# OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
# CALCULATION COVER SHEET

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1. Remarks

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## TABLES

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# 1. PURPOSE

The first objective of this calculation is the identification of the degraded configurations of the Enhanced Design Alternatives (EDA) II design that have some possibility of criticality and that can occur within 10,000 years of placement in the repository. The next objective is to evaluate the criticality of these configurations and to estimate the probability of occurrence for those configurations that could support criticality. The ultimate objective is to determine whether the total probability for any such critical configuration (occurring before 10,000 years) will be greater than the screening threshold given in the proposed regulation 10 CFR PART 63 Section 114(d) (Reference 13) and the interim guidance of Reference 22, which is to "consider only events that have at least one chance in 10,000 of occurring over 10,000 years." In this process, the evaluation of degradation scenarios and the identification of potentially critical configurations follow the methodology prescribed in Sections 3.1 through 3.5 of the *Disposal Criticality Analysis Methodology Topical Report* (Reference 1).

The scope of this calculation is the probability of a critical configuration that hypothetically can occur following waste package degradation or damage either during nominal performance or following igneous intrusion.

The scope of the igneous-intrusion calculation covers two damage zones according to the model used for Total System Performance Assessment-Site Recommendation (TSPA-SR) (Reference 21, Section 3.10, with damage zones defined specifically in Section 5.2.9.7). Damage Zone 1 applies to the few waste packages in the immediate vicinity of the igneous intrusion where they are subject to such high temperature and external overpressure that the waste package barriers are crushed and the contents are highly fragmented (Reference 21, Section 3.10). The conservative treatment of this damage zone assumes that seven waste packages are thrown together, by certain magma motions, so that their fissile contents could be combined into a larger mass while the neutron absorber materials are completely scattered and not considered in the criticality evaluation (Assumptions 3.2 and 3.3). It should be noted that although these assumptions are extremely conservative, this portion of the calculation is applicable to commercial spent nuclear fuel (CSNF) only. The more highly enriched waste forms, for example certain types of DOE spent nuclear fuel (DSNF), have not been addressed. The possibility of criticality in this configuration following destruction of the waste package by igneous intrusion is identified by features, events, and processes (FEP) 2.1.14.14.00 (1.2.04b, the Out-of-package criticality, fuel/magma mixture) (Reference 2).

Damage Zone 2 applies to waste packages sufficiently far from the point of intrusion that they do not experience extensive mechanical damage. Such packages experience damage from overpressure, either from a rapid buildup of external pressure from the impact of a rapid magma flow, or from the gradual buildup of internal temperature and pressure. Both these overpressure scenarios lead to breach of a waste package by the fracture of the weakest part of the waste package barriers, expected to be the welds for the closure lids.

The nominal performance waste package degradation scenario considered in this calculation fits into the standard scenario scheme set forth in Figures 3-2a and 3-2b of the *Disposal Criticality Analysis Methodology Topical Report* (Reference 1).

Since this initial event screening for the aqueous degradation scenario applies to all the waste packages (of the EDA II type) pre-10,000 year, the scope of the aqueous degradation scenarios may be considered to cover all waste forms. For reference purposes it should be noted that the question of criticality within the waste package following aqueous breach is addressed primarily by FEP 2.1.14.02.00 (2.1.14g, Criticality in-situ, nominal configuration, top breach) (Reference 2). Furthermore, this calculation can be considered to apply to all other primary criticality FEPs, both internal and external, since they require aqueous breach as an initiating event. With the exception of the fuel/magma mixture criticality FEP already discussed, this calculation does not address external criticality FEPs for behavior following igneous disruption, for all waste forms, including both CSNF and DSNF. Effects of seismicity on the waste package are addressed, and results are applicable to all criticality FEPs

Information provided by the sketch in Attachment I of this calculation is that of a representative potential design for a waste package considered in this calculation. The sketch in Attachment II of this calculation is referenced in Attachment I.

The development plan for this work is given in Reference 3. This work is associated with waste package degraded mode criticality evaluation.

This document has been prepared according to Procedure AP-3.12Q, *Calculations* (Reference 26).

## 2. METHOD

The methodology for this document follows that used in the *Disposal Criticality Analysis Methodology Topical Report* (Reference 1, Sections 3.1 through 3.5). The overall framework for degraded mode criticality consists of three basic steps. First the degradation scenarios are screened to identify potentially critical configurations. Next, the potentially critical configurations are evaluated for criticality using the Monte Carlo code, MCNP (Reference 10). The third step is to estimate an upper bound on the probability of occurrence of each identified critical configuration. The second and third steps will not be applied to those scenarios that cannot credibly cause a breach of the waste package before 10,000 years.

Potentially critical configurations for CSNF are all characterized by the separation of fissile material from the neutron absorber that has been added for criticality control (Reference 1, Section 3). This requires breach of the waste package permitting entry of water, which can cause significant degradation of the waste package internal components containing the neutron absorber. Following degradation of the neutron absorber carrier, the water flowing in and out of the package can separate the neutron absorber from the fissile material so that the criticality control effectiveness of the neutron absorber is reduced to such an extent that it no longer prevents criticality.

The analysis of early waste package failure (Reference 8) showed the earliest aqueous breach of the waste package barriers to be by stress corrosion cracking (SCC). The probability of breach from stress corrosion cracking before 10,000 years can be developed from the distributions of weld flaw size, depth, and orientation, and the residual stress in the weld. A summary of the breach probability calculation from Reference 8 is given in Section 5.1.1, with the results given in Section 6.1.1.

The calculations of probability of criticality for each of the three scenarios of igneous intrusion are given in Sections 5.2.1, 5.2.2, and 5.2.3. The results are summarized in Sections 6.2.1, 6.2.2, and 6.2.3.

With regard to the development of this calculation, the control of electronic management of data was evaluated in accordance with AP-SV.1Q, *Control of the Electronic Management of Information* (Reference 18). The evaluation (Reference 7) determined that current work processes and procedures are adequate for the control of electronic management of information for this activity.

## 3. ASSUMPTIONS

3.1 It is assumed that the top node of CSNF with 3.5 weight percent (wt. %) enrichment and 10 GWd/MTU burnup with 5 years decay is conservatively representative of all CSNF. The basis for this assumption is that this enrichment and burnup are bounding for CSNF allowed to be placed in a 21-PWR Waste Package (Reference 12, Figure 6-2). This assumption is used in Section 6.2.2.

3.2 For purposes of conservatively evaluating the possibility of criticality from CSNF following the igneous-intrusion, complete-destruction scenario, described in Section 5.2.2, seven CSNF waste packages are assumed to be piled up in a cube (transported by the magma from the igneous intrusion). In this calculation, this assumption is applied to the CSNF waste packages only; waste forms of higher enrichment may require a more refined analysis. The basis of this assumption is that it is a bounding conservative interpretation of the extent of waste package damage, as described in Reference 21 (Section 3.10). In determining the actual configuration of fissile material and neutron absorber, this assumption must be taken together with the following assumption. This assumption is used in Sections 5.3.2 and 6.2.2.

3.3 It is assumed that, following the destruction of the waste package by igneous intrusion, the magma motion will be of such turbulence that it will separate basket fragments containing neutron absorber from the fuel fragments, thereby increasing the probability of criticality. A direct consequence of this assumption is that all contents of the waste package and fuel assemblies are completely separated from the fuel pellets, thus only fuel pellets and magma are represented in the MCNP cases. However, this assumption does not result in the separation of the fission products from the fissile isotopes. As a consequence of this assumption, neither the boron in the stainless steel nor the iron in the carbon steel is included in the MCNP cases. The basis of this assumption is that it is conservative. It is possible that out of all the possible rearrangements of waste package internal components that could be caused by the turbulent magma motions, the one with all the added neutron absorber separated from the fissile material will occur. However, it is, obviously, extremely unlikely. This assumption is used in Sections 5.3.2 and 6.2.2.

3.4 It is assumed that the maximum water content in the igneous intrusion magma is 5 wt. %. The basis for this assumption is that it is the maximum given in Reference 9, Section 6.2.2. This is also conservative since water moderation will increase the likelihood of criticality. This assumption is used in Section 5.3.2.

3.5 For purposes of conservatively estimating the water flow from a single drip over the waste package into a waste package through a possible opening in a lid weld, it is assumed that the probability of such flow will be proportional to the area of the opening divided by the horizontal cross-sectional area of the entire waste package. The basis for this assumption is that it is conservative as shown in the following discussion. The area-ratio estimate would be more representative of an opening that is normal to the dripping direction. The lid-weld opening is on a vertical surface, and, therefore, presents no direct target to a dripping source. Furthermore, any water flowing down the vertical surface would not be driven into the opening by gravity. Of course, the waste package could be tilted slightly from the vertical so that it would present a small target (area of the opening multiplied by the sine of the tilt angle) which would somewhat vitiate the conservatism. However, it is equally likely that the tilt angle will be negative so that there is no possibility of water flow into the opening at all. This assumption is used in Section 5.3.1.

3.6 For those waste packages hit by an igneous intrusion that only puts a small hole in the waste package closure lid, it is assumed that the water entering the waste package is sufficient to completely corrode the borated stainless steel, and remove the neutron absorbing boron. The basis for this assumption is that it is conservative, because loss of boron from the waste package will generally increase the criticality ($k_{eff}$) of the fissile material remaining in the waste package. This assumption is used in Section 5.3

3.7 The pellet length is assumed to be 1 cm. The basis for this assumption is that this size is on the same order of CSNF pellets and the fact that the criticality evaluations in this calculation are not sensitive to the pellet size. This assumption is used in Section 5.3.2.

3.8 For purposes of calculating probability of criticality in the case of a single fracture breach of a single weld resulting from igneous intrusion credit for neutron absorbers is not considered, whereas burnup credit is taken into account. The basis for this assumption is that it is conservative. This assumption is used in Section 5.3.1.

3.9 It is assumed that the value of ultimate tensile strength of stainless steel 316 at 871 °C is 124 MPa (Reference 15, Table TYPE 316). The basis for this assumption is that this value is provided by a manufacturer of stainless steel. This assumption is used in Section 5.2.1.2.

# 4. USE OF COMPUTER SOFTWARE AND MODELS

## 4.1 SOFTWARE

The MCNP code was used to calculate $k_{eff}$ values for configurations that have been defined by the degradation analysis. The software specifications for MCNP are as follows:

- Software name: MCNP
- Software version/revision number: Version 4B2
- Computer Software Configuration Item (CSCI): 30033 V4B2LV
- Computer type: Hewlett Packard (HP) 9000 Series Workstations
- Computer processing unit number: Software is installed on the Civilian Radioactive Waste Management System (CRWMS) Management and Operating Contractor (M&O) workstation "bloom" whose CRWMS M&O Tag number is 700887

The input and output files for the various MCNP calculations are documented in Attachment III. The MCNP software used was: (a) appropriate for the application of CSNF $k_{eff}$ calculations, (b) used only within the range of validation as documented in Reference 11, and (c) obtained from the Software Configuration Manager in accordance with appropriate procedures.

## 4.2 SOFTWARE ROUTINES

None used.

## 4.3 MODELS

None used.

# 5. CALCULATION

## 5.1 EARLY FAILURE BY STRESS CORROSION CRACKING

SCC is primarily of concern as a threat to waste-package welds, because welding processes can potentially leave a tensile residual stress and, because there are many more flaws in the welds of the waste package than in the base metal (waste-package shell and lids). In Reference 8, Section 6.2.1.1.6, it is estimated that the probability that a flaw is present in the base metal is $10^{-4}$ lower than in the welds. Furthermore, except for the welds for the closure (outer and inner lids at the top end of the waste package), all the fabrication welds in the waste package can have their stress fully relieved by extensive annealing that can easily be done on the empty container. In contrast, the closure must be welded in a high-radiation environment, and it is not desirable to heat the closed waste package (containing the waste) in an oven to anneal the residual stress in the closure welds.

SCC processes are determined primarily by the residual stress state and weld flaw statistics (distribution of length, depth and orientation). The specific dependencies are evaluated in Reference 8, Section 6.2.1. The discussion in that reference can be summarized by the following. SCC can propagate from a pre-existing flaw (or a crack-initiation site) under the influence of three parameters: metallurgical susceptibility, exposure environment and residual stress. The key parameters in the current SCC modeling are the residual stress state and the depth reached by the crack (resulting from a pre-existing flaw). The conservative assumption is that the crack will propagate rapidly by SCC once it has reached the depth at which the stress changes from compressive to tensile, leading eventually to through-wall penetration. The residual stress calculated by ANSYS is given in Reference 6, particularly Figure 4, page 28. This reference shows the stress intensity factor as a function of depth below the weld outer surface. A SCC crack starts to grow when the crack has reached a "critical" depth where the residual stress becomes greater than the threshold stress and the associated stress intensity factor is positive.

## 5.2 WASTE PACKAGE DAMAGE FOLLOWING IGNEOUS INTRUSION

The probability and characteristics of an igneous intrusion are summarized in the TSPA-SR (Reference 21, Section 3.10). The approximate maximum temperature and pressure within the magma are given in Reference 21, Section 3.10.2.3.1, as 1170 °C and 7.5 MPa. There are two general levels of damage predicted. Section 3.10.2.3.1 of Reference 21 describes the extensive damage of up to 7 waste packages per drift per dike (Damage Zone 1, three waste packages on either side of the intrusion and one more right where the magma intruded) where an igneous intrusion intersects a drift. The waste packages in this zone can be thrown into each other with sufficient impulse that the barriers are destroyed to the extent that the disposal containers provide no further protection for the waste. Section 3.10.2.3.2 of Reference 21 describes the partial damage that could effect all remaining packages in any drift intersected by an igneous intrusion

(Damage Zone 2). Section 3.10.2.3.2 of Reference 21 also projects a mean damage to the weakest point of the waste package barrier as a 10 $cm^2$ penetration for Zone 2 waste packages. Table 3.10-5 of Reference 21 gives the median number of packages damaged (per igneous event) for the general level of damage from Section 3.10.2.3.2, as 1720 Zone 2 packages. This table also gives the mean probability of occurrence of an igneous intrusion event, as $1.6 \times 10^{-8}$ per year. This frequency is just above the screening threshold, so the calculation must proceed to the next step, which is to calculate the $k_{eff}$ values of the possible configurations to identify any possible criticalities. The possible configurations are described in Sections 5.2.1 and 5.2.2, and the resulting $k_{eff}$ values are all found to be below the critical limit, as described in Section 6.2.

### 5.2.1 Local Waste Package Breach from Weld Failure Due to Overpressure

For Damage Zone 2 the packages can fail from internal overpressure or external overpressure, and the extent of the failure is limited by the equalization of these pressures.

#### 5.2.1.1 Waste Package Breach from Internal Overpressure

For waste packages in Damage Zone 2 beyond the immediate vicinity of the intrusion, the principal stress on the waste package could come from the internal overpressure from the heating of the volatiles from the SNF. The internal overpressure from heating to 500 °C is 1.01 MPa (Reference 19, Table 6-4). Knowing that the internal pressure increases with temperature, pressure values higher than 1.01 MPa are beyond the yield strength of steel of 0.7 MPa at 1100 °C calculated in Section 5.2.1.2, which will cause some failure, or breach, of the waste package.

The following approximate analysis shows that the time required for the temperature increase is much longer than the time for stress propagation through the steel barrier. Consequently, the weakest location will fail gradually while the interior gas is heating up, rather than having a destructive blowout of a larger area.

The rate of internal thermal energy increase for the internal components of the waste package is equated to the heat flux into the waste package using Equation 2.1 from Reference 20 and representing the one-dimensional heat transfer rate ($q_x$) as shown in the following equation:

$$CV\frac{dT_i}{dt} = kA\frac{dT}{dx} \qquad \text{(Eq. 1)}$$

where $C$ is the volumetric heat capacity of the internal components (primarily steel) in Joules/°C /$cm^3$, $V$ is the volume of these components, $k$ is the thermal conductivity in Watts/cm/°C, $T_i$ is the temperature of the internal waste package components in °C, $T$ is the temperature in the waste package as a function of $x$, the distance from the exterior to the interior of the package, and

$t$ is the time in seconds. For a more precise analysis, the heat flux through the shell barriers would be expressed in cylindrical coordinates, and only the flux through the lids could be expressed in this planar form. This is also conservative because the temperature-gradient (heat flux) actually decreases with time as the waste package interior heats up. With the further approximation that the temperature gradient is independent of the location in the waste package barrier, the equation becomes a first order, linear differential equation in time with the solution.

$$T_i = T_o e^{-\lambda t} + T_f (1 - e^{-\lambda t}) \qquad \text{(Eq. 2)}$$

where the rate constant is given by

$$\lambda = kA/(CV\Delta x) \qquad \text{(Eq. 3)}$$

where $\Delta x$ is the barrier thickness in cm, and arises from the approximation of the temperature gradient by the difference between outer and inner temperatures divided by the thickness.

Using any reasonable values in the equation above results in a rate constant ($\lambda$) many orders of magnitude smaller than the rate constant for elastic wave propagation through steel. Thus, the waste package will respond to the relatively slow increase in internal temperature and pressure by failing gradually at the weakest weld point and releasing the internal pressure. It should be noted that the interior pressure buildup must be uniform over all interior surfaces, both because it is relatively slow, and because a gas will always be at a uniform pressure, unless there is some nonlinear disturbance such as a shock wave.

With this type of breach in the waste package due to localized weld failure, the remainder of the scenario for producing criticality consists of the following processes: drip onto the waste package, flow into the fracture opening, ponding of the water in the waste package, and corrosion of the material containing the neutron absorber (borated stainless steel for the commercial PWR waste package). In addition, all this must happen to a waste package containing a sufficient number of reactive assemblies in order to result in a criticality. The probabilities of each of these processes are estimated in Section 5.3.1 below.

#### 5.2.1.2 Waste Package Breach from External Overpressure

Since the flow and pressurization in Damage Zone 2 will be chaotic, it is possible that there could also be some lid failure due to the rapid onset of external overpressure at high temperatures. In the consideration of this case, basic relations of solid mechanics are used to determine the structural behavior of the waste package inner shell and inner lids under external pressure and high temperatures due to the contact between the waste package and the magma. These preliminary calculations are conservative since the closed-form relations are applicable to elastic deformations.

The waste package lid is thinner than the shell; therefore, it is more vulnerable to external pressures. Since there is a gap between the outer and inner lids at the lower end of the waste package and the outer lid is substantially thinner than the inner lid, the outer lid is expected to fail first (Attachment I). Therefore, no structural credit is taken for the waste package outer lid.

The maximum bending stress in the circular lid is obtained from the relation given in Reference 14, Page 398:

$$\sigma = \frac{6 \cdot M}{t^2} \qquad \text{(Eq. 4)}$$

where:

$\sigma$ = maximum bending stress

$M$ = maximum bending moment

$t$ = circular plate thickness

The maximum bending moment (Reference 14, Page 429) in a circular plate at the fixed edge is:

$$M = \frac{q \cdot a^2}{8} \qquad \text{(Eq. 5)}$$

where:

$q$ = external or internal pressure on the plate

$a$ = plate radius

Equations (4) and (5) are combined to give

$$q = \frac{8 \cdot t^2 \cdot \sigma}{6 \cdot a^2} \qquad \text{(Eq. 6)}$$

The maximum bending stress is equal to the ultimate tensile strength of 316 stainless steel (SS) at the temperature of interest. The value of ultimate tensile strength at 871 °C is 124 MPa (Assumption 3.9). It is also known that the yield strength is zero at the melting temperature, 1375 °C (Reference 16, Page 35). The yield strength at the intermediate temperature (1100 °C) is approximated by the following linear interpolation.

316 SS ultimate tensile strength at 1100 °C = 124 × (1375 – 1100) / (1375 – 871)
= 68 MPa

For reference purposes, we also note the 316 SS ultimate tensile strength at 350 °C (662 °F), as 495 MPa (71.8 ksi) (Reference 17, Table U).

Typical waste package plate thickness of 0.08 m and plate diameter of 1.886 m are taken from Attachment I for the waste package containing five Defense High Level Waste (DHLW) canisters.

Therefore, at 1100 °C:

$$q = \frac{8 \cdot (0.08)^2 \cdot (68)}{6 \cdot \left[\frac{1.886}{2}\right]^2} = 0.7 \text{ MPa} \qquad \text{(Eq. 7)}$$

At 350 °C:

$$q = \frac{8 \cdot (0.08)^2 \cdot (495)}{6 \cdot \left[\frac{1.886}{2}\right]^2} = 4.8 \text{ MPa} \qquad \text{(Eq. 8)}$$

Thus, the lids will fail completely if the external pressure exceeds 0.7 MPa at 1100 °C or exceeds 4.8 MPa at 350 °C. It is likely that the lid will fracture at its weakest point, which is the weld. It is also likely that the fracture will grow until enough gas has flowed through the opening to equalize the interior and exterior pressures. An analysis of this process summarized in Section 3.10.2.3.2 of Reference 21 indicates a mean value of 10 $cm^2$ for the final opening.

### 5.2.2 Major Waste Package Failure Due to High Impulse Collision

The waste packages in Damage Zone 1 will experience high-impulse collisions that could cause major damage to the waste package and scatter the contents to the extent described in Assumptions 3.2 and 3.3. The resulting configurations are described in Section 5.3.2.

## 5.3 EVALUATION OF THE CRITICALITY OF CONFIGURATIONS RESULTING FROM IGNEOUS INTRUSION

The magma temperature of an intrusion into an emplacement drift is expected to range between 1046 and 1169 °C (Reference 9, Table 4). As explained in Section 5.2 the waste package damage that could result from an igneous intrusion into the emplacement drift can be divided into two categories. The first is the complete destruction and pushing together of the 7 packages closest to the point of intrusion in what is called Damage Zone 1. The second is a single fracture breach of approximately 1720 packages that could be anywhere in the affected drifts; this is called Damage Zone 2. These alternative scenarios have been described in Sections 5.2.1 and 5.2.2. The following subsections describe the possible critical configurations that could result.

### 5.3.1 Criticality from a Single Fracture Breach of a Single Weld Resulting from Igneous Intrusion (Damage Zone 2)

In the event of a volcanic eruption at the repository, the magma, or ash, could conceivably flow through any drift contacted. The pressure inside the waste package could build as the waste package is heated by the magma, or ash. This free flow throughout the drift is only applicable beyond the conduit, where there is no high external pressure to overwhelm the interior pressure. This free flow can only occur if there is no backfill (which would not only impede the free flow of the magma, but would also limit the heating of the interior gas, and the consequent pressure buildup). As the pressure inside the waste package builds, the weakest point of the barrier will fail. As explained in Section 5.2.1 (specifically Sections 5.2.1.1 and 5.2.1.2), this will most likely be a closure weld (inner and outer lids), which is likely to be the weakest part of the barrier.

The small opening caused by this type of igneous intrusion breach may allow the magma to flow into the waste package, but silica moderation is insufficient to cause criticality in CSNF. In fact, the MCNP calculations for 7 merged CSNF waste packages presented in Section 6.2.2 can be viewed as bounding with respect to the criticality potential of the fissile material in a single CSNF waste package. Furthermore, the magma flowing into the waste package through a small opening will not be able to corrode the borated stainless steel and remove the boron, since water presence is essential to promote corrosion.

The only scenario that could lead to in-package criticality following this type of igneous intrusion has water returning after cool-down of the magma. Once the waste package is breached with a fracture that can allow entry of water, any scenario leading to a critical configuration must include the following additional processes: drip onto the waste package, flow into the fracture opening, ponding of the water in the waste package, and corrosion of the material containing the neutron absorber (borated stainless steel for the commercial PWR waste package). In addition, the waste package must contain sufficiently reactive spent nuclear fuel (SNF) to begin with. Conservative upper bounds for the probabilities of each of these processes, or occurrences, are derived in the following paragraphs.

The probability of drip onto any waste package is 0.13 (Reference 21, Page 4-4). The probability of flow into the small fracture opening is approximated by the ratio of the areas of the fracture opening (conservatively estimated at 10 $cm^2$, as explained in Section 5.2) to the total horizontal cross section of the waste package (72,877 $cm^2$) (Attachment I, WP outer shell diameter = 203 cm × WP length = 359), which gives 0.00014 (Assumption 3.5).

There will be ponding of water in the waste package if it flows in through an opening in the upper portion of the waste package, and there is no opening at the bottom. Since the location of the weakest point of the lid weld is random around the circumference, the probability that it will be in the upper half is 0.5.

The probability that a commercial PWR waste package has SNF of sufficient reactivity for $k_{eff}$ >0.98 is 0.07 as extracted from Section 5.1.1 and Table 11 in Reference 27 ((106+293)/(5690+106+293)), which is the ratio of the number of waste packages needed with additional absorbers to the total number of waste packages. The assemblies that if placed in the 21-PWR-absorber-plate WP would exceed the critical limit are placed in either 21-PWR-control-rod WP or 12-PWR-absorber-plate-long WP. Therefore, the ratio shown is an approximation of the desired probability.

### 5.3.2 Configurations Resulting from the Complete Destruction of the Waste Packages (Damage Zone 1)

Subsequent to this waste-package destruction, the turbulent magma could entrain the waste form (1-cm pellets for commercial PWR SNF) (Assumption 3.7), which hypothetically could be carried into a rearrangement that removed it from the proximity to any neutron absorber added for criticality prevention (Assumption 3.3 and Reference 5, Section 3.1.4).

For a convenient conservative evaluation of the possibility of criticality following igneous intrusion we make the assumptions that (1) the fissile material becomes separated from the neutron absorber material (which was incorporated into the waste package design), and (2) the fissile material (SNF pellets) from the damaged packages accumulates into its most critical configuration, as outlined in Assumptions 3.2 and 3.3. It will be shown in Section 6.2.1 that this optimum configuration for criticality has the pellets from the completely destroyed CSNF in a regular rectangular lattice, spaced 1.9 cm apart.

Since these configurations are found to be subcritical, it is not necessary to estimate the probability of occurrence of any of these configurations at this time.

Because of the uncertainty of the turbulent flow of magma in the drift, we have chosen the most conservative approach in assuming that the contents of each destroyed waste package can be re-arranged so that the fissile material (SNF pellets) can be completely separated from the neutron absorber material. As a further conservatism, it is assumed that the SNF pellets of all seven destroyed waste packages are brought together by the magma into a tuff reflected cubic geometry, in a regular lattice, with spacing that is varied to determine the worst case configuration (Assumptions 3.2 and 3.3). The maximum water content in the magma of 5 wt. % is represented as mentioned in Assumption 3.4. The top node of CSNF with an enrichment of 3.5% at a burnup of 10 GWd/MTHM with 5 years decay conservatively represents all CSNF as described in Assumption 3.1. The fuel description for the MCNP cases is taken from Reference 12, Attachment IV Case 3.5at10. This enrichment burnup combination was chosen to lie below the loading curve for commercial PWR SNF (Figure 6-3 of Reference 12). The magma composition is given in Table 5-1 as taken from Table 2 of Reference 9. The density of magma is the weighted average of the theoretical densities given in Table 6-1 as taken from Reference 23, Pages B-68 through B-161. As mentioned earlier, the fuel pellets-magma pile is reflected with tuff described in Table 5-2 (Extracted from Reference 24, pages F32-F33, and field numbers: 63L-128-B-1, 60ENH32, TO-41C, 63L-17-I, 63L-17-F, and 63L-17-4). The lattice spacing of the SNF pellets (or total volume surrounding the pellets) is varied in order to determine the optimum volume favorable to criticality. The results of these calculations are given in Section 6.2.1, below.

Table 5-1 Magma Composition

| Compound | Wt. % | Theoretical Density |
|---|---|---|
| $SiO_2$ | 48.5 | 2.32 |
| $TiO_2$ | 1.93 | 3.84 |
| $Al_2O_3$ | 16.74 | 3.965 |
| $Fe_2O_3$ | 11.63 | 5.24 |
| MnO | 0.17 | 5.46 |
| MgO | 5.83 | 3.58 |
| CaO | 8.60 | 3.38 |
| $Na_2O$ | 3.53 | 2.27 |
| $K_2O$ | 1.84 | 2.32 |
| $P_2O_5$ | 1.22 | 2.39 |
| $H_2O$ | 0.05 | 1 |

Table 5-2 Tuff Composition

| Compound | wt. % | Compound | wt. % |
|---|---|---|---|
| $SiO_2$ | 76.83 | $Na_2O$ | 3.59 |
| $Al_2O_3$ | 12.74 | $K_2O$ | 4.93 |
| FeO | 0.84 | $TiO_2$ | 0.1 |
| MgO | 0.25 | $P_2O_5$ | 0.02 |
| CaO | 0.56 | MnO | 0.07 |
| Particle Density = 2.54 g/cm$^3$ (Reference 25) | | | |

## 5.4 CRITICALITY DUE TO SEISMIC EVENTS

As part of the comprehensive criticality analysis methodology, the possibility of a seismic event leading directly to a criticality has been considered, and rejected for the following reasons. (1) A seismic event cannot increase the probability of occurrence of a critical configuration. The occurrence of a critical configuration is determined by any displacement between fissile material and neutron absorber added for criticality control, and by the geometry of the fissile material. The seismic event can only make the criticality occur sooner (by some small re-arrangement of the fissile material into a more reactive geometry). (2) The discussion of potential waste package damage due to a seismic event in Sections 6.2.5 and 6.2.6 of Reference 28 indicates subject to verification that any damage from vibratory motion of a seismic event would not be sufficient to cause a breach of a waste package. The only mechanism for such weakening is extensive corrosion of the waste package barriers. Since the worst case general corrosion rate of the waste package outer barrier material (Alloy 22) is 0.1 microns per year (Reference 4, Table 3-7, 95 percentile point), there can be only 1 millimeter general corrosion in 10,000 years. A loss of 1 millimeter would not significantly weaken the 2-centimeter-thick outer barrier. (3) If a waste package were placed across a fault, and were subsequently locked in place by extensive rock fall, then a subsequent displacement along the fault could cause a shear across the waste package sufficient to cause breach. This potential effect is expected to be completely prevented by maintaining a standoff distance for emplacement near such a known fault. Even if a seismic event were to break the waste package in this manner, damage would be sufficiently extensive that there could be very little retention of water in the waste package to serve as moderator for a criticality. For these reasons, a criticality caused by a seismic event can be excluded from consideration before 10,000 years.

# 6. RESULTS

This document may be affected by technical product input information that requires confirmation. Any changes to the document that may occur as a result of completing the confirmation activities will be reflected in subsequent revisions. The status of the input information quality may be confirmed by review of the Document Input Reference System database.

## 6.1 RESULTS FOR PROBABILITY OF BREACH FROM STRESS CORROSION CRACKING

### 6.1.1 Probability Estimated from Weld Flaw Statistics

The SCC model described in Section 5.1.1 is summarized by the following formula for the number of weld flaws per package (lid weld) that could propagate to waste package breach (Reference 8, Section 6.2.1.1),

$$n(x,z) = \frac{n_0}{\lambda t} \cdot e^{-\lambda(z-1)} \cdot e^{\lambda x}$$

where $x$ is the depth of corrosion (1 mm as the worst case for Alloy 22 corrosion in 10,000 years), $z$ is the depth at which the weld residual stress goes from compressive to tensile (11.5 mm), and $n_0$ is the number of flaws that are normal to the direction of the weld and remain undetected after double UT (0.18). As indicated in the discussion of Section 5.1.1, the distribution parameter $\lambda$ is estimated from experimental data (1.95/mm), and $t$ is the thickness of the weld (25 mm). With these parameter values the probability of the existence of a flaw that can propagate by stress corrosion cracking within 10,000 years following emplacement is calculated by using $x$=1 mm and $z$=11.5 mm, according to the reasoning developed in Section 5.1.1, as $2.7 \times 10^{-11}$.

When this per-package 10,000 year criticality probability is multiplied by the number of waste packages (approximately 10,000), the result, $2.7 \times 10^{-7}$, is well below the probability screening threshold specified by the proposed regulation 10 CFR PART 63 Section 114(d) (Reference 13) and interim guidance of Reference 22, one chance in 10,000 of occurring in over 10,000 years for the entire repository.

## 6.2 CRITICALITY RESULTS AND PROBABILITY OF CONFIGURATIONS RESULTING FROM IGNEOUS INTRUSION

For the partially damaged waste package discussed in Section 5.2.1, the probability of criticality for CSNF is calculated in Section 6.2.1, as a combination of the individual probabilities derived in Section 5.3.1. For the complete-destruction scenario, it is shown in Section 6.2.2 that there can be no criticality for CSNF, even for the worst case configuration that can result from the magma separation of the fuel from the added neutron absorber. Therefore, a complete probability calculation is unnecessary for the complete-destruction scenario.

### 6.2.1 Probability of Criticality Following Single Fracture Breach (Damage Zone 2)

The following discussion relates specifically to a 10 $cm^2$ opening in a lid weld, but it could apply to other breach situations. The relevant individual probabilities derived in Section 5.3.1 are the following: (1) drip onto the waste package (0.13); (2) flow into the waste package through the 10 $cm^2$ opening in a lid weld, given drip onto the waste package (0.00014); (3) ponding in the waste package, given that there is flow into the waste package (0.5); (4) the SNF in a given PWR waste package has sufficient reactivity for $k_{eff} > 0.98$ (0.07). The product of these probabilities is $6.4 \times 10^{-7}$. When multiplied by the $1.6 \times 10^{-4}$ mean probability of an igneous intrusion in 10,000 years, and multiplied by the number of waste packages affected, 1720, the result is approximately $1.8 \times 10^{-7}$. This is sufficiently far below the screening threshold of $10^{-4}$ that it is not necessary to address the question of how much of the threshold probability should be allocated to this single waste package type (commercial PWR SNF). If other, more highly enriched, waste forms are found to exceed the screening threshold, the uncertainty of those estimates will exceed the probability calculated for CSNF, so the issue of criticality impact can be evaluated on those more highly enriched waste forms alone.

### 6.2.2 Possible Internal or Near-Field Criticality Following Complete Waste Package Destruction (Damage Zone 1)

Using the parameters derived in Section 5.3.2, a set of cases was developed by varying the fuel pellet spacing to determine the volume for peak $k_{eff}$. As stated in Assumption 3.2, fuel pellets from seven CSNF waste packages were spread out in a regular cubic lattice that was otherwise filled with magma. The total volume was varied between 25 to 153 $m^3$, which corresponded to an inter-pellet spacing varying from 1.32 to 2.4 cm. The resulting values for $k_{eff}$ are shown in Table 6-1. The maximum $k_{eff}$ is seen to be 0.73; this demonstrates that criticality cannot be achieved by magma moderated CSNF, even with the extremely conservative assumptions of fuel pellets from seven waste packages combined, optimum spacing of the pellets, and 5% water in the magma.

Table 6-1 Summary of Criticality Calculations

| Case Name | Fuel/Magma Volume ($m^3$) | Pellet Spacing (cm) | $k_{eff}$ | Sigma |
|---|---|---|---|---|
| 003 | 25.552 | 1.32 | 0.68169 | 0.00073 |
| 001 | 51.11 | 1.66 | 0.74681 | 0.00075 |
| 006 | 63.889 | 1.78 | 0.75921 | 0.00091 |
| 005 | 76.665 | 1.90 | 0.76929 | 0.00079 |
| 007 | 89.447 | 2.00 | 0.76852 | 0.00083 |
| 002 | 102.23 | 2.10 | 0.76096 | 0.00076 |
| 004 | 153.34 | 2.40 | 0.71238 | 0.00084 |

It should be noted that the conservative assumptions leading to the configurations considered in Table 6-1 are intended only to demonstrate that CSNF with primarily magma (silica) moderation is very far from criticality. The criticality analysis for more highly enriched waste forms may indicate the possibility of criticality in configurations such as these, in which case there will be a need for additional analyses to demonstrate that the probability is of the occurrence of such configurations is well below the screening threshold.

## 6.3 CRITICALITY DUE TO SEISMIC EVENTS

As discussed in Section 5.4, criticality caused by a seismic event can be excluded from consideration before 10,000 years.

## 7. REFERENCES

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# 8. ATTACHMENTS

Table 8-1 lists the attachments to this calculation.

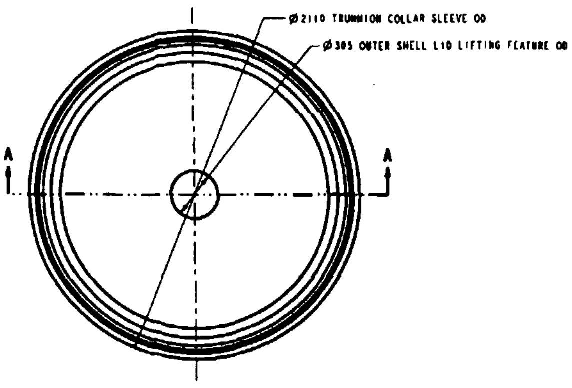
Table 8-1 List of Attachments

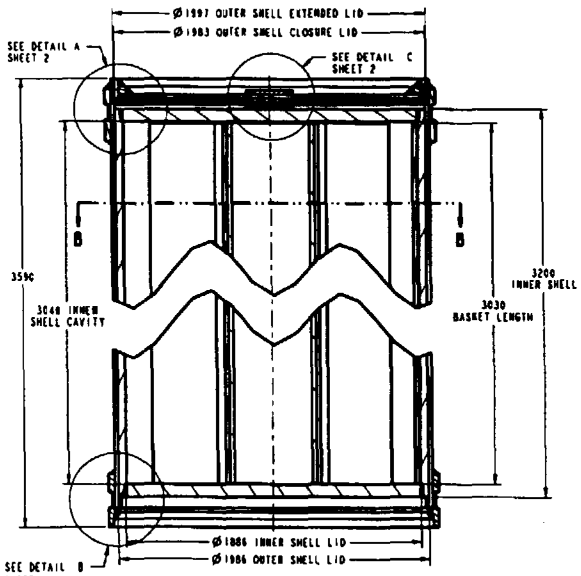
| Attachment | Content |
|---|---|
| I | SK-0196 REV 03 (5DHLW/DOE SNF – Short WP Assembly Configuration for Site Recommendation) |
| II | SK-0197 REV 00 (5DHLW/DOE SNF – Short Weld Configuration) |
| III | Compact Disc (CD) |

Table 8-2 lists the contents of Attachment III.

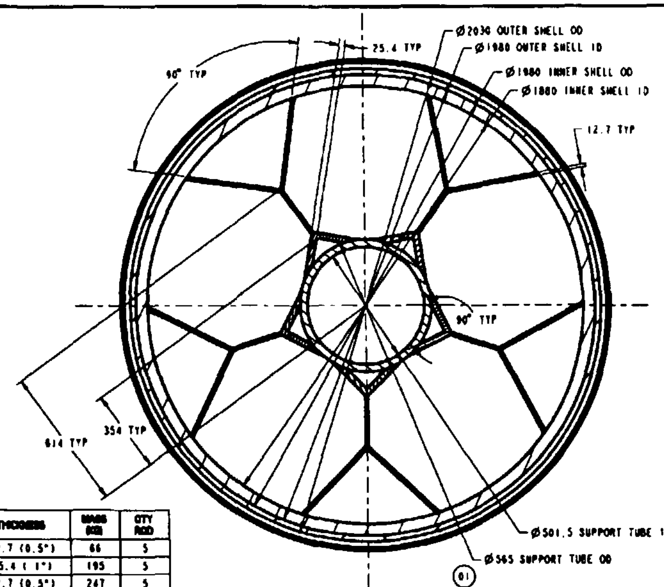
Table 8-2 Contents of Attachment III

| Name | Date | Time | Size (byte) |
|---|---|---|---|
| 001 | 10/21/2000 | 7:19a | 4,106 |
| 001o | 10/21/2000 | 7:19a | 217,313 |
| 002 | 10/21/2000 | 7:19a | 4,107 |
| 002o | 10/21/2000 | 7:19a | 216,898 |
| 003 | 10/21/2000 | 7:19a | 4,109 |
| 003o | 10/21/2000 | 7:19a | 218,202 |
| 004 | 10/21/2000 | 7:19a | 4,121 |
| 004o | 10/21/2000 | 7:19a | 217,452 |
| 005 | 10/21/2000 | 7:19a | 4,109 |
| 005o | 10/21/2000 | 7:19a | 216,995 |
| 006 | 10/21/2000 | 7:19a | 4,124 |
| 006o | 10/21/2000 | 7:19a | 216,353 |
| 007 | 10/21/2000 | 7:19a | 4,124 |
| 007o | 10/21/2000 | 7:19a | 216,353 |




SECTION A-A




SECTION B-B

| COMPONENT NAME | MATERIAL | THICKNESS | MASS (KG) | QTY RQD |
|---|---|---|---|---|
| DIVIDER PLATE | SA-516 K02700 | 12.7 (0.5") | 66 | 5 |
| INNER BRACKET | SA-516 K02700 | 25.4 ( 1") | 195 | 5 |
| OUTER BRACKET | SA-516 K02700 | 12.7 (0.5") | 247 | 5 |
| SUPPORT TUBE | SA-516 K02700 | 31.75 (1.25") | 1265 | 1 |
| INNER SHELL | SA-240 S31600 | 50 | 7621 | 1 |
| INNER SHELL LID | SA-240 S31600 | 80 | 1765 | 2 |
| INNER LID LIFTING FEATURE | SA-240 S31600 | 27 | 12 | 1 |
| OUTER SHELL | SB-575 N06022 | 25 | 4692 | 1 |
| EXTENDED OUTER SHELL LID | SB-575 N06022 | 25 | 172 | 1 |
| EXTENDED OUTER SHELL LID BASE | SB-575 N06022 | 25 | 620 | 1 |
| EXTENDED OUTER LID REINFORCING RING | SB-575 N06022 | 50 | 129 | 1 |
| OUTER LID LIFTING FEATURE | SB-575 N06022 | 27 | 13 | 2 |
| OUTER SHELL FLAT CLOSURE LID | SB-575 N06022 | 10 | 268 | 1 |
| OUTER SHELL FLAT BOTTOM LID | SB-575 N06022 | 25 | 669 | 1 |
| UPPER TRUNNION COLLAR SLEEVE | SB-575 N06022 | 40 | 855 | 1 |
| LOWER TRUNNION COLLAR SLEEVE | SB-575 N06022 | 40 | 642 | 1 |
| INNER SHELL SUPPORT RING | SB-575 N06022 | 20 | 53 | 1 |
| TOTAL ALLOY 22 WELDS | SFA-5.14 N06022 | - | 325 | *** |
| TOTAL 316 WELDS | SFA-5.9 S31680 | - | 133 | *** |
| WASTE PACKAGE ASSEMBLY | | - | 23380 | 1 |
| HLW GLASS ASSEMBLY | - | - | 2500* | 5 |
| 18" CANISTER SHORT | - | - | 2270** | 1 |
| WP ASSEMBLY WITH SNF | - | - | 38130 | - |

(03) * WASTE ACCEPTANCE SYSTEM REQUIREMENTS DOCUMENT. E00000000-00811-1708-00001 REV 03, DOE/RW-0351. ACC: MOO.19990226.0001, PAGE 18, SECTION 4.2.3.1.A.4.

** UNITED STATES DEPARTMENT OF ENERGY 1998. DESIGN SPECIFICATION FOR DEPARTMENT OF ENERGY STANDARDIZED SPENT NUCLEAR FUEL CANISTERS, VOLUME 1, DESIGN SPECIFICATION, REV 01. WASHINGTON D.C.: UNITED STATES DEPARTMENT OF ENERGY. TIC: 241528

*** SEE SK-0197 FOR WELD CONFIGURATION AND MASSES

UNITS: mm

DO NOT SCALE FROM SKETCH

**REVISIONS**

| REV | DESCRIPTION | DRW BY | DATE |
|---|---|---|---|
| 00 | ISSUED APPROVED | DGM | 1/26/00 |
| 01 | IN SECTION B-B Ø 565 SUPPORT TUBE OD "WAS" ID | DGM | 4/21/00 |
| 02 | "MODIFIED" REVISION TABLE, "ADDED" DIMENSION 4 TO DETAIL A, "MODIFIED" CROSS HATCHING ON DETAIL A | BM | 4/25/00 |
| 03 | IN NOTE **, DOE/RW-0351 "WAS" DOE/RW-315P, IN REVISION BLOCK REV 00, 1/26/00 "WAS" 1/25/00, "ADDED" REVISION BALLOONS TO SECTION B-B AND DETAIL "A" | EJC | 6/5/00 |

"FOR INFORMATION ONLY"

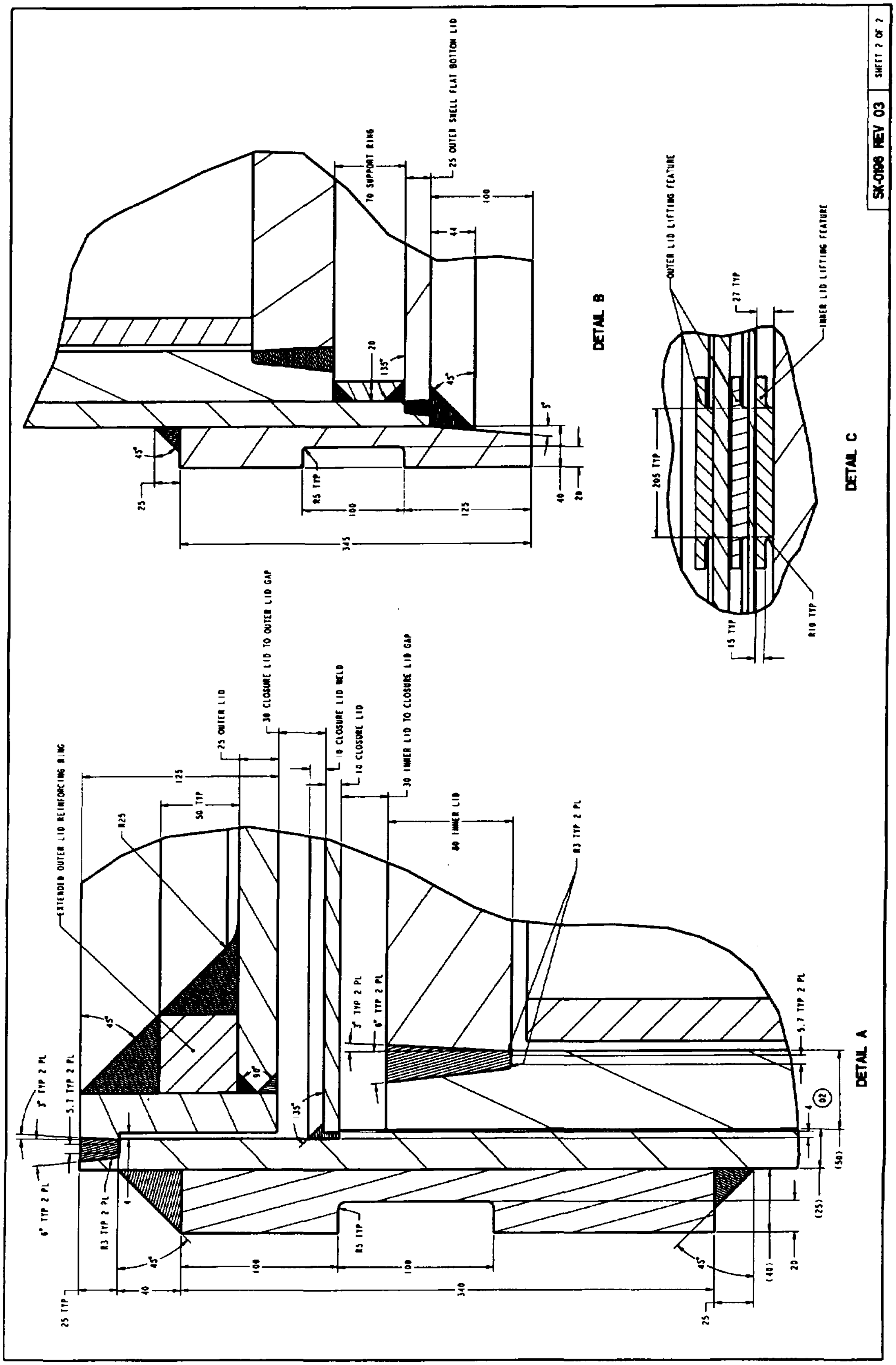
**5 DHLW/DOE SNF - SHORT WP ASSSEMBLY CONFIGURATION FOR SITE RECOMENDATION**

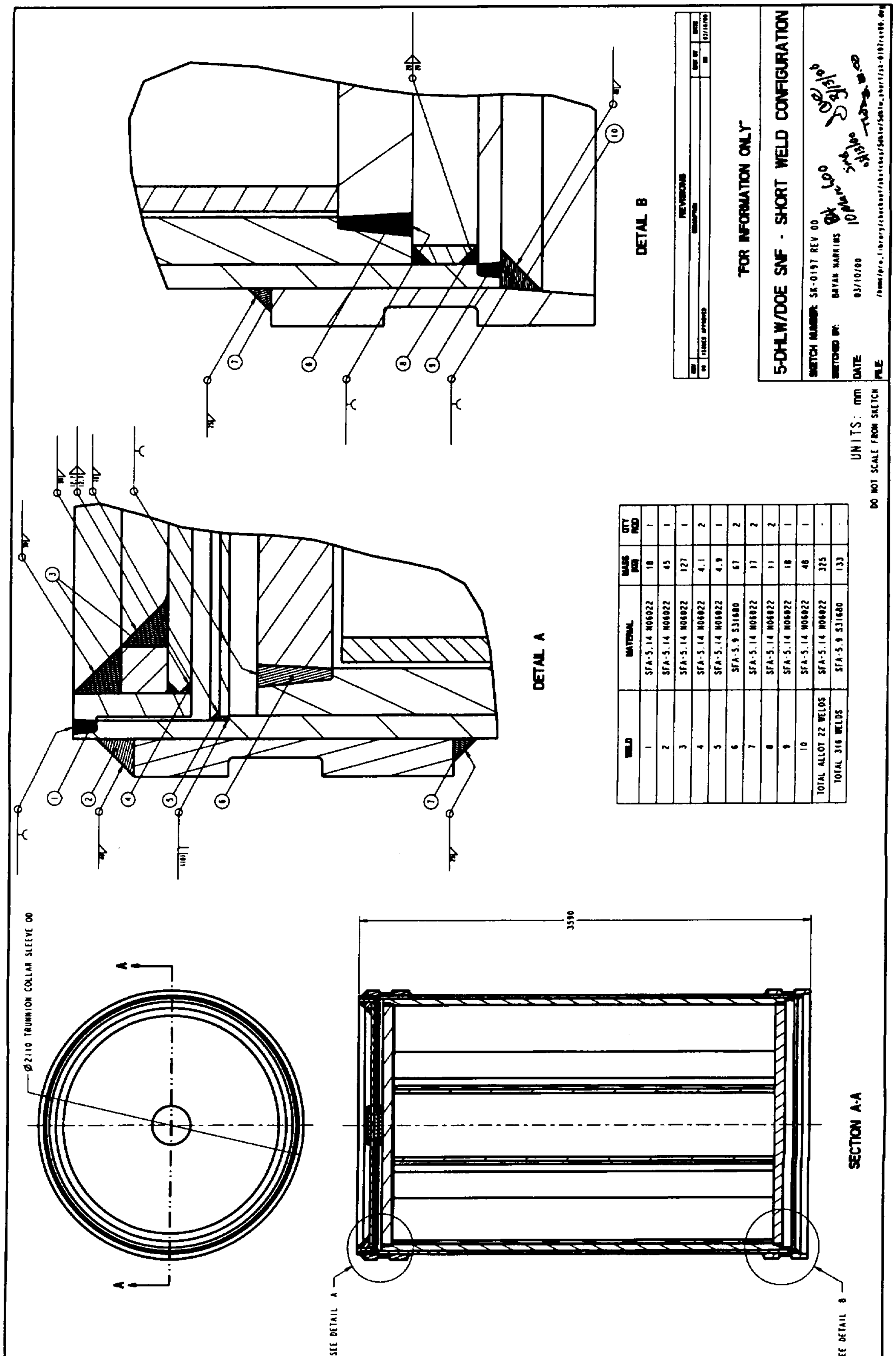
SKETCH NUMBER: SK-0196 REV 03 SHEET 1 OF 2

SKETCHED BY: EUGENE CONNELL EJC 06/06/00 SMB 06/06/00 SMB for MJA 06/06/00

DATE: 06/05/00

FILE: /home/pro_library/checkout/sketches/5dhlw_short/sk-0196_rev03.dwg


SK-0198 REV 03
SHEET 2 OF 2
DETAIL A
DETAIL B
DETAIL C
70 SUPPORT RING
25 OUTER SHELL FLAT BOTTOM LID
OUTER LID LIFTING FEATURE
INNER LID LIFTING FEATURE
EXTENDED OUTER LID REINFORCING RING
25 OUTER LID
30 CLOSURE LID TO OUTER LID GAP
10 CLOSURE LID WELD
10 CLOSURE LID
30 INNER LID TO CLOSURE LID GAP
40 INNER LID




| WELD | MATERIAL | MASS (KG) | QTY RQD |
|---|---|---|---|
| 1 | SFA-5.14 N06022 | 18 | 1 |
| 2 | SFA-5.14 N06022 | 45 | 1 |
| 3 | SFA-5.14 N06022 | 127 | 1 |
| 4 | SFA-5.14 N06022 | 4.1 | 2 |
| 5 | SFA-5.14 N06022 | 4.9 | 1 |
| 6 | SFA-5.9 S31680 | 67 | 2 |
| 7 | SFA-5.14 N06022 | 17 | 2 |
| 8 | SFA-5.14 N06022 | 11 | 2 |
| 9 | SFA-5.14 N06022 | 18 | 1 |
| 10 | SFA-5.14 N06022 | 48 | 1 |
| TOTAL ALLOY 22 WELDS | SFA-5.14 N06022 | 325 | - |
| TOTAL 316 WELDS | SFA-5.9 S31680 | 133 | - |

dk BE 11/7/00

# OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT SPECIAL INSTRUCTION SHEET

1. QA: QA

Page: 1 of: 2

*Complete Only Applicable Items*

**This is a placeholder page for records that cannot be scanned or microfilmed**

| | |
|---|---|
| 2. Record Date<br>10/25/2000 | 3. Accession Number<br>ATT-TO MOL.20001107.0303 |
| 4. Author Name(s)<br>ABDELHALIM ALSAED - PETER GOTTLEIB | 5. Author Organization<br>N/A |
| 6. Title<br>PROBABILITY OF CRITICALITY BEFORE 10,000 YEARS (ATTACHMENT III) | |
| 7. Document Number(s)<br>CAL-EBS-NU-000014, | 8. Version<br>REV. 00 |
| 9. Document Type<br>DATA | 10. Medium<br>CD-ROM |
| 11. Access Control Code<br>PUB | |
| 12. Traceability Designator<br>DC #25435 | |

13. Comments

THIS IS A SPECIAL PROCESS CD-ROM AND CAN BE LOCATED THROUGH THE RPC

NOTE: PER AP-17.1Q, REV.1, ICN 2, (ELECTRONIC FILES) THE ELECTRONIC INFORMATION ON THIS CD-ROM IS LOCATED AS AN ATTACHMENT TO THIS PAGE

files open in
MS WORD
BE
11/7/00

DC#25435

# OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
# ELECTRONIC SOURCE FILE VERIFICATION

QA: N/A

2 of 2

| | |
|---|---|
| 1. DOCUMENT TITLE: Probability of Criticality Before 10,000 Years | |
| 2. DOCUMENT IDENTIFIER: CAL-EBS-NU-000014 | 3. REVISION DESIGNATOR: 00 |

**ELECTRONIC SOURCE FILE INFORMATION**

| | | |
|---|---|---|
| 4. ELECTRONIC SOURCE FILE NAME WITH FILE EXTENSION PROVIDED BY THE SOFTWARE: 10k-00.doc | | |
| 5. DATE LAST MODIFIED: 09/24/00 | 6. ELECTRONIC SOURCE FILE APPLICATION: (I.E., EXCEL, WORD, CORELDRAW) WORD | 7. FILE SIZE IN KILOBYTES: 736 |
| 8. FILE LINKAGE INSTRUCTIONS/INFORMATION: N/A | | |
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| 11. PRINTER SPECIFICATION (i. e., HP4SI) INCLUDING POSTSCRIPT INFORMATION (I.E., PRINTER DRIVER) AND PRINTING PAGE SETUP (I.E., LANDSCAPE, 11 X 17 PAPER) HP4SI | | |
| 12. COMPUTING PLATFORM USED: (I.E., SUN) IBM Compatible PC | 13. OPERATING EQUIPMENT USED: (I.E., UNIX, SOLARIS) Microsoft Windows, Dell | |
| 14. ADDITIONAL HARDWARE/SOFTWARE REQUIREMENT USED TO CREATE FILE(S): NONE | 15. ACCESS RESTRICTIONS: (IF ANY) N/A | |

**COMMENTS/SPECIAL INSTRUCTIONS**

16. N/A

**CERTIFICATION**

| | | | |
|---|---|---|---|
| 17. NAME (Print and Sign) Halim Alsaed [signature] | | | 18. DATE: 10/27/2000 |
| 19. ORGANIZATION M&O | 20. DEPARTMENT WPD | 21. LOCATION/MAIN STOP 423 | 22. PHONE 295-3437 |

**DC USE ONLY**

| | | |
|---|---|---|
| 23. DATE RECEIVED: 10/27/2000 | 24. DATE REVIEWED: 11-06-2000 | 25. DATE FILES TRANSFERRED: 10/30/00 |
| 26. NAME (Print and Sign): ALICE V. BOYLES [signature: Alice V. Boyles] | | 27. DATE: 11-06-2000 |