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EVALUATION OF THE CONFINEMENT OPTION FOR FFTF

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1.0 SUMMARY AND CONCLUSIONS

1.1 Description of the Confinement Option

The principle mitigator of the radiological consequences of a hypothetical core disruptive accident (HCDA) is the reactor containment building (RCB). The usually assumed mode of operation of the RCB in such an event is to act as a nearly gas-tight barrier to contain the particulate and gaseous fission products for as long a period as possible to allow interior fallout/plateout and decay to reduce the releasable inventory. If the internal pressure approaches the design pressure, the RCB can be vented through a filter/scrubber in the containment margins sytem (CMS). For these cases the radiological consequences are a sensitive function of the leak-tightness of the RCB due to unfiltered leakage.

The "confinment" option assumes that for all events the RCB is vented immediately through the filter/scrubber so as to maintain the internal pressure at or below atmospheric (after the initial pressure pulse). In this way most of the release is made through the filter/scrubber and the radiological consequences are much less dependent on the RCB leakrate. The leaktightness requirements on the RCB might, therefore, be relaxed to a large degree thereby simplifying testing requirements

1.2 Scope

This document reports the results of a study of operating the FFTF containment as a confinement system during an FFTF HCDA. The HCDA provides the most limiting source term for containment evaluations and is themost challenging for the confinement option. This evaluation included calculations of exposed receptor (control distance and site boundary) and control room doses for reasonably achievable confinement procedures. The results were then evaluated relative to the applicable limits and possible means of reducing doses considered. Control room doses were of particular interest in this study since, although the confinement option has previously been studied to a limited degree[1], control room habitability was not addressed.

For purposes of this study, two operating scenarios for the CMS were considered: (1) an optimistic case including a very high initial vent rate (to reduce the time of positive pressure in containment and, therefore, unfiltered leakage) and relatively low allowed RCB leakrate (10%/day at 10psig); and (2) a more realistic case assuming a lower initial vent rate, and a higher allowed RCB leakrate (100%/day at 10psig).

The source term for this study was identical to that assumed in Ref. 1, i.e., 3-cycle core inventory, with 1% release of solid fission products and 100% release of noble gases, along with combustion of 300 lb. of sodium coolant.

1.3 Exposed Receptor Doses

The parameters assumed for the two release plans analyzed are shown in Table 1-1. Resulting doses are shown in Table 1-2 for Case A and Table 1-3 for Case B. At the site boundary the only doses large enough to be a problem are those to the lungs in Case B which are due principally to the containment leakage during the initial 15 minute purge. Reduction of the RCB leakrate by about 30% would reduce the lung doses to permissible levels.

The control distance doses for Case A are within 10CFR100 limits, but the whole body, bone and lung doses at 2400m for Case B are not. The whole body dose is mainly due to noble gas submersion over the 30 day duration of the accident. If the control distance receptors were evacuated after 2 hours, this dose would probably be within the allowed 25 rem. The bone and lung doses, however, are primarily due to particulate leakage during the first 15 minutes so evacuation would be of limited help. Even with evacuation to reduce submersion doses, the containment leakrate would have to be drastically reduced to about 10%/day @ 10psig in order to bring the lung dose within limits.

More detailed breakdowns of the dose results given in Tables 1-1 and 1-2 are given in Section 4.2.

1.4 Control Room Doses

The control room doses for Case A and Case B are shown in Tables 1-4 and 1-5, respectively. The estimates far exceed the limits in both cases. Most of the dose arises from submersion in the noble gas cloud inside the control room. Particulate inhalation is not a problem except for iodine, due to lack of a halogen filter in the system.

Since the dose codes are designed to analyze exposed receptor doses, effective dispersion coefficients and cloud geometry correctors were derived. Methods for calculating control room doses and more detailed breakdowns of the results in Tables 1-4 and 1-5 are given in Section 3.4 and 4.3.

1.5 Possibilities for Mitigation

As already discussed, the exposed receptor doses at the site boundary can be made acceptable merely by reducing the allowable RCB leakrate to, for example, 70%/day @ 10psig. This is not considered a problem. The control distance doses can be reduced somewhat by evacuation, but the major portions of the bone and lung doses are due to particulate leakage during the Phase 1 initial purge so leakage would have to be drastically reduced either by making the containment more leaktight, or by decreasing the leakage time using a larger initial vent purge rate.

TABLE 1-1

PARAMETERS FOR CASES ANALYSED

ITEM	CASE A	CASE B
Initial (Phase 1) Vent Rate	10,000 CFM	3,000 CFM
Time for initial (Phase 1) Vent Purge	5 min.	15 min.
Time to reduce initial pressure surge to 0 psig	4 min.	13.33 min.
RCB Leakage during initial pressure surge	10%/day @ 10psig	100%/day @ 10psig
Post initial (Phase 2) Vent Rate	100 CFM	500 CFM

TABLE 1-2

EXPOSED RECEPTOR DOSES FOR CASE A

DISTANCE (m)	ORGAN	Combined Inhalation & Submersion *Doses (rem) PHASE 1 (5 MIN.)	PHASE 1+2 (30 DAYS)	10 CFR 100 LIMITS
2400	Whole Body	8.3	23.	25
	Bone	14.	30.	150
	Lungs	21.	39.	75
	Thyroid	9.8	25.	300
	Skin	49.	130.	300
7200	Whole Body	2.5	7.7	25
	Bone	3.8	9.3	150
	Lungs	5.6	11.	75
	Thyroid	2.9	8.2	300
	Skin	11.	32.	300

*Submersion doses for the whole body and internal organs in this report are assumed to be equal to the gamma dose at 5cm tissue depth[2]. Skin submersion dose is surface gamma dose plus beta dose to a tissue depth corresponding to an areal density of 7 mg/cm^2.

TABLE 1-3

EXPOSED RECEPTOR DOSES FOR CASE B

DISTANCE (m)	ORGAN	Combined Inhalation & Submersion Doses (rem) PHASE 1 (15 Min.)	PHASE 1+2 (30 Days)	10 CFR 100 LIMITS
2400	Whole Body	15.	58.	25
	Bone	150.	190.	150
	Lungs	320.	370.	75
	Thyroid	52.	97.	300
	Skin	52.	300.	300
7200	Whole Body	4.1	19.	25
	Bone	36.	51.	150
	Lungs	78.	95.	75
	Thyroid	13.	28.	300
	Skin	12.	73.	300

TABLE 1-4

CONTROL ROOM RECEPTOR DOSES FOR CASE A

	Combined Inhalation & Submersion Doses (rem)		
ORGAN	PHASE 1 (5 MIN.)	PHASE 1+2 (30 DAYS)*	10 CFR 50 LIMITS
Whole Body	17.	59.	5
Bone	17.	59.	30
Lungs	17.	59.	15
Thyroid	34.	83.	60
Skin	25.	110.	60

* Does not inlcude 2.2 rem direct dose from material inside containment (1).

TABLE 1-5

CONTROL ROOM RECEPTOR DOSES FOR CASE B

ORGAN	Combined Inhalation & Submersion Doses (rem) PHASE 1 (15 MIN.)	PHASE 1+2 (30 DAYS)*	10 CFR 50 LIMITS
Whole Body	7.2	130.	5
Bone	7.3	130.	30
Lungs	8.5	130.	15
Thyroid	130.	270.	60
Skin	9.6	230.	60

* Does not include 2.2 rem direct dose from material inside containment (1).

1.5 Possibilities for Mitigation (cont'd)

The mitigation of the control room doses does not look promising, mainly due to release of noble gases through the CMS vent. The non-halogen particulate inhalation doses in the control room are quite low due to HEPA filtration and are not a concern. The iodine caused thyroid doses are a problem, but could be corrected relatively easily by addition of a halogen filter to the control room H&V system.

The major problems follow from release of the noble gases through the CMS vent. The associated doses come from two sources: (1) gamma radiation coming through the control room walls from the noble gas cloud exterior to the control room, and (2) submersion in the noble gases drawn into the control room through the air intakes. Gamma radiation from the exterior noble gas cloud could be reduced either by exhausting the CMS vent through a stack, or more attractively, by a small increase in the amount of shielding on the north and east walls of the control room.

The most severe problem is the submersion dose due to the cloud of noble gases interior to the control room. This could be eliminated either by exhausting the CMS vent through a stack, or by experimentally verifying under a wide range of atmospheric conditions, that relatively uncontaminated air would always be available through one of the two control room air intakes. The other two obvious alternatives are (1) to build an airtight containment around the control room with internal air supply and treatment facilities, or (2) supply control room air through a noble gas filter, e.g. cryogenic charcoal. Changes of this magnitude are not recommended for a facility with an existing high quality containment building such as FFTF.

1.6 Conclusions

The analyses performed in this study show that conversion to the containment option is not straightforward from the standpoint of off-site or on-site dose limits. Off-site doses are adversely affected by an initial positive pressure spike postulated in the accident scenario. The resultant leakage of particulates controls the lung and bone doses. Control room habitability is adversely affected by release of noble gases. The first problem, release of particulates, can be mitigated by maintaining a building leak-tightness equivalent to 10-15 volume%/24 hrs at 10psig. The potential control room noble gas dose can probably be accomodated by conducting field tests to show that at least one air intake will remain clean under a complete spectrum of wind velocity and direction at the FFTF site. These same tests may show that the direct radiation dose through the control room back wall is reduced if accumulation of noble gases in building lee-side eddies proves to be less than assumed here.

In addition to implementing the foregoing mitigators, equipment changes would be necessary to convert to a confinement system. These changes are beyond the scope of this report, but would involve converting the CMS to safety grade equipment. This conversion would require larger and redundant exhaust blowers and redundant power supplies.

2.0 INTRODUCTION

This study of the radiological consequences of an HCDA using the confinement approach was done to support an investigation of reduction in requirements for the integrated leak rate test (ILRT) of the FFTF containment. The confinement approach potentially offers reduced dependence on the leak-tightness of the RCB.

Previous studies of the radiological consequences of an FFTF HCDA have generally assumed a sealed RCB containing the material for as long a period as possible in order to reduce the releasable inventory by fallout/plateout and decay. If the design pressure of the RCB is approached, material can be vented through a filter/scrubber. For these cases the radiological consequences are due mainly to the unfiltered leakage and are a demanding and sensitive function of the containment leak-tightness.

In the confinement option case, the RCB is vented through the containment margin system (CMS) at, time zero so as to rapidly reduce the pressure to, and maintain it, at or below atmospheric. This strategy greatly decreases the amount of unfiltered effluent and could therefore permit relaxation of RCB leak-tightness requirements.

3.0 METHOD OF ANALYSIS

3.1 Source Assumptions

The source term used for this study was the FSAR HCDA where the damaged core is cooled by natural convection. One percent of the core inventory of solid fission products and fuel along with 100% of the noble gases are assumed to be released into the containment at time zero. In addition, 300 lb. of sodium is assumed to burn to form Na_2O. The net effect is equivalent to injecting 40,000 $ft.^3$ of additional gas into the RCB producing an initial pressure of 1.84psig with the containment gas temperature rising to 149°F (65°C).[3] The total core inventory is identical to the 3-cycle core assumed in Ref. 1.

3.2 Containment Release Assumptions

The strategy investigated here for the confinement option was an initial high purge rate (Phase 1) through the CMS vent in order to quickly reduce the containment pressure to less than one atmosphere followed by a low vent rate (Phase 2) to maintain the containment at or below one atmosphere for the duration of the accident (assumed to be 30 days). Unfiltered leakage occurs only during the initial purge phase when the containment pressure is still above one atmosphere. The material vented passes through a venturi scrubber and a fibrous scrubber with a transmission factor of 1.0×10^{-3}. The vent blower has a normal capacity of 3300 CFM. Material may also be vented directly through a 3 inch flow-limiting orifice designed to release 4000 CFM at 10psig and 250°F.[4,5] The physical arrangement of the CMS vent system is shown in Figure 3-1.

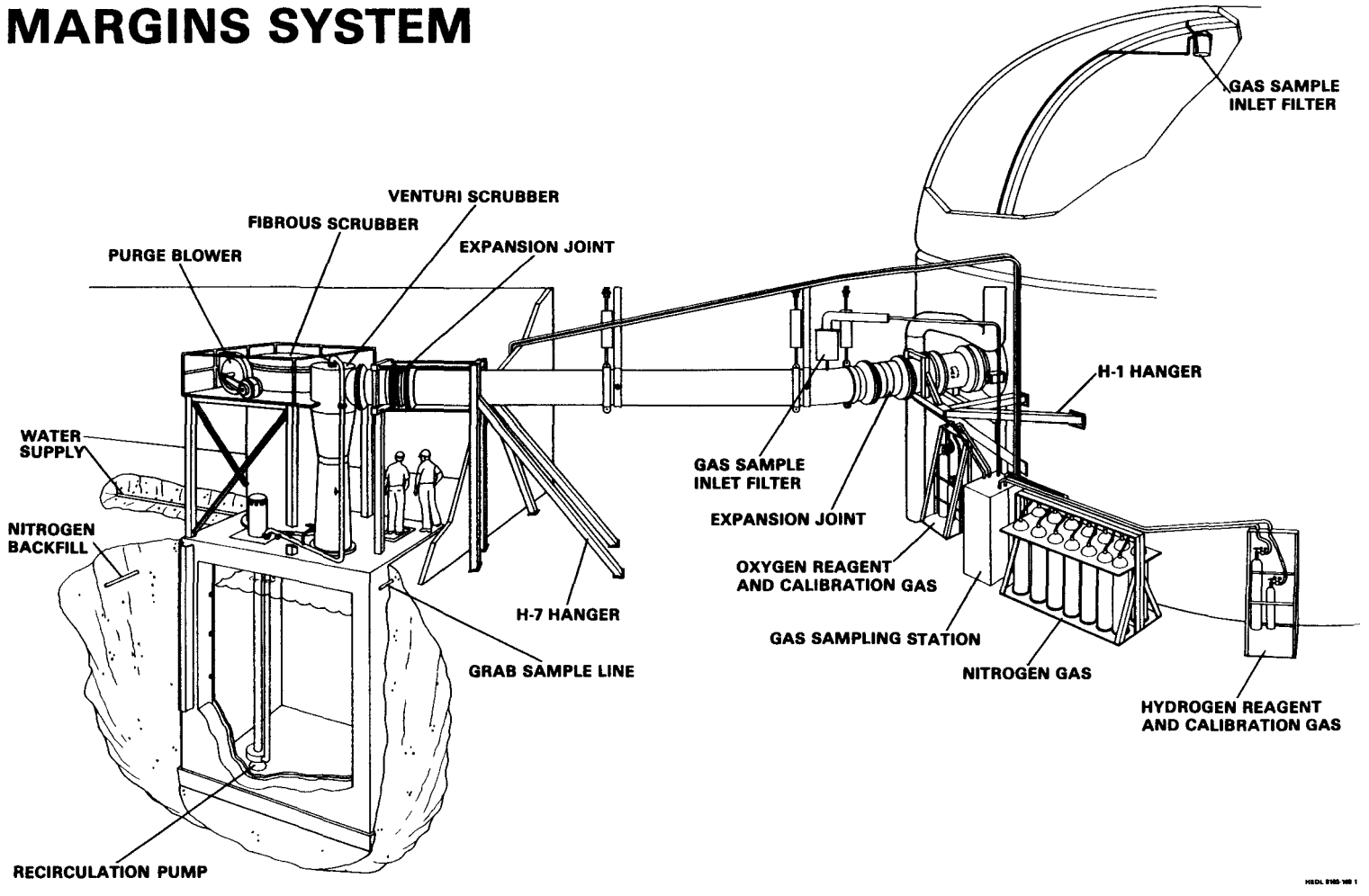

FIGURE 3-1. Containment Margins Systems.

3.2 Containment Release Assumptions (Cont'd)

The three parameters which characterize the release are, therefore, (1) the RCB leakrate, (2) the initial (phase 1) purge rate, and (3) the subsequent (phase 2) purge rate. For purposes of this study two cases were investigated. The first case (A) is an optimistic case where containment leakage is assumed to be 10%/day at 10psig with a high 10,000 CFM phase 1 purge rate and a low 100 CFM phase 2 purge rate. The second case (B) is more pessimistic and assumes a high 100%/day at 10psig leakage with a phase 1 purge rate of 3000 CFM and a phase 2 rate of 500 CFM. In case A the containment gage pressure is reduced to zero after 4 minutes with the initial purge lasting for 5 minutes. Case B produces zero gage pressure after 13.33 minutes with the phase 1 purge lasting for 15 miniutes before downshift to phase 2.

As in Ref. 1, the conservative assumption is made that suspended particulates in the containment atmosphere leak at the same rate as the gases and that all particulates leaked or vented are of respirable size.

3.3 Calculational Methods-Codes

The chain of computer codes used for this analysis is the same as that used for the HCDA cases in Ref. 1 with the overall scheme as shown in Figure 3-2. The program PROGLEAK (described in Appendix 5.3 of Ref. 1) is used to generate the containment leakage history during the initial purge phase. The input to PROGLEAK consists of a table of RCB pressure vs. time based on the purge vent rate and the assumption that removal of 40,000 ft^3 of gas reduces gage pressure to zero. It is assumed that the constant vent rate reduces containment gage pressure linearly to zero with leakage having a negligible effect on the pressure history. PROGLEAK generates a file called HAAIN containing a table of containment leakrate (fraction/s) and temperature (assumed constant at 149°F) for a series of time increments. HAAIN is then input to the code HAA3C[6] which produces a table of fallout/plateout and effluent leakrate (fraction/s) as functions of time called HAAOUT.

In order to analyze the effects of venting the RCB through the CMS blower, the input file for HAA3C (HAAIN) is manually constructed to reflect the assumed linear pressure decay. The contents of the HAAIN file describing the vent exhaust for the two cases studied are shown in Table 3-1. HAA3C linearly interpolates between points in the table, and, as in Ref. 1, the release is assumed to last for 30 days (2.59E+6s).

HAAOUT is then input to CRACOME[7] along with the file NULIB2 containing the assumed initial core inventory. CRACOME accounts for release fractions from the core inventory, applicable filter effects, and radioactive decay in containment along with the fallout/plateout and leakage rates supplied by HAA3C to produce an inventory of radionuclides released from containment. The released inventories are then input to the dose codes SUBDOSA[8] and DACRIN[9] to calculate

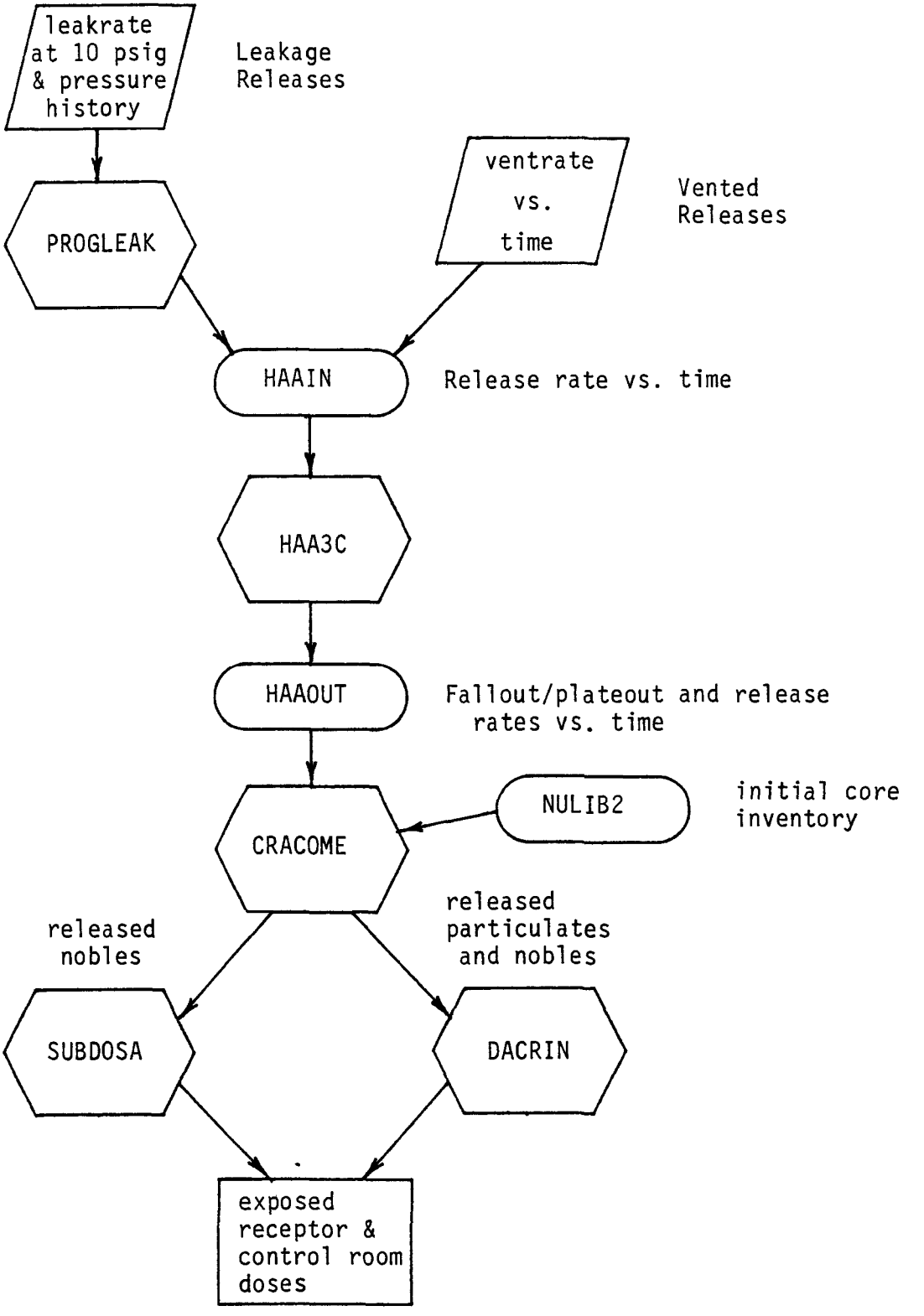

FIGURE 3-2. Computational method of dose calculations.

TABLE 3-1

INPUT TABLE HAAIN FOR VENT RELEASES

CASE	TIME (s)	EXHAUST RATE (l/s)*
CASE A	0	1.19E-4
Phase 1: 10,000 CFM	3.00E+2	1.19E-4
Phase 2: 100 CFM	3.10E+2	1.19E-6
	2.59E+6	1.19E-6
CASE B	0	3.57E-5
Phase 1: 3,000 CFM	9.00E+2	3.57E-5
Phase 2: 500 CFM	9.10E+2	5.95E-6
	2.59E+6	5.95E-6

* Based on a containment volume of 1.4E+6 ft^3.

3.3 Calculational Methods-Codes (Cont'd)

submersion and inhalation doses, respectively, for the various receptors. Doses were calculated for two exposed receptor distances (2400m control distance and 7200m site boundary) and for the FFTF control room.

The release was assumed to occur at ground level under site-specific 95 percentile worst case meteorology. The corresponding dispersion parameters are X/Q=2.98E-4 s/m^3 at 2400m and X/Q=7.22E-5 s/m^3 at 7200m with a windspeed of 0.78m/s.[10] All particulate releases were assumed to be respirable with a mass mean particle diameter of 1 m. All receptors were assumed to breathe at the rate of 347 cm^3/s and internal doses were calculated for a 50-year commitment. Total whole body and organ doses were calculated as the sum of the doses from internal and external sources. No credit was taken for evacuation for any of the receptors during the assumed 30 day duration of the accident. Finally, since most of the release occurs during the first 8 hours, no credit was taken for relaxation of dispersion conditions after 8 hours.

3.4 Control Room Habitability

For purposes of this analysis, the control room is assumed to be operating in the positive pressure mode of the life support system.[5] In this mode up to 1000 CFM is collected through either of two separate remote air intakes. The air is passed through a HEPA filter and is exhausted by outleakage through the control area boundary. The filter transmission factor is 5×10^{-4} for nonhalogen particulates and the control room volume is assumed to be 49,000 ft^3.[11] The air within the control room is also recirculated at a rate of 2900 CFM through a roughing filter with a transmission factor of 0.8.

The concentration of radionuclides in the air external to the control room and air intakes is calculated using a concentration coefficient defined by

$$K = \frac{X_e}{X_R} \qquad (3\text{-}1)$$

where X_e is the air concentration in the local building wake, and X_R is a reference concentration given by

$$X_R = \frac{Q}{Au} \qquad (3\text{-}2)$$

where:

Q = release rate from the RCB,
A = effective building cross-sectional area normal to the wind direction, and
u = wind speed.

3.4 Control Room Habitability (Cont'd)

The effective dispersion coefficient for the air external to the control room is therefore given by

$$\frac{X_e}{Q} = \frac{K}{Au} \qquad (3\text{-}3)$$

The volume averaged value of K for the FFTF control room was determined to be 5 in Ref. 5 based on data given in Ref. 12. A is assumed equal to the RCB area = 1110m^2 and u is 0.78 m/s consistent with 95 percentile worst case site specific meteorology.[13] Equation (3-3) is assumed to describe the air concentrations at the control room air intakes as well as external to the control room walls. The two remote air intakes, with associated radiation monitors, are intended to provide at least one source of relatively uncontaminated air under nearly all atmospheric conditions. In the absence of supporting experimental data, however, no credit was taken for this option.

Interior Cloud Inhalation Dose

In order to determine the air concentration of radionuclides within the control room, a time dependent solution for an inventory with constant source, constant removal (outleakage), internal removal (recirculation filtration), and radioactive decay was developed. The analysis of the time dependent behavior of such a system is shown in Appendix 6.1 and only needed results are presented here. The source rate from the RCB changes at the end of phase 1 (downshift of the purge vent rate) so the solution is given in two parts. During phase 1 (initial purge and associated leakage due to the pressure spike) the concentration in the control room climbs rapidly, but reaches only a fraction of its equilibrium value before the phase 2 vent rate commences. A time averaged effective X/Q was therefore derived and is given by

$$\frac{X}{Q}_1 = \frac{X_e}{Q} \frac{\lambda_v F_H}{\lambda_T} \left\{1 - \frac{1}{t_1 \lambda_T} [1 - \exp(-\lambda_T t_1)]\right\} \qquad (3\text{-}4)$$

where:

$\frac{X_e}{Q}$ = volume average exterior dispersion coefficient given by Eq. (3-3) = 5.76x10^{-3} m^3/s;

λ_v = control room ventilation time constant (as fraction/s = v/v);

λ_t = total removal time constant
$= \lambda_v + \lambda_r(1-F_r) + \lambda_d$, where

3.4 Control Room Habitability (Cont'd)

Interior Cloud Inhalation Dose (Cont'd)

λ_r = recirculation time constant ($\dot{v}/_V$);

λ_d = radioactive decay time constant, and

F_r = recirculation filter transmission factor;

F_H = intake HEPA filter transmission factor;

t_1 = time at end of phase 1.

The duration of phase 2 (30 days) is long compared to $1/\lambda_t$ so the equilibrium solution is used and is given by:

$$\left(\frac{X}{Q}\right)_2 = \frac{X_e}{Q} \frac{\lambda_v F_H}{\lambda_t} \qquad (3\text{-}5)$$

Particulate inhalation doses in the control room during phases 1 and 2 were calculated by the DACRIN dose code using effective dispersion coefficients given by Eq. (3-4) and (3-5), respectively with λ_d assumed equal to zero since the nuclides of interest are long-lived.

Interior Cloud Submersion Doses

For purposes of calculating submersion doses due to the noble gas cloud within the control room, air concentrations were also calculated using Eqs. (3-4) and (3-5). Some simplification is possible, however, due to the fact that the nobles are not filtered and therefore $F_r = F_H = 1$ and $\lambda_t = \lambda_v$ (again, neglecting decay). Including the effects of decay in Eqs. (3-4) and (3-5) makes the effective dispersion coefficients isotope dependent. This could be handled (as discussed in Appendix 6.1) but the effect was investigated and found to be much less than the uncertainty in the analysis as a whole (usually less than 10% in this case). Radioactive decay was, therefore, neglected since only a relatively small error was introduced in a conservative direction. The resulting effective dispersion coefficients for interior cloud inhalation and submersion doses are given in Table 3-2 for the two release scenarios considered (Case A and Case B). Notice that for the noble gases and halogens (no filtration) the equilibrium X/Q given by Eq. (3-5) is equal to X_e/Q.

The interior cloud control room submersion doses were calculated using SUBDOSA in a semi-infinite cloud dose mode while the control room is modeled as a finite hemispherical cloud with a volume equal to the control room volume of 1390m^3. The resulting hemisphere radius is 8.72m. A cloud geometry correction is therefore required. An analysis of submersion doses due to generalized hemispherical clouds and derivations of required geometry correctors are attached as Appendix 6.2. As before, only needed results are shown here. The

TABLE 3-2

EFFECTIVE CONTROL ROOM DISPERSION COEFFICIENTS

FOR INTERIOR CLOUD DOSES

		EFFECTIVE X/Q (s/m^3)	
CASE	RELEASE PHASE	NON-HALOGEN PARTICULATES	HALOGENS AND NOBLE GASES
A	1	1.39E-7	2.84E-3
	2	1.81E-6	5.76E-3
B	1	3.77E-7	7.98E-4
	2	1.81E-6	5.76E-3

3.4 Control Room Habitability (Cont'd)

Interior Cloud Submersion Doses (Cont'd)

correction factor to convert a semi-infinite (i.e. an infinite hemispherical) cloud dose to a finite hemispherical cloud dose is given by

$$CF_i = 1 - (\mu_s b+1) \exp(-\mu b) \qquad (3\text{-}6)$$

where b = the cloud radius (no central void)
μ_s = scattering coefficient for air, and
μ = total attenuation (scattering plus absorption) coefficient for air.

Assuming an average gamma energy of 0.7 MeV for the noble gas cloud, μ_s = 5.9E-3 1/m and μ = 9.7E-3 1/m.[12] Then for b = 8.72m, CF_i, the interior cloud geometry corrector, is 3.38E-2. Cloud geometry correctors were input to SUBDOSA as inventory multipliers.

Exterior Cloud Submersion Doses

The control room doses due to the effluent material external to the control room is conservatively assumed to be due to a hemispherical cloud centered on the control room with an outer radius of 72m (far wall of the RCB) and a central void with radius 8.72m (the equivalent control room radius). The cloud is assumed to contain a uniform radionuclide concentration given by Eq. (3-3). From Appendix 6.2, the correction factor to convert a semi-infinite cloud dose to that for a finite hemisherical cloud with a central void is given by

$$CF_e = (\mu_s a+1) \exp(-\mu a) - (\mu_s b+1) \exp(-\mu b) \qquad (3\text{-}7)$$

where a and b are the inner and outer cloud radii, respectively. For a = 8.72m and b = 72m, the exterior cloud geometry corrector is equal to 2.58E-1.

For this case, an additional correction must be applied to account for the absorption and scattering in the control room walls. The south wall (facing the RCB) is 39 in. of poured concrete while the west wall and roof are 36 in. thick and the north and east walls are 15 in. thick. The effect of the wall shielding would vary greatly depending on the position of the receptor inside the control room so no credit is taken for the heavier walls and the shield is modeled as a hemispherical shell 15 in. (38 cm) thick with the receptor at the center. The correction factor for the shield is given by

$$CF_s = B \exp(-\mu_s X) \qquad (3\text{-}8)$$

Assuming an average gamma energy of 0.7 MeV[12], the buildup factor, B, and linear attenuation coefficient, μ_s, are given by[14]

$$B = 14.6$$
$$\text{and } \mu_s = 0.182 \text{ /cm}$$

3.4 Control Room Habitability (Cont'd)

Exterior Cloud Submersion Doses (Cont'd)

for 38 cm of common concrete. The shield corrector is then equal to 1.45E-2 and the combined cloud geometry and shield corrector is 3.74E-3. As before, this factor was input to SUBDOSA as an inventory multiplier.

4.0 RESULTS AND DISCUSSION

4.1 Benchmarking of Codes

The procedures and results for benchmarking the code system used here against previous work was discussed in Section 3.1 of Ref. 1. In order to check present results against those of Ref. 1, the HCDA case with 3%/day design leakage at 10psig was reproduced using the same meteorology and dispersion assumptions. The results are shown in Table 4-1 for inhalation doses for exposed receptors at 2400m and 7200m. The new results shown are higher in some cases due to the use of an abbreviated source term in the older calculation. The release inventory produced by CRACOME was the same in both cases and a calculation using a similarly summarized source term gave results which match the results in Ref. 1 exactly.

In the present work the full release inventory is always used for calculation of inhalation doses. The same recalculation using the revised atmospheric dispersion factors recommended by Ref. 14 is also shown.

4.2 Exposed Receptor Doses

Three components of the receptor doses are calculated: (1) that due to the RCB leakage during the time the pressure is being drawn down to 0 psig by the initial (phase 1) purge; (2) that due to the vent exhaust during phase 1; and (3) that due to the vent exhaust for the full 30 day assumed duration of the release. The doses due to leakage are then added to either of the two vent exhaust terms to obtain total doses during only phase 1 or over the full 30 days.

For the leakage term, PROGLEAK was run for a linearly decreasing pressure from 1.84 psig[3] to 0 psig over the applicable time period as discussed in Section 3.3. HAA3C and CRACOME were then used to obtain a release inventory from the RCB. This inventory was input to the dose codes DACRIN and SUBDOSA to calculate exposed receptor doses at 2400m and 7200m. The resulting doses are shown in Tables 4-2 through 4-5.

TABLE 4-1

COMPARISON OF RESULTS FOR

3%/DAY LEAKRATE HCDA (CASE H3) WITH REFERENCE 1

DISTANCE (M)	ORGAN	50 Yr. Dose Commitments (rem) OLD CALC.*	NEW CALC. OLD X/Q**	NEW CALC. NEW W/Q***
2400	Whole Body	0.4	0.49	3.1
	Bone	9.5	10.	64.
	Lungs	23.	23.	150.
	Thyroid	2.2	3.1	20.
7200	Whole Body	0.1	0.1	0.75
	Bone	1.9	2.1	16.
	Lungs	4.7	4.8	36.
	Thyroid	0.4	0.63	4.7

* Tables 1.2-1 and 1.2-2 in Reference 1.

** X/Q = 4.7E-5 s/m^3 and 9.6E-6 s/m^3 at 2400m and 7200m, resp.

*** X/Q = 3.0E-4 s/m^3 and 7.2E-5 s/m^3 at 2400m and 7200m, resp.

TABLE 4-2

EXPOSED RECEPTOR DOSES AT 2400m FOR CASE A

(10,000 and 100 CFM Purge Rates, 10%/Day Leakrate at 10psig)

SOURCE	ORGAN	INHALATION DOSE COMMITMENT (rem)	SUBMERSION DOSE (rem)*	TOTAL DOSE (rem)
Unfiltered Leakage (10% /Day at 10psig)	Whole Body	1.91E-1	1.79E-2	2.09E-1
	Bone	4.01E 0	1.79E-2	4.03E 0
	Lungs	9.16E 0	1.79E-2	9.18E 0
	Thyroid	1.28E 0	1.79E-2	1.30E 0
	Skin	-----	1.11E-1	1.11E-1
Combined Leakage & Vent Phase 1 (10,000 CFM for 300s)	Whole Body	2.77E-1	7.97E 0	8.25 E0
	Bone	5.82E 0	7.97E 0	1.38E+1
	Lungs	1.33E+1	7.97E 0	2.13E+1
	Thyroid	1.86E 0	7.97E 0	9.83E 0
	Skin	-----	4.93E+1	4.93E+1
Combined Leakage & Vent Phase 1 & 2 (Phase 1 + 100 CFM for balance of 30 days)	Whole Body	3.27E-1	2.31E+1	2.34E+1
	Bone	6.87E 0	2.32E+1	3.00E+1
	Lungs	1.57E+1	2.31E+1	3.88E+1
	Thyroid	2.18E 0	2.31E+1	2.53E+1
	Skin	----	1.32E+2	1.32E+2

* Submersion doses for the whole body and internal organs considered here are assumed to be equal to the gamma dose at 5cm tissue depth.(2) Skin submersion dose is surface gamma dose plus beta dose to a tissue depth corresponding to an areal density of 7 mg/cm^2.

TABLE 4-3

EXPOSED RECEPTOR DOSES AT 7200m FOR CASE A

(10,000 & 100 CFM Purge Rates, 10%/Day Leakrate at 10psig)

SOURCE	ORGAN	INHALATION DOSE COMMITMENT (rem)	SUBMERSION DOSE (rem)	TOTAL DOSE (rem)
Unfiltered Leakage (10% /Day at 10psig)	Whole Body	4.63E-2	5.41E-3	5.17E-2
	Bone	9.71E-1	5.41E-3	9.76E-1
	Lungs	2.22E 0	5.41E-3	2.23E 0
	Thyroid	3.03E-1	5.41E-3	3.08E-1
	Skin	-----	2.49E-2	2.49E-2
Combined Leakage & Vent Phase 1 (10,000 CFM for 300s)	Whole Body	6.72E-2	2.42E 0	2.49E 0
	Bone	1.41E 0	2.42E 0	3.83E 0
	Lungs	3.22E 0	2.42E 0	5.64E 0
	Thyroid	4.40E-1	2.42E 0	2.86E 0
	Skin	-----	1.11E+1	1.11E+1
Combined Leakage & Vent Phase 1 &2 (Phase 1 + 100 CFM for balance of 30 days)	Whole Body	7.93E-2	7.63E 0	7.71E 0
	Bone	1.66E 0	7.63E 0	9.29E 0
	Lungs	3.80E 0	7.63E 0	1.14E+1
	Thyroid	5.17E-1	7.63E 0	8.15E 0
	Skin	-----	3.22E+1	3.22E+1

TABLE 4-4

EXPOSED RECEPTOR DOSES AT 2400m FOR CASE B

(3,000 & 500 CFM Purge Rates, 100%/Day Leakrate at 10psig)

SOURCE	ORGAN	INHALATION DOSE COMMITMENT (rem)	SUBMERSION DOSE (rem)	TOTAL DOSE (rem)
Unfiltered Leakage (100% /Day at 10psig)	Whole Body	6.47E 0	6.02E-1	7.07E 0
	Bone	1.36E+2	6.02E-1	1.37E+2
	Lungs	3.09E+2	6.02E-1	3.10E+2
	Thyroid	4.32E+1	6.02E-1	4.38E+1
	Skin	----	3.73E 0	3.73E 0
Combined Leakage & Vent Phase 1 (3000 CFM for 900s)	Whole Body	6.55E 0	8.40E 0	1.50E+1
	Bone	1.38E+2	8.40E 0	1.46E+2
	Lungs	3.13E+2	8.40E 0	3.21E+2
	Thyroid	4.38E+1	8.40E 0	5.22E+1
	Skin	----	5.20E+1	5.20E+1
Combined Leakage &Vent Phase 1 & 2 (Phase 1 + 500CFM for Balance of 30 Days)	Whole Body	6.74E 0	5.15E+1	5.82E+1
	Bone	1.42E+2	5.15E+1	1.94E+2
	Lungs	3.22E+2	5.15E+1	3.74E+2
	Thyroid	4.50E+1	5.15E+1	9.65E+1
	Skin	----	2.95E+2	2.95E+2

TABLE 4-5

EXPOSED RECEPTOR DOSES AT 7200m FOR CASE B

(3,000 & 500 CFM Purge Rates, 100%/Day Leakrate at 10psig)

SOURCE	ORGAN	INHALATION DOSE COMMITMENT (rem)	SUBMERSION DOSE (rem)	TOTAL DOSE (rem)
Unfiltered Leakage (100% /Day at 10psig)	Whole Body	1.57E 0	1.83E-1	1.75E 0
	Bone	3.28E+1	1.83E-1	3.30E+1
	Lungs	7.48E+1	1.83E-1	7.50E+1
	Thyroid	1.02E+1	1.83E-1	1.04E+1
	Skin	-----	8.40E-1	8.40E-1
Combined Leakage & Vent Phase 1 (3000 CFM for 900s)	Whole Body	1.59E 0	2.55E 0	4.14E 0
	Bone	3.32E+1	2.55E 0	3.58E+1
	Lungs	7.58E+1	2.55E 0	7.84E+1
	Thyroid	1.03E+1	2.55E 0	1.29E+1
	Skin	----	1.17E+1	1.17E+1
Combined Leakage & Vent Phase 1 & 2 (Phase 1 plus 500CFM for balance of 30 Days)	Whole Body	1.64E 0	1.72E+1	1.88E+1
	Bone	3.42E+1	1.72E+1	5.14E+1
	Lungs	7.80E+1	1.72E+1	9.52E+1
	Thyroid	1.06E+1	1.72E+1	2.78E+1
	Skin	----	7.25E+1	7.25E+1

4.3 Control Room Doses

Control room doses were calculated by the methods outlined in Section 3.4 using DACRIN and SUBDOSA. The dispersion coefficients, X/Q, were the effective values given in Table 3-2 with geometry and shielding corrections input as inventory multipliers. The transport distance was assumed to be 10m. The intake and recirculation filters were assumed to attenuate only the non-halogen particulates.

The initial buildup of concentration in the control room during phase 1 (the initial vent purge) and the decay to equilibrium during phase 2 was investigated for Case B using the full time-dependent solutions developed in Appendix 6.1. The result, normalized to a phase 1 purge rate from the RCB of 1 Ci/s is shown in Figure 4-1. Note that transport times and the holdup effect of the air mass outside the control room were not included in this analysis. The concentration is seen to rise rapidly during phase 1 while remaining almost constant during phase 2. Note also that assuming an equilibrium value for X/Q during phase 1 would have produced large errors in the phase 1 doses. The resulting doses to a control room receptor are shown in Tables 4-6 and 4-7.

4.4 Discussion

The Case A site boundary and control distance are well within the 10CFR100 limits, however the 10,000 CFM initial purge rate assumed is far beyond the installed capacity of the CMS. For this case (high initial vent rate and low leakrate) the doses to the exposed receptors are primarily due to exposure to the noble gas cloud, about 30% of which occurs during the initial 5 min. RCB purge.

Case B is a more realistic situation relative to the existing CMS equipment although an unrealistically high containment leakage was assumed (100%/day at 10psig). The particulate inhalation doses due to the initial leakage and exposure to the noble gas cloud are both important contributors to the exposed receptor doses in this case. The 10CFR100 limits at the site boundary are exceeded only by the lung dose which in this case is dominated by particulate inhalation due to the RCB leakage during the initial purge phase (15 min.). Control distance doses far exceed limits and are primarily caused by noble gas emissions over the 30 day exposure (whole body), and by unfiltered particulate leakage during the initial purge phase (bone and lungs).

The control room doses for both Case A and Case B far exceed habitability limits with most of the dose arising from the noble gas cloud inside the control room. As can be seen by examining the rightmost column in Table 4-6, the particulate inhalation doses for Case A are all well within limits, but the noble gas submersion dose from either the interior or exterior cloud would exceed the whole body limit of 5 rem. For Case B, the results are even more severe for the noble gas doses and, in addition, the thyroid dose exceeds the limit of 60 rem due to the absence of a halogen filter in the control room air intake system.

TABLE 4-6

CONTROL ROOM RECEPTOR DOSES FOR CASE A

(10,000 & 100 CFM Purge Rates, 10%/Day Leakrate at 10psig)

DOSE TYPE	ORGAN	PHASE 1 DOSE (rem) 0 - 5 MIN.	PHASE 2 DOSE (rem) 5 MIN-30 DAYS	TOTAL DOSE (rem) 0 - 30 DAYS
Inhalation	Whole Body	3.61E-2	1.28E-2	4.89E-2
	Bone	3.21E-2	1.71E-2	4.92E-2
	Lungs	1.83E-1	6.95E-2	2.53E-1
	Thyroid	1.79E+1	6.32E 0	2.42E+1
Submersion Due to Interior Cloud	Whole Body, Bone, Lungs, & Thyroid	1.35E+1	3.82E+1	5.17E+1
	Skin ($\gamma + \beta$)	2.22E+1	7.52E+1	9.74E+1
Submersion Due to Exterior Cloud	Whole Body, Bone, Lungs & Thyroid	3.03E 0	4.23E 0	7.26E 0
	Skin (γ only)	3.22E 0	4.91E 0	8.13E 0
Inhalation plus Total Submersion	Whole Body	1.65E+1	4.24E+1	5.89E+1
	Bone	1.65E+1	4.24E+1	5.89E+1
	Lungs	1.67E+1	4.25E+1	5.92E+1
	Thyroid	3.44E+1	4.87E+1	8.31E+1
	Skin	2.54E+1	8.01E+1	1.06E+2

TABLE 4-7

CONTROL ROOM RECEPTOR DOSES FOR CASE B

(3000 & 500 CFM Purge Rates, 100%/Day Leakrate at 10psig)

DOSE TYPE	ORGAN	PHASE 1 DOSE (rem) 0 - 15 MIN.	PHASE 2 DOSE (rem) 15 MIN-30 DAYS	TOTAL DOSE (rem) 0 - 30 DAYS
Inhalation	Whole Body	2.47E-1	4.72E-2	2.94E-1
	Bone	3.69E-1	6.39E-2	4.33E-1
	Lungs	1.57E 0	2.52E-1	1.82E 0
	Thyroid	1.19E+2	2.35E+1	1.43E+2
Submersion Due to Interior Cloud	Whole Body, Bone, Lungs & Thyroid	3.85E 0	1.07E+2	1.11E+2
	Skin ($\gamma + \beta$)	6.33E 0	2.04E+2	2.10E+2
Submersion Due to Exterior Cloud	Whole Body, Bone, Lungs & Thyroid	3.11E 0	1.30E+1	1.61E+1
	Skin (γ only)	3.30E 0	1.46E+1	1.79E+1
Inhalation Plus Total Submersion	Whole Body	7.21E 0	1.20E+2	1.27E+2
	Bone	7.33E 0	1.20E+2	1.27E+2
	Lungs	8.53E 0	1.20E+2	1.29E+2
	Thyroid	1.26E+2	1.44E+2	2.70E+2
	Skin	9.63E 0	2.19E+2	2.29E+2

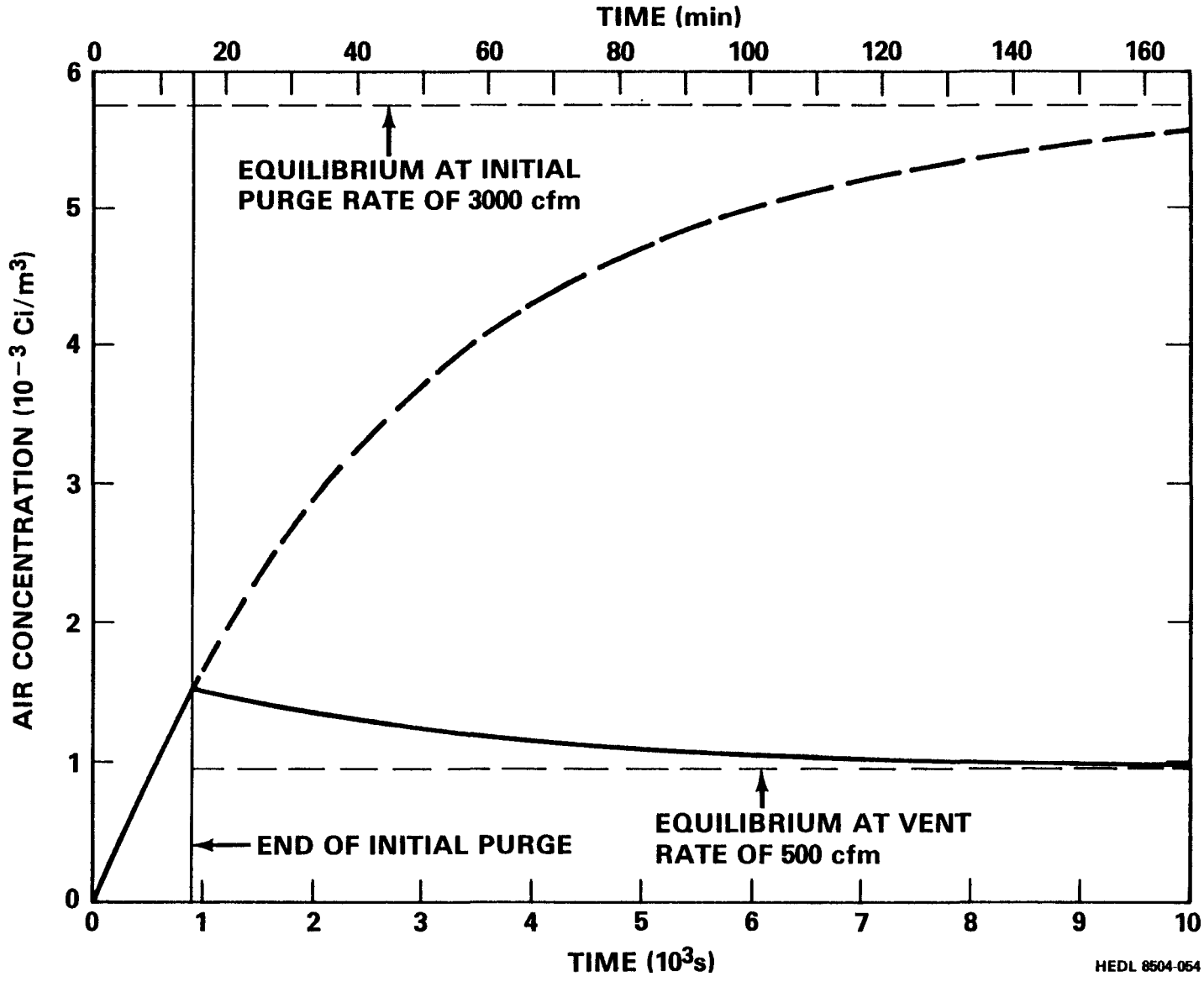

Figure 4-1. Time Behavior of Control Room Concentration.

4.4 Discussion (Cont'd)

It should be noted that the control room doses resulting from this analysis should, in principle, be added to that due to direct shine from inside the containment although the latter dose calculated by ISOSHLD[15], and is a relatively insignificant 2.2 rem [16] over the 30 day release period.

5.0 REFERENCES

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6.0 APPENDICES

6.1 Analysis of a Radionuclide Inventory with Constant Source and Removal Rates

6.1.1 Basic Derivation

Consider an inventory, N, with a constant source, a, and n depletion mechanisms characterized by time constants $_i$ where $_i$ = 1,2,3,...,n. For an inventory of N Curies of a particular isotope, the source rate would by a $^{Ci}/_{s}$ and λ_i would be fraction of N removed /s by the i^{th} removal mechanism. We seek a solution over an arbitrary time interval t_1 to t_2 with initial conditions

$$N = N_1 \text{ at } t=t_1$$
$$\text{and } N_i = N_{i1} \text{ at } t=t_1 \text{ for } i=1,2,3,\ldots,n$$

where N_i represents total inventory removed by the i^{th} mechanism since t=0.

The process can be modeled by a rate equation for each removal mechanism

$$\frac{dN_i}{dt} = \lambda_i N \qquad i = 1,2,3,\ldots,n \qquad (6.1\text{-}1)$$

coupled with a conservation of total inventory

$$\frac{dN}{dt} + \sum_{i=1}^{n} \frac{d\,N_i}{dt} = a. \qquad (6.1\text{-}2)$$

Combining (6.1-1) and (6.1-2) produces

$$\frac{dN}{dt} + \sum_{i=1}^{n} \lambda_i N = a. \qquad (6.1\text{-}3)$$

First solve the homogenous equation

$$\frac{dN}{dt} + \sum_{i=1}^{n} \lambda_i N = 0 \qquad (6.1\text{-}4)$$

Rearranging as usual to produce the logarithmic derivative,

$$\frac{1}{N}\frac{dN}{dt} = -\sum_{i=1}^{n} \lambda_i$$

$$\frac{d}{dt} \ln N = -\sum_{i=1}^{n} \lambda_i ,$$

6.1.1 Basic Derivation (Cont'd)

integration then leads easily to the general homogeneous solution

$$N_H = C \exp(-\lambda_T t) \qquad (6.1\text{-}5)$$

where C is an arbitrary constant and

$$\lambda_T = \sum_{i=1}^{n} \lambda_i$$

Only a particular solution to the inhomogeneous equation (6.1-3) is then needed to obtain a complete solution. Such an inhomogeneous solution is given by

$$N_I = \frac{a}{\lambda_T} \qquad (6.1\text{-}6)$$

Note that inhomogeneous solutions are also available for time dependent sources expressable as a polynomial of arbitrary degree.

The complete solution is then

$$N = N_H + N_I$$

$$N = C \exp(-\lambda_T t) + \frac{a}{\lambda_T} . \qquad (6.1\text{-}7)$$

Now apply the initial condition on N,

$$N_1 = C \exp(-\lambda_T t_1) + \frac{a}{\lambda_T}$$

$$\text{or} \quad C = (N_1 - \frac{a}{\lambda_T}) \exp(\lambda_T t_1$$

$$N = (N_1 - \frac{a}{\lambda_T}) \exp[-\lambda_T (t-t_1)] + \frac{a}{\lambda_T} \qquad (6.1\text{-}8)$$

Equation (6.1-8) gives the central inventory contents for any $t \geq t_1$. At the end of the time interval, $t=t_2$, the inventory is

$$N_2 = (N_1 - \frac{a}{\lambda_T}) \exp[-\lambda_T(t_2-t_1)] + \frac{a}{\lambda_T} . \qquad (6.1\text{-}9)$$

As t_2 increases, the solution approaches the equilibrium value

$$N_\infty = \frac{a}{\lambda_T} \qquad (6.1\text{-}10)$$

which is just the inhomogeneous solution selected for (6.1-6) based on inspection of (6.1-3).

6.1.2 Application to Dose Calculations

The parameter of primary concern for dose calculations is the air concentration of radionuclides. Dividing (6.1-8) by the inventory volume, V, gives the solution in terms of concentration

$$X = \left(X_1 - \frac{a}{\lambda_T V}\right) \exp\left[-\lambda_T (t-t_1)\right] + \frac{a}{\lambda_T V}. \qquad (6.1\text{-}11)$$

If X is changing rapidly over the time interval of interest, a time averaged value is required for dose calculations. The time averaged solution is given by

$$\bar{X} = \frac{1}{t_2-t_1} \int_{t_1}^{t_2} X dt$$

$$= \left(\frac{X_1 - \frac{a}{\lambda_T V}}{t_2-t_1}\right) \int_{t_1}^{t_2} \exp[-\lambda_T (t-t_1)]dt$$

$$+ \frac{1}{t_2-t_1} \frac{a\,t}{\lambda_T V} \Bigg|_{t_1}^{t_2}$$

or

$$\bar{X} = \frac{X_1 - \frac{a}{\lambda_T V}}{\lambda_T (t_2-t_1)} \left\{ 1 - \exp\left[-\lambda_T (t_2-t_1)\right] \right\} + \frac{a}{\lambda_T V}. \qquad (6.1\text{-}12)$$

For the special case of $t_1 = 0$ and $X_1 = 0$ (phase 1 in the text)

$$\bar{X} = \frac{a}{\lambda_T V} \left\{ 1 - \frac{1}{\lambda_T t} \left[1 - \exp\left(-\lambda_T t\right)\right] \right\} \qquad (6.1\text{-}13)$$

where t is the time at the end of the time increment of interest.

For this application, the source rate, a, is derived from a release rate as follows:

$$a = X_e \dot{V} F_H \qquad (6.1\text{-}14)$$

where X_e is the concentration external to the control room, $\dot{V}$ is the volumetric air intake rate, and F_H is the intake filter transmission factor. If Q is the release rate from containment, then

6.1.2 Application to Dose Calculations (Cont'd)

$$a = Q\left(\frac{X_e}{Q}\right)\dot{V}\,F_H \qquad (6.1\text{-}15)$$

and (6.1-13) becomes

$$\left(\frac{\bar{X}}{Q}\right) = \frac{X_e}{Q}\,\frac{\lambda_V F_H}{\lambda_T}\left\{1 - \frac{1}{\lambda_T t}\,[1-\exp(-\lambda_T t)]\right\} \qquad (6.1\text{-}16)$$

where $\lambda_V = \dot{V}/V$ is just the ventilation time constant. For a long time interval, (6.1-16) approaches the equilibrium value

$$\left(\frac{X}{Q}\right)_\infty = \frac{X_e}{Q}\,\frac{\lambda_V F_H}{\lambda_T}\,. \qquad (6.1\text{-}17)$$

The total removal time constant, λ_T, is given in this case by

$$\lambda_T = \lambda_V + \lambda_R\,(1-F_R) + \lambda_d \qquad (6.1\text{-}18)$$

where λ_V = ventilation time constant (fraction /s) assuming flow rate in = flow rate out,

λ_R = recirculation time constant (fraction /s),

F_R = recirculation filter transmission factor,

and λ_d = radioactive decay constant (fraction/s).

Since inclusion of radioactive decay effects makes the results isotope dependent, it is desirable to neglect λ_d when appropriate.

For the case of particulate inhalation, the nuclides of interest are generally long lived and $\lambda_d \approx 0$. For noble gas submersion dose calculations the effects of decay can be important, and here the question is whether λ_d is significant compared to $\lambda_V + \lambda_R(1-F_R)$. In any case, the effects of decay can be accounted for over a given time interval by using (6.1-16) to generate a corrector for each isotope amount given by:

$$\bar{F}_D = \frac{\lambda_T}{\lambda'_T}\left\{\frac{1 - \frac{1}{t\lambda'_T}\,[1 - \exp(-\lambda'_T t)]}{1 - \frac{1}{t\lambda_T}\,[1 - \exp(-\lambda_T t)]}\right\} \qquad (6.1\text{-}19)$$

6.1.2 Application to Dose Calculations (Cont'd)

and for equilibrium conditions:

$$F_{D_\infty} = \frac{\lambda_T}{\lambda'_T} \qquad (6.1\text{-}20)$$

where, now, $\lambda_T = \lambda_V + \lambda_R\ (1 - F_R)$ (6.1-21)

and $\lambda'_T = \lambda_V + \lambda_R(1-F_R) + \lambda_D$. (6.1-22)

It is assumed that the filter transmission factors F_H and $F_R = 1$ for halogens and noble gases. Then, neglecting decay, $\lambda_T = \lambda_V$ and:

$$\left(\frac{\bar{X}}{Q}\right) = \frac{X_e}{Q}\left\{1 - \frac{1}{\lambda_V t}\left[1 - \exp\left(-\lambda_V t\right)\right]\right\} \qquad (6.1\text{-}23)$$

and

$$\left(\frac{X}{Q}\right)_\infty = \frac{X_e}{Q} \qquad (6.1\text{-}24)$$

for noble gases and halogens.

6.2 Analysis of Submersion Doses due to Finite Hemispherical Clouds

6.2.1 Dose Rate from a Point Source

The gamma dose rate in air at a distance r from a point source of strength q is given by:

$$\dot{D} = \frac{\mu_a\, q\, (3.7\times10^{10}\ \frac{\text{dis./s}}{\text{Ci}})\, \bar{E}_\gamma (1.6\times10^{-6}\ \frac{\text{ergs}}{\text{MeV}})\ \text{Ce}}{4\pi\, r^2\, \rho\, (100\ \frac{\text{ergs/g}}{\text{rad}})}$$

$$\times\ (1+k\mu r)\ \exp\ (-\mu r) \qquad (6.2\text{-}1)$$

where

$\dot{D}$ = dose rate ($^{\text{rads}}/_{\text{s}}$),
r = distance (m),
q = source strength (C_i)

$\bar{E}_\gamma$ = average energy per disintegration ($^{\text{MeV}}/_{\text{dis.}}$),
μ_a = linear absorption coefficient for air ($^1/_{\text{m}}$),
μ_s = linear scattering coefficient for air ($^1/_{\text{m}}$),
μ = $\mu_a+\mu_s$ = linear attenuation coefficient for air ($^1/_{\text{m}}$),
k = μ_s/μ_a = scattering to absorption ratio, and
ρ = 1293 g/m^3 = density of air at STP

The term $(1+k\mu r)$ is the well known Gamertsfelder buildup factor which corrects for dose due to air-scattered photons. This factor is strictly correct only for an infinite medium and over estimates the scatter component of the dose for small r and under estimates for large r. Evaluating the numerical factors, (6.2-1) becomes

$$\dot{D} = 0.0404\ \frac{\mu_a\, q\, \bar{E}\gamma\ (1+k\mu r)\ \exp\ (-\mu r)}{r^2} \qquad (6.2\text{-}2)$$

6.2.2 Application to Hemispherical Geometries

A point receptor is assumed to be situated at the center of a hemispherical cloud with concentration X ($^{\text{Ci}}/_{\text{m}^3}$). The cloud is assumed to have an outer radius of R_2(m) and a central void with radius R_1(m). The differential source at r is a hemispherical shell of thickness dr and is given by

$$dq = X\, 2\pi\, r^2\, dr. \qquad (6.2\text{-}3)$$

The corresponding differential dose rate then becomes

$$d\dot{D} = 0.254\ X\ \bar{E}\gamma\ (\mu_a + \mu_s\ \mu r)\ \exp\ (-\mu r)\ dr \qquad (6.2\text{-}4)$$

Integrating (6.2-4) from $r=R_1$ to R_2 yields

6.2.2 Application to Hemispherical Geometries (Cont'd)

$$\dot{D}\Big|_{R_1}^{R_2} = 0.254 \times \bar{E}_\gamma \left[\mu_a \int_{R_1}^{R_2} \exp(-\mu r)\, dr + \mu_s \mu \int_{R_1}^{R_2} r \exp(-\mu r)\, dr\right] \qquad (6.2\text{-}5)$$

or

$$\dot{D}\Big|_{R_1}^{R_2} = 0.254 \times \bar{E}_\gamma \left\{\frac{\mu_a}{\mu}\left[\exp(-\mu R_1) - \exp(-\mu R_2)\right] + \frac{\mu_s}{\mu}\left[(\mu R_1 + 1)\exp(-\mu R_1) - (\mu R_2 + 1)\exp(-R_2)\right]\right\}, \qquad (6.2\text{-}6)$$

and finally, with some rearranging,

$$\dot{D}\Big|_{R_1}^{R_2} = 0.254 \times \bar{E}_\gamma [(1 + \mu_s R_1)\exp(-\mu R_1) - (1 + \mu_s R_2)\exp(-\mu R_2)]\,. \qquad (6.2\text{-}7)$$

6.2.3 Correction Factors

Consider the special case of the usual semi-infinite cloud where $R_1 = 0$ and $R_2 \to \infty$. Equation (6.2-7) then becomes

$$\dot{D}\Big|_0^\infty = 0.254 \times \bar{E}_\gamma \qquad (6.2\text{-}8)$$

Equation (6.2-8) is just the familiar recipe for a semi-infinite cloud submersion dose which can easily be derived from purely thermodynamic considerations.

Next, consider a cloud with no central void ($R_1 = 0$) but with a finite outer radius, R_2. Equation (6.2-7) becomes

$$\dot{D}\Big|_0^{R_2} = 0.254 \times \bar{E}_\gamma [1 - (1+\mu_s R_2)\exp(-\mu R_2)] \qquad (6.2\text{-}9)$$

For completeness consider an infinite cloud with a void of radius R_1. (6.2-7) becomes

6.2.3 Correction Factors (Cont'd)

$$\dot{D}\Big|_{R_1}^{\infty} = 0.254 \times \bar{E}_\gamma \ (1 + \mu_s R_1) \exp(-\mu R_1) \ . \quad (6.2\text{-}10)$$

Finally notice from Equations (6.2-7,8,9, and 10) that

$$\dot{D}\Big|_{o}^{\infty} = \dot{D}\Big|_{o}^{R_1} + \dot{D}\Big|_{R_1}^{R_2} + \dot{D}\Big|_{R_2}^{\infty} \quad (6.2\text{-}11)$$

as would be expected.

Submersion doses are often calculated assuming a semi-infinite cloud and using EQ. (6.2-8). If a finite hemispherical cloud is more appropriate, it may be convenient to correct available semi-infinite cloud doses using one of the following correctors.

For a finite cloud with no void

$$\frac{\dot{D}\Big|_{o}^{R_2}}{\dot{D}\Big|_{o}^{\infty}} = 1 - (1 + \mu_s R_2) \exp(-\mu R_2) \ , \quad (6.2\text{-}12)$$

for a finite cloud with central void

$$\frac{\dot{D}\Big|_{R_1}^{R_2}}{\dot{D}\Big|_{o}^{\infty}} = (1+ \mu_s R_1) \exp(-\mu R_1) - (1+ \mu_s R_2) \exp(-\mu R_2), \quad (6.2\text{-}13)$$

and for an infinite cloud with central void

$$\frac{\dot{D}\Big|_{R_1}^{\infty}}{\dot{D}\Big|_{o}^{\infty}} = (1 + \mu_s R_1) \exp(- \mu R_1) \ . \quad (6.2\text{-}14)$$

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