Entergy

Entergy Operations, Inc.

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Subject: Arkansas Nuclear One - Unit 2
Docket No. 50-368
License No. NPF-6
Non-Proprietary Version of Radiological Dose
Consequence Calculation to Support ANO-2 Power Uprate

Gentlemen:

Four radiological dose consequence calculations related to the proposed power uprate were provided to the NRC in a letter dated July 3, 2001 (2CAN070103). One of the calculations, the ANO-2 Radiological Dose Analysis for RSG and Power Uprate (Attachment 4 of the letter), contains information that is proprietary to the Westinghouse Electric Company, LLC (WEC). A non-proprietary version of the calculation is attached. Brackets are used to indicate those areas in which proprietary information has been removed. As stated in "a" through "e" of item vi of the affidavit in the July 3, 2001, letter, the information is considered to be proprietary and should be withheld from public disclosure.

Correspondence regarding the proprietary aspects of the dose consequence calculation should be addressed to Mehran Golbabai, Project Manager, ANO-2 Power Uprate, Westinghouse Electric Company, CE Nuclear Power LLC, 2000 Day Hill Road, Windsor, CT 06095.

This submittal contains no regulatory commitments.

Very truly yours,

Dale E. James
Acting Director, Nuclear Safety Assurance

DEJ/dwb
Attachment

A009

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Attachment to
2CAN080103

Non-Proprietary Version of the
ANO-2 Radiological Dose Analysis for RSG and Power Uprate (137 pages)
(Includes Steam Generator Tube Rupture and
Control Element Assembly Ejection - Secondary Side Release)

Design Analysis Title Page

Title: **ANO-2 Radiological Dose Analysis for RSG and Power Uprate**

Document Number: A-AN-FE-0233 ANO-2 Calc. #98-E-0036-04 Revision Number: 04

1. **Verification Status:**

☒ Complete ☐ Incomplete / Not Verified ☐ Complete with Internal Contingencies / Assumptions

2. **Approval of Completed Analysis**

This Design Analysis is complete and verified. Management authorizes the use of its results and attests to the qualification of the Cognizant Engineer(s), Mentor and Independent Reviewer(s).

	Printed Name	Signature	Date
Cognizant Engineer(s)	R. Hicks	[signature]	11/21/00
Mentor ☒ **None**			
Independent Reviewer(s)	K.A. Jones	K.A. Jones	11-27-00
Management Approval	I. C. Rickard	I. C. Rickard	11/27/00

3. **Package Contents** (this section may be completed after Management approval):

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4. **Distribution:**

QR A M. Kasparian M. Golbabai P. Hoffspiegel E. J. Schulz P. I. Wengloski

2. Analysis Input Data

2.1 Assumptions

In addition to those listed below, many assumptions are made through the course of the calculation and are documented in the Analysis section. Also, Section 5.3 documents some assumptions made to cover apparent non-conservatisms in the calculation.

2.1.1 Operator Action

No credit for operator action occurs until plant stabilization, 30 minutes after the transient. Hence, no credit for plant cooldown toward shutdown cooling conditions is taken until 30 minutes into the transient.

2.1.2 Reactor Coolant System (RCS) Subcooling

An assumption was made that operators keep the RCS subcooled by 20 °F during the cooldown to ensure that no voiding would occur in the upper head which would make the pressure control provided by the heaters and sprays less effective. This assumption is for the sake of a target. It has no impact on the cooldown. Only changes in temperature (enthalpy) between time steps are of importance.

2.1.3 Fuel Pins in the Core

An assumption was made that all pins in the core were fuel pins (no poison pins or shims). This assumption maximizes the amount of fuel pins and activity in the core.

2.1.4 SGTR Leakage

A total of no more than 70,000 lbm is assumed to leak from primary to secondary as a result of the rupture. This is considered conservative as it exceeds the SGTR Analysis of Record value for leakage. The mass transfer and flashing fractions were modeled for two intervals. For the first [ ] seconds, a [ ] flashing fraction was applied to a primary mass transfer of [ ] lbm. For the interval from [ ] seconds, a flashing fraction of [ ] was applied to a primary mass transfer of [ ] lbm. The flashing fractions were also considered conservative as they exceeded those calculated in the SGTR Analysis of Record. As a requirement of this calculation, the new SGTR Analysis of Record must calculate a total mass transfer of less than 70,000 lbm and flashing fractions of less than [ ] and [ ] for the above listed time intervals.

2.2 Bounding Input Data

2.2.1 Dose Conversion Factors (DCF)

This calculation used two sets of DCFs. Fuel failure events were based upon the new DCFs, hereafter known as ICRP-30. Non-fuel failure events used ICRP-2 DCFs.

Table 2.2-1 (Appendix C, Item 1) lists the DCFs for various isotopes of iodine used in the calculation of thyroid doses for fuel failure events. Also listed is their normalization to, or dose equivalent of (DEQ), I-131. A dose equivalent was then calculated for each species of iodine by applying the I-131 DCF:

TABLE 2.2-1
ICRP-30 Iodine Thyroid Dose Conversion Factors

Isotope	DCF (rem/Ci)	DEQ I-131
I-131	1.10E+06	1.000E-00
I-132	6.30E+03	5.727E-03
I-133	1.80E+05	1.636E-01
I-134	1.10E+03	1.000E-03
I-135	3.10E+04	2.818E-02

Table 2.2-2 (Appendix C, Item 2) lists the DCFs for various isotopes of iodine used in the calculation of thyroid doses for non-fuel failure events. Also listed is their DEQ I-131. A dose equivalent was then calculated for each species of iodine by applying the I-131 DCF:

TABLE 2.2-2
ICRP-2 Iodine Thyroid Dose Conversion Factors

Isotope	DCF (rem/Ci)	DEQ I-131
I-131	1.48E+06	1.000E-00
I-132	5.35E+04	3.615E-02
I-133	4.00E+05	2.703E-01
I-134	2.50E+04	1.689E-02
I-135	1.24E+05	8.378E-02

Table 2.2-3 (Appendix C, Item 3) lists the DCFs for various isotopes of iodine used in the calculation of whole body and skin doses for fuel failure events:

TABLE 2.2-3
ICRP-30 Iodine Whole Body and Skin Dose Conversion Factors

Isotope	Whole Body DCF (rem-m^3/s-Ci)	Skin DCF (rem-m^3/s-Ci)
I-131	5.59E-02	1.10E-01
I-132	3.55E-01	6.17E-01
I-133	9.11E-02	2.20E-01
I-134	4.11E-01	7.28E-01
I-135	2.49E-01	4.31E-01

Table 2.2-4 (Appendix C, Item 4) lists the DCFs for various isotopes of iodine used in the calculation of whole body and skin doses for non-fuel failure events:

TABLE 2.2-4
ICRP-2 Iodine Whole Body and Skin Dose Conversion Factors

Isotope	Whole Body – Off Site DCF (rem-m^3/s-Ci)	Skin – CR Gamma DCF (rem-m^3/s-Ci)	Skin – CR Beta DCF (rem-m^3/s-Ci)
I-131	1.38E-01	9.30E-02	4.49E-02
I-132	6.95E-01	5.98E-01	9.71E-02
I-133	2.54E-01	1.60E-01	9.38E-02
I-134	5.84E-01	4.58E-01	1.26E-01
I-135	5.13E-01	4.43E-01	7.08E-02

Table 2.2-5 (Appendix C, Item 5) lists the DCFs for noble gas isotopes used in the calculation of whole body and skin doses for fuel failure events:

TABLE 2.2-5
ICRP-30 Noble Gas Whole Body and Skin Dose Conversion Factors

Isotope	Whole Body DCF (rem-m^3/Ci-s)	Skin – Off Site DCF (rem-m^3/Ci-s)	Skin – CR Gamma DCF (rem-m^3/Ci-s)	Skin – CR Beta DCF (rem-m^3/Ci-s)
Kr-85	3.31E-04	4.89E-02	4.75E-04	4.84E-02
Kr-85m	2.31E-02	8.17E-02	3.20E-02	4.97E-02
Kr-87	1.33E-01	5.21E-01	1.85E-01	3.36E-01
Kr-88	3.38E-01	5.47E-01	4.69E-01	7.76E-02
Xe-131m	1.25E-03	1.60E-02	2.71E-03	1.33E-02
Xe-133	4.96E-03	1.76E-02	7.89E-03	9.67E-03
Xe-133m	4.29E-03	3.66E-02	7.00E-03	2.96E-02
Xe-135	3.59E-02	1.14E-01	5.07E-02	6.32E-02
Xe-135m	6.37E-02	1.13E-01	9.16E-02	2.14E-02
Xe-138	1.87E-01	4.08E-01	2.61E-01	1.47E-01

Table 2.2-6 (Appendix C, Item 6) lists the DCFs for noble gas isotopes used in the calculation of whole body and skin doses for non-fuel failure events:

TABLE 2.2-6
ICRP-2 Noble Gas Whole Body and Skin Dose Conversion Factors

Isotope	Whole Body – Off Site DCF (rem-m^3/Ci-s)	Whole Body – CR Skin – CR Gamma DCF (rem-m^3/Ci-s)	Skin – CR Beta DCF (rem-m^3/Ci-s)
Kr-85	5.16E-02	5.28E-04	5.11E-02
Kr-85m	9.39E-02	3.80E-02	5.59E-02
Kr-87	5.97E-01	3.55E-01	2.42E-01
Kr-88	5.13E-01	4.35E-01	7.82E-02
Xe-131m	3.83E-02	6.78E-03	3.15E-02
Xe-133	4.60E-02	1.24E-02	3.36E-02
Xe-133m	5.49E-02	1.42E-02	4.07E-02
Xe-135	1.35E-01	6.20E-02	7.27E-02
Xe-135m	1.30E-01	1.07E-01	2.25E-02
Xe-138	5.50E-01	2.74E-01	2.76E-01

2.2.2 Iodine Source Terms

Table 2.2-7 (Appendix B, Item 1) lists the core maximum iodine fuel rod activity inventories divided by the number of pins (radioactive source terms):

TABLE 2.2-7
Maximum Volatile Fission Product Activities
for Non-LOCA Transients
(Iodines)

Isotope	Maximum Activity (Ci)
I-131	2.002E+03
I-132	2.882E+03
I-133	4.072E+03
I-134	4.517E+03
I-135	3.788E+03

2.2.3 Noble Gas Sources

As with iodines in Section 2.2.2, Table 2.2-8 (Appendix B, Item 2) lists the noble gas source terms used in this analysis.

TABLE 2.2-8
Maximum Volatile Fission Product Activities
for Non-LOCA Transients
(Noble Gases)

Isotope	Maximum Activity (Ci)
Kr-85	2.281E+01
Kr-85m	6.473E+02
Kr-87	1.279E+03
Kr-88	1.805E+03
Xe-131m	2.249E+01
Xe-133	4.055E+03
Xe-133m	1.263E+02
Xe-135	1.055E+03
Xe-135m	7.993E+02
Xe-138	3.540E+03

2.2.4 Radial Peaking Factor

For this analysis, an all rods out radial peaking factor of 1.65 (Appendix B, Item 3) was used. The average source terms from Sections 2.2.2 and 2.2.3 were adjusted to reflect postulated failure of the pins operating at this peak.

2.2.5 Noble Gas Release

For pins failing by violation of departure from nucleate boiling ratio (DNBR) criteria, the 10% of noble gas activity residing in the gas gap is assumed to escape to the RCS (Reference 1, Appendix B). An exception to this is Kr-85. 30% of this noble gas is assumed to escape to the RCS upon DNBR fuel failure (Appendix C, Item 7). Upon failure by centerline melt (CLM), 100% of all noble gas activity in the pin is assumed to escape to the RCS (Reference 1, Appendix B).

2.2.6 Disintegration Energies β and γ

Table 2.2-9 lists the β and γ energies assumed for noble gases in this analysis (Appendix C, Item 8).

TABLE 2.2-9
Disintegration Energies

Isotope	Beta Energy (MeV/dis)	Gamma Energy (MeV/dis)
Kr-85	2.220E-01	2.110E-03
Kr-85m	2.430E-01	1.520E-01
Kr-87	1.050E-00	1.420E-00
Kr-88	3.400E-01	1.740E-00
Xe-131m	1.370E-01	2.710E-02
Xe-133	1.460E-01	4.970E-02
Xe-133m	1.770E-01	5.670E-02
Xe-135	3.160E-01	2.480E-01
Xe-135m	9.800E-02	4.290E-01
Xe-138	1.198E-00	1.096E-00

2.2.7 Breathing Rates, χ/Q, Iodine Protection Factor (IPF), and Geometry Factor (GF)

Table 2.2-10 lists the breathing rates used in this analysis (Appendix C, Item 9).

TABLE 2.2-10
Breathing Rates

Time After Accident	Breathing Rate, m^3/s
0-8 hr	3.47E-04
8-24 hr	1.75E-04
1-30 days	2.32E-04

Table 2.2-11 (Appendix C, Item 10) lists the values for χ/Q used in this analysis:

TABLE 2.2-11A
Atmospheric Dispersion Factors
χ/Q, s/m^3

Time Period	EAB	LPZ
0-2 hr	6.5E-04	-
0-8 hr	-	3.1E-05
8-24 hr	-	3.6E-06
1-4 days	-	2.3E-06
4-30 days	-	1.4E-06

TABLE 2.2-11B
Control Room Atmospheric Dispersion Factors
χ/Q, s/m^3

Time Period	From ADVs	From MSSVs	From MSLB Pipe	From FHA Ventilation
0-2 hr	4.96E-02	3.92E-02	5.42E-04	7.64E-05
2-8 hr	2.13E-02	2.00E-02	3.21E-04	6.06E-05
8-24 hr	2.62E-03	2.89E-03	1.57E-04	2.95E-05
1-4 days	3.17E-03	3.35E-03	1.11E-04	1.61E-05
4-30 days	2.90E-03	3.01E-03	8.15E-05	1.14E-05

Control Room doses due to iodine have an IPF applied to them that takes into account the filtration of the emergency ventilation system and the recirculation rates of the control room. This factor is 144 (Appendix C, Item 11). Control Room doses due to noble gases have a GF applied to them that takes into account the limited volume that can interact with the occupants in the Control Room. This factor is 32.24 (Appendix C, Item 12).

2.2.8 RCS and Steam Generator (SG) Metal Masses

Energy, in the form of heat, is stored within the metal components of the primary and secondary systems during normal operation. This energy is an additional load on the secondary system following a reactor trip. Metal masses were necessary in determining the amount of energy, in addition to decay energy, removed by the secondary side. The following is a summary of the mass inventories used in this calculation:

RCS Metal Mass (including cladding)	1,785,787 lbm	Appendix C, Item 13
SG Metal Mass, including 1% uncertainty (both generators)	2,357,340 lbm	Appendix C, Item 29

All events with the exception of SGTR and CEA Ejection used a SG mass of 2,285,200 lbm. The use of this smaller mass has no significant impact (<0.15%) on radiological consequences for those events (Reference 20, Page 21).

2.2.9 RCS and SG Metal Specific Heat

A metal specific heat was also required to determine the additional load after reactor trip. An RCS metal specific heat value was obtained from the ANO-2 CENTS basedeck calculation (Appendix C, Item 30). The maximum specific heat value listed for all materials and temperatures is 0.141 BTU/lbm-°F. The steam generators consist of carbon and stainless steel materials also listed in the basedeck calculation (Appendix C, Item 31). Therefore, to conservatively bound specific heat for all metals, a value of 0.150 BTU/lbm-°F was used in this analysis.

2.2.10 RCS Fluid Mass

An RCS fluid mass was needed for the calculation of RCS DEQ I-131 concentration. This fluid mass was obtained through the CENTS code. Upon loading the appropriate basedeck and control files, the commands to dump the liquid and steam masses of each of the RCS nodes was given. They were then totaled. The results are listed below and can be verified by performing an identical operation.

Mass Non-Pressurizer RCS Liquid	[ ]
Mass Pressurizer RCS Liquid	[ ]
Mass Pressurizer RCS Steam	[ ]

2.2.11 Shutdown Cooling Information

A 75 °F/hr (Appendix C, Item 14) cooldown rate was assumed for 2 hour events. For 8 hour events, the cooldown was set to that value which put the plant at shutdown cooling conditions in 8 hours. A shutdown cooling initiation temperature of 294 °F was assumed (Appendix C, Item 15).

2.2.12 Steam Generator Masses

This analysis used two values to represent the initial SG fluid mass. When it was conservative to use a [ ] value for initial SG mass, the [ ] (Appendix C, Item 32) was used. A [ ] SG inventory is conservative as it [ ] in the SG. When it was conservative to use a [ ] value, the [ ] (Appendix C, Item 33) was used. A [ ] initial SG inventory is conservative as it [ ] in the SG.

2.2.13 SG Iodine Decontamination Factor (DF)

An intact or unaffected SG is defined as a SG which maintains a water-steam interface (not dried out). All events covered in this analysis with the exception of Feedwater Line Break had at least one SG that fit this description. All of the events analyzed in this calculation used a DF of 100 for an unaffected steam generator (Appendix C, Item 16).

For a SG that dries out (such as in SLB or FWLB) a DF of 1.0 was assumed (Appendix C, Item 17).

2.2.14 Maximum Initial Activity Concentrations

The maximum initial RCS iodine activity concentration under normal operation is 1.0 μCi/g DEQ I-131 (Appendix C, Item 18). This initial concentration was used for all events, regardless if they failed fuel or not. The maximum initial steady state RCS noble gas activity is limited to 100/E μCi/g (Appendix C, Item 19), where 100/E is the sum of the average β and γ disintegration energies (MeV/dis). The maximum initial SG iodine activity concentration is 0.1 μCi/g DEQ I-131 (Appendix C, Item 20).

2.2.15 Iodine Spiking

Several events considered iodine spiking for their dose consequences. Two types of spiking were considered. For pre-existing iodine spiking, a straight multiplier of 60 (Appendix C, Item 34) was placed on the maximum initial RCS activity concentration. For event generated iodine spiking, a spiking model was used, which assumed that the iodine release rate from the fuel rods to the primary coolant (spiking factor) increased to a value of 500 times greater than the release rate corresponding to the iodine concentration at the equilibrium value (Appendix C, Item 35).

2.2.16 Charging Flow and Ion Exchanger Efficiency

During normal operation, only one charging pump is active. For the purposes of RCS purification during an event generated iodine spike, only one charging pump was assumed. A maximum flow to that pump of 46 gpm (Appendix C, Item 21) was also assumed. A maximum ion exchanger efficiency is conservative to maximize the amount iodine in the RCS during a spike. A maximum fraction of [ ] was used (Appendix C, Item 22).

2.2.17 Decay Heat Curve

The 1979 American National Standard (ANS) Decay Heat Curve (Appendix C, Item 36), including a +2 sigma uncertainty, was used in this analysis to model decay heat.

2.2.18 Core Power and Reactor Coolant Pump (RCP) Heat

The maximum reactor core power (plus a 2% uncertainty) of 3087 MWt was used in this analysis (Appendix C, Item 23). A maximum RCP heat of 18 MWt was used in this analysis (Appendix C, Item 24). Maximum power and RCP heat maximize the amount of energy needing removal by the secondary side during cooldown.

2.2.19 Secondary Safety Valves

The pressure setpoint on the first bank of safety valves used in this analysis is 1130.9 psia, or 1092.7 psia (Appendix C, Item 25) plus 3.5% uncertainty (Appendix C, Item 26). A maximum pressure setpoint allows a higher equilibrium pressure and temperature from which cooldown commences.

2.2.20 Emergency Feedwater (EFW) Temperature

A maximum EFW temperature of 121 °F (Appendix C, Item 27) was used in this analysis. A maximum EFW temperature and enthalpy minimizes the energy needed to turn EFW to steam and maximizes the amount of steam needed to remove system energy.

2.2.21 Primary to Secondary Leakage

The maximum primary to secondary leakage of 720 gal/day (0.5 gpm) per SG at a constant density of 62.4 lbm/ft^3 (Appendix C, Item 28) was assumed for this analysis. This amount of leakage is overly conservative since it must bound Design Basis Events (DBEs) involving steam line and feedwater line breaks that create a large pressure differential across the primary to secondary boundary due to the opening of the secondary side to atmospheric pressure. DBEs that do not have secondary side pipe breaks do not cause a secondary side depressurization and a much lower pressure differential between the primary and secondary side will exist. For these DBEs, the value of primary to secondary leakage that could be used is 150 gal/day (0.105 gpm) per SG. A maximum leak rate will transfer more primary activity to the secondary side where it is available for release to the atmosphere.

2.2.22 Steam Generator Formulation

The following pages were extracted from Reference 2, Appendix A and modified where appropriate. They present the formulation and sample solution for releases from a SG, which maintains a steam-water interface, known interchangeably as an unaffected or intact generator. This formulation was used in Section 4. for unaffected generators.

Alternate Exact Solution of the Dose Contribution of DEQ I-131 from Unaffected Steam Generators

The method used to determine the site boundary doses from leakage and steaming in the unaffected steam generator contained large conservatisms in that large time intervals were selected and the maximum activity in each interval was applied throughout the interval.

Two possible reduction paths exist:

1. Computerize the calculation to select very small time steps
2. Obtain an exact mathematical solution for the concentration and release from the unaffected generator

Note that benefit might be obtained from both improvement in the detail of both the decay heat removal steaming term and the time dependent concentration of the release from the generator.

This section determines the benefit from the SG concentration. The rate of steaming from the unaffected units will be that determined in the four major time intervals calculated in the main body.

Drawing the problem:

[ ]

[ ]

[ ]

<u>0-900 Seconds</u>

Working through the numerics for an example unaffected steam generator (see Section 4.1) in the 0-900 second interval:

[ ]

900-1800 Seconds

This interval is mathematically treated as a second 0-900 second interval. Working through the numerics for an example unaffected steam generator (see Section 4.1) in the 900-1800 second interval:

[ ]

3. Calculation

3.1 Heat Generation and Removal

3.1.1 Primary System Power Production

One of the components in the amount of steam released to the environment is that which is sufficient to remove excess heat production in the primary system (core and RCS). Core heat is in the form of decay heat. RCS heat comes from the operating of the RCPs.

The 1979 ANS Decay Heat Curve, including a +2 sigma uncertainty, was used in this analysis to model decay heat. Decay heat entries were taken at 900 second (15 minute) intervals. For each interval, the decay heat fraction listed at the begin time was used for the entire interval for conservatism. When an interval time was not listed in the reference decay heat curve, the fraction from the next earlier time step was used. This was an overprediction of decay fraction for that time interval and was conservative in this analysis.

As stated above, primary system power is a function of decay power plus RCP heat. RCP heat was conservatively added to all time periods regardless if an event had suffered a loss of power. Primary system power was calculated, for any time interval, as follows:

Primary System Power = (Analysis Rated Power × Decay Power Fraction) + RCP Heat

where:

Analysis Rated Power	= 3087 MWt, assumes a +2% uncertainty
RCP Heat	= 18 MWt, all 4 pumps

Table 3.1-1 lists primary system power generated as a function of time. Included is the decay heat fraction assumed for each time interval referenced from the 1979 ANS Decay Heat Curve. The conversion from MWt to BTU/s was handled as follows:

$$\text{MWt} \times \frac{1000\ \text{kW}}{\text{MWt}} \times \frac{3412.9\ \text{BTU}}{\text{kW hr}} \times \frac{\text{hr}}{3600\ \text{s}} = \text{BTU}/\text{s}$$

Reference 3, Appendix 1.A, is the source of the BTU/kW-hr conversion factor. It should be noted that cooldown events, such as Post-Trip SLB, cause a return to power. This added fission power has a substantially smaller effect on heat removal than the credit associated with the cooldown of the RCS. [

]

TABLE 3.1-1
Primary System Power Generation

Begin Time	End Time	Decay Fraction	Primary Power Generation	
			MWt	BTU/s
0	900	6.599E-02	221.71	210,188
900	1800	2.184E-02	85.40	80,966
1800	2700	1.800E-02	73.56	69,737
2700	3600	1.622E-02	68.07	64,536
3600	4500	1.454E-02	62.88	59,611
4500	5400	1.340E-02	59.38	56,292
5400	6300	1.296E-02	58.01	54,996
6300	7200	1.225E-02	55.81	52,906
7200	8100	1.170E-02	54.12	51,305
8100	9000	1.126E-02	52.75	50,012
9000	9900	1.089E-02	51.61	48,932
9900	10800	1.089E-02	51.61	48,932
10800	11700	1.057E-02	50.64	48,010
11700	12600	1.057E-02	50.64	48,010
12600	13500	1.053E-02	50.50	47,875
13500	14400	1.053E-02	50.50	47,875
14400	15300	1.013E-02	49.28	46,716
15300	16200	1.013E-02	49.28	46,716
16200	17100	9.802E-03	48.26	45,751
17100	18000	9.802E-03	48.26	45,751
18000	18900	9.516E-03	47.38	44,914
18900	19800	9.516E-03	47.38	44,914
19800	20700	9.516E-03	47.38	44,914
20700	21600	9.272E-03	46.62	44,200
21600	22500	9.272E-03	46.62	44,200
22500	23400	9.272E-03	46.62	44,200
23400	24300	9.272E-03	46.62	44,200
24300	25200	9.272E-03	46.62	44,200
25200	26100	8.765E-03	45.06	42,716
26100	27000	8.765E-03	45.06	42,716
27000	27900	8.765E-03	45.06	42,716
27900	28800	8.765E-03	45.06	42,716

3.1.2 Heat Removal from RCS and SG Metal

In addition to removal of energy produced during the recovery from the transient, energy stored in the RCS and SG metal during normal operation must also be removed to achieve shutdown cooling entry conditions.

For a 2 hour event, a 75 °F/hr cooldown was assumed in the RCS. Since this heat removal calculation was broken up into 15 minute segments, an 18.75 °F temperature drop was assumed for each interval. Section 2.2.8 lists the RCS and SG masses while Section 2.2.9 lists the specific heats assumed for this analysis. To calculate the amount of heat removed in any one segment, the following equation was used:

$$Q_{removed} = 18.75\ ^\circ F \times 0.150\ BTU/lbm\text{-}^\circ F \times (1{,}785{,}787 + 2{,}357{,}340\ lbm)$$

Cooldown of the RCS metal was assumed to occur after plant stabilization, 30 minutes into the transient. Table 3.1-2a charts the cooldown and energy removal from each component from 0 to 120 minutes.

TABLE 3.1-2a
Energy Removed from Metal vs. Time
2 Hour Event

Time (min)	ΔT (°F)	ΔE RCS Metal (BTU)	ΔE SG Metal (BTU)	Energy Removal Rate (BTU/s)
0-15	No cooldown credited			
15-30	No cooldown credited			
30-45	18.75	5,022,526	6,630,019	12,947
45-60	18.75	5,022,526	6,630,019	12,947
60-75	18.75	5,022,526	6,630,019	12,947
75-90	18.75	5,022,526	6,630,019	12,947
90-105	18.75	5,022,526	6,630,019	12,947
105-120	18.75	5,022,526	6,630,019	12,947

For an 8 hour event, a cooldown was assumed such that a shutdown cooling temperature of 294 °F was reached at 8 hours into the event. Since no cooldown is credited for 30 minutes, a temperature equilibrium would be reached between the primary and secondary systems. This temperature is controlled through the secondary safety valves. It would be no greater than the saturation temperature corresponding to the pressure to open the first bank of safety valves. The first bank of secondary safety valves opens at a maximum of 1130.9 psia. This corresponds to a saturation temperature of 560 °F. This is the maximum primary and secondary temperature that could exist 30 minutes after a transient. Thus, a total of 266 °F of cooling is necessary to reach shutdown cooling conditions. Assuming no cooldown occurs in the first 30 minutes of the transient, this leaves 7.5 hours in which to cool the RCS by 266 °F. This is equivalent to a cooldown rate of 35.5 °F/hr, or 8.88 °F per 15 minute interval. Table 3.1-3a charts the 8 hour RCS metal cooldown.

TABLE 3.1-3a
Energy Removed from Metal vs. Time
8 Hour Event

Time (min)	RCS Temp. (°F)	ΔT (°F)	ΔE RCS Metal (BTU)	ΔE SG Metal (BTU)	Energy Removal Rate (BTU/s)
0-15	560.0	No cooldown credited			
15-30	560.0	No cooldown credited			
30-45	551.1	8.88	2,378,668	3,139,977	6,132
45-60	542.2	8.88	2,378,668	3,139,977	6,132
60-75	533.4	8.88	2,378,668	3,139,977	6,132
75-90	524.5	8.88	2,378,668	3,139,977	6,132
90-105	515.6	8.88	2,378,668	3,139,977	6,132
105-120	506.7	8.88	2,378,668	3,139,977	6,132
120-135	497.8	8.88	2,378,668	3,139,977	6,132
135-150	489.0	8.88	2,378,668	3,139,977	6,132
150-165	480.1	8.88	2,378,668	3,139,977	6,132
165-180	471.2	8.88	2,378,668	3,139,977	6,132
180-195	462.3	8.88	2,378,668	3,139,977	6,132
195-210	453.4	8.88	2,378,668	3,139,977	6,132
210-225	444.6	8.88	2,378,668	3,139,977	6,132
225-240	435.7	8.88	2,378,668	3,139,977	6,132
240-255	426.8	8.88	2,378,668	3,139,977	6,132
255-270	417.9	8.88	2,378,668	3,139,977	6,132
270-285	409.0	8.88	2,378,668	3,139,977	6,132
285-300	400.2	8.88	2,378,668	3,139,977	6,132
300-315	391.3	8.88	2,378,668	3,139,977	6,132
315-330	382.4	8.88	2,378,668	3,139,977	6,132
330-345	373.5	8.88	2,378,668	3,139,977	6,132
345-360	364.6	8.88	2,378,668	3,139,977	6,132
360-375	355.8	8.88	2,378,668	3,139,977	6,132
375-390	346.9	8.88	2,378,668	3,139,977	6,132
390-405	338.0	8.88	2,378,668	3,139,977	6,132
405-420	329.1	8.88	2,378,668	3,139,977	6,132
420-435	320.2	8.88	2,378,668	3,139,977	6,132
435-450	311.4	8.88	2,378,668	3,139,977	6,132
450-465	302.5	8.88	2,378,668	3,139,977	6,132
465-480	293.6	8.88	2,378,668	3,139,977	6,132

As stated in Section 2.2.8, all events with the exception of SGTR and CEA Ejection used a smaller SG metal mass. Use of this mass alters the cooling profile for the 2 and 8 hour events. Tables 3.1-2b and 3.1-3b provide identical information for the smaller SG metal mass of 2,285,200 lbm.

TABLE 3.1-2b
Energy Removed from Metal vs. Time
2 Hour Event (SG Metal Mass = 2,285,200)

Time (min)	ΔT (°F)	ΔE RCS Metal (BTU)	ΔE SG Metal (BTU)	Energy Removal Rate (BTU/s)
0-15	No cooldown credited			
15-30	No cooldown credited			
30-45	18.75	5,022,526	6,427,125	12,722
45-60	18.75	5,022,526	6,427,125	12,722
60-75	18.75	5,022,526	6,427,125	12,722
75-90	18.75	5,022,526	6,427,125	12,722
90-105	18.75	5,022,526	6,427,125	12,722
105-120	18.75	5,022,526	6,427,125	12,722

TABLE 3.1-3b
Energy Removed from Metal vs. Time
8 Hour Event (SG Metal Mass = 2,285,200)

Time (min)	RCS Temp. (°F)	ΔT (°F)	ΔE RCS Metal (BTU)	ΔE SG Metal (BTU)	Energy Removal Rate (BTU/s)
0-15	560.0	No cooldown credited			
15-30	560.0	No cooldown credited			
30-45	551.1	8.88	2,378,668	3,043,886	6,025
45-60	542.2	8.88	2,378,668	3,043,886	6,025
60-75	533.4	8.88	2,378,668	3,043,886	6,025
75-90	524.5	8.88	2,378,668	3,043,886	6,025
90-105	515.6	8.88	2,378,668	3,043,886	6,025
105-120	506.7	8.88	2,378,668	3,043,886	6,025
120-135	497.8	8.88	2,378,668	3,043,886	6,025
135-150	489.0	8.88	2,378,668	3,043,886	6,025
150-165	480.1	8.88	2,378,668	3,043,886	6,025
165-180	471.2	8.88	2,378,668	3,043,886	6,025
180-195	462.3	8.88	2,378,668	3,043,886	6,025
195-210	453.4	8.88	2,378,668	3,043,886	6,025
210-225	444.6	8.88	2,378,668	3,043,886	6,025
225-240	435.7	8.88	2,378,668	3,043,886	6,025
240-255	426.8	8.88	2,378,668	3,043,886	6,025
255-270	417.9	8.88	2,378,668	3,043,886	6,025
270-285	409.0	8.88	2,378,668	3,043,886	6,025
285-300	400.2	8.88	2,378,668	3,043,886	6,025
300-315	391.3	8.88	2,378,668	3,043,886	6,025
315-330	382.4	8.88	2,378,668	3,043,886	6,025
330-345	373.5	8.88	2,378,668	3,043,886	6,025
345-360	364.6	8.88	2,378,668	3,043,886	6,025
360-375	355.8	8.88	2,378,668	3,043,886	6,025
375-390	346.9	8.88	2,378,668	3,043,886	6,025
390-405	338.0	8.88	2,378,668	3,043,886	6,025
405-420	329.1	8.88	2,378,668	3,043,886	6,025
420-435	320.2	8.88	2,378,668	3,043,886	6,025
435-450	311.4	8.88	2,378,668	3,043,886	6,025
450-465	302.5	8.88	2,378,668	3,043,886	6,025
465-480	293.6	8.88	2,378,668	3,043,886	6,025

3.1.3 Heat Removal from RCS Liquid

The determination of the heat removed from the RCS liquid assumed that the operators are keeping the RCS subcooled by 20 °F during the cooldown.

As discussed in Section 3.1.2, the maximum average core temperature is 560 °F. Therefore, the pressurizer is at saturation conditions corresponding to 580 °F. Assuming the pressurizer remains at saturation conditions and always 20 °F higher than the RCS, fluid enthalpy for 15 minute time intervals can easily be determined. An example of how this information was used is as follows:

1) At 30 minutes, the RCS is at 560 °F and 20 °F subcooled. The pressurizer is at 580 °F and saturated.

2) The following data is then taken from the steam tables:

   T_{sat} = 580 °F P_{sat} = 1326.2 psia

   @ 580 °F and 1326.2 psia: H_f = 589.1 BTU/lbm H_g = 1179.0 BTU/lbm
   @ 560 °F and 1326.2 psia: H = 561.8 BTU/lbm

3) The energy of the fluids is then:

   RCS Liquid [ ]
   Pressurizer Liquid [ ]
   Pressurizer Steam [ ]

4) After 15 minutes, the RCS cools by 18.75 °F, to 541.25 °F, and remains 20 °F subcooled. The pressurizer is at saturation conditions corresponding to 561.25 °F. Step 3 is repeated to find the energy of the fluids.

Table 3.1-4 charts the RCS liquid cooldown for the 2 hour event. As in Section 3.1.2, a 75 °F/hr (18.75 °F/15 min) cooldown was assumed.

TABLE 3.1-4
Energy Removed from Liquid vs. Time
2 Hour Event

Time (min)	Temperature (°F)		Sat. P (psia)	Enthalpy (BTU/lbm)			Total E (BTU)	ΔEnergy (BTU)	Total (BTU/s)
	RCS	PZR		H (RCS)	H_f (PZR)	H_g (PZR)			
0-15	560.00	580.00	1326.2	561.9	589.0	1178.3	[ ]	[ ]	
15-30	560.00	580.00	1326.2	561.9	589.0	1178.3	[ ]	[ ]	
30-45	541.25	561.25	1144.1	538.0	564.0	1186.7	[ ]	[ ]	[ ]
45-60	522.50	542.50	982.4	514.9	539.9	1193.3	[ ]	[ ]	[ ]
60-75	503.75	523.75	838.8	492.3	516.6	1198.1	[ ]	[ ]	[ ]
75-90	485.00	505.00	711.8	470.3	493.9	1201.6	[ ]	[ ]	[ ]
90-105	466.25	486.25	600.0	448.7	471.8	1203.8	[ ]	[ ]	[ ]
105-120	447.50	467.50	502.2	427.4	450.1	1205.0	[ ]	[ ]	[ ]

For an 8 hour event, a similar approach was taken to the above with the exception of the degree of cooldown. As discussed in Section 3.1.2, a 35.5 °F/hr (8.88 °F/15 min) cooldown was assumed. Table 3.1-5 charts the RCS liquid cooldown for the 8 hour event.

TABLE 3.1-5
Energy Removed from Liquid vs. Time
8 Hour Event

Time (min)	Temperature (°F) RCS	PZR	Sat. P (psia)	Enthalpy (BTU/lbm) H (RCS)	H_f (PZR)	H_g (PZR)	Total E (BTU)	ΔEnergy (BTU)	Total (BTU/s)
0-15	560.00	580.00	1326.2	561.9	589.0	1178.3	[ ]	[ ]	
15-30	560.00	580.00	1326.2	561.9	589.0	1178.3	[ ]	[ ]	
30-45	551.12	571.12	1237.0	550.5	577.1	1182.5	[ ]	[ ]	[ ]
45-60	542.24	562.24	1153.2	539.3	565.3	1186.3	[ ]	[ ]	[ ]
60-75	533.36	553.36	1073.8	528.2	553.8	1189.7	[ ]	[ ]	[ ]
75-90	524.48	544.48	998.6	517.3	542.4	1192.7	[ ]	[ ]	[ ]
90-105	515.60	535.60	927.5	506.5	531.3	1195.2	[ ]	[ ]	[ ]
105-120	506.72	526.72	860.4	495.9	520.2	1197.5	[ ]	[ ]	[ ]
120-135	497.84	517.84	797.0	485.3	509.4	1199.4	[ ]	[ ]	[ ]
135-150	488.96	508.96	737.3	474.9	498.6	1201.0	[ ]	[ ]	[ ]
150-165	480.08	500.08	681.0	464.6	488.0	1202.3	[ ]	[ ]	[ ]
165-180	471.20	491.20	628.1	454.3	477.5	1203.4	[ ]	[ ]	[ ]
180-195	462.32	482.32	578.4	444.2	467.2	1204.2	[ ]	[ ]	[ ]
195-210	453.44	473.44	531.8	434.1	456.9	1204.7	[ ]	[ ]	[ ]
210-225	444.56	464.56	488.1	424.1	446.7	1205.0	[ ]	[ ]	[ ]
225-240	435.68	455.68	447.2	414.2	436.6	1205.1	[ ]	[ ]	[ ]
240-255	426.80	446.80	409.0	404.4	426.6	1205.0	[ ]	[ ]	[ ]
255-270	417.92	437.92	373.4	394.6	416.7	1204.7	[ ]	[ ]	[ ]
270-285	409.04	429.04	340.2	384.9	406.8	1204.3	[ ]	[ ]	[ ]
285-300	400.16	420.16	309.3	375.3	397.0	1203.6	[ ]	[ ]	[ ]
300-315	391.28	411.28	280.6	365.7	387.3	1202.7	[ ]	[ ]	[ ]
315-330	382.40	402.40	254.1	356.2	377.6	1201.7	[ ]	[ ]	[ ]
330-345	373.52	393.52	229.5	346.7	368.0	1200.6	[ ]	[ ]	[ ]
345-360	364.64	384.64	206.9	337.3	358.5	1199.2	[ ]	[ ]	[ ]
360-375	355.76	375.76	186.0	327.9	349.0	1197.8	[ ]	[ ]	[ ]
375-390	346.88	366.88	166.8	318.5	339.6	1196.2	[ ]	[ ]	[ ]
390-405	338.00	358.00	149.2	309.2	330.2	1194.4	[ ]	[ ]	[ ]
405-420	329.12	349.12	133.1	299.9	320.8	1192.5	[ ]	[ ]	[ ]
420-435	320.24	340.24	118.4	290.7	311.5	1190.5	[ ]	[ ]	[ ]
435-450	311.36	331.36	105.0	281.5	302.2	1188.4	[ ]	[ ]	[ ]
450-465	302.48	322.48	92.9	272.3	293.0	1186.1	[ ]	[ ]	[ ]
465-480	293.60	313.60	81.8	263.2	283.8	1183.8	[ ]	[ ]	[ ]

3.1.4 Steam Production

The previous sections have determined the amount of heat that must be removed by the secondary system to reach shutdown cooling conditions. This section calculated the amount of steam production necessary to remove this heat.

Calculation of the steaming rate to cooldown the plant was as follows:

Steam Production Rate (lbm/s) = [ ]

where:
The Total Energy Removal is a sum of that found in Sections 3.1.1-3.
Energy to Turn EFW to Steam is that energy required to raise enthalpy of EFW to that of steam.

To maximize the above relationship, a minimization of the denominator was necessary. Since the denominator is the difference between the steam enthalpy and EFW enthalpy, a minimum steam enthalpy and maximum EFW enthalpy will minimize the denominator. The maximum EFW temperature is 121 °F. The maximum SG pressure is 1130.9 psia. Thus, the maximum EFW enthalpy is 92 BTU/lbm. Examination of the steam tables for vapor enthalpy over the range of possible saturation temperatures, 212-560 °F, yields a minimum value of 1150 BTU/lbm at 212 °F. This value was used as the minimum enthalpy for steam.

Table 3.1-6a charts the steaming necessary to cool the plant 75 °F/hr for the 2 hour event. Table 3.1-7a charts the steaming necessary to cool the plant down to shutdown cooling conditions in an 8 hour period.

TABLE 3.1-6a
Steaming Necessary for Heat Removal
2 Hour Event

Time (min)	Heat Generation (BTU/s)	Metal Cooldown (BTU/s)	RCS Fluid Cooldown (BTU/s)	Total Heat Removal (BTU/s)	Steam Production Rate (lbm/s)
0-15	210,188	No cooldown credited		[ ]	[ ]
15-30	80,966	No cooldown credited		[ ]	[ ]
30-45	69,737	12,947	[ ]	[ ]	[ ]
45-60	64,536	12,947	[ ]	[ ]	[ ]
60-75	59,611	12,947	[ ]	[ ]	[ ]
75-90	56,292	12,947	[ ]	[ ]	[ ]
90-105	54,996	12,947	[ ]	[ ]	[ ]
105-120	52,906	12,947	[ ]	[ ]	[ ]

From Tables 3.1-6a and 3.1.7a, the Steam Production Rate was summed over 120 minutes to determine the 2 hour steam mass release and 480 minutes for the 8 hour steam mass release.

2-hour steam release =[ ] lbm/s * 15 min * 60sec/min
=[ ]

8-hour steam release =[ ] lbm/s * 15 min * 60sec/min
=[ ]

TABLE 3.1-7a
Steaming Necessary for Heat Removal
8 Hour Event

Time (min)	Heat Generation (BTU/s)	Metal Cooldown (BTU/s)	RCS Fluid Cooldown (BTU/s)	Total Heat Removal (BTU/s)	Steam Production Rate (lbm/s)
0-15	210,188	No cooldown credited		[ ]	[ ]
15-30	80,966	No cooldown credited		[ ]	[ ]
30-45	69,737	6,132	[ ]	[ ]	[ ]
45-60	64,536	6,132	[ ]	[ ]	[ ]
60-75	59,611	6,132	[ ]	[ ]	[ ]
75-90	56,292	6,132	[ ]	[ ]	[ ]
90-105	54,996	6,132	[ ]	[ ]	[ ]
105-120	52,906	6,132	[ ]	[ ]	[ ]
120-135	51,305	6,132	[ ]	[ ]	[ ]
135-150	50,012	6,132	[ ]	[ ]	[ ]
150-165	48,932	6,132	[ ]	[ ]	[ ]
165-180	48,932	6,132	[ ]	[ ]	[ ]
180-195	48,010	6,132	[ ]	[ ]	[ ]
195-210	48,010	6,132	[ ]	[ ]	[ ]
210-225	47,875	6,132	[ ]	[ ]	[ ]
225-240	47,875	6,132	[ ]	[ ]	[ ]
240-255	46,716	6,132	[ ]	[ ]	[ ]
255-270	46,716	6,132	[ ]	[ ]	[ ]
270-285	45,751	6,132	[ ]	[ ]	[ ]
285-300	45,751	6,132	[ ]	[ ]	[ ]
300-315	44,914	6,132	[ ]	[ ]	[ ]
315-330	44,914	6,132	[ ]	[ ]	[ ]
330-345	44,914	6,132	[ ]	[ ]	[ ]
345-360	44,200	6,132	[ ]	[ ]	[ ]
360-375	44,200	6,132	[ ]	[ ]	[ ]
375-390	44,200	6,132	[ ]	[ ]	[ ]
390-405	44,200	6,132	[ ]	[ ]	[ ]
405-420	44,200	6,132	[ ]	[ ]	[ ]
420-435	42,716	6,132	[ ]	[ ]	[ ]
435-450	42,716	6,132	[ ]	[ ]	[ ]
450-465	42,716	6,132	[ ]	[ ]	[ ]
465-480	42,716	6,132	[ ]	[ ]	[ ]

As stated in Section 2.2.8, all events with the exception of SGTR and CEA Ejection used a smaller SG metal mass. Use of this mass alters the steaming profile for the 2 and 8 hour events. Tables 3.1-6b and 3.1-7b provide identical information for the smaller SG metal mass of 2,285,200 lbm.

TABLE 3.1-6b
Steaming Necessary for Heat Removal
2 Hour Event (SG Metal Mass = 2,285,200)

Time (min)	Heat Generation (BTU/s)	Metal Cooldown (BTU/s)	RCS Fluid Cooldown (BTU/s)	Total Heat Removal (BTU/s)	Steam Production Rate (lbm/s)
0-15	210,188	No cooldown credited		[ ]	[ ]
15-30	80,966	No cooldown credited		[ ]	[ ]
30-45	69,737	12,722	[ ]	[ ]	[ ]
45-60	64,536	12,722	[ ]	[ ]	[ ]
60-75	59,611	12,722	[ ]	[ ]	[ ]
75-90	56,292	12,722	[ ]	[ ]	[ ]
90-105	54,996	12,722	[ ]	[ ]	[ ]
105-120	52,906	12,722	[ ]	[ ]	[ ]

From Tables 3.1-6b and 3.1.7b, the Steam Production Rate was summed over 120 minutes to determine the 2 hour steam mass release and 480 minutes for the 8 hour steam mass release.

2-hour steam release =[ ] lbm/s * 15 min * 60sec/min
= [ ]

8-hour steam release =[ ] lbm/s * 15 min * 60sec/min
= [ ]

TABLE 3.1-7b
Steaming Necessary for Heat Removal
8 Hour Event (SG Metal Mass = 2,285,200)

Time (min)	Heat Generation (BTU/s)	Metal Cooldown (BTU/s)	RCS Fluid Cooldown (BTU/s)	Total Heat Removal (BTU/s)	Steam Production Rate (lbm/s)
0-15	210,188	No cooldown credited		[ ]	[ ]
15-30	80,966	No cooldown credited		[ ]	[ ]
30-45	69,737	6,025	[ ]	[ ]	[ ]
45-60	64,536	6,025	[ ]	[ ]	[ ]
60-75	59,611	6,025	[ ]	[ ]	[ ]
75-90	56,292	6,025	[ ]	[ ]	[ ]
90-105	54,996	6,025	[ ]	[ ]	[ ]
105-120	52,906	6,025	[ ]	[ ]	[ ]
120-135	51,305	6,025	[ ]	[ ]	[ ]
135-150	50,012	6,025	[ ]	[ ]	[ ]
150-165	48,932	6,025	[ ]	[ ]	[ ]
165-180	48,932	6,025	[ ]	[ ]	[ ]
180-195	48,010	6,025	[ ]	[ ]	[ ]
195-210	48,010	6,025	[ ]	[ ]	[ ]
210-225	47,875	6,025	[ ]	[ ]	[ ]
225-240	47,875	6,025	[ ]	[ ]	[ ]
240-255	46,716	6,025	[ ]	[ ]	[ ]
255-270	46,716	6,025	[ ]	[ ]	[ ]
270-285	45,751	6,025	[ ]	[ ]	[ ]
285-300	45,751	6,025	[ ]	[ ]	[ ]
300-315	44,914	6,025	[ ]	[ ]	[ ]
315-330	44,914	6,025	[ ]	[ ]	[ ]
330-345	44,914	6,025	[ ]	[ ]	[ ]
345-360	44,200	6,025	[ ]	[ ]	[ ]
360-375	44,200	6,025	[ ]	[ ]	[ ]
375-390	44,200	6,025	[ ]	[ ]	[ ]
390-405	44,200	6,025	[ ]	[ ]	[ ]
405-420	44,200	6,025	[ ]	[ ]	[ ]
420-435	42,716	6,025	[ ]	[ ]	[ ]
435-450	42,716	6,025	[ ]	[ ]	[ ]
450-465	42,716	6,025	[ ]	[ ]	[ ]
465-480	42,716	6,025	[ ]	[ ]	[ ]

3.1.5 Steam Generator Time Constant

A term was developed which was used in the calculation of releases. It is here referred to as the steam generator time constant. [

]:

[ ]

Table 3.1-8a lists the steam generator time constant values versus time for the 2 and 8 hour cooldowns. Note that this value is twice the constant that would be obtained if both SGs were involved in steaming the plant. Therefore, for events in which two steam generators are involved in steaming the plant (Seized Rotor), the time constants were divided by two.

TABLE 3.1-8a
SG Time Constants vs. Time
2 and 8 Hour Events

Time (min)	2 Hour Event		8 Hour Event	
	Steam Production Rate (lbm/s)	SG Time Constant (1/s)	Steam Production Rate (lbm/s)	SG Time Constant (1/s)
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As stated in Section 2.2.8, all events with the exception of SGTR and CEA Ejection used a smaller SG metal mass. Use of this mass alters the SG time constants for the 2 and 8 hour events. Table 3.1-8b provides identical information for the smaller SG metal mass of 2,285,200 lbm.

TABLE 3.1-8b
SG Time Constants vs. Time
2 and 8 Hour Events (SG Metal Mass = 2,285,200)

Time (min)	2 Hour Event: Steam Production Rate (lbm/s)	2 Hour Event: SG Time Constant (1/s)	8 Hour Event: Steam Production Rate (lbm/s)	8 Hour Event: SG Time Constant (1/s)
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3.2 Primary to Secondary Leakage

The maximum primary to secondary leakage of 720 gal/day (0.5 gpm) per SG at a constant density of 62.4 lbm/ft^3 was assumed for this analysis for DBEs except the Seized Rotor and CEA Ejection events. For these, a primary to secondary leakage of 150 gal/day (0.105 gpm) per SG at a constant density of 62.4 lbm/ft^3 was assumed. These leak rate values and density were held constant throughout this radiological consequence calculation, even though most of the time, the primary to secondary system pressure differential is much lower than the typical full power value at which the 0.5 gpm or 0.105 gpm is preserved.

A conversion of gallons per minute to grams per second was convenient for application in this analysis. The conversion is as follows for DBEs except Seized Rotor and CEA Ejection:

$$\frac{0.5\,\text{gal}}{\text{min}} \times \frac{1\,\text{ft}^3}{7.48\,\text{gal}} \times \frac{1\,\text{min}}{60\,\text{s}} \times \frac{62.4\,\text{lbm}}{\text{ft}^3} \times \frac{453.6\,\text{g}}{\text{lbm}} = 31.5\,{}^{\text{g}}\!/\!_{\text{s}}$$

For Seized Rotor and CEA Ejection, the following primary to secondary leak rate is used:

$$\frac{0.105\,\text{gal}}{\text{min}} \times \frac{1\,\text{ft}^3}{7.48\,\text{gal}} \times \frac{1\,\text{min}}{60\,\text{s}} \times \frac{62.4\,\text{lbm}}{\text{ft}^3} \times \frac{453.6\,\text{g}}{\text{lbm}} = 6.7\,{}^{\text{g}}\!/\!_{\text{s}}$$

3.3 Thyroid Dose Calculation

3.3.1 Calculation of Release from Average Fuel to RCS

The iodine source terms discussed in Section 2.2.2 were provided on a 'per pin' basis representing a single pin operating at core average power. For the purposes of fuel-to-RCS release, it was conservative for the entire core to be assumed to be fuel pins. For ANO-2:

177 Assemblies × {(16×16)-20} Pins/Assembly = 41,772 Total Pins in the Core

For the events being considered, two possible scenarios of release were modeled. First, some fraction of the fuel pins may fail via violation of DNBR criteria. In this case, only 12% of the iodines resident in the fuel pins are assumed to be present in the fuel-clad gas gap and available for release to the RCS upon failure (Reference 4, Table 3.6). The amount of each iodine isotope released in the core under DNBR failure criteria was given by the following relationship and summarized by isotope and fuel failure fraction in Table 3.3-1.

Total Iodine Release (DNBR) = Per Pin Activity × 41,772 Pins × 0.12 × Fraction of Pins Failed

Second, some fraction of the fuel may fail via violation of the CLM criteria. In this case, 50% of the iodines resident in the fuel pins are available for release to the RCS upon failure (Reference 5, Section 15.4.8, Appendix B). The amount of each isotope released in the core under CLM failure criteria was given by the following relationship and summarized by isotope and fuel failure fraction in Table 3.3-2.

Total Iodine Release (CLM) = Per Pin Activity × 41,772 Pins × 0.5 × Fraction of Pins Failed

3.3.2 Initial Steam Generator Iodine Activity

The maximum initial concentration of iodines in the secondary is 0.1 μCi/g DEQ I-131. To [ ] in the SG, a maximum initial steam generator inventory of [ ] is used to calculate activity as discussed in Section 2.2.12.

Initial SG Iodine Activity = [ ]

TABLE 3.3-1
Iodine Releases to RCS
DNBR Criteria

	Iodine Isotope (Per Pin Activity, Ci)				
Fraction of Pins Failed	**I-131 (2,002)**	**I-132 (2,882)**	**I-133 (4,072)**	**I-134 (4,517)**	**I-135 (3,788)**
0.005	50,177	72,232	102,057	113,210	94,939
0.010	100,353	144,464	204,115	226,421	189,879
0.015	150,530	216,696	306,172	339,631	284,818
0.020	200,706	288,929	408,229	452,842	379,758
0.025	250,883	361,161	510,287	566,052	474,697
0.030	301,059	433,393	612,344	679,263	569,636
0.035	351,236	505,625	714,401	792,473	664,576
0.040	401,412	577,857	816,459	905,684	759,515
0.045	451,589	650,089	918,516	1,018,894	854,455
0.050	501,765	722,321	1,020,574	1,132,105	949,394
0.055	551,942	794,554	1,122,631	1,245,315	1,044,333
0.060	602,118	866,786	1,224,688	1,358,526	1,139,273
0.065	652,295	939,018	1,326,746	1,471,736	1,234,212
0.070	702,471	1,011,250	1,428,803	1,584,947	1,329,152
0.075	752,648	1,083,482	1,530,860	1,698,157	1,424,091
0.080	802,824	1,155,714	1,632,918	1,811,368	1,519,030
0.085	853,001	1,227,946	1,734,975	1,924,578	1,613,970
0.090	903,177	1,300,179	1,837,032	2,037,789	1,708,909
0.095	953,354	1,372,411	1,939,090	2,150,999	1,803,849
0.100	1,003,531	1,444,643	2,041,147	2,264,209	1,898,788
0.105	1,053,707	1,516,875	2,143,204	2,377,420	1,993,727
0.110	1,103,884	1,589,107	2,245,262	2,490,630	2,088,667
0.115	1,154,060	1,661,339	2.347,319	2,603,841	2,183,606
0.120	1,204,237	1,733,571	2,449,376	2,717,051	2,278,546
0.125	1,254,413	1,805,804	2,551,434	2,830,262	2,373,485
0.130	1,304,590	1,878,036	2,653,491	2,943,472	2,468,424
0.135	1,354,766	1,950,268	2,755,548	3,056,683	2,563,364
0.140	1,404,943	2,022,500	2,857,606	3,169,893	2,658,303
0.145	1,455,119	2,094,732	2,959,663	3,283,104	2,753,243
0.150	1,505,296	2,166,964	3,061,721	3,396,314	2,848,182

TABLE 3.3-2
Iodine Releases to RCS
CLM Criteria

Fraction of Pins Failed	Iodine Isotope (Per Pin Activity, Ci) I-131 (2,002)	I-132 (2,882)	I-133 (4,072)	I-134 (4,517)	I-135 (3,788)
0.005	209,069	300,967	425,239	471,710	395,581
0.010	418,138	601,935	850,478	943,421	791,162
0.015	627,207	902,902	1,275,717	1,415,131	1,186,743
0.020	836,275	1,203,869	1,700,956	1,886,841	1,582,323
0.025	1,045,344	1,504,836	2,126,195	2,358,552	1,977,904
0.030	1,254,413	1,805,804	2,551,434	2,830,262	2,373,485
0.035	1,463,482	2,106,771	2,976,673	3,301,972	2,769,066
0.040	1,672,551	2,407,738	3,401,912	3,773,682	3,164,647
0.045	1,881,620	2,708,705	3,827,151	4,245,393	3,560,228
0.050	2,090,689	3,009,673	4,252,390	4,717,103	3,955,808
0.055	2,299,757	3,310,640	4,677,629	5,188,813	4,351,389
0.060	2,508,826	3,611,607	5,102,868	5,660,524	4,746,970
0.065	2,717,895	3,912,574	5,528,106	6,132,234	5,142,551
0.070	2,926,964	4,213,542	5,953,345	6,603,944	5,538,132
0.075	3,136,033	4,514,509	6,378,584	7,075,655	5,933,713
0.080	3,345,102	4,815,476	6,803,823	7,547,365	6,329,293
0.085	3,554,171	5,116,443	7,229,062	8,019,075	6,724,874
0.090	3,763,239	5,417,411	7,654,301	8,490,786	7,120,455
0.095	3,972,308	5,718,378	8,079,540	8,962,496	7,516,036
0.100	4,181,377	6,019,345	8,504,779	9,434,206	7,911,617
0.105	4,390,446	6,320,312	8,930,018	9,905,917	8,307,198
0.110	4,599,515	6,621,280	9,355,257	10,377,627	8,702,778
0.115	4,808,584	6,922,247	9,780,496	10,849,337	9,098,359
0.120	5,017,653	7,223,214	10,205,735	11,321,047	9,493,940
0.125	5,226,722	7,524,182	10,630,974	11,792,758	9,889,521
0.130	5,435,790	7,825,149	11,056,213	12,264,468	10,285,102
0.135	5,644,859	8,126,116	11,481,452	12,736,178	10,680,683
0.140	5,853,928	8,427,083	11,906,691	13,207,889	11,076,264
0.145	6,062,997	8,728,051	12,331,930	13,679,599	11,471,844
0.150	6,272,066	9,029,018	12,757,169	14,151,309	11,867,425

3.3.3 RCS DEQ I-131 Activity and Concentration

The previous sections calculated the activity of each iodine isotope released. For radiological purposes, these isotopes were converted into an I-131 equivalent via its DCF. Section 2.2.1 lists the DCFs for each iodine isotope for fuel failure events. In addition, a radial peaking factor of 1.65 was applied on the peak pin, per Section 2.2.4. Tables 3.3-3 (DNBR) and 3.3-4 (CLM) were constructed for fuel failure events using the following equation for activity for radiological consequence:

$$\text{Total RCS Radiological Activity, DEQ I-131 (Ci)} = 1.65 \times \sum_i \left(\text{Activity}_i \times \text{DEQ}_i\right)$$

where i is an individual isotope of iodine.

RCS concentrations in Tables 3.3-3 and 3.3-4 were found by dividing the resulting DEQ I-131 activity values by the mass of the non-pressurizer RCS liquid only [ ] from Section 2.2.10 and converting to grams:

RCS Concentration (Ci/g) = [ ]

TABLE 3.3-3
RCS DEQ I-131 and Concentration
DNBR Criteria

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TABLE 3.3-4
RCS DEQ I-131 and Concentration
CLM Criteria

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3.4 Whole Body Dose Common Items

3.4.1 Noble Gas Average Disintegration Energies

Section 2.2.6 lists the disintegration energies for each of the noble gas isotopes. Section 2.2.3 lists the noble gas activity source terms for each of the isotopes considered in this analysis. From this, the weighted average γ and β disintegration energies were found. Below is listed the procedure for finding each:

$$\overline{E_{\gamma \text{ or } \beta}} = \frac{\sum_i (\text{Activity } (i) \times E_{\gamma \text{ or } \beta}(i))}{\sum_i \text{Activity } (i)}$$

where i is an individual noble gas isotope.

As the ratios of the activity of the individual isotopes to the total activity do not vary with fuel failure, the average disintegration energy can be determined once in this section.

Performing the calculation of each yields:

$$\overline{E_\gamma} = 0.7301 \, {}^{\text{MeV}}\!/\!_{\text{dis}}$$

$$\overline{E_\beta} = 0.5534 \, {}^{\text{MeV}}\!/\!_{\text{dis}}$$

$$\overline{E_\gamma} + \overline{E_\beta} = 1.284 \, {}^{\text{MeV}}\!/\!_{\text{dis}}$$

3.4.2 Initial RCS Noble Gas Activity

The maximum initial steady state RCS noble gas activity is limited to 100/E μCi/g, where 100/E is the average β and γ disintegration energies found in the previous section (MeV/dis). Thus, the initial activity in the RCS is described by:

$$\text{RCS Noble Gas Activity (Ci)} = \sum \text{RCS masses (lbm)} \times \frac{100}{1.284} \times 10^{-6} \left(\frac{\text{Ci}}{\text{g}}\right) \times \frac{453.6\ \text{g}}{\text{lbm}}$$

$$= [\qquad\qquad] \times 77.88 \times 10^{-6} \times 453.6$$

$$= [\qquad]$$

The amount of noble gas activity released to the RCS from the perforated clad is based upon the radial peak of 1.65 and either 10% (DNBR criteria)[2] or 100% (CLM criteria) of the initial pin inventory. For example, in Section 2.2.3, the initial inventory of Kr-85m is 647.3 Ci per pin. The total core activity due to Kr-85m then becomes:

Total Core Activity (Kr-85m) = 41,772 pins × 647.3 Ci/pin = 27,039,016 Ci

For calculation of doses due to violation of DNBR criteria, an all rods out operating F_r of 1.65 and a 10% inventory resident in the gas gap are assumed. If 0.5% (0.005 fraction) of the fuel fails, the release to the RCS is:

Activity Release to RCS, DNBR (Kr-85m) = 27,039,016 Ci × 1.65 × 0.1 × 0.005 = 22,307 Ci

For calculation of doses due to violation of CLM criteria, an operating F_r of 1.65 and a 100% inventory resident in the gas gap are assumed. If 0.5% (0.005 fraction) of the fuel fails, the release to the RCS is:

Activity Release to RCS, CLM (Kr-85m) = 27,039,016 Ci × 1.65 × 1.0 × 0.005 = 223,072 Ci

This calculation was carried out for each of the noble gas isotopes. The sum of the individual isotope contributions was then found. The initial RCS noble gas activity was added to that released via fuel failure to determine the total RCS noble gas activity. Tables 3.4-1 (DNBR criteria) and 3.4-2 (CLM criteria) list the total RCS noble gas activity versus fuel failure used in this analysis.

[2] 10% covers all noble gases with the exception of Kr-85. 30% is the assumed release percentage of Kr-85.

TABLE 3.4-1
RCS Noble Gas Activity
DNBR Criteria

	Noble Gas Isotope (Per Pin Activity, Ci)					
Fraction of Pins Failed	**Kr-85 (22.81)**	**Kr-85m (647.3)**	**Kr-87 (1279)**	**Kr-88 (1805)**	**Xe-131m (22.49)**	**Xe-133 (4055)**
0.005	2,358	22,307	44,077	62,204	775	139,743
0.010	4,716	44,614	88,154	124,407	1,550	279,486
0.015	7,075	66,922	132,230	186,611	2,325	419,229
0.020	9,433	89,229	176,307	248,815	3,100	558,972
0.025	11,791	111,536	220,384	311,019	3,875	698,715
0.030	14,149	133,843	264,461	373,222	4,650	838,458
0.035	16,508	156,150	308,537	435,426	5,425	978,201
0.040	18,866	178,458	352,614	497,630	6,200	1,117,944
0.045	21,224	200,765	396,691	559,834	6,975	1,257,687
0.050	23,582	223,072	440,768	622,037	7,750	1,397,430
0.055	25,941	245,379	484,844	684,241	8,526	1,537,173
0.060	28,299	267,686	528,921	746,445	9,301	1,676,916
0.065	30,657	289,993	572,998	808,648	10,076	1,816,659
0.070	33,015	312,301	617,075	870,852	10,851	1,956,402
0.075	35,373	334,608	661,152	933,056	11,626	2,096,145
0.080	37,732	356,915	705,228	995,260	12,401	2,235,888
0.085	40,090	379,222	749,305	1,057,463	13,176	2,375,631
0.090	42,448	401,529	793,382	1,119,667	13,951	2,515,374
0.095	44,806	423,837	837,459	1,181,871	14,726	2,655,117
0.100	47,165	446,144	881,535	1,244,075	15,501	2,794,860
0.105	49,523	468,451	925,612	1,306,278	16,276	2,934,603
0.110	51,881	490,758	969,689	1,368,482	17,051	3,074,346
0.115	54,239	513,065	1,013,766	1,430,686	17,826	3,214,089
0.120	56,597	535,373	1,057,842	1,492,890	18,601	3,353,832
0.125	58,956	557,680	1,101,919	1,555,093	19,376	3,493,575
0.130	61,314	579,987	1,145,996	1,617,297	20,151	3,633,318
0.135	63,672	602,294	1,190,073	1,679,501	20,926	3,773,061
0.140	66,030	624,601	1,234,150	1,741,704	21,701	3,912,804
0.145	68,389	646,908	1,278,226	1,803,908	22,476	4,052,547
0.150	70,747	669,216	1,322,303	1,866,112	23,251	4,192,290

TABLE 3.4-1 (Cont.)
RCS Noble Gas Activity
DNBR Criteria

Fraction of Pins Failed	Noble Gas Isotope (Per Pin Activity, Ci)					Total Activity (Ci)
	Xe-133m (126.3)	Xe-135 (1055)	Xe-135m (799.3)	Xe-138 (3540)	Initial Activity	
0.005	4,353	36,357	27,545	121,995	15,818	477,532
0.010	8,705	72,715	55,091	243,990	15,818	939,247
0.015	13,058	109,072	82,636	365,985	15,818	1,400,961
0.020	17,410	145,429	110,182	487,981	15,818	1,862,675
0.025	21,763	181,787	137,727	609,976	15,818	2,324,390
0.030	26,115	218,144	165,272	731,971	15,818	2,786,104
0.035	30,468	254,501	192,818	853,966	15,818	3,247,818
0.040	34,820	290,858	220,363	975,961	15,818	3,709,533
0.045	39,173	327,216	247,909	1,097,956	15,818	4,171,247
0.050	43,525	363,573	275,454	1,219,951	15,818	4,632,961
0.055	47,878	399,930	302,999	1,341,946	15,818	5,094,676
0.060	52,230	436,288	330,545	1,463,942	15,818	5,556,390
0.065	56,583	472,645	358,090	1,585,937	15,818	6,018,104
0.070	60,936	509,002	385,636	1,707,932	15,818	6,479,819
0.075	65,288	545,360	413,181	1,829,927	15,818	6,941,533
0.080	69,641	581,717	440,726	1,951,922	15,818	7,403,247
0.085	73,993	618,074	468,272	2,073,917	15,818	7,864,962
0.090	78,346	654,431	495,817	2,195,912	15,818	8,326,676
0.095	82,698	690,789	523,363	2,317,907	15,818	8,788,390
0.100	87,051	727,146	550,908	2,439,903	15,818	9,250,105
0.105	91,403	763,503	578,453	2,561,898	15,818	9,711,819
0.110	95,756	799,861	605,999	2,683,893	15,818	10,173,533
0.115	100,108	836,218	633,544	2,805,888	15,818	10,635,248
0.120	104,461	872,575	661,090	2,927,883	15,818	11,096,962
0.125	108,813	908,933	688,635	3,049,878	15,818	11,558,676
0.130	113,166	945,290	716,180	3,171,873	15,818	12,020,391
0.135	117,519	981,647	743,726	3,293,868	15,818	12,482,105
0.140	121,871	1,018,005	771,271	3,415,864	15,818	12,943,819
0.145	126,224	1,054,362	798,817	3,537,859	15,818	13,405,534
0.150	130,576	1,090,719	826,362	3,659,854	15,818	13,867,248

TABLE 3.4-2
RCS Noble Gas Activity
CLM Criteria

	Noble Gas Isotope (Per Pin Activity, Ci)					
Fraction of Pins Failed	Kr-85 (22.81)	Kr-85m (647.3)	Kr-87 (1279)	Kr-88 (1805)	Xe-131m (22.49)	Xe-133 (4055)
0.005	7,861	223,072	440,768	622,037	7,750	1,397,430
0.010	15,722	446,144	881,535	1,244,075	15,501	2,794,860
0.015	23,582	669,216	1,322,303	1,866,112	23,251	4,192,290
0.020	31,443	892,288	1,763,071	2,488,149	31,002	5,589,720
0.025	39,304	1,115,359	2,203,839	3,110,186	38,752	6,987,150
0.030	47,165	1,338,431	2,644,606	3,732,224	46,503	8,384,580
0.035	55,025	1,561,503	3,085,374	4,354,261	54,253	9,782,010
0.040	62,886	1,784,575	3,526,142	4,976,298	62,004	11,179,440
0.045	70,747	2,007,647	3,966,909	5,598,336	69,754	12,576,870
0.050	78,608	2,230,719	4,407,677	6,220,373	77,505	13,974,300
0.055	86,468	2,453,791	4,848,445	6,842,410	85,255	15,371,730
0.060	94,329	2,676,863	5,289,212	7,464,448	93,006	16,769,161
0.065	102,190	2,899,934	5,729,980	8,086,485	100,756	18,166,591
0.070	110,051	3,123,006	6,170,748	8,708,522	108,507	19,564,021
0.075	117,911	3,346,078	6,611,516	9,330,559	116,257	20,961,451
0.080	125,772	3,569,150	7,052,283	9,952,597	124,008	22,358,881
0.085	133,633	3,792,222	7,493,051	10,574,634	131,758	23,756,311
0.090	141,494	4,015,294	7,933,819	11,196,671	139,509	25,153,741
0.095	149,354	4,238,366	8,374,586	11,818,709	147,259	26,551,171
0.100	157,215	4,461,438	8,815,354	12,440,746	155,010	27,948,601
0.105	165,076	4,684,509	9,256,122	13,062,783	162,760	29,346,031
0.110	172,937	4,907,581	9,696,889	13,684,820	170,511	30,743,461
0.115	180,797	5,130,653	10,137,657	14,306,858	178,261	32,140,891
0.120	188,658	5,353,725	10,578,425	14,928,895	186,012	33,538,321
0.125	196,519	5,576,797	11,019,193	15,550,932	193,762	34,935,751
0.130	204,380	5,799,869	11,459,960	16,172,970	201,513	36,333,181
0.135	212,241	6,022,941	11,900,728	16,795,007	209,263	37,730,611
0.140	220,101	6,246,013	12,341,496	17,417,044	217,013	39,128,041
0.145	227,962	6,469,084	12,782,263	18,039,082	224,764	40,525,471
0.150	235,823	6,692,156	13,223,031	18,661,119	232,514	41,922,901

TABLE 3.4-2 (Cont.)
RCS Noble Gas Activity
CLM Criteria

Fraction of Pins Failed	Noble Gas Isotope (Per Pin Activity, Ci)					Total Activity (Ci)
	Xe-133m (126.3)	Xe-135 (1055)	Xe-135m (799.3)	Xe-138 (3540)	Initial Activity	
0.005	43,525	363,573	275,454	1,219,951	15,818	4,617,240
0.010	87,051	727,146	550,908	2,439,903	15,818	9,218,662
0.015	130,576	1,090,719	826,362	3,659,854	15,818	13,820,083
0.020	174,102	1,454,292	1,101,816	4,879,805	15,818	18,421,505
0.025	217,627	1,817,865	1,377,270	6,099,756	15,818	23,022,927
0.030	261,152	2,181,438	1,652,724	7,319,708	15,818	27,624,349
0.035	304,678	2,545,011	1,928,178	8,539,659	15,818	32,225,771
0.040	348,203	2,908,584	2,203,632	9,759,610	15,818	36,827,192
0.045	391,728	3,272,157	2,479,086	10,979,561	15,818	41,428,614
0.050	435,254	3,635,730	2,754,540	12,199,513	15,818	46,030,036
0.055	478,779	3,999,303	3,029,994	13,419,464	15,818	50,631,458
0.060	522,305	4,362,877	3,305,448	14,639,415	15,818	55,232,880
0.065	565,830	4,726,450	3,580,902	15,859,366	15,818	59,834,302
0.070	609,355	5,090,023	3,856,356	17,079,318	15,818	64,435,723
0.075	652,881	5,453,596	4,131,810	18,299,269	15,818	69,037,145
0.080	696,406	5,817,169	4,407,263	19,519,220	15,818	73,638,567
0.085	739,931	6,180,742	4,682,717	20,739,171	15,818	78,239,989
0.090	783,457	6,544,315	4,958,171	21,959,123	15,818	82,841,411
0.095	826,982	6,907,888	5,233,625	23,179,074	15,818	87,442,832
0.100	870,508	7,271,461	5,509,079	24,399,025	15,818	92,044,254
0.105	914,033	7,635,034	5,784,533	25,618,976	15,818	96,645,676
0.110	957,558	7,998,607	6,059,987	26,838,928	15,818	101,247,098
0.115	1,001,084	8,362,180	6,335,441	28,058,879	15,818	105,848,520
0.120	1,044,609	8,725,753	6,610,895	29,278,830	15,818	110,449,941
0.125	1,088,134	9,089,326	6,886,349	30,498,782	15,818	115,051,363
0.130	1,131,660	9,452,899	7,161,803	31,718,733	15,818	119,652,785
0.135	1,175,185	9,816,472	7,437,257	32,938,684	15,818	124,254,207
0.140	1,218,711	10,180,045	7,712,711	34,158,635	15,818	128,855,629
0.145	1,262,236	10,543,618	7,988,165	35,378,587	15,818	133,457,051
0.150	1,305,761	10,907,191	8,263,619	36,598,538	15,818	138,058,472

3.5 Iodine Spiking

3.5.1 Pre-Existing Iodine Spiking (PIS)

As stated in Section 2.2.15, a multiplier of 60 was placed on the maximum initial RCS activity concentration. Therefore, the maximum initial RCS activity concentration became 60 μCi/g.

3.5.2 Event Generated Iodine Spiking (GIS)

For the GIS scenario, it was assumed that an increase in the iodine activity concentration during the transient was a result of an increased iodine appearance, not being in balance with a continuous removal via the coolant purification system. The following equation for iodine activity concentration was derived in Reference 6, Section 7.5.3:

$$C_i(t) = C_{oi} \times \left\{ 1 + \left(Sp \times \frac{B_{oi}}{B_i} - 1 \right) \times \left(1 - e^{-B_i t} \right) \right\}$$

where:

t	=	Time (s)
$C_i(t)$	=	RCS iodine activity concentration of iodine isotope i at time t (μCi/g.)
C_{oi}	=	Equilibrium concentration of iodine isotope i prior to GIS (μCi/g.)
Sp	=	Spiking factor (500)
B_{oi}	=	Activity combined removal constant prior to the event (s^{-1})
B_i	=	Activity combined removal constant after the event (s^{-1})

and:

$$B_i = \lambda_i$$

$$B_{oi} = \frac{F \times n}{M} + \lambda_i = \lambda_{RCS} + \lambda_i$$

where:

F	=	Charging flow rate (gal/s)
n	=	Ion exchanger efficiency (fraction)
λ_i	=	Radioactive decay constant of iodine isotope i (s^{-1})
M	=	Reactor coolant mass (g)
λ_{RCS}	=	Iodine cleanup constant (s^{-1})

Upon initiation of the event, no credit was taken for the purification system due to letdown being secured on a Safety Injection Actuation Signal (SIAS). This explains the difference in the activity combined removal constants listed above. The iodine cleanup constant was calculated using input from Section 2.2. Note, charging pump action was assumed at a density of 62.4 lbm/ft^3:

$$\lambda_{RCS} = \frac{F \times n}{M} = \frac{46\,{}^{gal}\!/_{min} \times 1.0}{[\qquad]} \times \frac{min}{60\,s} \times \frac{lbm}{1.603E-02\,ft^3} \times \frac{ft^3}{7.481\,gal} = [\qquad]$$

Since each iodine isotope has a unique decay constant, the RCS iodine activity concentration calculation was carried out individually for each isotope. The activity concentration for each isotope corresponding to 1.0 μCi/g DEQ I-131 total was found. Table 2.2-7 can be used for scaling purposes. It is repeated here:

TABLE 2.2-7
Maximum Volatile Fission Product Activities
for Non-LOCA Transients
(Iodines)

Isotope	Maximum Activity (Ci)
I-131	2.002E+03
I-132	2.882E+03
I-133	4.072E+03
I-134	4.517E+03
I-135	3.788E+03

Table 3.5-1 scales the individual isotopes to a total of 1.0 μCi/g DEQ I-131. Note that the unit conversion was not important since it was the ratios of iodines that was needed. Column four applies the isotope DEQ. Column five scales the individual isotope sum to 1.0 μCi/g DEQ I-131. Column six then takes off the isotope DEQ to obtain the individual isotope activities corresponding to 1.0 μCi/g DEQ I-131.

TABLE 3.5-1
Iodine Isotope Activity Concentration
(Scaled to 1.0 μCi/g)

Nuclide	DEQ I-131	Maximum Activity (Ci)	DEQ I-131 (μCi/g)	Scaled to 1.0 μCi/g	Initial Activity (μCi/g)
I-131	1.000E-00	2.002E+03	2.002E+03	5.560E-01	0.556
I-132	3.615E-02	2.882E+03	1.042E+02	2.894E-02	0.801
I-133	2.703E-01	4.072E+03	1.101E+03	3.058E-01	1.131
I-134	1.689E-02	4.517E+03	7.629E+01	2.119E-02	1.254
I-135	8.378E-02	3.788E+03	3.174E+02	8.814E-02	1.052
Total			3.601E+03	1.000	

Table 3.5-2 lists the RCS iodine activity concentrations of each isotope versus time for a 2 hour event with a GIS. Table 3.5-3 lists the RCS iodine activity concentrations of each isotope versus time for an 8 hour event. Both tables also total the activity concentrations, applying the proper dose equivalence. Decay constants used in the following tables come from Reference 6.[3]

[3] The current ANO-2 FSAR incorrectly lists the decay constant for I-131. The decay constant should read 3.59E-03 hr^{-1}. It currently reads 3.59E-06 hr^{-1}.

TABLE 3.5-2
RCS Iodine Activity Concentration vs. Time
2 Hour Event

Time (min)	Time End (s)	Iodine Isotope Activity Concentration (Ci/g) Isotope Decay Constant (s^{-1})					
		I-131 9.900E-07	I-132 8.370E-05	I-133 9.630E-06	I-134 2.220E-04	I-135 2.870E-05	Total
0-15	900	4.374E-06	3.476E-05	1.324E-05	1.219E-04	2.111E-05	1.304E-05
15-30	1800	8.189E-06	6.626E-05	2.524E-05	2.207E-04	4.066E-05	2.454E-05
30-45	2700	1.200E-05	9.547E-05	3.714E-05	3.016E-04	5.971E-05	3.559E-05
45-60	3600	1.581E-05	1.226E-04	4.893E-05	3.678E-04	7.827E-05	4.624E-05
60-75	4500	1.961E-05	1.477E-04	6.063E-05	4.221E-04	9.636E-05	5.654E-05
75-90	5400	2.342E-05	1.710E-04	7.222E-05	4.665E-04	1.140E-04	6.655E-05
90-105	6300	2.721E-05	1.926E-04	8.371E-05	5.028E-04	1.312E-04	7.629E-05
105-120	7200	3.101E-05	2.126E-04	9.511E-05	5.326E-04	1.479E-04	8.579E-05

TABLE 3.5-3
RCS Iodine Activity Concentration vs. Time
8 Hour Event

Time (min)	Time End (s)	Iodine Isotope Activity Concentration (Ci/g) Isotope Decay Constant (s^{-1})					
		I-131 9.900E-07	I-132 8.370E-05	I-133 9.630E-06	I-134 2.220E-04	I-135 2.870E-05	Total
0-15	900	4.374E-06	3.476E-05	1.324E-05	1.219E-04	2.111E-05	1.304E-05
15-30	1800	8.189E-06	6.626E-05	2.524E-05	2.207E-04	4.066E-05	2.454E-05
30-45	2700	1.200E-05	9.547E-05	3.714E-05	3.016E-04	5.971E-05	3.559E-05
45-60	3600	1.581E-05	1.226E-04	4.893E-05	3.678E-04	7.827E-05	4.624E-05
60-75	4500	1.961E-05	1.477E-04	6.063E-05	4.221E-04	9.636E-05	5.654E-05
75-90	5400	2.342E-05	1.710E-04	7.222E-05	4.665E-04	1.140E-04	6.655E-05
90-105	6300	2.721E-05	1.926E-04	8.371E-05	5.028E-04	1.312E-04	7.629E-05
105-120	7200	3.101E-05	2.126E-04	9.511E-05	5.326E-04	1.479E-04	8.579E-05
120-135	8100	3.480E-05	2.312E-04	1.064E-04	5.570E-04	1.642E-04	9.509E-05
135-150	9000	3.859E-05	2.485E-04	1.176E-04	5.770E-04	1.801E-04	1.042E-04
150-165	9900	4.237E-05	2.645E-04	1.287E-04	5.934E-04	1.956E-04	1.131E-04
165-180	10800	4.615E-05	2.793E-04	1.397E-04	6.068E-04	2.107E-04	1.219E-04
180-195	11700	4.993E-05	2.930E-04	1.506E-04	6.177E-04	2.254E-04	1.306E-04
195-210	12600	5.370E-05	3.058E-04	1.614E-04	6.267E-04	2.398E-04	1.391E-04
210-225	13500	5.748E-05	3.176E-04	1.722E-04	6.341E-04	2.537E-04	1.475E-04
225-240	14400	6.124E-05	3.286E-04	1.828E-04	6.401E-04	2.674E-04	1.557E-04
240-255	15300	6.501E-05	3.388E-04	1.933E-04	6.450E-04	2.806E-04	1.639E-04
255-270	16200	6.877E-05	3.482E-04	2.038E-04	6.491E-04	2.936E-04	1.720E-04
270-285	17100	7.253E-05	3.570E-04	2.141E-04	6.524E-04	3.062E-04	1.800E-04
285-300	18000	7.628E-05	3.651E-04	2.244E-04	6.551E-04	3.184E-04	1.879E-04
300-315	18900	8.003E-05	3.726E-04	2.346E-04	6.573E-04	3.304E-04	1.957E-04
315-330	19800	8.378E-05	3.796E-04	2.447E-04	6.591E-04	3.421E-04	2.034E-04
330-345	20700	8.752E-05	3.861E-04	2.547E-04	6.606E-04	3.534E-04	2.111E-04
345-360	21600	9.126E-05	3.921E-04	2.646E-04	6.618E-04	3.645E-04	2.187E-04
360-375	22500	9.500E-05	3.976E-04	2.744E-04	6.628E-04	3.753E-04	2.262E-04
375-390	23400	9.874E-05	4.028E-04	2.842E-04	6.636E-04	3.858E-04	2.336E-04
390-405	24300	1.025E-04	4.076E-04	2.938E-04	6.643E-04	3.961E-04	2.410E-04
405-420	25200	1.062E-04	4.120E-04	3.034E-04	6.649E-04	4.060E-04	2.484E-04
420-435	26100	1.099E-04	4.162E-04	3.129E-04	6.653E-04	4.158E-04	2.556E-04
435-450	27000	1.136E-04	4.200E-04	3.223E-04	6.657E-04	4.253E-04	2.628E-04
450-465	27900	1.174E-04	4.235E-04	3.317E-04	6.660E-04	4.345E-04	2.700E-04
465-480	28800	1.211E-04	4.268E-04	3.409E-04	6.662E-04	4.435E-04	2.771E-04

4.3 Steam Generator Tube Rupture (SGTR)

SGTR does not assume any fuel failure. The evaluation of the radiological doses associated with this event assumes no credit for operator action is taken in the first 30 minutes. In the first 30 minutes, steaming is conservatively assumed to occur only in the ruptured unit. This allows a greater release due to a flashing fraction of primary liquid being released at a DF of 1.0 instead of the normal DF of 100. At 30 minutes into the event, the operator isolates the ruptured unit. Only the unaffected steam generator is then used for the controlled 75 °F/hr cooldown (2 hour event) or 35.5 °F/hr cooldown (8 hour event). A primary to secondary leakage of 0.5 gpm to each generator was modified to 1.0 gpm to the intact unit for the cooldown stage.

A total primary to secondary mass transfer through the rupture of 70,000 lbm was assumed. The mass transfer and flashing fractions were modeled for two intervals. For the first [ ] seconds, a [ ] flashing fraction was applied to a primary mass transfer of [ ] lbm. For the interval from [ ] seconds, a flashing fraction of [ ] was applied to a primary mass transfer of [ ] lbm. Both the flashing fractions and mass transfer totals were considered conservative as they exceeded those calculated in the SGTR Analysis of Record. For the purposes of noble gas release, the 70,000 lbm is equivalent to a 17,640 g/s average leak rate.

A LOAC renders the main condenser unavailable. Thus, the entire cooldown must be performed by dumping steam to the atmosphere from the intact steam generator that is assumed to contain the maximum limit for steam generator activity. This bounds the no LOAC scenario. Since SGTR is not a fuel failure event, iodine spiking was considered.

4.3.1 Offsite Dose

Offsite thyroid dose is given by:

$$D_{Thyroid} = \sum A_I \times BR \times \chi/Q \times DCF_{I\text{-}131}$$

where:

$D_{Thyroid}$	=	Thyroid dose (rem)
A_I	=	Activity of iodine (Ci)
BR	=	Breathing Rate (m^3/s)
χ/Q	=	Atmospheric dispersion (s/m^3)
$DCF_{I\text{-}131}$	=	Dose Conversion Factor of I-131 (rem/Ci)

Offsite whole body dose is given by:

$$D_{WB} = \left[\sum_i A_{I,i} \times DCF(\gamma+\beta)_{I,i} + A_N \times [\gamma+\beta]\right] \times \chi/Q$$

where:

D_{WB}	=	Whole body dose (rem)
$A_{I,i}$	=	Activity of iodine isotope *i* (Ci)
$DCF(\gamma+\beta)_{I,i}$	=	Gamma and Beta Dose Conversion Factor of iodine isotope *i* (rem-m^3/s-Ci)
A_N	=	Activity of noble gas (Ci)
$\gamma+\beta$	=	Gamma and Beta conversion constant
	=	$(0.25 \times E_\gamma) + (0.23 \times E_\beta)$ rem-m^3/s-Ci
χ/Q	=	Atmospheric dispersion (s/m^3)

4.3.1.1 Offsite Thyroid – No Spiking

For activity release from the generator with the rupture, methodology from Section 2.2.22 was used, modified for leakage due to the ruptured SG tube. Activity release from this generator occurs for the first 30 minutes of the transient only through the main steam safety valves (MSSVs). After that, it is isolated by the operator. Steam generator time constants developed in Section 3.1.5 were utilized, corrected for the unaffected SG DF of 100. It is conservatively assumed that the following will occur. The flashing fraction portion of the rupture amount will immediately flash to steam and leave the SG, taking all primary activity with it. The non-flashing portion of the rupture amount will enter the generator and mix with the secondary fluid. Steam release from this unit will have a DF of 100. This is conservative in that it assumes no mixing of the flashing portion, hence no dilution of the activity carried from the primary side.

Assuming [ ] lbm was transferred in the first [ ] seconds and a [ ] flashing fraction, [ ] lbm will immediately flash to steam and escape through the safety valves. At an initial concentration of 1.0 μCi/g:

$$\text{Activity, Flashing (Ci)} = [\quad] \times \frac{453.6\,\text{g}}{\text{lbm}} \times \frac{1.0\,\mu\text{Ci}}{\text{g}}$$

Activity, Flashing = [ ]

Subtracting the [ ] lbm from the rupture amount in the first [ ] seconds leaves a non-flashing mass of [ ]. A new rupture rate was calculated:

[ ]

Assuming [ ] lbm was transferred in the interval from [ ] seconds and a [ ] flashing fraction, [ ] lbm will immediately flash to steam and escape through the safety valves. At an initial concentration of 1.0 μCi/g:

$$\text{Activity, Flashing (Ci)} = [\quad] \times \frac{453.6\,\text{g}}{\text{lbm}} \times \frac{1.0\,\mu\text{Ci}}{\text{g}}$$

Activity, Flashing = [ ]

Subtracting the [ ] lbm from the rupture amount in the second interval leaves a non-flashing mass of [ ]. A new rupture rate was calculated:

[ ]

Adding the activity released over both intervals yields a 30 minute total:

[ ]

Table 4.3-1 charts the non-flashing release from the generator with the tube rupture over the first 30 minutes.

For activity release from the unaffected generator, methodology from Section 2.2.22 was also used. Steam generator time constants developed in Section 3.1.5 were utilized and corrected for the unaffected SG DF of 100. Table 4.3-2 charts the release from the unaffected generator over a 2 hour time span. Table 4.3-3 charts the release from the unaffected generator for the 8 hour event. Note, that since only the affected generator was assumed to steam the plant in the first 30 minutes, dose release from the unaffected SG in the first 30 minutes was ignored in the summation of releases.

Releases from both generators were added. The appropriate breathing rate and χ/Q from Section 2.2.7, and the DCF for I-131 for non-fuel failure from Section 2.2.1 were applied. For EAB dose (2 hour):

EAB $D_{Thyroid}$ = [ ]

EAB $D_{Thyroid}$ = [ ] = 1.4 rem

For LPZ boundary dose (8 hour):

LPZ Boundary $D_{Thyroid}$ = [ ]

LPZ Boundary $D_{Thyroid}$ = [ ] = <0.1 rem

TABLE 4.3-1
Ruptured Tube SG Release, No Iodine Spiking
First 30 Minutes

								[ ]	
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

TABLE 4.3-2
Unaffected SG Release, No Iodine Spiking
2 Hour Event

								[ ]	
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
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TABLE 4.3-3
Unaffected SG Release, No Iodine Spiking
8 Hour Event

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4.3.1.2 Offsite Thyroid – PIS

A similar flashing calculation was performed for a PIS. Using the [ ] flashing fraction for the first [ ] second interval and an initial concentration of 60 μCi/g:

$$\text{Activity, Flashing (Ci)} = \left[\quad \right] \times \frac{453.6\text{ g}}{\text{lbm}} \times \frac{60\ \mu\text{Ci}}{\text{g}}$$

Activity, Flashing = [ ]

Using a [ ] flashing fraction for the second interval and an initial concentration of 60 μCi/g:

$$\text{Activity, Flashing (Ci)} = \left[\quad \right] \times \frac{453.6\text{ g}}{\text{lbm}} \times \frac{60\ \mu\text{Ci}}{\text{g}}$$

Activity, Flashing = [ ]

Adding the activity released over both intervals yields a 30 minute total:

[ ]

Table 4.3-4 charts the non-flashing release from the generator with the tube rupture over the first 30 minutes.

For activity release from the unaffected generator, methodology from Section 2.2.22 was also used. Steam generator time constants developed in Section 3.1.5 were utilized and corrected for the unaffected SG DF of 100. Table 4.3-5 charts the release from the unaffected generator over a 2 hour time span. Table 4.3-6 charts the release from the unaffected generator for the 8 hour event. Note, that since only the affected generator was assumed to steam the plant in the first 30 minutes, dose release from the unaffected SG in the first 30 minutes was ignored in the summation of releases.

Releases from both generators were added. The appropriate breathing rate and χ/Q from Section 2.2.7, and the DCF for I-131 for non-fuel failure from Section 2.2.1 were applied. For EAB dose (2 hour):

EAB $D_{Thyroid}$ = [ ]

EAB $D_{Thyroid}$ = [ ] = 70.0 rem

For LPZ boundary dose (8 hour):

LPZ Boundary $D_{Thyroid}$ = [ ]

LPZ Boundary $D_{Thyroid}$ = [ ] = 3.5 rem

TABLE 4.3-4
Ruptured Tube SG Release, PIS
First 30 Minutes

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[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
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TABLE 4.3-5
Unaffected SG Release, PIS
2 Hour Event

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TABLE 4.3-6
Unaffected SG Release, PIS
8 Hour Event

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4.3.1.3 Offsite Thyroid – GIS

A similar calculation was performed for a GIS. Iodine concentrations vary with time for a GIS. Section 3.5.2 calculated the RCS iodine concentration for 15 minute intervals. To apply these properly, the [ ] second interval was further broken down into [ ] and [ ] segments. The [ ] lbm primary to secondary transfer was also divided into [ ] lbm and [ ] lbm for these intervals. Using a [ ] flashing fraction and a concentration of [ ] for the first [ ] seconds:

$$\text{Activity, Flashing (Ci)} = [\quad] \times \frac{453.6\,\text{g}}{\text{lbm}} \times \frac{1.304\text{E}-05\,\text{Ci}}{\text{g}}$$

Activity, Flashing = [ ]

Using a [ ] flashing fraction for the interval from [ ] seconds and a concentration of 1.304E-05 Ci/g:

Activity, Flashing (Ci) = [ ]

Activity, Flashing = [ ]

Using a [ ] flashing fraction for the interval from [ ] seconds and a concentration of 2.454E-05 Ci/g:

$$\text{Activity, Flashing (Ci)} = [\quad] \times \frac{453.6\,\text{g}}{\text{lbm}} \times \frac{2.454\text{E}-05\,\text{Ci}}{\text{g}}$$

Activity, Flashing = [ ]

Adding the activity released over all intervals yields a 30 minute total:

[ ]

Table 4.3-7 charts the non-flashing release from the generator with the tube rupture over the first 30 minutes.

For activity release from the unaffected generator, methodology from Section 2.2.22 was also used. Steam generator time constants developed in Section 3.1.5 were utilized and corrected for the unaffected SG DF of 100. Table 4.3-8 charts the release from the unaffected generator over a 2 hour time span. Table 4.3-9 charts the release from the unaffected generator for the 8 hour event. Note, that since only the affected generator was assumed to steam the plant in the first 30 minutes, dose release from the unaffected SG in the first 30 minutes was ignored in the summation of releases.

Releases from both generators were added. The appropriate breathing rate and χ/Q from Section 2.2.7, and the DCF for I-131 for non-fuel failure from Section 2.2.1 were applied. For EAB dose (2 hour):

EAB $D_{Thyroid}$ = [ ]

EAB $D_{Thyroid}$ = [ ] = 21.4 rem

For LPZ boundary dose (8 hour):

LPZ Boundary $D_{Thyroid}$ = [ ]

LPZ Boundary $D_{Thyroid}$ = [ ] = 1.2 rem

TABLE 4.3-7
Ruptured Tube SG Release, GIS
First 30 Minutes

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TABLE 4.3-8
Unaffected SG Release, GIS
2 Hour Event

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TABLE 4.3-9
Unaffected SG Release, GIS
8 Hour Event

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4.3.1.4 Offsite Whole Body – No Spiking

Table 4.3-10 shows the breakdown of activity into individual iodine isotopes for a 2 hour event. The breakdown to individual isotopes was handled using the scaling factors from Section 3.5.2. Each isotope was then multiplied by its unique DCF. The sum of these terms is the contribution of whole body dose due to iodine.

TABLE 4.3-10
Iodine Activity Distribution for a 2 Hour Event
No Iodine Spiking

[ ]	[ ]	[ ]				
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Table 4.3-11 shows the breakdown of activity into individual iodine isotopes for an 8 hour event. The breakdown to individual isotopes was handled using the scaling factors from Section 3.5.2. Each isotope was then multiplied by its unique DCF. The sum of these terms is the contribution of whole body dose due to iodine.

TABLE 4.3-11
Iodine Activity Distribution for an 8 Hour Event
No Iodine Spiking

[ ]	[ ]	[ ]				
		[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
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[ ]						

Noble gas contribution for cases with no fuel failure was found by taking the initial steady state RCS noble gas activity released over the course of 2 hours through 2 SGs, accounting for the rupture in the first 30 minutes, and applying the $\gamma+\beta$ factor.

For 0-30 minutes:

[ ]

[ ]

[ ]

For 30-120 minutes:

[ ]

[ ]

[ ]

For 2-8 hours:

[ ]

[ ]

[ ]

For the EAB dose (2 hour event):

EAB D_{WB} = [ ]

EAB D_{WB} = [ ] = 0.6 rem

For the LPZ boundary dose (8 hour event):

LPZ Boundary D_{WB} = [ ]

LPZ Boundary D_{WB} = [ ] = <0.1 rem

4.3.1.5 Offsite Whole Body – PIS

Table 4.3-12 shows the breakdown of activity into individual iodine isotopes for a 2 hour event. The breakdown to individual isotopes was handled using the scaling factors from Section 3.5.2. Each isotope was then multiplied by its unique DCF. The sum of these terms is the contribution of whole body dose due to iodine.

TABLE 4.3-12
Iodine Activity Distribution for a 2 Hour Event
PIS

		[ ]				
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
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Table 4.3-13 shows the breakdown of activity into individual iodine isotopes for an 8 hour event. The breakdown to individual isotopes was handled using the scaling factors from Section 3.5.2. Each isotope was then multiplied by its unique DCF. The sum of these terms is the contribution of whole body dose due to iodine.

TABLE 4.3-13
Iodine Activity Distribution for an 8 Hour Event
PIS

		[ ]				
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
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Noble gas contributions are identical to those calculated for the no iodine spiking case.

For the EAB dose (2 hour event):

EAB D_{WB} = [ ]

EAB D_{WB} = [ ] = 0.9 rem

For the LPZ boundary dose (8 hour event):

LPZ Boundary D_{WB} [ ]

LPZ Boundary D_{WB} = [ ] = <0.1 rem

4.3.1.6 Offsite Whole Body – GIS

Table 4.3-14 shows the breakdown of activity into individual iodine isotopes for a 2 hour event. The breakdown to individual isotopes was handled using the scaling factors from Section 3.5.2. Each isotope was then multiplied by its unique DCF. The sum of these terms is the contribution of whole body dose due to iodine.

TABLE 4.3-14
Iodine Activity Distribution for a 2 Hour Event
GIS

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Table 4.3-15 shows the breakdown of activity into individual iodine isotopes for an 8 hour event. The breakdown to individual isotopes was handled using the scaling factors from Section 3.5.2. Each isotope was then multiplied by its unique DCF. The sum of these terms is the contribution of whole body dose due to iodine.

TABLE 4.3-15
Iodine Activity Distribution for an 8 Hour Event
GIS

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Noble gas contributions are identical to those calculated for the no iodine spiking case.

For the EAB dose (2 hour event):

EAB D_{WB} = [ ]

EAB D_{WB} = [ ]= 0.7 rem

For the LPZ boundary dose (8 hour event):

LPZ Boundary D_{WB} = [ ]

LPZ Boundary D_{WB} = [ ] = <0.1 rem

4.3.2 Control Room Doses

Control Room thyroid dose is given by:

$$D_{Thyroid} = \sum A_I \times BR \times \chi/Q \times DCF_{I\text{-}131} \times 1/IPF$$

where:

$D_{Thyroid}$	=	Thyroid dose (rem)
A_I	=	Activity of iodine (Ci)
BR	=	Breathing Rate (m^3/s)
χ/Q	=	Atmospheric dispersion (s/m^3)
$DCF_{I\text{-}131}$	=	Dose Conversion Factor of I-131 (rem/Ci)
IPF	=	Iodine Protection Factor (144)

Control Room whole body dose is given by:

$$D_{WB} = \left[\frac{1}{IPF} \times \frac{1}{GF} \times \sum_i A_{I,i} \times DCF(\gamma)_{I,i} + \frac{1}{GF} \times A_N \times \gamma \right] \times \chi/Q$$

where:

D_{WB}	=	Whole body dose (rem)
IPF	=	Iodine Protection Factor (144)
GF	=	Geometry Factor (32.24)
$A_{I,i}$	=	Activity of iodine isotope *i* (Ci)
$DCF(\gamma)_{I,i}$	=	Dose Conversion Factor of iodine isotope *i* (rem-m^3/s-Ci)
A_N	=	Activity of noble gas (Ci)
γ	=	Gamma conversion constant
	=	$(0.25 \times E_\gamma)$ rem-m^3/s-Ci
χ/Q	=	Atmospheric dispersion (s/m^3)

Control Room skin dose is given by:

$$D_{Skin} = \left[\frac{1}{IPF} \times \sum_i \left[A_{I,i} \left[\frac{DCF(\gamma)_{I,i}}{GF} + DCF(\beta)_{I,i} \right] \right] + A_N \left[\frac{\gamma}{GF} + \beta \right] \right] \times \chi/Q$$

where:

D_{Skin}	=	Skin dose (rem)
IPF	=	Iodine Protection Factor (144)
$A_{I,i}$	=	Activity of iodine isotope *i* (Ci)
$DCF(\gamma)_{I,i}$	=	Gamma Dose Conversion Factor of iodine isotope *i* (rem-m^3/s-Ci)
$DCF(\beta)_{I,i}$	=	Beta Dose Conversion Factor of iodine isotope *i* (rem-m^3/s-Ci)
GF	=	Geometry Factor (32.24)
A_N	=	Activity of noble gas (Ci)
γ	=	Gamma conversion constant
	=	$(0.25 \times E_\gamma)$ rem-m^3/s-Ci
β	=	Beta conversion constant
	=	$(0.23 \times E_\beta)$ rem-m^3/s-Ci
χ/Q	=	Atmospheric dispersion (s/m^3)

4.3.2.1 Control Room Thyroid – No Spiking

The flashing and affected SG releases were assumed through the MSSVs in the first 30 minutes. The releases from the unaffected SG were broken down into 30-120 minutes and 2-8 hours for the purposes of applying the correct atmospheric dispersion factors:

Control Room $D_{Thyroid}$ = [ ]

Control Room $D_{Thyroid}$ = [ ] = 0.7 rem

4.3.2.2 Control Room Whole Body – No Spiking

For iodine contribution, Table 4.3-16 follows identical methodology used in Table 4.3-11. Only gamma DCFs are applied, however.

TABLE 4.3-16
Iodine Activity Distribution for the Control Room
No Iodine Spiking

				[ ]		
[ ]	**[ ]**	**[ ]**	**[ ]**	**[ ]**	**[ ]**	**[ ]**
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
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[ ]		[ ]	[ ]	[ ]	[ ]	[ ]
[ ]		[ ]	[ ]	[ ]	[ ]	[ ]
			[ ]			

Noble gas contribution for cases with no fuel failure was found by taking the initial steady state RCS noble gas activity released over the course of 8 hours through 2 SGs, accounting for the rupture, and applying the γ factor. It was necessary to break the 8 hour event into 0-30 minute, 30-120 minute, and 2-8 hour segments, to account for the different release paths of each SG and to facilitate using multiple atmospheric dispersion factors:

For 0-30 minutes:

[ ]

For 30-120 minutes:

[ ]

For 2-8 hours:

[ ]

The iodine releases were assumed at the most adverse atmospheric dispersion factor for convenience:

Control Room D_{WB} = [ ]

Control Room D_{WB} = [ ] = 0.7 rem

4.3.2.3 Control Room Skin – No Spiking

For iodine contribution, Table 4.3-17 follows identical methodology used in Table 4.3-11. However, the Geometry Factor is applied to the gamma DCF before it is added to the beta DCF.

TABLE 4.3-17
Iodine Activity Distribution for the Control Room
No Iodine Spiking

		[ ]				
[ ]	**[ ]**	**[ ]**	**[ ]**	**[ ]**	**[ ]**	**[ ]**
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
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[ ]		[ ]	[ ]	[ ]	[ ]	[ ]
[ ]		[ ]	[ ]	[ ]	[ ]	[ ]
[ ]						

Noble gas contribution for cases with no fuel failure was found by taking the initial steady state RCS noble gas activity released over the course of 8 hours through 2 SGs, accounting for the rupture, and applying the γ/GF+β factor. It was necessary to break the 8 hour event into 0-30 minute, 30-120 minute, and 2-8 hour segments, to account for the different release paths of each SG and to facilitate using multiple atmospheric dispersion factors.

For 0-30 minutes:

[ ]

For 30-120 minutes:

[ ]

For 2-8 hours:

[ ]

The iodine releases were assumed at the most adverse atmospheric dispersion factor for convenience:

Control Room D_{Skin} = [ ]

Control Room D_{Skin} = [ ] = 14.8 rem

4.3.2.4 Control Room Thyroid – PIS

The flashing and affected SG releases were assumed through the MSSVs in the first 30 minutes. The releases from the unaffected SG were broken down into 30-120 minutes and 2-8 hours for the purposes of applying the correct atmospheric dispersion factors:

Control Room $D_{Thyroid}$ = [ ]

Control Room $D_{Thyroid}$ = [ ] = 29.8 rem

4.3.2.5 Control Room Whole Body – PIS

For iodine contribution, Table 4.3-18 follows identical methodology used in Table 4.3-13. Only gamma DCFs were applied, however.

TABLE 4.3-18
Iodine Activity Distribution for the Control Room
PIS

				[ ]		
[ ]	**[ ]**	**[ ]**	**[ ]**	**[ ]**	**[ ]**	**[ ]**
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]		[ ]	[ ]	[ ]	[ ]	[ ]
[ ]		[ ]	[ ]	[ ]	[ ]	[ ]
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			[ ]			

Noble gas contributions are identical to those calculated for the no iodine spiking case. The iodine releases were assumed at the most adverse atmospheric dispersion factor for convenience:

Control Room D_{WB} = [ ]

Control Room D_{WB} = [ ] = 0.7 rem

4.3.2.6 Control Room Skin – PIS

For iodine contribution, Table 4.3-19 follows identical methodology used in Table 4.3-13. However, the Geometry Factor was applied to the gamma DCF before it was added to the beta DCF.

TABLE 4.3-19
Iodine Activity Distribution for the Control Room
PIS

		[ ]				
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
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[ ]		[ ]	[ ]	[ ]	[ ]	[ ]
[ ]						

Noble gas contributions are identical to those calculated for the no iodine spiking case. The iodine releases were assumed at the most adverse atmospheric dispersion factor for convenience:

Control Room D_{Skin} = [ ]

Control Room D_{Skin} = [ ] = 14.8 rem

4.3.2.7 Control Room Thyroid – GIS

The flashing and affected SG releases were assumed through the MSSVs in the first 30 minutes. The releases from the unaffected SG were broken down into 30-120 minutes and 2-8 hours for the purposes of applying the correct atmospheric dispersion factors:

Control Room $D_{Thyroid}$ = [ ]

Control Room $D_{Thyroid}$ = [ ] = 9.8 rem

4.3.2.8 Control Room Whole Body – GIS

For iodine contribution, Table 4.3-20 follows identical methodology used in Table 4.3-15. Only gamma DCFs were applied, however.

TABLE 4.3-20
Iodine Activity Distribution for the Control Room
GIS

		[ ]				
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
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Noble gas contributions are identical to those calculated for the no iodine spiking case. The iodine releases were assumed at the most adverse atmospheric dispersion factor for convenience:

Control Room D_{WB} = [ ]

Control Room D_{WB} = [ ] = 0.7 rem

4.3.2.9 Control Room Skin – GIS

For iodine contribution, Table 4.3-21 follows identical methodology used in Table 4.3-15. However, the Geometry Factor was applied to the gamma DCF before it was added to the beta DCF.

TABLE 4.3-21
Iodine Activity Distribution for the Control Room
GIS

		[ ]				
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
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[ ]						

Noble gas contributions are identical to those calculated for the no iodine spiking case. The iodine releases were assumed at the most adverse atmospheric dispersion factor for convenience:

Control Room D_{Skin} = [ ]

Control Room D_{Skin} = [ ] = 14.8 rem

4.5 CEA Ejection

CEA Ejection is a fuel failure event for ANO-2. No credit for operator action is taken and the primary to secondary leakage of 0.105 gpm continues throughout the 2 and 8 hour event period. It is assumed that the operator does not begin to cooldown the plant until 30 minutes after event initiation, at which point both steam generators are then used for the controlled 75 °F/hr cooldown (2 hour event) or 35.5 °F/hr cooldown (8 hour event).

A LOAC renders the main condenser unavailable. Thus, the entire cooldown must be performed by dumping steam to the atmosphere from the steam generators that are assumed to contain the maximum limit for steam generator activity. Fuel failure may occur by either Clad Damage Threshold (CDT) [200 cal/gram total average enthalpy] or CLM for this event. Since CEA Ejection is a fuel failure event for ANO-2, iodine spiking was not considered.

4.5.1 Offsite Dose

Offsite thyroid dose is given by:

$$D_{Thyroid} = \sum A_I \times BR \times \chi/Q \times DCF_{I-131}$$

where:

- $D_{Thyroid}$ = Thyroid dose (rem)
- A_I = Activity of iodine (Ci)
- BR = Breathing Rate (m^3/s)
- χ/Q = Atmospheric dispersion (s/m^3)
- DCF_{I-131} = Dose Conversion Factor of I-131 (rem/Ci)

Offsite whole body dose is given by:

$$D_{WB} = \left[\sum_i A_{I,i} \times DCF(\gamma)_{I,i} + \sum_j A_{N,j} \times DCF(\gamma)_{N,j} \right] \times \chi/Q$$

where:

- D_{WB} = Whole body dose (rem)
- $A_{I,i}$ = Activity of iodine isotope *i* (Ci)
- $DCF(\gamma)_{I,i}$ = Gamma Dose Conversion Factor of iodine isotope *i* (rem-m^3/s-Ci)
- $A_{N,j}$ = Activity of noble gas isotope *j* (Ci)
- $DCF(\gamma)_{I,i}$ = Gamma Dose Conversion Factor of noble gas isotope *j* (rem-m^3/s-Ci)
- χ/Q = Atmospheric dispersion (s/m^3)

4.5.1.1 Offsite Thyroid

For activity release from the generators, methodology from Section 2.2.22 was used. Steam generator time constants developed in Section 3.1.5 were utilized, corrected for the unaffected SG DF of 100 and divided by two to account for the use of both SGs to steam the plant. As dose consequences were calculated as a function of fuel failure, RCS iodine concentrations from Section 3.3.3 were also used in the leakage term.

Release from one generator was doubled. Tables 4.5-1 and 4.5-2 apply the appropriate breathing rate and χ/Q from Section 2.2.7, and the DCF for I-131 for fuel failure from Section 2.2.1 for CDT and CLM fuel failures, respectively. An example calculation is performed below for 0.5% fuel failed (CDT) to illustrate how the tables were calculated.

For EAB dose (2 hour):

EAB $D_{Thyroid}$ = [ ]

EAB $D_{Thyroid}$ = [ ]

For LPZ boundary dose (8 hour):

LPZ Boundary $D_{Thyroid}$ = [ ]

LPZ Boundary $D_{Thyroid}$ = [ ]

TABLE 4.5-1
Steam Generator Release and Thyroid Dose
Clad Damage Threshold (CDT) Criteria

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TABLE 4.5-2
Steam Generator Release and Thyroid Dose
CLM Criteria

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4.5.1.2 Offsite Whole Body

Tables 4.5-3 and 4.5-4 were generated to calculate offsite whole body dose as a function of CDT and CLM fuel failure due to steaming two SGs. As dose consequences were calculated as a function of fuel failure, noble gas concentrations from Section 3.4.2 were used.

For a fuel failure event, the noble gas release is 10,000 times greater than the iodine release. Since the calculation of whole body dose due to iodine is similar to that of noble gases, the whole body dose due to iodine is negligible when compared to that due to noble gases. Hence, they were neglected in the dose calculation.

Dose was found by taking the taking the RCS noble gas activity for each isotope for that fraction of failed fuel and applying the individual gamma DCF. A release over the course of the event through 2 SGs was calculated. The appropriate χ/Q from Section 2.2.7 was then applied. An example calculation is performed below for 0.5% fuel failed (CDT) to illustrate how the tables were calculated.

$$\sum_j A_{N,j} \times DCF(\gamma)_{N,j} \left[\qquad \right]$$

For EAB dose (2 hour):

EAB D_{WB} = [ ]

EAB D_{WB} = [ ]

For LPZ boundary dose (8 hour):

LPZ Boundary D_{WB} = [ ]

LPZ Boundary D_{WB} = [ ]

TABLE 4.5-3
Whole Body Dose
Clad Damage Threshold (CDT) Criteria

		[ ]	
[ ]	[ ]	[ ]	[ ]
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TABLE 4.5-4
Whole Body Dose
CLM Criteria

Fraction of Pins Failed	$\Sigma A_N \times DCF_N$ (rem-m^3/s) Whole Body	Whole Body Dose (rem)	
		EAB	LPZ
0.005	539,884	0.18	0.03
0.010	1,079,767	0.36	0.07
0.015	1,619,651	0.53	0.10
0.020	2,159,534	0.71	0.14
0.025	2,699,418	0.89	0.17
0.030	3,239,301	1.07	0.20
0.035	3,779,185	1.25	0.24
0.040	4,319,068	1.43	0.27
0.045	4,858,952	1.60	0.31
0.050	5,398,835	1.78	0.34
0.055	5,938,719	1.96	0.37
0.060	6,478,602	2.14	0.41
0.065	7,018,486	2.32	0.44
0.070	7,558,369	2.50	0.48
0.075	8,098,253	2.67	0.51
0.080	8,638,136	2.85	0.54
0.085	9,178,020	3.03	0.58
0.090	9,717,903	3.21	0.61
0.095	10,257,787	3.39	0.65
0.100	10,797,670	3.56	0.68
0.105	11,337,554	3.74	0.71
0.110	11,877,437	3.92	0.75
0.115	12,417,321	4.10	0.78
0.120	12,957,204	4.28	0.82
0.125	13,497,088	4.46	0.85
0.130	14,036,971	4.63	0.88
0.135	14,576,855	4.81	0.92
0.140	15,116,738	4.99	0.95
0.145	15,656,622	5.17	0.99
0.150	16,196,505	5.35	1.02

4.5.2 Control Room Doses

Control Room thyroid dose is given by:

$$D_{Thyroid} = \sum A_I \times BR \times \chi/Q \times DCF_{I\text{-}131} \times 1/IPF$$

where:

$D_{Thyroid}$	=	Thyroid dose (rem)
A_I	=	Activity of iodine (Ci)
BR	=	Breathing Rate (m^3/s)
χ/Q	=	Atmospheric dispersion (s/m^3)
$DCF_{I\text{-}131}$	=	Dose Conversion Factor of I-131 (rem/Ci)
IPF	=	Iodine Protection Factor (144)

Control Room whole body dose is given by:

$$D_{WB} = \left[\frac{1}{IPF} \times \frac{1}{GF} \times \sum_i A_{I,i} \times DCF(\gamma)_{I,i} + \frac{1}{GF} \times \sum_j A_{N,j} \times DCF(\gamma)_{N,j}\right] \times \chi/Q$$

where:

D_{WB}	=	Whole body dose (rem)
IPF	=	Iodine Protection Factor (144)
GF	=	Geometry Factor (32.24)
$A_{I,i}$	=	Activity of iodine isotope i (Ci)
$DCF(\gamma)_{I,i}$	=	Dose Conversion Factor of iodine isotope i (rem-m^3/s-Ci)
$A_{N,j}$	=	Activity of noble gas isotope j (Ci)
$DCF(\gamma)_{I,i}$	=	Gamma Dose Conversion Factor of noble gas isotope j (rem-m^3/s-Ci)
χ/Q	=	Atmospheric dispersion (s/m^3)

Control Room skin dose is given by:

$$D_{Skin} = \left[\frac{1}{IPF} \times \sum_i \left[A_{I,i}\left[\frac{DCF(\gamma)_{I,i}}{GF} + DCF(\beta)_{I,i}\right]\right] + \sum_j \left[A_{N,j}\left[\frac{DCF(\gamma)_{N,j}}{GF} + DCF(\beta)_{N,j}\right]\right]\right] \times \chi/Q$$

where:

D_{Skin}	=	Skin dose (rem)
IPF	=	Iodine Protection Factor (144)
$A_{I,i}$	=	Activity of iodine isotope i (Ci)
$DCF(\gamma)_{I,i}$	=	Gamma Dose Conversion Factor of iodine isotope i (rem-m^3/s-Ci)
$DCF(\beta)_{I,i}$	=	Beta Dose Conversion Factor of iodine isotope i (rem-m^3/s-Ci)
GF	=	Geometry Factor (32.24)
$A_{N,j}$	=	Activity of noble gas isotope j (Ci)
$DCF(\gamma)_{N,j}$	=	Gamma Dose Conversion Factor of noble gas isotope j (rem-m^3/s-Ci)
$DCF(\beta)_{N,j}$	=	Beta Dose Conversion Factor of noble gas isotope j (rem-m^3/s-Ci)
χ/Q	=	Atmospheric dispersion (s/m^3)

4.5.2.1 Control Room Thyroid

The 8 hour event releases were broken down into 0-2 and 2-8 hour releases so an appropriate χ/Q could be applied. Table 4.5-5 lists the release from one generator versus fraction of failed fuel for 0-2 and 2-8 hours and the thyroid dose consequence under CDT criteria. Table 4.5-6 lists the release from one generator versus fraction of failed fuel for 0-2 and 2-8 hours and the thyroid dose consequence under CLM criteria. It can be seen that these releases add to the 8 hour event release listed in Tables 4.5-1 and 4.5-2. It was conservatively assumed that all releases were via the ADVs. An example calculation is performed below for 0.5% fuel failed (CDT) to illustrate how the tables were calculated.

Control Room $D_{Thyroid}$ = [ ]

Control Room $D_{Thyroid}$ = [ ]

TABLE 4.5-5
Control Room Thyroid Dose
Clad Damage Threshold (CDT) Criteria

	[ ]		
[ ]	**[ ]**	**[ ]**	**[ ]**
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TABLE 4.5-6
Control Room Thyroid Dose
CLM Criteria

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4.5.2.2 Control Room Whole Body

Tables 4.5-7 and 4.5-8 were generated to calculate Control Room whole body dose as a function of CDT and CLM fuel failure due to steaming two SGs. As dose consequences were calculated as a function of fuel failure, noble gas concentrations from Section 3.4.2 were used.

For a fuel failure event, the noble gas release is 10,000 times greater than the iodine release. Since the calculation of whole body dose due to iodine is similar to that of noble gases, the whole body dose due to iodine is negligible when compared to that due to noble gases. Hence, they were neglected in the dose calculation.

Dose was found by taking the taking the RCS noble gas activity for each isotope for that fraction of failed fuel and applying the individual gamma DCF. A release over the course of the event through 2 SGs was calculated. Unique atmospheric dispersion factors were applied to the 0-2 hour and 2-8 hour portions of the event. It was conservatively assumed that all release was via the ADVs. An example calculation is performed below for 0.5% fuel failed (CDT) to illustrate how the tables were calculated.

$$\sum_{J} A_{N,J} \times DCF(\gamma)_{N,J} \left[\qquad \right]$$

Control Room D_{WB} = [ ]

Control Room D_{WB} = [ ]

4.5.2.3 Control Room Skin

Skin doses were calculated in the same manner as whole body doses. The only difference was that the DCF for skin doses contain both gamma and beta factors. The Geometry Factor was only applied to the gamma DCF portion. Tables 4.5-7 and 4.5-8 includes skin doses as a function of CDT and CLM fuel failure due to steaming two SGs. Iodines were neglected in these calculations for the same reasons listed above. An example calculation is performed below for 0.5% fuel failed (CDT) to illustrate how the tables were calculated.

$\sum_j A_{N,j} \times DCF(\gamma)_{N,j}$ [ ]

Control Room D_{Skin} = [ ]

Control Room D_{Skin} = [ ]

TABLE 4.5-7
Control Room Whole Body and Skin Dose
Clad Damage Threshold (CDT) Criteria

	[ ]		[ ]	
[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]
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TABLE 4.5-8
Control Room Whole Body and Skin Dose
CLM Criteria

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