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1. PURPOSE

The purpose of this calculation is to determine the quantity and significance of annual Monitored Geologic Repository (MGR) subsurface normal radiological releases due to neutron activation of air and silica dust in emplacement drifts.

This calculation includes the following items:

- Calculate activation of ventilation airflow through emplacement drifts to quantify radioactive gaseous releases
- Calculate the bounding potential activated silica dust concentration and releases. The sources of silica dust may arise from air supply to emplacement drifts as well as host rock around emplacement drifts. For this calculation, the source of dust is conservatively assumed to be the host rock (Assumption 3.6), which is subject to long-term neutron exposure resulting in saturated radioactivity.

The scope of this calculation is limited to releases from activated air and silica dust only, excluding natural radioactive releases such as radon or releases from defective waste packages (breached or contaminated).

This work supports the repository ventilation system design and Preclosure Safety Analysis. This includes MGR items classified as Quality Level 1, for example, the Uncanistered Spent Nuclear Fuel Waste Package (CRWMS M&O [Civilian Radioactive Waste Management and Operation Contractor] 1999a, page 7). Therefore, this calculation is subject to the requirements of the *Quality Assurance Requirements and Description* (DOE [U.S. Department of Energy] 2003). The performance of the calculation and development of this document are carried out in accordance with AP-3.12Q, *Design Calculation and Analyses* and LP-3.30Q-BSC, *Hazards Analysis System*.

2. METHOD

The quantity of radioactive species produced by neutron activation depends on the neutron intensity, irradiation time, and neutron interaction cross sections of the target nuclides. For activation of air by neutrons emitted from the spent nuclear fuel (SNF) in the emplacement drifts, the irradiation time depends on the air ventilation rate. A lower air ventilation rate will result in a longer residence time for a volume of air moving through the emplacement drifts, and consequently more activation for a given volume of air. For the host rock, the irradiation time is much longer than the half-life for each activation product, and is also independent of the ventilation rate. The maximum possible (saturation) activity is assumed for activated silica dust concentrations from the host rock, based on a maximum dust emission of less than 250 tons per year (Assumption 3.7) to surface atmosphere.

The 21-PWR waste package containing average SNF assemblies is assumed to represent the average radiation environment in the emplacement drifts (Assumption 3.1). Line loading of waste packages in the emplacement drifts is used in the calculation (Assumption 3.4). The

MCNP Monte Carlo transport code (Briesmeister 1977) is employed to obtain the reaction rates for the various target elements in air and host rock. The reaction rate for each element is then used in the activation analysis, which takes account of the irradiation time in an emplacement drift and decay time during air exhaust through the exhaust main drift and exhaust shaft.

10 CFR 20.1101(d) requires the implementation of the ALARA [as low as is reasonably achievable] requirements of § 20.1101(b) by establishing a constraint on air emissions of radioactive material to the environment, excluding radon-222 and its daughters. The resulting activity concentrations determined in this calculation are compared with 20% of the values in Column 1 of Table 2 in Appendix B of 10 CFR Part 20, consistent with the screening method in Regulatory Guide 4.20 (Section 2.2).

3. ASSUMPTIONS

- 3.1 The 21-PWR waste package loaded with average SNF is assumed to represent the average radiation environment of the emplacement drifts. This assumption is based on comparison of the total dose rates on the surfaces of the various waste package types, which indicates that the 21-PWR waste package has the highest gamma and neutron dose rates (BSC [Bechtel SAIC Company] 2001a, p. 41 and BSC 2001b, p. 37). Therefore, this assumption results in higher (more conservative) neutron activation in an average emplacement drift. This assumption is used in Sections 2 and 5.
- 3.2 It is assumed that the chemical composition of the SNF is the same as that of the unirradiated fuel. The rationale for this assumption is that using unirradiated fuel results in higher (more conservative) neutron activation because more fission occurs in the fuel zone. This assumption is used in Section 5.3.2.
- 3.3 It is assumed that the materials and the radiation sources of the fuel region is homogenized and fill the waste package cavity volume. The radius of the source region is 69.7 cm, which is the inner radius of the cavity, 71.2 cm, minus 1.5 cm for the fuel basket tubes and basket corer guides. The effect of source homogenization is twofold: it decreases the density of the source region and places the source points closer to the outside of the waste package, hence, decreasing radiation attenuation. Also, previous results indicate that the radial surface gamma and neutron dose rates for a 21-PWR waste package with this homogenized source geometry are higher or comparable to those with explicit fuel region model (CRWMS M&O 1998c, Section 6). The rationale for this simplified representation of the fuel regions is that it generates maximum activation. This assumption is used in Section 5.3.2.
- 3.4 Line loading of waste packages in emplacement drifts is assumed. The rationale for this assumption is that line loading provides maximum activation. This assumption is used in Sections 2 and 5.
- 3.5 It is assumed that the emplacement drift airway area equals the maximum excavated cross-sectional area. The rationale for this assumption is that it results in maximum activation. This assumption is used in Section 5.4.1.

- 3.6 It is assumed that the origin of silica dust is produced homogeneously from the host rock throughout emplacement drift walls. This is the total amount of dust considered in this calculation. The rationale of this assumption is that the rock receives maximum neutron exposure with respect to spatial position and time. Therefore, this assumption gives maximum activation of dust and results in maximum radioactive dust production. This assumption is used in Sections 1 and 5.
- 3.7 It is assumed that the maximum total dust emission to surface atmosphere is less than metric 250 tons/yr. The rationale for this assumption is that this emission rate stays within the limit specified in the US Environmental Protection Agency (EPA) 40 CFR 51.166(1)(i)(b). Dust generation is normally expected from the construction side where no activation will occur. Using this emission rate for the emplacement drifts is conservative. This assumption is used in Sections 2, 5.3.3, and 5.7.2.
- 3.8 It is assumed that the maximum exhaust air velocity from any exhaust shaft is 10.2 m/s. The rationale for this assumption is that this value was used in CRWMS M&O 1999b (p. 13) and it represents the maximum velocity recommended by the ventilation industry. This assumption is used in Section 5.4.2.
- 3.9 It is assumed that mass of uranium oxide in a PWR fuel pin equals 2.53105 kg (DOE 1988, p. 2A-34). The rationale for this assumption is that this mass is used to compute the atom density of oxygen in the active fuel region. Since unirradiated fuel (Assumption 3.2) is used to fill the entire cavity of the waste package (Assumption 3.3), higher neutron activation rate will occur. This assumption is used in Section 5.3.2.
- 3.10 The majority of the emplacement exhaust airflow is coming from various emplacement drifts far away from the bottom of the exhaust shafts. For the purpose of computing the decay time of the activated products, it is assumed that the traverse time from various emplacement drifts to the bottom of the exhaust shafts is negligible and the decay time is determined from the minimum exhaust shaft height. The rationale for this assumption is that this assumption yields the smallest decay time and provides the highest activated products emission. This assumption is used in Sections 5.4.2 and 6.1.
- 3.11 The representative chemical composition of the host rock (tuff) is assumed to be that in CRWMS M&O 1997 (p. 17). The rationale for this assumption is that the composition and density of tuff are used to compute the atom densities of the elements composing the tuff. The host rock reflects and slows down neutrons and at the same time is activated by thermal neutrons. Since the composition is mainly silicon oxide, the concentration of the activated isotopes in the silicon dust from the host rock is sensitive to the density of the tuff and not to the exact composition of the tuff. This assumption is used in Section 5.3.

4. USE OF COMPUTER SOFTWARE AND MODELS

4.1 SOFTWARE APPROVED FOR QA WORK

The MCNP code (CRWMS M&O 1998b) is used to calculate the reaction rates for the various target elements of interest. The software specifications are as follows:

- Program Name: MCNP
- Version/Revision Number: Version 4B2LV
- Status/Operating System: Qualified/HP-UX B.10.20
- Computer Software Configuration Item Number: 30033 V4B2LV
- Computer Type: HP 9000 Series Workstations
- CPU Number: 700887

The MCNP software used was: (a) appropriate for the fixed source calculations, (b) used only within the range of validation as documented throughout in Briesmeister and CRWMS M&O 1998a, and (c) obtained from Software Configuration Management in accordance with appropriate procedures

The input and output files for the various MCNP calculations are contained on a compact disc which is Attachment II of this calculation.

4.2 EXEMPT SOFTWARE

In addition to the qualified software described in Section 4.1, the following computational support software is used for spreadsheets:

- Software title: Excel
- Version/revision number: Microsoft Excel 97

The Excel spreadsheet program was used to perform simple numeric calculations as documented in Section 5.7 of this calculation. The user-defined formulas, input, and results are provided in sufficient detail in Section 5.7 to allow independent verification of the various computations without recourse to the originator. This software is considered exempt from the requirements of AP-SI.1Q, *Software Management* (Section 2.1.6).

5. CALCULATIONS

5.1 THE 21-PWR WASTE PACKAGE

The 21-PWR waste package consists of an inner vessel made of stainless steel, an outer barrier, inner lids, outer lids, and a basket assembly (BSC 2003c, Attachment I). The 21-PWR waste package contains 21 representative PWR SNF assemblies with average characteristics. The representative PWR SNF assembly is a Babcock & Wilcox (B&W) 15x15 Mark B assembly, and the average SNF characteristics are: 4.0% initial U-235 enrichment, 48 gigawatt-days per metric ton uranium (GWD/MTU) burnup, and 25 years cooling time (BSC 2003a, p. 23). The geometry and material specifications of the waste package are presented in Table 5-1

Table 5-1. Geometry and Material Specifications for the 21-PWR Waste Package

Component	Material	Characteristic	Dimension (mm)
Inner vessel	SA-240 S31600	Thickness	50
Outer barrier	SB-575 N06022	Thickness	20
Cavity	Void	Inner diameter	1,424
Basket A-sideguide	SA-516 K02700	Thickness	10
Basket B-sideguide	SA-516 K02700	Thickness	10
Basket corner guide	SA-516 K02700	Thickness	10
Fuel basket tube	SA-516 K02700	Thickness	5
		Inner transverse dimension	226.4
Assemblies	N/A	Number	21

SOURCE: BSC 2003c, Attachment I.

5.2 NEUTRON SOURCE OF THE AVERAGE PWR SNF

The neutron source for the average PWR SNF is obtained from BSC (2003a, Attachment X, File: CD3/Waste.Stream.E5.R1.B9.cut). The neutron source intensity and the normalized spectrum per assembly are listed in Table 5-2.

Table 5-2. Neutron Source Spectrum

Neutron Energy Range (MeV)	Intensity (n/s)	Normalized Spectrum
6.43 – 20.0	3.65E+06	0.0183
3.00 – 6.43	4.18E+07	0.2097
1.85 – 3.00	4.69E+07	0.2353
1.40 – 1.85	2.61E+07	0.1309
0.90 – 1.40	3.52E+07	0.1766
0.40 – 0.90	3.82E+07	0.1916
0.10 – 0.40	7.48E+06	0.0375
0.00 – 0.10	0.00E+00	0.0
Total	1.99E+08	1.0

5.3 MATERIAL COMPOSITION

This calculation uses either elemental/isotopic compositions, in weight percent (wt%) or in atom densities, $\left(\frac{\text{atoms}}{\text{b} \cdot \text{cm}}\right)$, of the materials composing the waste package and emplacement drift. Table

5-3 presents the chemical compositions and densities of the waste package components, the drift wall, and air in the emplacement drifts. The source of information for each material is noted in the table. The atom densities of the components of each material are determined, based on the densities and weight percents in Table 5-3, in the section immediately follows.

Table 5-3. Material Compositions of Waste Package and Emplacement Drift

Design Component	Drift Interior	Host Rock	WP Basket	WP Inner Shell	WP Outer Shell
Material	Dry Air ^a	Tuff ^c	SA-516 K02700 ^e	SA-240 S31600 ^g	SB-575 N06022 ⁱ
Density (g/cm ³)	0.001205 ^b	2.0434 ^d	7.85 ^f	7.98 ^h	8.69
Element	Elemental Composition (wt%)				
H	N/A	N/A	N/A	N/A	N/A
C	0.014	N/A	0.27	0.08	0.015
N	75.521	N/A	N/A	0.1	N/A
O	23.177	49.226	N/A	N/A	N/A
Na	N/A	2.665	N/A	N/A	N/A
Mg	N/A	0.151	N/A	N/A	N/A
Al	N/A	6.747	N/A	N/A	N/A
Si	N/A	35.938	0.275	0.75	0.08
P	N/A	0.009	0.035	0.045	0.02
S	N/A	N/A	0.035	0.03	0.02
K	N/A	4.096	N/A	N/A	N/A
Ca	N/A	0.401	N/A	N/A	N/A
Ti	N/A	0.060	N/A	N/A	N/A
Mn	N/A	0.054	1.025	2.00	0.5
V	N/A	N/A	N/A	N/A	0.35
Cr	N/A	N/A	N/A	17	21.25
Fe	N/A	0.653	98.36	65.495	4
Co	N/A	N/A	N/A	N/A	2.5
Ni	N/A	N/A	N/A	12	54.765
Mo	N/A	N/A	N/A	2.5	13.5
W	N/A	N/A	N/A	N/A	3
Ar	1.288	N/A	N/A	N/A	N/A

SOURCE: ^a Weast and Astle 1979, p. F-211. See worksheet *dry-air* of EXCEL file *at_dens* in Attachment II for calculation of weight percent of each element.

^b Weast and Astle 1979, p. F-10. Density at 20° C and one atmosphere.

^c CRWMS M&O 1997, p. 17, (Assumption 3.11). See worksheet *tuff* of EXCEL file *at_dens* in Attachment II for computing elemental wt% from compound wt%.

^d DTN: SN0208T0503102.007. Average dry bulk density of the Ttpul, Ttpmn, Ttppl, and Ttppln units.

^e ASME (American Society of Mechanical Engineers) 2001, SEC II A, SA-516/SA-516M, Table 1.

^f ASME 2001, SEC II A, SA-20/SA-20M, Item 14.

^g ASME 2001, SEC II A, SA-240, Table 1.

^h ASTM G 1-90, Table X1.

ⁱ ASME 2001, SEC II B SB-575, Table 1 and Item 7.1.

5.3.1 Atom Density

The atom densities of the element/isotope contents, in atoms/b-cm, are calculated according to the following equation (Harmon et al. 1994, p. B-2):

$$N_i = \frac{\rho_{\text{mix}} \cdot w f_i \cdot N_a}{A_i} \quad (\text{Eq. 1})$$

where:

$$N_i = \text{atom density of the element } i \left(\frac{\text{atoms}}{\text{b-cm}} \right)$$

$$\rho_{\text{mix}} = \text{mass density of mixture (g} \cdot \text{cm}^{-3}\text{)}$$

$$w f_i = \text{weight fraction of the element } i$$

$$A_i = \text{atomic weight of the element } i$$

$$N_a = \text{Avogadro constant} = 6.0221367\text{E}+23 \text{ atoms/mole (Parrington et al. 1996, p. 59)}$$

From the weight percent and density of each mixture given in Table 5-3, the atom densities of the of the elements for each mixture are computed using Equation 1. This is performed in the EXCEL spreadsheet *at_dens*, which is included in Attachment II. Table 5-4 summarizes the atom densities of the five mixtures in Table 5-3

Table 5-4. Atom Densities of Waste Package and Emplacement Drift Components

Material	Dry Air	Tuff	SA-516 K02700	SA-240 S31600	SB-575 N06022
Element	Atom Density (atoms/b-cm)				
H	N/A	N/A	N/A	N/A	N/A
C	8.26782E-09	N/A	1.0627E-03	3.2009E-04	6.5357E-05
N	3.91263E-05	N/A	N/A	3.4310E-04	N/A
O	1.05122E-05	3.7860E-02	N/A	N/A	N/A
Na	N/A	1.4265E-03	N/A	N/A	N/A
Mg	N/A	7.6381E-05	N/A	N/A	N/A
Al	N/A	3.0772E-03	N/A	N/A	N/A
Si	N/A	1.5746E-02	4.6288E-04	1.2833E-03	1.4907E-04
P	N/A	3.4701E-06	5.3419E-05	6.9819E-05	3.3791E-05
S	N/A	N/A	5.1599E-05	4.4960E-05	3.2640E-05
K	N/A	1.2890E-03	N/A	N/A	N/A
Ca	N/A	1.2297E-04	N/A	N/A	N/A
Ti	N/A	1.5418E-05	N/A	N/A	N/A
Mn	N/A	1.2151E-05	8.8200E-04	1.7211E-03	4.7629E-04
V	N/A	N/A	N/A	N/A	3.5956E-04
Cr	N/A	N/A	N/A	1.5712E-02	2.1387E-02
Fe	N/A	1.4397E-04	8.3263E-02	5.6361E-02	3.7484E-03
Co	N/A	N/A	N/A	N/A	2.2200E-03

Ni	N/A	N/A	N/A	9.8253E-03	4.8830E-02
Mo	N/A	N/A	N/A	1.2523E-03	7.3638E-03
W	N/A	N/A	N/A	N/A	8.5399E-04
Ar	2.34004E-07	N/A	N/A	N/A	N/A
Total	4.98807E-05	5.9773E-02	8.5776E-02	8.6933E-02	8.5520E-02

5.3.2 Isotopic Composition of Unirradiated B&W 15x15 Fuel Assembly

The chemical composition of the SNF is assumed to be the same as that of the unirradiated fuel (Assumption 3.2). The isotopic composition, in weight percent, for commercially available enriched uranium is calculated according to the following equations (Bowman et al. 1995, p. 20).

$$\begin{aligned} \text{wt}\%^{234}\text{U} &= 0.007731 \cdot (\text{wt}\%^{235}\text{U})^{1.0837} \\ \text{wt}\%^{236}\text{U} &= 0.0046 \cdot (\text{wt}\%^{235}\text{U}) \\ \text{wt}\%^{238}\text{U} &= 100 - (\text{wt}\%^{234}\text{U}) - (\text{wt}\%^{235}\text{U}) - (\text{wt}\%^{236}\text{U}) \end{aligned} \quad (\text{Eq. 2})$$

Equation 2 is used in the spreadsheet *at_dens*, worksheet *fuel* to calculate the isotopic composition of uranium for the fuel enrichment of 4.0 wt%. For the light elements in the fuel assembly, the composition is obtained from BSC 2001 (Attachment I, Table I-7). The atom densities of the uranium isotopes and light elements in the waste package cavity are also computed in the spreadsheet *at_dens*, worksheet *fuel*, which is included in Attachment II. Table 5-5 presents the atom densities of the uranium isotopes and light elements in the average PWR assembly and in the 21-PWR waste package cavity. The following PWR fuel assembly input data are used to calculate the atom densities in Table 5-5. Mass of uranium per B&W 15x15 Mark B assembly is 463.63 kg (Punatar 2001, Table 3-1). Fuel pin stack height equals 360.172 cm and total number of fuel pins in an assembly equals 208 (Punatar 2001, Table 2-2). The transverse dimensions of an assembly equals 21.6814 cm (Punatar 2001, p. 2-3). The mass of uranium oxide per fuel pin is 2.53105 kg (Assumption 3.9). The materials and radiation sources of the fuel assemblies and basket are homogenized inside the waste package cavity region, which has a radius of 69.7 cm (Assumption 3.3).

Table 5-5. Atom Densities of Uranium Isotopes and Light Elements (atoms/b-cm)

Element/Isotope	Atom Density in Assembly	Atom Density of Homogenized Active Fuel in WP Cavity
U-235	2.8064E-04	1.8152E-04
U-234	2.4470E-06	1.5827E-06
U-236	1.2855E-06	8.3145E-07
U-238	6.6466E-03	4.2991E-03
Ni	1.5292E-04	9.8911E-05
Cr	7.2742E-05	4.7051E-05
Fe	7.0977E-05	4.5909E-05
Nb	9.6141E-06	6.2185E-06
Mo	5.5406E-06	3.5837E-06
Ti	3.2769E-06	2.1195E-06
Al	3.2297E-06	2.0890E-06
Co	2.9573E-06	1.9128E-06

Mn	1.1103E-06	7.1816E-07
Si	2.1719E-06	1.4048E-06
Cu	8.2280E-07	5.3220E-07
C	1.1609E-06	7.5089E-07
S	8.1528E-08	5.2734E-08
P	8.4403E-08	5.4593E-08
B-10	1.9249E-08	1.2451E-08
B-11	7.7478E-08	5.0114E-08
Sn	5.0015E-05	3.2350E-05
Zr	4.4033E-03	2.8481E-03
O	1.4003E-02	9.0574E-03
Total	2.5714E-02	1.6632E-02

5.3.3 Concentration of Silica Dust Emission

The concentration of silica dust is computed from the ratio of the maximum annual dust emission to the exhaust airflow rate. From Assumption 3.7, the maximum dust emission rate is less than 250 tons per year. The annual discharge of less than 250 tons is intended to include dust from all sources. However, per Assumption 3.6, the origin of silica dust is conservatively assumed to be all from host rock on emplacement drift walls where the rock receives maximum neutron exposure with respect to spatial position and time. The exhaust airflow rate is the total airflow rate through all emplacement drifts. Given a forced ventilation airflow rate of 15 m³/s (Williams 2002, Table 2) and the total number of drifts of 107 (BSC 2003b, pp. 37, 39, 44, and 54), the exhaust airflow rate is the product of the two quantities.

The computation of the concentration of silica dust emission is as follows:

$$\text{Maximum annual dust discharge} = 250 \text{ metric tons/yr (Assumption 3.7)}$$

$$\begin{aligned} \text{Maximum dust emission rate} &= (250 \text{ metric tons/yr}) / (3.156 \times 10^7 \text{ s/yr}) \\ &= 7.921 \times 10^{-6} \text{ metric tons/s} \\ &= 7.921 \text{ g/s} \end{aligned}$$

$$\begin{aligned} \text{Exhaust airflow rate} &= (15 \text{ m}^3/\text{s})(107 \text{ drifts}) \\ &= 1605 \text{ m}^3/\text{s} \end{aligned}$$

$$\begin{aligned} \text{Concentration of dust emission} &= (7.921 \text{ g/s}) / (1605 \text{ m}^3/\text{s}) \\ &= 4.935 \times 10^{-3} \text{ g/m}^3 \\ &= 4.935 \times 10^{-9} \text{ g/cm}^3 \end{aligned}$$

where one year equals 3.156×10^7 seconds is obtained from Parrington et al. 1996 (p. 55).

5.4 ACTIVATION ANALYSIS

The activation analysis is performed with the following equation:

$$A = \Sigma \Phi (1 - e^{-\lambda T}) (e^{-\lambda t}) / (3.7E+04) \quad (\text{Eq. 3})$$

where A = activity ($\mu\text{Ci/ml}$)

Σ = macroscopic activation cross section (cm^{-1})

Φ = neutron flux ($\text{n/cm}^2\text{-s}$)

λ = decay constant (hr^{-1})

T = irradiation time (hr)

t = decay time following irradiation (hr)

$(3.7\text{E}+04)$ = conversion constant (disintegrations/s per μCi) (Parrington et al. 1996 p. 58).

In Eq. 3, $\Sigma\Phi$ represents the reaction rate, which is a summation over all neutron energies. The term $(1-e^{-\lambda T})$ is the activity buildup factor over an irradiation period of T hours. Following the irradiation, the activity decays according to $(e^{-\lambda t})$.

5.4.1 Irradiation Time

The irradiation time varies with the type of activation. The host rock around the emplacement drifts will be subject to a long period of neutron exposure, resulting in saturation in radioactivity. Therefore, all the activation products in the host rock are assumed to reach saturation. In other words, the irradiation time is effectively infinite, relative to the half-life of each activation product.

For air activation in an emplacement drift, the irradiation time depends on the ventilation flow rate as given below:

$$T = (\text{average emplacement drift length})(\text{drift airway area})/(\text{ventilation rate})$$

The average emplacement drift length is calculated from the ratio of the total length of the emplacement drifts to the total number of drifts. From BSC 2003b (pp. 37, 39, 44, and 54), the total number of drifts is 107 and the total length is 61,281 meters. Therefore the average drift length is $61,281/107 = 572.7$ meters.

The emplacement drift airway area is assumed to be equal to the maximum excavated cross-section area (Assumption 3.5). Since the diameter of the drifts is 5.5 meters (Williams 2002, Table 2), drift airway area is 23.76 m^2 . With the ventilation rate of $15 \text{ m}^3/\text{s}$ (Williams 2002, Table 2), the irradiation time for air activation becomes:

$$T = (572.7 \text{ m})(23.76 \text{ m}^2)/(15 \text{ m}^3/\text{s}) = 907.16 \text{ s} = 0.252 \text{ h}$$

5.4.2 Decay Time

The decay time in Eq. 3 represents the exhaust air travel time from the bottom to the top of the exhaust shaft. The traverse time from various emplacement drifts to the bottom of the exhaust shafts is assumed to be negligible (Assumption 3.10). For the maximum exhaust air velocity of 10.2 m/s (Assumption 3.8) and the minimum exhaust shaft height is 292 m (BSC 2003b, p. 57), the minimum decay time following irradiation is equal to:

$$t = (292 \text{ m})/(10.2 \text{ m/s}) = 28.63 \text{ s} = 0.477 \text{ min} = 0.00795 \text{ h}$$

This decay time is directly related to the exhaust shaft height and is the minimum decay time since it is determined from the maximum exhaust air velocity. For lower exhaust air velocity, the decay time will be proportionally higher.

5.5 ACTIVATION PRODUCTS CONSIDERED

5.5.1 Activation in Air

The two most significant activation products in air are N-16 and Ar-41 that are produced from the reactions listed in Table 5-6.

Table 5-6. Activation Products in Air^a

Target	Abundance	Reaction	Product	Half-life
O-16	99.76%	(n, p) ^b	N-16	7.13 s
Ar-40	99.60%	(n, γ)	Ar-41	1.83 hr

Source: ^aParrington et al. 1996, pp. 19 and 23.

^bLederer et al. 1978, p. 6.

5.5.2 Activation in Host Rock

The activation products considered in the host rock include N-16, Na-24, Al-28, Si-31, K-42 and Fe-55, for which the target elements are present in significant quantities. The reaction mechanisms for these products are given in Table 5-7.

Table 5-7. Activation Products in Host Rock^a

Target	Abundance	Reaction	Product	Half-life
O-16	99.76%	(n, p) ^b	N-16	7.13 s
Na-23	100%	(n, γ)	Na-24	14.95 hr
Al-27	100%	(n, γ)	Al-28	2.25 m
Si-30	3.1%	(n, γ)	Si-31	2.62 hr
K-41	6.7302%	(n, γ)	K-42	12.36 hr
Fe-54	5.85%	(n, γ)	Fe-55	2.73 yr

Source: ^aParrington et al. 1996, pp. 19-21 and 23-25.

^bLederer et al. 1978, p. 6.

5.6 REACTION RATE CALCULATION

The reaction rate calculation uses the MCNP4B code, which yields the product of Σ and Φ for all neutron energies in units of reactions/cm³-s. For air activation, neutron fluxes (Φ) are calculated for the air space between the waste package and emplacement drift wall on a volume-averaged basis. For host rock activation, neutron fluxes are calculated on the drift wall surface.

The physical dimensions and material data of the 21-PWR waste package are shown in Table 5-1. The neutron source spectrum per assembly is shown in Table 5-2. For modeling purposes, the

waste package is centrally located in the emplacement drift with a diameter of 5.5 m and surrounded by the host rock (tuff). With the line loading concept (Assumption 3.4), the waste package and emplacement drift are modeled infinitely in the longitudinal direction by using a representative 10-cm axial segment with a reflective boundary on both ends. Figure 5-1 shows the lateral geometry of the MCNP representation.

Figure 5-1. MCNP Representation of the Emplacement Drift

The MCNP calculation is made on a per-unit-source basis. In other words, the MCNP output gives the normalized results for a unit source of 1 n/s in the 10-cm axial segment model. The results need to be multiplied by the total number of source particles in the model as follows:

$$S = (1.993\text{E}+08 \text{ n/s/assembly})(21 \text{ assembly})(10/360.172) \\ = 1.16\text{E}+08 \text{ n/s in the model}$$

The factor (10/360.172) denotes the fractional length of fuel used in the model, i.e., 10 cm out of the full active fuel length of 360.172 cm for B&W 15x15 Mark B fuel.

The unnormalized and absolute results of the reaction rates are provided in Tables 5-8 for air activation and 5-9 for host rock activation. A listing of the input files is given in Attachment I, and electronic copies of the output files are provided in Attachment II, which is a compact disc.

Table 5-8. Neutron Reaction Rates for N-16 and Ar-41 in Air

Neutron Reaction Rates in Air (reactions/cm ³ -s)							
Activation Product	Atom Density of Target Nuclide (atoms per b-cm)	Abundance of Target Nuclide	Atom Density of Target Nuclide (atoms per b-cm)	Reaction Rate per Target Nuclide and Source Neutron	Reaction Rate per Source Neutron	React. Rate (reactions per cm ³ -s)	Relative Error
N-16	1.0512E-05	0.9976	1.0487E-05	2.7325E-09	2.8656E-14	3.3240E-06	0.0327
Ar-41	2.3400E-07	0.996	2.3307E-07	1.0015E-05	2.3341E-12	2.7076E-04	0.002

NOTE: MCNP4B input file: air04, output file: air04o.

Table 5-9. Neutron Reaction Rates for Activation Products in Host Rock

Neutron Reaction Rates in Host Rock (reactions/cm ³ -s)							
Activation Product	Atom Density of Target Nuclide (atoms per b-cm)	Abundance of Target Nuclide	Atom Density of Target Nuclide (atoms per b-cm)	Reaction Rate per Target Nuclide and Source Neutron	Reaction Rate per Source Neutron	React. Rate (reactions per cm ³ -s)	Relative Error
N-16	3.7860E-02	0.9976	3.7770E-02	1.7975E-09	6.7890E-11	7.8752E-03	0.0677
Na-24	1.4265E-03	1	1.4265E-03	8.2574E-06	1.1779E-08	1.3664E+00	0.0045
Al-28	3.0772E-03	1	3.0772E-03	4.0711E-06	1.2528E-08	1.4532E+00	0.0043
Si-31	1.5746E-02	0.031	4.8812E-04	3.4320E-06	1.6753E-09	1.9433E-01	0.0035
K-42	1.2890E-03	0.0673	8.6748E-05	2.9354E-05	2.5464E-09	2.9538E-01	0.0043
Fe-55	1.4397E-04	0.0585	8.4225E-06	3.1073E-05	2.6171E-10	3.0359E-02	0.0045

NOTE: MCNP4B input file: dust04, output file: dust04o.

5.7 ACTIVITY CONCENTRATION CALCULATION

5.7.1 Activation in Air

Eq. 3 is used to calculate the concentrations of N-16 and Ar-41 in air at two key locations: inlet and outlet of the exhaust shaft. The concentrations at the inlet of the exhaust shaft (A_1) denote the maximum possible concentrations immediately following irradiation in the emplacement drift. The concentrations at the outlet of the exhaust shaft (A_2) represent the release to the surface surrounding areas after radioactive decay during air exhaust from the emplacement drifts to the release point. The formulas for calculations are:

$$\begin{aligned} \text{At the exhaust shaft inlet} \quad A_1 &= \Sigma\Phi(1-e^{-\lambda T})/(3.7E+04) \\ \text{At the exhaust shaft outlet} \quad A_2 &= A_1 * e^{-\lambda t} \end{aligned}$$

The units for A_1 and A_2 are $\mu\text{Ci/ml}$. The irradiation time (T) varies with the ventilation rate as discussed in Section 5.4.1. The decay time (t) varies depending upon the volume of air in the emplacement drifts and can be as low as 0.477 minutes (0.00795 h) per Section 5.4.2 when the maximum exhaust air velocity is 10.2 m/s and the average ventilation rate is 15 m³/s in each

emplacement drift. For lower ventilation rate, the exhaust air velocity will be proportionally lower and the decay time will also be proportionally higher.

With the absolute reaction rate, $\Sigma\Phi$ for each target element from Table 5-8, A_1 and A_2 are computed with the Microsoft Excel 97 spreadsheet program and shown in Table 5-10. This table includes ventilation rates 5, 10, and 15 m³/s for sensitivity considerations.

Table 5-10. N-16 and Ar-41 Concentrations in Air versus Ventilation Rate

Ventilation Rate (m ³ /s)	Irradiation Time (hours)	Decay Time (hours)	N-16 Concentration (μCi/ml)		Ar-41 Concentration (μCi/ml)	
			Exhaust Shaft Inlet	Exhaust Shaft Outlet	Exhaust Shaft Inlet	Exhaust Shaft Outlet
5	0.756	0.023856	8.9839E-11	2.12944E-14	1.8217E-09	1.8053E-09
10	0.378	0.011928	8.9839E-11	1.38314E-12	9.7593E-10	9.7153E-10
15	0.252	0.007952	8.9839E-11	5.55987E-12	6.6601E-10	6.6401E-10

An example calculation is illustrated below:

Activation product: Ar-41

Ventilation rate = 15 m³/s (Williams 2002, Table 2)

$\Sigma\Phi = 2.7076\text{E-}04$ reactions/cm³-s (Table 5-8)

T = 0.252 hr (Section 5.4.1)

t = 0.00795 hr (Section 5.4.2)

$\lambda = 0.693/1.83 \text{ hr}^{-1} = 0.3787 \text{ hr}^{-1}$ (half-life from Table 5-6)

$A_1 = (2.7076\text{E-}04)(1 - e^{-0.3787 \cdot 0.252}) / (3.7\text{E+}04) = 6.660\text{E-}10 \text{ } \mu\text{Ci/ml}$

$A_2 = (6.660\text{E-}10)e^{-0.3787 \cdot 0.00795} = 6.640\text{E-}10 \text{ } \mu\text{Ci/ml}$

5.7.2 Activation in Host Rock

The saturated activity for each activation product in the host rock is determined at the peak position (i.e., drift wall surface) by dividing the absolute reaction rate in Table 5-9 by (3.7E+04) to obtain the quantity in units of μCi/ml. This quantity represents the maximum concentration in the host rock.

The maximum concentration of dust emission is 4.935 mg/m³ or 4.935x10⁻⁹ g/cm³ (Section 5.3.3), which are results of the assumed maximum dust emission of less than 250 tons/y (Assumption 3.7) and the ventilation rate of 15 m³/s. The maximum saturated concentration of activated dust is obtained from the maximum dust emission concentration as follows:

Maximum saturated activity in silica dust = (4.935x10⁻⁹/2.0434) x saturated activity in host rock

The factor (4.935x10⁻⁹/2.0434) represents the ratio of the airborne dust concentration to the host rock density used to scale the saturated activity in the host rock.

Release of activated dust from the exhaust shaft includes a decay factor over a period of 28.63 s or 0.00795 hours (Section 5.4.2). The decay factor is significant only for short-lived activation products such as N-16.

Table 5-11 summarizes the results associated with activation in the host rock around the emplacement drifts.

Table 5-11. Activity Concentrations in Host Rock and Silica Dust

Activation Product	Saturated Activity in Host Rock ($\mu\text{Ci/ml}$)	Saturated Activity in Silica Dust ($\mu\text{Ci/ml}$)	Activated Dust Release from Exhaust Shaft ($\mu\text{Ci/ml}$)
N-16	2.1284E-07	5.1404E-16	3.1283E-17
Na-24	3.6930E-05	8.9189E-14	8.9156E-14
Al-28	3.9276E-05	9.4855E-14	8.1819E-14
Si-31	5.2522E-06	1.2684E-14	1.2658E-14
K-42	7.9833E-06	1.9281E-14	1.9272E-14
Fe-55	8.2051E-07	1.9816E-15	1.9816E-15

6. RESULTS

The section presents the results of this calculation. The outputs of this calculation are reasonable compared to the inputs, and the results are suitable for the intended use. The uncertainties are taken into account by consistently using the most conservative approach; the calculations, therefore, yield a conservatively bounding set of results.

6.1 ACTIVATION IN AIR

As shown in Table 5-10, the concentration of N-16 in air at the inlet of the exhaust shaft is independent of the ventilation rate since the traverse time from various emplacement drifts to the bottom of the exhaust shafts is assumed negligible (Assumption 3.10). The short half-life of N-16 of 7.13 seconds also helps reduce the concentration of N-16 released from the top of the exhaust shaft to a much lower level.

Table 5-10 shows that the concentration of Ar-41 varies significantly with the ventilation rate. The concentration increases as the ventilation rate decreases, because of a longer irradiation time for neutron activation. The decay of Ar-41 from the inlet of the exhaust shaft to the top of the exhaust shaft is small since the half-life of Ar-41 is 1.83 hours, which is about two orders of magnitude higher than the decay times shown in Table 5-10. Figure 6-1 plots the Ar-41 release concentration from the exhaust shaft as a function of the ventilation rate. For the ventilation rate of $15 \text{ m}^3/\text{s}$, the release concentration is $6.6401\text{E-}10$.

The activation products in air, N-16 and Ar-41, released from the exhaust shaft for the ventilation rate of $15 \text{ m}^3/\text{s}$ are presented in Table 6.1. The table also includes the 10 CFR 20 limits (Appendix B, Table 2) for the two isotopes. It is noted that the computed release is less than 1% of the limit for N-16 and is 6.6% of the limit for Ar-41.

Since the HEPA filters will not remove any radioactive gases, neutron activation of airflow through the emplacement drifts will not impact the need for the HEPA filters.

The 10 CFR 20 limit refers to the concentration at the boundary of a restricted area, which is usually at some distance from the release point. Atmospheric dispersion from the release point to the site boundary will further reduce the N-16 and Ar-41 concentrations.

6.2 ACTIVATION IN SILICA DUST

The activation in the host rock presents a potential for generation of radioactive silica dust, which will be carried by the air stream and released from the exhaust shafts to the general environment. The activated products in silica dust released from the exhaust shaft given in the last column of Table 5-11 are presented in Table 6-1, along with the 10 CFR 20 limits for the activation products. Table 6-1 also includes the ratio of each activated isotope to the corresponding 10 CFR 20 effluent concentration limits. Furthermore, the table gives the sum of the effluent concentration limit of each isotope and the sum of the activities of all isotopes. The ratio of the total isotopic activity to the sum of the limits is included as well.

The ratio of the total isotopic activity to the sum of the limits is 0.97% that is far below the 20% value recommended in Regulatory Guide 4.20 (Section 2.2) as the screening criterion. The use of HEPA filters should be considered only if emissions of radioactive material exceeds the screening value. From the ratio of the total radioactive release to the 10 CFR 20 limit, it can be concluded that there is no need for using the HEPA filters for removal of activated products.

The 10 CFR 20 limit refers to the concentration at the boundary of a restricted area, which is usually at some distance from the release point. Atmospheric dispersion from the release point to the site boundary will further reduce the concentrations of all activated products.

Figure 6-1. Ar-41 Release Concentration

Table 6-1. Comparison with 10 CFR 20 Release Limits

Activation Product	10 CFR 20 Effluent Release Limit ^a ($\mu\text{Ci/ml}$)	Activated Product Release from Exhaust Shaft ($\mu\text{Ci/ml}$)	Ratio (product activity/ 10 CFR 20 limit)
Activated Products in Air			
N-16	1E-09	5.5599E-12	5.5599E-03
Ar-41	1E-08	6.6401E-10	6.6401E-02
Activated Products in Silica Dust			
N-16	1E-09	3.1283E-17	3.13E-08
Na-24	7E-09	8.9156E-14	1.27E-05
Al-28	1E-09	8.1819E-14	8.18E-05
Si-31	4E-08	1.2658E-14	3.16E-07
K-42	7E-09	1.9272E-14	2.75E-06
Fe-55	3E-09	1.9816E-15	6.61E-07
Total Activated Products			
Total	6.90E-08	6.69775E-10	9.71E-03

NOTES: ^aAppendix B, Table 2.

6.3 ANNUAL RELEASES

The annual normal radiological releases due to activated air and silica dust from the subsurface facility with no filtration to the environment are estimated from the airborne release concentrations given in Table 6-1, with the following parameters:

Emplacement drift ventilation rate = $15 \text{ m}^3/\text{s}$

Exhaust airflow rate = $1605 \text{ m}^3/\text{s}$ (Section 5.3.3) = $5.065\text{E}+16 \text{ cm}^3/\text{yr}$

The annual release for each radionuclide is simply the product of the release concentration ($\mu\text{Ci/ml}$) and annual total exhaust air volume (cm^3/yr) with a conversion from μCi to Ci by a factor of 10^{-6} ($\text{Ci}/\mu\text{Ci}$). The results are provided in Table 6-2. Atmospheric dispersion from the release point to the site boundary will further reduce the annual release of all activated products indicated in Table 6-2.

Table 6-2. Annual Releases due to Activated Air and Dust

Activation Product	Release from Exhaust Shaft ($\mu\text{Ci/ml}$)	Annual Release (Ci/yr)
Activated Products in Air		
N-16	5.5599E-12	2.8163E-01
Ar-41	6.6401E-10	3.3635E+01
Activated Products in Silica Dust		
N-16	3.1283E-17	1.5846E-06
Na-24	8.9156E-14	4.5161E-03
Al-28	8.1819E-14	4.1444E-03
Si-31	1.2658E-14	6.4116E-04
K-42	1.9272E-14	9.7619E-04
Fe-55	1.9816E-15	1.0038E-04

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7.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

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8. ATTACHMENTS

The list of attachments is presented in Table 8-1. Electronic files of MCNP calculations and other spread sheet files are provided on a compact disk that is Attachment II of this calculation. The attributes of the electronic files are listed in Table 8-2. Each file is identified by its name, size (in bytes), and the date and time. The files can be read using Word-Pad or Excel applications in Microsoft Windows Explorer. It should be noted that the date and time of the MCNP output files reflect the time of transfer from the HP to the personal computer. The actual date and time of each run completion can be found in its corresponding file.

Table 8-1. List of Attachments

Description	Attachment Number	No. of Pages
MCNP Input Files Listing	I	5
Compact Disk of MCNP Output and Other Files	II	N/A

Table 8-2 Files in the Compact Disc

File Name	Description	Size (bytes)	Date	Time
air04	MCNP input file for air activation	4,546	4/1/2003	10:02a
dust04	MCNP input file for dust activation	4,788	4/1/2003	10:02a
air04o	MCNP output file for air activation	56,450	4/1/2003	10:02a
dust04o	MCNP output file for dust activation	69,193	4/1/2003	10:01a
at_dens	Excel file of atom densities calculation	38,400	4/25/2003	11:27a
results-4	Excel file of results	39,936	5/1/2003	02:32p
N-Source-4%48gwd	Excel file of neutron source	75,264	3/26/2003	12:31p
AverageNeutronSource	Notepad file of neutron source listing	4,512	3/27/2003	08:41a

ATTACHMENT I

MCNP Input File air04

```

MGR emplacement drift air activation (N-16 and Ar-41)
c   neutrons from 21 PWR fuel assemblies in waste package
c   infinite axial height model (10-cm reflected drift segment)
c   emplacement drift diameter=5.5 m
c   calculation on a per-unit-source basis
c   ****
c   fuel region (homogenized in cavity)
1   1 1.6632-2   -1   12 -13
c   carbon steel 1.5 cm
111  4 -7.85     1 -111 12 -13
c   1st WP inner barrier (2.5 cm)
2   8 -7.98     111 -2   12 -13
c   2nd WP inner barrier (2.5 cm)
3   8 -7.98     2   -3   12 -13
c   WP outer barriers (2 cm)
4   2 -8.69     3   -4   12 -13
c   air space between WP and emplacement drift wall
5   5 -0.001205  4   -5   12 -13
c   tuff medium (30 cm modeled)
6   6 -2.04335   5   -6   12 -13
c   zero importance cell
7   0           6:-12:13

1   cz 69.70     $Cavity outer radius
111  cz 71.20     $1.5-cm layer
2   cz 73.70     $1st 2.5 cm inner barrier (ss316)
3   cz 76.20     $2nd 2.5 cm inner barrier (ss316)
4   cz 78.20     $2 cm outer barrier (alloy C-22)
5   cz 275.0     $emplacement drift wall surface
6   cz 305.0     $30 cm into tuff
*12  pz 0.0      $model lower axial boundary (reflective)
*13  pz 10.0     $model upper axial boundary (reflective)

c   active fuel region, fresh fuel 4wt% u-235
m1   28000.50c 9.8911-5
      24000.50c 4.7051-5
      26000.55c 4.5909-5
      41093.50c 6.2185-6
      42000.50c 3.5837-6
      22000.50c 2.1195-6
      13027.50c 2.0890-6
      27059.50c 1.9128-6
      25055.50c 7.1816-7
      14000.50c 1.4048-6
      29000.50c 5.3220-7
      6000.50c 7.5089-7
      16000.60c 5.2734-8
      15031.50c 5.4593-8
      5010.50c 1.2451-8
      5011.55c 5.0114-8
      50000.35c 3.2350-5
      40000.60c 2.8481-3
      8016.50c 9.0574-3
      92235.50c 1.8152-4
      92234.50c 1.5827-6
      92236.50c 8.3145-7
      92238.50c 4.2991-3
c   Alloy-22 (8.69 g/cc)
m2   6000.50c -0.015 14000.50c -0.08 23000.50c -0.35
      24000.50c -21.25 25055.50c -0.50 26000.55c -4.0
      27059.50c -2.50 28000.50c -54.765 42000.50c -13.50
      74000.55c -3.00 15031.50c -0.02 16000.60c -0.02
c   argon for activation analysis
m3   18000.59c 1.0
c   Grade 70 A516 Carbon Steel (7.85 g/cc)

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m4      6000.50c -0.27  25055.50c -1.025  14000.50c -0.275
        16000.60c -0.035 15031.50c -0.035  26000.55c -98.36
c      air (0.001205 g/cc)
m5      7014.50c -0.75521
        18000.59c -0.01288
        6000.50c -0.00014
        8016.50c -0.23177
c      dry tuff material (2.04335 g/cc)
m6      8016.50c -0.49226
        11023.50c -0.02665
        12000.50c -0.00151
        13027.50c -0.06747
        14000.50c -0.35938
        15031.50c -0.00009
        19000.50c -0.04096
        20000.50c -0.00401
        22000.50c -0.00060
        25055.50c -0.00054
        26000.55c -0.00653
c      oxygen for air activation
m7      8016.50c  1.0
c SS 316 (7.98 g/cc)
m8      6000.50c -0.08  25055.50c -2.0  15031.50c -0.045
        16000.60c -0.03  14000.50c -0.75  24000.50c -17.0
        28000.50c -12.0  42000.50c -2.5  7014.50c -0.1  26000.55c -65.495
mode n
imp:n    1 1 2 4 8 8 8 0
phys:n   20.0 1.0-7
sdef     cel=1 pos=0 0 5.0 rad=d4 ext=d2 erg=d3 axs=0 0 1
c        uniform axial distribution from 0 to 10 cm p(x)=c
si2      5.0
c        unbiased neutron source spectrum
si3      0.10  0.40  0.9  1.4  1.85  3.0  6.43  20.0
sp3      0.0  0.0375 0.1916 0.1766 0.1309 0.2353 0.2097 0.0183
c        uniform radial source distribution
si4      0.0  69.7
sp4      -21  1
fc2      surface neutron flux (n/cm**2-s per n/s in model)
f2:n     5
e0       6.25-7 0.1 1.0 20.0
fc12     surface neutron dose rat--ANSI 6.1.1-1977 (mrem/hr per n/s in model)
f12:n    5
del12    2.5-8 1.0-7 1.0-6 1.0-5 1.0-4
          1.0-3 1.0-2 1.0-1 5.0-1 1.0
          2.5 5.0 7.0 10.0 14.0 20.0
df12     3.67-3 3.67-3 4.46-3 4.54-3 4.18-3
          3.76-3 3.56-3 2.17-2 9.26-2 1.32-1
          1.25-1 1.56-1 1.47-1 1.47-1 2.08-1 2.27-1
fc4      ave. flux in air between WP and drift wall (n/cm**2-s per n/s in model)
f4:n     5
fc14     reaction rate for air activation (reactions/nuclide-s per n/s in model)
f14:n    5
fm14     (1.0 3 102) (1.0 7 103)
fq0      e f
ctme     600.0

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MCNP Input File dust04

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MGR emplacement drift TSw2 activation: N-16/Na-24/Al-28/Si-31/K-42/Fe-55
c      neutrons from 21 PWR fuel assemblies in waste package
c      infinite axial height model (10-cm reflected drift segment)
c      emplacement drift diameter=5.5 m
c      calculation on a per-unit-source basis
c      *****
c      fuel region (homogenized in cavity)
1      1 1.6632-2 -1 12 -13
c      carbon steel 1.5 cm
111    4 -7.85 1 -111 12 -13
c      1st WP inner barrier (2.5 cm)
2      8 -7.98 111 -2 12 -13

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c      2nd WP inner barrier (2.5 cm)
3      8 -7.98      2  -3      12 -13
c      WP outer barriers (2 cm)
4      2 -8.69      3  -4      12 -13
c      air space between WP and emplacement drift wall
5      5 -0.001205  4  -5      12 -13
c      tuff medium (30 cm modeled)
6      6 -2.04335   5  -6      12 -13
c      zero importance cell
7      0              6:-12:13

1      cz 69.70      $Cavity outer radius
111    cz 71.20      $1.5-cm layer
2      cz 73.70      $1st 2.5 cm inner barrier (ss316)
3      cz 76.20      $2nd 2.5 cm inner barrier (ss316)
4      cz 78.20      $2 cm outer barrier (alloy C-22)
5      cz 275.0      $emplacement drift wall surface
6      cz 305.0      $30 cm into tuff
*12    pz 0.0        $model lower axial boundary (reflective)
*13    pz 10.0       $model upper axial boundary (reflective)

c      active fuel region, fresh fuel 4wt% u-235
m1     28000.50c 9.8911-5
        24000.50c 4.7051-5
        26000.55c 4.5909-5
        41093.50c 6.2185-6
        42000.50c 3.5837-6
        22000.50c 2.1195-6
        13027.50c 2.0890-6
        27059.50c 1.9128-6
        25055.50c 7.1816-7
        14000.50c 1.4048-6
        29000.50c 5.3220-7
        6000.50c 7.5089-7
        16000.60c 5.2734-8
        15031.50c 5.4593-8
        5010.50c 1.2451-8
        5011.55c 5.0114-8
        50000.35c 3.2350-5
        40000.60c 2.8481-3
        8016.50c 9.0574-3
        92235.50c 1.8152-4
        92234.50c 1.5827-6
        92236.50c 8.3145-7
        92238.50c 4.2991-3
c      Alloy-22 (8.69 g/cc)
m2     6000.50c -0.015 14000.50c -0.08 23000.50c -0.35
        24000.50c -21.25 25055.50c -0.50 26000.55c -4.0
        27059.50c -2.50 28000.50c -54.765 42000.50c -13.50
        74000.55c -3.00 15031.50c -0.02 16000.60c -0.02
c      argon for activation analysis
m3     18000.59c 1.0
c      Grade 70 A516 Carbon Steel (7.85 g/cc)
m4     6000.50c -0.27 25055.50c -1.025 14000.50c -0.275
        16000.60c -0.035 15031.50c -0.035 26000.55c -98.36
c      air (0.001205 g/cc)
m5     7014.50c -0.75521
        18000.59c -0.01288
        6000.50c -0.00014
        8016.50c -0.23177
c      dry tuff material (2.04335 g/cc)
m6     8016.50c -0.49226
        11023.50c -0.02665
        12000.50c -0.00151
        13027.50c -0.06747
        14000.50c -0.35938
        15031.50c -0.00009
        19000.50c -0.04096
        20000.50c -0.00401
        22000.50c -0.00060
    
```

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25055.50c -0.00054
26000.55c -0.00653
c oxygen for air activation
m7 8016.50c 1.0
c SS 316 (7.98 g/cc)
m8 6000.50c -0.08 25055.50c -2.0 15031.50c -0.045
16000.60c -0.03 14000.50c -0.75 24000.50c -17.0
28000.50c -12.0 42000.50c -2.5 7014.50c -0.1 26000.55c -65.495
c target elements for silica dust activation
m9 11023 1.0
m10 13027 1.0
m11 14030.30y 1.0
m12 19041.30y 1.0
m13 26054.30y 1.0
mode n
imp:n 1 1 2 4 8 8 8 0
phys:n 20.0 1.0-7
sdef cel=1 pos=0 0 5.0 rad=d4 ext=d2 erg=d3 axs=0 0 1
c uniform axial distribution from 0 to 10 cm p(x)=c
si2 5.0
c unbiased neutron source spectrum
si3 0.10 0.40 0.9 1.4 1.85 3.0 6.43 20.0
sp3 0.0 0.0375 0.1916 0.1766 0.1309 0.2353 0.2097 0.0183
c uniform radial source distribution
si4 0.0 69.7
sp4 -21 1
fc2 neutron flux at drift wall (n/cm**2-s per n/s in model)
f2:n 5
e0 6.25-7 0.1 1.0 20.0
c basis = 1 g/cc silica dust
c activation product order: N-16/Na-24/Al-28/Si-31/K-42/Fe-55
fc12 reaction rate for dust activation (reactions/cc-s per n/s in model)
f12:n 5
fm12 (1.0 7 103) (1.0 9 102) (1.0 10 102)
(1.0 11 102) (1.0 12 102) (1.0 13 102)
fc4 ave. flux in air between WP and drift wall (n/cm**2-s per n/s in model)
f4:n 5
c activation product order: N-16/Na-24/Al-28/Si-31/K-42/Fe-55
fc14 reaction rate for dust activation (reactions/nuclide-s per n/s in model)
f14:n 5
fm14 (1.0 7 103) (1.0 9 102) (1.0 10 102)
(1.0 11 102) (1.0 12 102) (1.0 13 102)
fq0 e f
ctme 200.0

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