagulate into single aggregates and settle as one material.

An evaluation of the first premise, based on the physical conditions associated with the release of volatile fission products from the sodium pool, residence in the RCB and release from the RCB has been made. The volatiles are assumed to be released from the sodium pool as a gas at a temperature corresponding to the temperature of burning sodium. The time required for these volatile fission products to reach thermal equilibrium with the RCB atmosphere (minutes) is short compared to the average residence time in the RCB (hours). The RCB atmosphere temperature (peak  $\sim 900^{\circ}\text{F}$ , average  $< 750^{\circ}\text{F}$  over the release period) is well below the boiling points of the volatile fission products and their oxides so they would condense to liquids or solids very quickly and have ample time to agglomerate before being vented. Experimental evidence supporting the second premise is reported in Reference 4-11.

The non-volatile fission products would be quenched in the sodium and form particulates. Based on measurements of particle size distributions in the ANL M-series tests, approximately 15% of the fuel could exist in particles small enough to remain suspended in the sodium pool (Reference 4-4). These suspended fuel particles would contain a proportionate amount of solid fission products.



Based on a recent survey (Reference 4-5) of experimental data on liquid carry-over from commercial evaporators and entrainment of solid particles in the vapor stream from an evaporating liquid pool, it was concluded that the decontamination factor (partitioning factor) for plutonium particles would be at least a factor of 1000.

Partitioning of solid fission products in the sodium as it vaporizes is based on the method summarized in Reference 4-6. The combined partitioning of the fuel and sodium results in a release of 1% of the total non-volatile solid fission product inventory. A more detailed evaluation of the overall solid fission product release is presented in Appendix E.

The fuel release during the sodium boilup phase is estimated by considering the two attenuating mechanisms discussed above, i.e., 15% of the fuel particulate remaining in suspension following meltdown and reparticulation, and a partition factor of 1000. This would result in approximately 320 grams of plutonium being carried into the RCB atmosphere with the boiling sodium. See Appendix E for a more detailed discussion of plutonium release from the boiling sodium.

Additional mechanisms for transporting plutonium from the reactor cavity to the RCB have been investigated and found to be negligible in comparison to the 320 grams considered above. These additional mechanisms are also discussed in Appendix E.

The initial release phase and boilup phase source terms described above for a non-energetic core meltdown are used in Case 1 in Table 4-1.

#### Post Boil-Dry Phase

After the sodium pool in the reactor cavity has evaporated a bare fuel/steel debris bed is left. Most of the fission product release is expected to occur prior to boil-off (Reference 4-1). Potential mechanisms

for further release of fission products and plutonium from the dry debris bed are: (1) surface vaporization; (2) particle levitation; and (3) gas sparging. The first two mechanisms are considered for plutonium in Appendix E and are shown to result in a negligible contribution to the release associated with the boiling sodium pool. The volatile fission products are assumed to have been completely released. The non-volatile fission products have vapor pressures similar to or lower than the vapor pressure of fuel (Reference 4-4). Thus, like the fuel, no significant fraction of the remaining fission products would be released from the molten surface due to the first two mechanisms.

The release of fission products and plutonium due to gas sparging has also been evaluated (see Appendix E). The results of this evaluation show that those products whose releases are enhanced the most by sparging are the more volatile products which the analysis already considers to be totally released. The release of the other less volatile products by sparging is accounted for by the 1% release fraction assigned to the non-volatile fission products in the boil-up phase source term. Plutonium release from the molten pool by sparging could be on the order of 26 grams over a several month period and this has been assumed to be released to the RCB. The evaluation of this additional plutonium source is discussed in Appendix E. Assuming a 99% filter efficiency and taking credit for aerosol fallout and plate-out, about 0.1 gram of plutonium could be released to the atmosphere over a several month period beginning at sodium boil-dry (~ 5 days) after the start of the accident.

#### 4.1.2 Energetic HCDA

##### Initial Release Phase

The case described in Section 4.1.1 is based on the expected consequence of a hypothetical core disruptive accident; namely a non-energetic condition and consequently, no significant immediate release of sodium or

non-volatile fission products through the reactor vessel head. Several variations of the expected case were analyzed using successively more pessimistic assumptions on the initial releases through the reactor vessel head.

The second case analyzed (Case 2 in Table 4-1) is similar to the expected case (Case 1) except that an energetic hypothetical core disruptive accident is assumed. The available work energy, if the fuel vapor were expanded to one atmosphere, is 661 MJ. The fraction of the core inventory of fuel which is vaporized and transported to the cover gas region as a vapor is conservatively based on a single hemispherical bubble model which takes no credit for heat losses from the bubble while rising through the sodium pool and core structure (Reference 4-3). The results of this analysis indicate that 7.3% of the core fuel inventory could reach the cover gas space in the form of vapor. Since the reactor vessel, head and primary system are designed to retain their structural integrity for the dynamic loadings corresponding to the 661 MJ condition, the immediate releases would still be limited. To represent this condition, an immediate release of 1000 pounds of sodium and gas leak rate of 1000 standard cubic centimeters per second for the first 1000 seconds are used.

The combination of the 1000 scc/sec leak rate and aerosol depletion in the cover gas region would limit the amount of fuel and fission products in the initial release phase to 0.026% of the core inventory. This fraction was assumed to be released at time zero in Case 2 described in Table 4-1.

The two additional cases evaluated (Cases 3 and 4) arbitrarily employed progressively larger initial releases of fuel, sodium, and the less volatile fission products. These cases were useful to examine the sensitivity of the consequences to releases that are much larger than expected.

### Boil-Up Phase

The release associated with the sodium vapor phase for Case 2 is similar to that of Case 1. As Cases 3 and 4 were considered more severe and released more fuel and fission products in the initial phase, correspondingly lesser amounts of these products would be present in the sodium boil-up phase. The source terms for these four hypothetical accident scenarios are summarized in Table 4-1.

Fission product and activation product activity levels are based on the end-of-equilibrium-cycle core inventory identified in Table 12.1-32 of the PSAR. The end-of-equilibrium-cycle plutonium inventory was used because it results in a slightly higher dose value than the beginning-of-equilibrium-cycle plutonium for an initial core loading of FFTF grade fuel.

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### Post Boil-Dry Phase

The same considerations apply here as discussed in Section 4.1.1.

## 4.2 RADIOLOGICAL DOSES FROM ATMOSPHERIC RELEASES

### 4.2.1 Methods and Data Base

#### Aerosol Depletion

The radiological release from the RCB to the environment depends on the concentration of suspended radioactivity in the RCB and the RCB vent rate. The RCB vent rate (which includes the effect of purging) is varied as required to maintain the hydrogen concentration at an acceptable level (<6%) (see Section 3.2.2). The suspended concentration of radioactivity in the RCB is a function of the source generation rate, RCB vent rate, and aerosol deposition rate. The HAA-3 computer code calculates the time dependent suspended aerosol concentration taking these interacting effects into account. For a more detailed discussion of the HAA-3 code and its basis see Appendix D. The rate of aerosol depletion calculated by HAA-3 is input to the COMRADEX code.

#### COMRADEX Radiological Analysis

COMRADEX computes the time-rate of release of radioactivity from the RCB. The COMRADEX calculations include the effects of radioactivity decay and aerosol depletion within containment. COMRADEX also determines, as a function of time and downwind location, doses resulting from direct gamma shine, inhalation of radioactive material, and cloud submersion taking into account atmospheric dispersion.

#### Meteorology

The atmospheric dispersion parameters (X/Q's) used for the TMBDB evaluation are provided in Table 4-2. These dispersion factors are based on the "50% cumulative frequency" (atmospheric dispersion more favorable 50% of the time) X/Q values (Reference 4-7).

### Dose Factors

Dose conversion factors (rem/ci) for bone surface and red marrow were taken from Reference 4-10, while values for the other organs were taken from Reference 4-9.

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### Containment Modeling

The time dependent radiological source term is released directly to the RCB. The release rate from the RCB is that calculated by the CACECO code. For the first 36 hours of the scenario the RCB atmosphere leaks at a low rate (based on 0.1%/day at 10 psig) to the annulus filter system (described in Section 6.2.5 of the PSAR). During this 36 hour period unfiltered bypass leakage at the rate of 1% of the filtered leakage is considered. After 36 hours the RCB is vented and subsequently purged (Figures 3-13 and 3-14) to maintain the hydrogen concentration at an acceptable level. During this phase filtering is by the TMBDB filter system which is designed for the higher vent rates. The efficiency of the TMBDB filter system is 99% for solid fission products and fuel and 97% for condensible fission products (halogens, Se, and Sb). Noble gases are assumed to pass through the filter system unattenuated. (There is some question of the effectiveness of the filter system to remove  $\text{Na}_2\text{CO}_3$  and the fission products which may be tied up with this aerosol component. This subject is addressed in Appendix E.) Because the bypass leakage rate is expected to be so small relative to the high vent rate after 36 hours, the bypass leakage is not expected to make a significant contribution to the released radioactivity and is therefore not considered beyond 36 hours.

The direct gamma contribution to the whole body dose considers the shielding provided by the steel RCB and the concrete confinement building.

Figure 4-1 shows the dose rate inside the reactor containment building for Case 2.

#### 4.2.2 Radiological Doses

Using the methods described in Section 4.2.1 the radiological doses at the Exclusion Boundary (0.42 miles) and the Low Population Zone (2.5 miles) were calculated for the four different source terms described in Section 4.1. These doses are summarized in Table 4-3. The 30 day LPZ doses include the plutonium released after boil-dry to 30 days. Plutonium release beyond 30 days could result in an additional 0.03 rem to the LPZ bone surface dose. Control room doses were provided in Section 2.2.15.

The 30 day dose consequences of the four cases that assumed varying degrees of severity of the hypothetical accident are all quite low for accidents beyond the design base. For example, the maximum whole body dose is predicted to be about 2.1 rem and the maximum thyroid dose would be about 85 rem. The maximum bone surface dose is about 6.1 rem.

The results also show that the 30 day consequences are not strongly sensitive to the degree of severity of the initial release source term. As the initial release to the RCB increases, the rate of aerosol depletion increases which acts as an inverse feedback to limit the release from the RCB. The 2 hour dose consequences are somewhat more sensitive to the magnitude of the initial head release. This is because the aerosol depletion effects are a somewhat delayed reaction, and therefore do not reach their full effectiveness until later in the event. The 2 hour dose consequences of all four cases are still quite low. Consequently, so long as the initial release does not result in failure of the containment barrier, the radiological consequences are relatively insensitive to the magnitude of the release. For the full range of releases considered in Cases 1 through 4, the RCB pressure and temperatures would not result in failure of the containment barrier.

Table 4-4 compares the consequences, in terms of curies released, of a comparable scenario (core meltdown with enough containment leakage to prevent containment failure by overpressure) for CRBRP and light water



reactors (LWR). The CRBRP values are for the worst of the above four cases. The LWR releases are for the accident scenarios PWR-6 and BWR-4 described in Section 2 of Appendix VI of WASH-1400. This comparison shows the atmospheric releases for CRBRP to be comparable to those for LWRs. Figure 4-1 shows the integrated radioactivity released to the environment for case 2.

4.4 INTENTIONALLY DELETED

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#### 4.5 CONCLUSIONS ON RADIOLOGICAL CONSEQUENCES

Radiological releases associated with the TMBDB accident scenario have been assessed. The consequences of both atmospheric releases and groundwater releases were considered. To examine the sensitivity of the atmospheric consequences to larger releases than expected, several cases of varying degrees of severity were evaluated. The results of these analyses show the radiological dose consequences to be acceptably low and insensitive to the initial release phase over the range of releases considered.

Groundwater contamination levels resulting from reactor cavity melt-through were shown to be lower than the predicted concentrations following an assumed LWR meltdown and even lower than the 10CFR20 MPC values for routine releases.

It is concluded that the radiological consequences of a hypothetical core disruptive accident would be acceptable considering the highly improbable nature of the conditions analyzed.

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4-10. D. E. Dunning, Jr., et al., "Estimates of Internal Dose Equivalent to 22 Target Organs for Radionuclides Occurring in Routine Releases From Nuclear Fuel-Cycle Facilities," Volume 3, NUREG/CR-0150, October 1981.

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TABLE 4-1

CORE SOURCE TERMS RELEASED TO THE REACTOR CONTAINMENT BUILDING  
FOR HYPOTHETICAL ACCIDENT SCENARIOS CONSIDERED

	<u>Initial Release Phase</u>	<u>Sodium Boil-Up Phase</u>
Case 1	100% Noble Gases	100% Halogens
	100% Cs and Rb	100% other Volatile F.P. 1% solid F.P. 0.015% Fuel $1.1 \times 10^6$ lb. of Na
Case 2	100% Noble Gases	100% Halogens
	100% Cs and Rb	100% other Volatile F.P.
	1000 lb. of Na with 100PPB Pu	1% solid F.P.
	0.026% Fuel*, Solid F.P., Halogen	0.015% Fuel $1.1 \times 10^6$ lb. of Na
Case 3	100% Noble Gases	1% of remaining 99% of solid F.P.
	100% Halogens	0.015% Fuel
	100% all Volatiles	$1.1 \times 10^6$ lb. of Na
	1% Fuel*	
	1% Solid F.P.	
	1000 lb. of Na	
Case 4	100% Noble Gases	1% of remaining 95% of solid F.P.
	100% Halogens	0.015% Fuel
	100% all Volatiles	$1.1 \times 10^6$ lb. of Na
	5% Fuel*	
	5% Solid F.P.	
	3300 lb. of Na	

Note: After boil-dry the only significant contribution to the source term is plutonium release due to gas sparging. This additional source amounts to about 26 grams of plutonium released from the molten pool, which has been assumed to be freely transmitted to the RCB over a several month period and is considered the same for all four cases.

\*Includes plutonium in blankets and core.

TABLE 4-2  
ATMOSPHERIC DILUTION FACTORS

50% X/Q Values\*

<u>Exclusion Boundary (0.42 miles)</u>	<u>X/Q (sec/M<sup>3</sup>)</u>	
0-2 hours	$1.01 \times 10^{-3}$	5
<u>Low Population Zone (2.5 miles)</u>		
0-2 hours	$1.59 \times 10^{-4}$	5
2-8 hours	$2.30 \times 10^{-5}$	
8-24 hours	$3.58 \times 10^{-6}$	
1-4 days	$2.29 \times 10^{-6}$	
4-30 days	$2.60 \times 10^{-6}$	

\*See Section 2.3 of the CRBRP PSAR.



TABLE 4-3

DOSE SUMMARY FOR HYPOTHETICAL ACCIDENT  
SCENARIOS CONSIDERED

		Doses in REM			
	<u>Organ</u>	<u>Case 1</u>	<u>Case 2</u>	<u>Case 3</u>	<u>Case 4</u>
2 Hour Exclusion Boundary	Bone Surface	0.027	0.19	6.47	27.0
	Red Bone Marrow	0.026	0.040	0.56	2.18
	Lung	0.020	0.032	0.72	1.77
	Liver	0.052	0.060	0.44	1.21
	Thyroid	0.014	0.020	23.4	19.6
	Whole Body	0.82	0.82	1.09	1.22
30 Day Low Population Zone	Bone Surface	0.92	0.95	2.45	6.07
	Red Bone Marrow	0.19	0.19	0.27	0.56
	Lung	1.54	1.55	0.82	1.00
	Liver	0.36	0.36	0.18	0.32
	Thyroid	85.3	85.4	8.13	5.43
	Whole Body	2.10	2.09	1.73	1.65

TABLE 4-4

COMPARISON OF RADIONUCLIDE RELEASES TO ATMOSPHERE FOR CRBRP  
WITH LWR'S FOR A COMPARABLE MELTDOWN SCENARIO

Element	Radioactivity Released (curies)		
	CRBRP	PWR(3)	BWR(3)
Xe-Kr	$3.6 \times 10^7$	$1.0 \times 10^8$	$2.1 \times 10^8$
I	$2.1 \times 10^5$	$2.0 \times 10^6$	$1.1 \times 10^6$
Cs, Rb	$5.2 \times 10^1$	$1.2 \times 10^4$	$7.6 \times 10^4$
Te, Sb	$4.8 \times 10^4$	$2.2 \times 10^5$	$8.6 \times 10^5$
Ba, Sr	$7.5 \times 10^2$	$3.3 \times 10^4$	$2.2 \times 10^5$
Ru <sup>(1)</sup>	$2.8 \times 10^3$	$3.9 \times 10^4$	$3.3 \times 10^5$
La <sup>(2)</sup>	$4.1 \times 10^3$	$2.9 \times 10^4$	$2.9 \times 10^5$

(1) Includes: Ru, Rh, Co, Mo, Tc

(2) Includes: Y, La, Zr, Nb, Ce, Pr, Nd, Np, Pu, Am, Cm

(3) From WASH-1400 Appendix VI, Calculation of Reactor Accident Consequences, October 1975. The LWR scenarios used for comparison here are PWR-6 and BWR-4 described in Section 2 of WASH-1400 Appendix VI.

TABLE 4-5

COMPARISON OF CALCULATED GROUNDWATER EFFLUENT  
CONCENTRATIONS FOR CRBRP AND TYPICAL LWR

Nuclide	Concentration ( $\mu\text{Ci/cc}$ )		
	CRBRP	LWR	MPC (10CFR20)*
Sr 90	$3.6 \times 10^{-9}$	$7.1 \times 10^{-4}$	$3 \times 10^{-7}$
Tc 99	$6.8 \times 10^{-8}$	$3.6 \times 10^{-6}$	$2 \times 10^{-4}$
Pu 239	$7.1 \times 10^{-7}$	$8.0 \times 10^{-7}$	$5 \times 10^{-6}$

\*The 10CFR20 MPC values are for routine releases and are not required to be met for accidental releases. They are presented here simply to illustrate the very low levels of radioactivity predicted in the groundwater following an assumed penetration of the basemat.

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TABLE 4-6

INTENTIONALLY DELETED

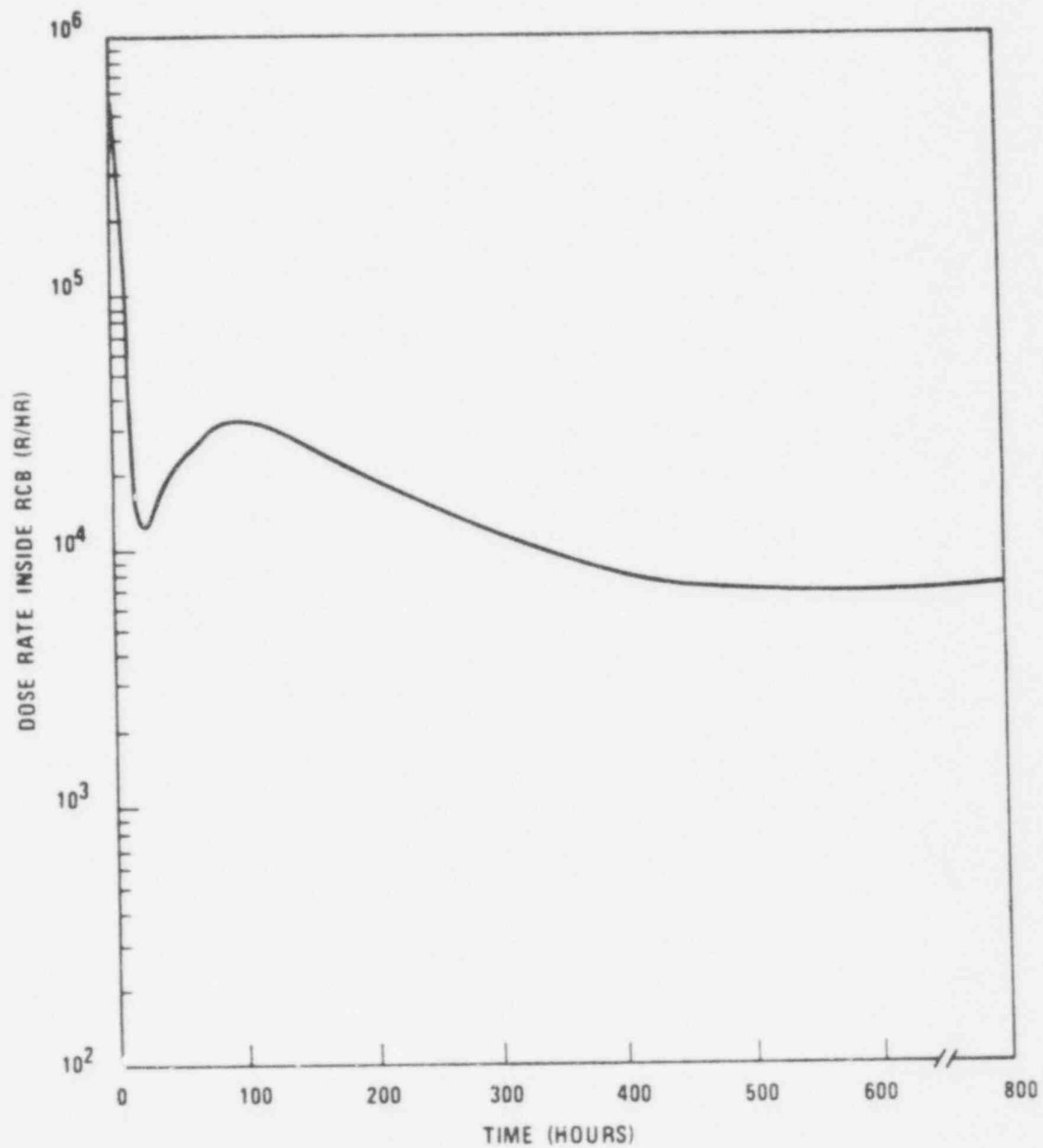


Figure 4-1 Dose Rate Inside the Reactor Containment Building for Case 2

3379-2

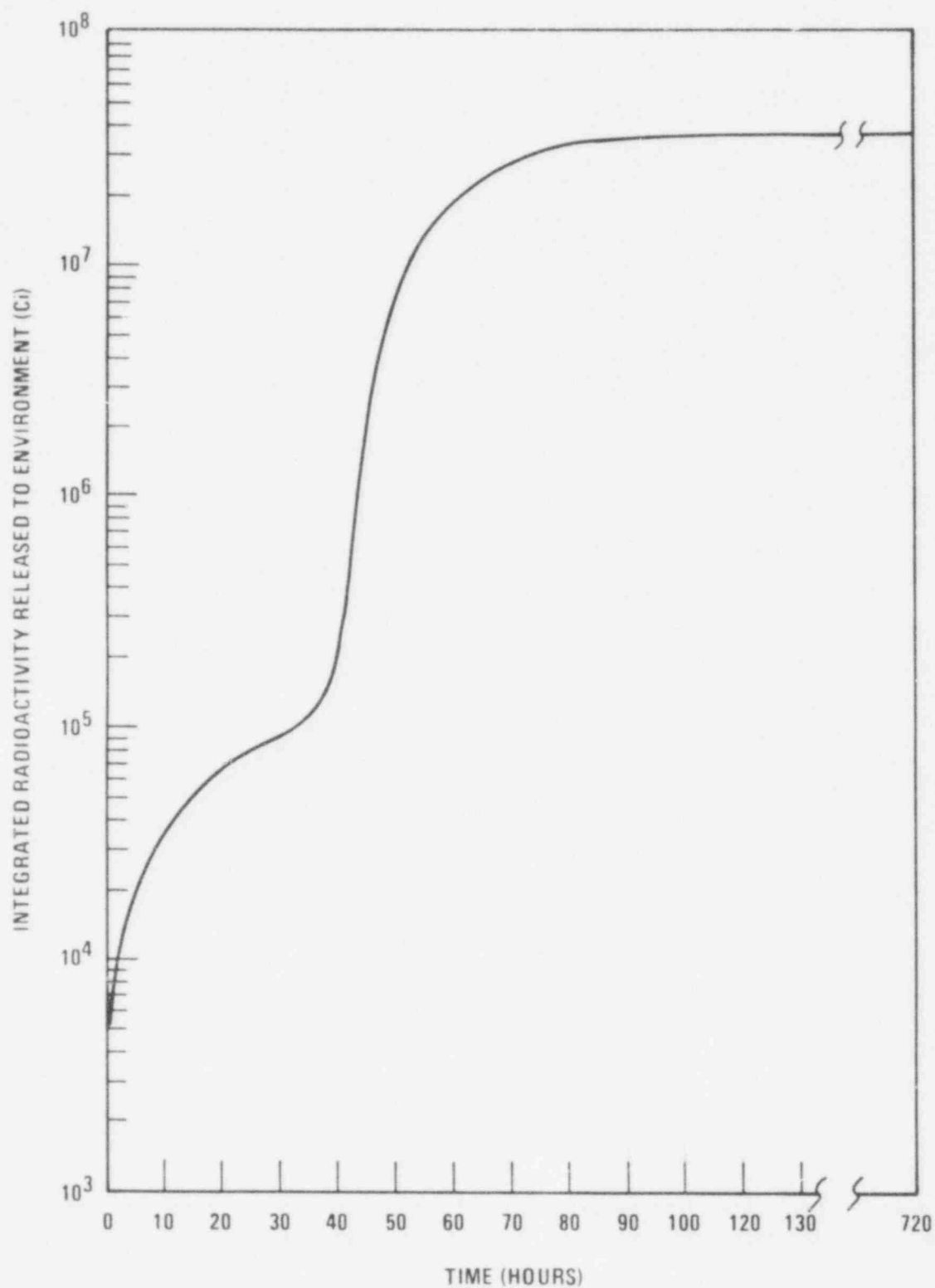


Figure 4-2. Integrated Radioactivity Released to Environment for Case 2

APPENDIX E  
RELEASE OF PLUTONIUM AND FISSION PRODUCTS

E.1 INTRODUCTION

This section considers the potential release of plutonium to the RCB subsequent to that assumed released as part of the initial release phase. Possible mechanisms for transporting plutonium from the reactor cavity to the RCB have been investigated. These mechanisms include potential plutonium release from burning the oxygen originally available in the reactor cavity, plutonium release from the boiling pool of sodium, plutonium release from the dry debris bed, and release due to gas sparging.

E.2 PLUTONIUM RELEASE FROM SODIUM-OXYGEN REACTIONS IN THE INERTED CELLS

Because primary sodium could be released to the RC and PHTS cells, sodium burning can be postulated. The amount of sodium burned would be limited however because of the 2% oxygen level present. This Section addresses the potential plutonium source associated with postulated sodium reactions.

When a sodium pool containing plutonium burns, a small amount of plutonium is released along with the sodium reaction products. This release has been quantified experimentally.

In Reference E-1, Chatfield determined that a plutonium release fraction of  $2.9 \times 10^{-5}$  resulted from the burning of sodium containing  $\text{PuO}_2$ .

Recent experiments at Atomics International (Reference E-2) have further assessed the airborne concentration of plutonium resulting from the combustion of plutonium contaminated sodium. In these tests, sodium was doped with from 13 to 250 ppm  $\text{PuO}_2$  or  $\text{Na}_4\text{PuO}_5$  and then ignited in air at temperatures of 500 to 550°C. The aerosol released from this burning



pool of sodium was collected and analyzed for plutonium content. For the sodium containing  $\text{PuO}_2$ , nine experiments resulted in plutonium release fractions ranging from  $1 \times 10^{-6}$  to  $8.7 \times 10^{-5}$ . The average release fraction was  $2.0 \times 10^{-5}$ . For sodium-plutonate, the preliminary results indicate the release fractions are several orders of magnitude less than for  $\text{PuO}_2$ . The fractional release of plutonium from burning sodium used in these analyses is  $3 \times 10^{-5}$ . This is consistent with the data in References E-4 and E-5 and may be highly conservative if a substantial amount of the plutonium is in the form of sodium plutonate.

If the total amount of oxygen present in the RC and three PHTS cells completely reacts with sodium, the amount of sodium burned would be 1785 pounds.

Based on the particle distributions from the M-Series tests at ANL, about 15% of the fuel would be in small enough particulates to be suspended in the sodium. If it is assumed that 15% of the total plutonium inventory (2096 Kg) is uniformly distributed throughout the total primary sodium inventory ( $1.1 \times 10^6$  lbs) then the amount of plutonium contained in the burning sodium is  $(0.15) (2096 \text{ Kg}) (1785 / 1.1 \times 10^6) = 510$  grams. Applying the  $3 \times 10^{-5}$  release fraction gives a plutonium release of 0.015 grams to the RCB. This is an insignificant amount compared to that assumed in the initial release phase source term.

### E.3 PLUTONIUM RELEASE FROM A BOILING POOL OF SODIUM

The primary sodium which drains out of the reactor vessel and primary piping forms a pool in the reactor cavity. The pool contains the fuel debris from the core. The interaction of molten fuel with sodium results in a fuel particle distribution. Based on measurements of particle size distributions in the ANL M-series tests (Reference E-3), approximately 15% of the fuel could exist in particles small enough to remain in suspension in the sodium pool. The remaining fuel would form a settled bed on the bottom of the

sodium pool. The fuel debris heats the sodium to boiling due to decay heat. As the sodium pool boils, plutonium is released from the pool by vaporization of the plutonium and plutonium particle entrainment in sodium droplets carried from the pool by the sodium vapor. Based on a recent survey (Reference E-4) of experimental data on liquid carry-over from commercial evaporators and entrainment of solid particles in the vapor stream from an evaporating liquid pool, it was concluded that the experimental data of Jordan and Ozawa (Reference E-5) is most directly applicable for estimating the potential plutonium release from a boiling pool of sodium. Their results show a minimum decontamination factor of about 1000. Thus if 15% of fuel is suspended in the sodium and if 1/1000 of this is released, then the net fuel release is 0.015% of the total inventory. Since there are approximately 2100 kg of plutonium in the CRBRP core the plutonium release from the boiling sodium pool to the RCB atmosphere could be about 320 grams. However, because of aerosol depletion and filtering less than one gram would actually be released from the RCB cleanup system.

Once the fuel and core debris penetrates the RC liner, carbon dioxide and steam would be released and bubble through the sodium pool. The effect of this gas sparging on additional plutonium and fission product release has been investigated by Parsly and Fontana (Reference E-6). The model developed in this reference was used to determine the effect of gas sparging on additional releases from CRBRP. Most of the fission products fall into one of two categories: (1) those with predicted high fractional releases due to sparging, which are the more volatile products that have already been considered totally released either initially or during sodium boiling, (2) those with low release fractions which are conservatively covered by the assumed 1% solid fission product release during the sodium boiling phase. A few isotopes do have sparging release fractions larger than the 1% used in the TMBDB analysis; however, these represent a less significant contribution to the dose consequences than does the increased plutonium release (Reference E-7). Additional plutonium release during the boil-up phase due

to sparging is not significant relative to that resulting from the boiling sodium pool. Sparging effects after boil-dry were found to be more significant as discussed below.

#### E.4 PLUTONIUM RELEASE AFTER SODIUM BOIL-DRY

After the sodium pool in the reactor cavity has evaporated, a bare fuel/steel debris melt is left. This debris melt continues to decompose the concrete beneath it, releasing carbon dioxide and steam which bubbles through the pool. The remaining concrete constituents melt and become mixed with the fuel/steel melt as a result of the bubbling action.

The conditions described above give rise to several possible modes of release of plutonium which have been investigated. These are: (a) plutonium vapor transport, (b) plutonium particle levitation, and (c) plutonium gas sparging. Each of these plutonium release modes will be addressed in the following paragraphs.

During the post sodium boil-dry period communication is assumed between the reactor cavity and the reactor containment building. This results in a natural convection current through the cavity. The potential mass transport of plutonium via this convection depends on the debris temperature and the convection velocity. The debris surface temperature at the top of the crust was determined to be  $\sim 2500^{\circ}\text{F}$ . The methods and assumptions related to the calculation of bed surface temperature are discussed in Section 3.2.3.1 of this report. The convection velocity was calculated as follows: First, the natural circulation heat transfer rate was calculated (for a specified  $\text{PuO}_2$  surface temperature) using the correlation in Reference E-8 for heat transfer from a hot disk to a large volume of gas. Next, an expression for the temperature rise of the circulating gas was derived as a function of gas flow rate. Finally, expressions for the form pressure loss were derived and set equal to an expression for the buoyancy pressure driving forces (acceleration and frictional losses were conservatively ignored). This last

expression, which contained only flow rate as unknown, was solved and the maximum velocity was calculated as that through the opening between the reactor cavity and the RCB.

The analysis of the convection velocity used the following assumptions:

1. The temperature of the debris surface was  $5500^{\circ}\text{F}$ . This is highly conservative for the calculation of the convection velocity since the predicted surface temperature is  $\sim 2500^{\circ}\text{F}$ .\*
2. The temperature of the gas in the reactor containment building (RCB) was  $500^{\circ}\text{F}$ .

\*Because mass transfer from the debris surface is a function of the convective velocities within the reactor cavity, a  $3000^{\circ}\text{F}$  margin was added to the debris temperature to enable the calculation of a higher than expected mass transfer coefficient. This coefficient, when applied at the predicted condition, will result in higher mass transfer rates, providing margin in the calculation.

3. The temperature of the air outside the RCB was 70°F.
4. The debris bed was uniformly distributed over the bottom of the reactor cavity. | 5
5. The natural circulation velocity was based on the open reactor cavity (no reactor head) with the vessel in place.

The resulting peak natural convection velocity is 12 ft/sec. | 5

The plutonium vapor transport release mode is due to the plutonium in the debris trying to establish a vapor pressure corresponding to the surface temperature and the convection current removing the vapor. This establishes a concentration gradient down which the vapor molecules move. This subject of mass transfer is treated in Reference E-9. Based on a maximum convection velocity of 12 ft/sec and maximum bed surface temperature of 2500°F the vapor removal rate was calculated to be only  $5 \times 10^{-5}$  grams/hour. At this rate the amount of plutonium released to the RCB in a period of one month is only 0.04 grams. | 5

Plutonium removal by particles being physically swept up from the surface of the bed by the convection current (levitation) was also considered.

The surface of the debris would be solid, i.e., covered with a layer of steel, or in the form of molten iron oxide. In either case, plutonium particles are not present to be picked up by the convection current. Even if the debris were composed of plutonium particles in a molten steel pool, a velocity of only 12 ft/sec would not be sufficient to detach particles from the liquid steel.

The effect of gas sparging after boil-dry has also been evaluated. With the molten sodium gone, the dilution of the core materials is reduced, tending to increase the amount of sparging. The molten concrete, however, does tend to continue to dilute the core melt, thus reducing the vapor pressure of the | 5

dissolved plutonium and reducing somewhat the sparging that could occur. Using the model of reference E-6 as before, coupled with data from reference E-14 to evaluate the released fraction of plutonium, a sparged plutonium mass of 23 grams is predicted during the first 30 days of the event. This amount is based on a highly conservative temperature of 4500°F for the molten concrete and core debris mixture. More realistic temperatures lower than 4500°F would greatly reduce the sparged mass. Beyond 30 days, another 3 grams of plutonium could be sparged.

The 26 grams of plutonium sparged during the entire course of the event would be reduced by aerosol effects within the RCB such that less than half would be released to the TMBDB cleanup system. The release to the environment would be reduced by another factor of ~100 by the 99% efficient cleanup system, leaving only about one-tenth of one gram of sparged plutonium to escape into the environment during the course of the event.

#### E.5 CONCLUSIONS ON PLUTONIUM RELEASE

An evaluation of potential plutonium release from the reactor cavity to the RCB during sodium boiling and following boil-dry has been made. This evaluation indicates that, in addition to that considered in the initial release phase, about 320 grams of plutonium could be released from the boiling sodium, and about 26 grams could be released to the RCB over a several month period following boil-dry due to gas sparging.

#### E.6 FISSION PRODUCT RELEASE TO THE RCB

The overall release fraction of fission products from the fuel to the RCB atmosphere is the product of the release fraction from the molten fuel and the release fraction from the sodium pool. References E-10 and E-11 present the results of an evaluation of existing experimental and theoretical data on the volatility of elements in molten fuel. This study developed a list of volatility factors for fission products. These factors represent conservative estimates of the percent release of elements from molten fuel. The volatility

of those elements in the categories of noble gases and halogens is 100%. Those elements in the category of volatile fission products have volatility factors of 90%. The remaining fission products, in the category of solid fission products, have volatility factors of 4% or less. Of those in the 4% group only a few are present in the CRBRP EOE fission product inventory in sufficient quantities to be significant. Strontium and barium have factors of 2%. All other fission products have factors of 1%. These release fractions from molten fuel are summarized in Table E-1.

Once released from the fuel to the liquid sodium, additional partitioning of the fission products can occur during vaporization of the sodium. A method for calculating the extent of fission product release from a sodium pool as a function of sodium vaporized using the Rayleigh equation is reported in References E-12 and E-13.

$$F_i = 1 - (1 - F_{Na})^{A_i}$$

where:

- $F_i$  = fraction of a given element released
- $F_{Na}$  = fraction of sodium vaporized
- $A_i$  = parameter for given element (from Ref. E-12)

Reference E-12 shows that measured values of cesium release from vaporized sodium agree with values predicted by this method.

The TMBDB base case CACECO analysis indicates that 76% of the sodium pool is vaporized. Using 0.76 for  $F_{Na}$  and the  $A_i$  values from Reference E-12, the fraction of fission products released can be calculated for a number of products of interest. The fractions of these products released from sodium are given in Table E-2.

For the TMBDB analysis the overall release of fission products from the molten fuel to the RCB atmosphere is determined by considering the product of the



factors in Tables E-1 and E-2. A complete set of release factors for all elements is not available; however, values for some elements from each group are available and were applied to the other elements within the group. The noble gases are assumed to be released directly from the fuel to the RCB with no attenuation or delay by the sodium pool. The volatile elements cesium and rubidium are also assumed to be released with no attenuation or delay by the sodium. The early release of Cs and Rb is suggested by Reference E-13 which shows almost 100% release of these elements before less than 10% of the sodium has vaporized. Table E-2 indicates that on the order of one third of the iodine, in the form of NaI, would be released from the sodium. It is conservatively assumed that 100% of the iodine is released as the sodium vaporizes.

Of the remaining fission products, the next largest release fraction from the sodium is 0.074. Applying this factor to the fuel release fractions for the solid fission product group gives overall release fractions of 0.003 for those few elements in the 4% group, 0.0015 for Sr and Ba, and 0.0007 for the remaining majority of the solid fission products. Thus the largest overall release of any single solid fission product is about 0.3%.

The TMDBB radiological analysis conservatively assumes the overall release of all the solid fission products to be 1% during the sodium boiling phase.

The majority of the fission products reaching the RCB would be in the form of liquid or solid oxides. Some chemically uncombined fission products may also be released from the sodium as vapor but would condense in the RCB atmosphere (Section 4.1.1 discusses the behavior of the volatile fission products). These fission products would physically co-agglomerate and settle with the predominately  $\text{Na}_2\text{O}$  aerosol. Co-agglomeration of a mixture of aerosol products is addressed in Section 4.1.1. A kinetic analysis of the conversion of iodine to sodium-iodide shows that on the order of 0.2% of the available iodine could remain in the elemental form and, as such, would be less subject to aerosol depletion and filtration. If the entire 0.2% of elemental iodine



were released unattenuated by the containment cleanup system, it would result in an additional 30 day LPZ dose to the thyroid of about 40 rem.

#### E.7 EFFECT OF $\text{CO}_2$ REACTION WITH NaOH ON FISSION PRODUCT RELEASE FROM THE RCB

This section addresses the effect of  $\text{CO}_2$  reactions with airborne NaOH, as it may affect the behavior and release of airborne radioactivity.

Because of the slow reaction rate of  $\text{CO}_2$  with NaOH, relative to the high RCB vent rate during the TMBDB scenario, it is not likely that a significant amount of  $\text{CO}_2$  would react with NaOH before being vented. Any  $\text{CO}_2$  that does react would most likely react directly with Na to form  $\text{Na}_2\text{CO}_3$ . Even if an infinite heat transfer coefficient between the reactor cavity atmosphere and the cell liner is assumed to estimate the  $\text{CO}_2$  release and all of this  $\text{CO}_2$  reacted completely with either Na or NaOH, the resulting  $\text{Na}_2\text{CO}_3$  would be no more than 8% of the total aerosol products. This amount of sodium carbonate would not have a significant effect on the overall aerosol behavior and amount of radioactivity reaching the filter system.

Because of the limited solubility of  $\text{Na}_2\text{CO}_3$  in water, more water must be used in a wet filter/scrubber system to remove  $\text{Na}_2\text{CO}_3$  than would be needed to remove pure NaOH. Results of the TMBDB Air Cleaning System Performance Tests as described in Appendix A.7 show that removal efficiencies for  $\text{Na}_2\text{CO}_3$  are comparable to those for other aerosol products (99% or greater), when sufficient quantities of water are used. Thus, the formation of  $\text{Na}_2\text{CO}_3$  presents no increased radiological consequence.

## E.8 REFERENCES

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TABLE E-1

RELEASE OF FISSION PRODUCTS FROM MOLTEN FUEL

<u>Group</u>	<u>Elements</u>	<u>Fraction Released From Fuel</u>
Noble Gases	Kr, Xe	1.0
Halogens	Br, I	1.0
Volatile F.P.	Se, Rb, Sb, Te, Cs	0.9
Solid F.P.	Ge, Tc, Ru, Rh, Pd	0.04
	Sr, Ba	0.02
	all others	0.01

#### G.4 EFFECT OF INITIAL HEAD RELEASE ON TMDB DOSE CONSEQUENCES AND RCB ATMOSPHERE CONDITIONS

##### G.4.1 Introduction

Section 4 discussed the dose consequences of four cases, representing varying degrees of immediate leakage through the head. These cases covered initial fuel and fission products released from 0 to 5% along with the sodium release expected to accompany such fuel releases. The analysis presented here extends the range of these four cases and evaluates the sensitivity of the dose consequences to (1) changes in fuel release without an accompanying change in sodium release and (2) changes in sodium release for a fixed fuel release. Additional analyses were performed to evaluate the RCB atmosphere response, and therefore containment integrity, to these various releases.

##### G.4.2 Radiological Consequences

Table G.4-1 gives the dose consequences of three cases of initial release of fuel, fission products, and associated sodium assuming containment integrity (containment integrity is addressed in Section G.4.3). The results indicate that, for releases beyond 5%, the mitigating effect of aerosol depletion is stronger than the effect a larger initial source term might have on increasing the dose. The overall effect of various initial releases is best seen by looking at the 2 hour bone surface doses. From 1% to 5% fuel release, the bone surface dose increases about in proportion to the increase in the fuel release. However, at higher releases, the attenuating effect of the larger sodium releases exceeds the effect of the larger quantity of fuel and the overall 2 hour bone surface dose decreases as noted in the table.

The aerosol depletion effect alone of these releases can be seen by comparison of the thyroid doses. The thyroid dose is the result of the halogen release which is 100% for each of these cases. As the initial source term of fuel and sodium increases, the aerosol depletion rate increases which causes more of the halogen source to fall out leaving less available to leak out.

Table G.4-2 shows the dose consequences of from 1 to 50% fuel and fission products released initially without the accompaniment of the sodium which would be expected to be associated with such initial releases. Here the 2 hour bone surface dose is seen to be in direct proportion to the percent fuel released. The 2 hour thyroid doses show no benefit from aerosol depletion during the first two hours. The results in Table G.4-2 show that even for a 50% initial release, with minimal credit for aerosol depletion from sodium, the dose consequences are not excessive.

Finally, Table G.4-3 shows the effect of reducing the sodium in the initial release for the case of a 10% fuel and fission product release through the head assuming an integral containment. The lower bound case of no sodium is compared to the case with 1,000 pounds of sodium. There is very little difference in the 2 hour doses between the 0 and 1,000 pounds of sodium cases because there is little aerosol depletion during the first two hours. The 30 day doses are slightly higher with no sodium but are not highly sensitive to the aerosol effects of the initial release. This is due to the 30 day doses being more dependent on the boilup phase of the scenario.

The overall conclusion to be drawn from the results of this analysis is that the TMBDB scenario is not sensitive to a wide range of initial releases through the head with an integral containment barrier.

#### G.4.3 RCB Atmosphere Response To Initial Head Release

##### CACECO Code Model

The CACECO Code model, described in Section 3.2 and Appendix C.1, was modified to simulate the initial release of sodium and fuel through the head. To simulate the initial release of fuel and fission products, the latent heats of the fuel and various fission products were calculated up to the fuel vapor point. The energy calculated was then superimposed on top of the decay curve for a ten second interval. The appropriate partitioning factors were then

calculated (i.e., code input that distributes decay heat to a designated cell). Similarly the sodium at 1000°F was assumed to be injected to containment and burn completely within a ten second interval.

### Results

Using the revised CACECO model, the containment conditions computed are listed in Tables G.4-1, 2 and 3 for the various cases. Tables G.4-2 and 3 indicate containment atmosphere temperature and pressure are more sensitive to the initial sodium release assumed than to the initial fuel release. The most severe results were found when 7,000 pounds of sodium and 7.5% of the fuel and solid fission products were assumed initially released to containment. The containment atmosphere temperature and pressure were found to be 1030°F and 24.4 psig. The containment metal temperature is not significantly affected by the sharp transient in atmosphere temperature because of its large heat capacity (at 1000 seconds the metal temperature is only 140°F). The containment could withstand all of the short term transients resulting from the initial head releases considered.

### Conclusions

The calculations indicate that containment integrity after the initial release of fuel and fission products and sodium is not challenged for a wide range of assumptions. Considering the worst assumption (7,000 pounds of sodium and 7.5% fuel and fission products) containment integrity would be maintained following the initial head release. The general conclusion is that the TMBDB scenario has sufficient margin with respect to the amount of sodium and fuel assumed to be initially released.

TABLE G.4-1

EFFECT OF INITIAL FUEL, FISSION PRODUCT AND SODIUM RELEASE\*

		Dose (rem)		
		1% Fuel & F.P. 1000 lb. Na	5% Fuel & F.P. 3300 lb. Na	7.5% Fuel & F.P. 7000 lb. Na
2 Hour EB	Bone Surface	6.47	27.0	22.0
	Red Marrow	0.56	2.18	1.77
	Lung	.72	1.77	1.42
	Liver	0.18	1.21	0.95
	Thyroid	23.4	19.6	10.7
	Whole Body	1.09	1.22	1.05
30 Day LPZ	Bone Surface	2.45	6.07	4.90
	Red Marrow	0.27	0.56	0.45
	Lung	0.82	1.00	0.88
	Liver	0.18	0.32	0.25
	Thyroid	8.13	5.43	2.91
	Whole Body	1.73	1.65	1.60

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RCB Atmosphere Conditions\*\*

Temperature (°F)	270	580	1030
Pressure (psig)	4.6	12.7	24.4

\*Initial release of noble gases, halogens, and volatile fission products to RCB = 100%.

\*\*Peak values for 1 hour.



TABLE G.4-2  
EFFECT OF INITIAL FUEL AND FISSION PRODUCT RELEASE  
WITH SODIUM RELEASE FIXED AT 1000 LB.

		Dose (rem) Initial Release of Fuel and Fission Products*			
		1%	5%	10%	50%
2 Hour EB	Bone Surface	6.47	32.1	64.2	320.8
	Red Marrow	0.56	2.60	5.15	25.5
	Lung	0.72	2.19	3.93	17.8
	Liver	0.18	1.44	2.70	12.7
	Thyroid	23.4	23.3	23.3	23.3
	Whole Body	1.09	1.30	1.57	3.71
30 Day LPZ	Bone Surface	2.45	8.17	14.6	70.2
	Red Marrow	0.27	0.72	1.24	5.68
	Lung	0.82	1.15	1.49	4.75
	Liver	0.18	0.42	0.70	3.10
	Thyroid	8.13	7.67	7.21	7.21
	Whole Body	1.73	1.75	1.77	2.20

RCB Atmosphere Conditions\*\*

Temperature (°F)	270	290	310	450
Pressure (psig)	4.6	5.0	5.7	9.5

\*Initial release of noble gases, halogens, and volatile fission products to RCB = 100%.

\*\*Peak values for 1 hour.

TABLE G.4-3

EFFECT OF SODIUM RELEASE FOR A GIVEN 10% FUEL-FISSION PRODUCT RELEASE\*

		Dose (rem)	
		<u>Pounds of Sodium in Initial Release</u>	
		<u>0</u>	<u>1000</u>
2 Hour EB	Bone Surface	63.4	64.2
	Red Marrow	5.09	5.15
	Lung	3.90	3.93
	Liver	2.66	2.70
	Thyroid	23.1	23.3
	Whole Body	1.56	1.57
30 Day LPZ	Bone Surface	16.3	14.6
	Red Marrow	1.37	1.24
	Lung	1.61	1.49
	Liver	0.78	0.70
	Thyroid	8.05	7.21
	Whole Body	1.84	1.77

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RCB Atmosphere Conditions\*\*

Temperature (°F)	260	310
Pressure (psig)	4.6	5.7

\*Initial release of noble gases, halogens, and volatile fission products to RCB = 100%.

\*\*Peak value for 1 hour.