Duratek ™

140 Stoneridge Drive
Columbia, South Carolina 29210
803-256-0450 fax 803-256-0968
www.duratekinc.com

8 April 2005
E&L-029-05

Meraj Rahimi, Senior Project Manager
Licensing Section
Spent Fuel Project Office
Office of Nuclear Material Safety and Safeguards, NMSS
U.S. Nuclear Regulatory Commission
Washington, DC 20555

Dear Mr. Rahimi:

Subject: Response to Request for Additional Information – Docket No. 71-9204

Duratek respectfully submits the enclosed materials as clarification to our
response, dated 7 March 2005, to your request for additional information (RAI)
dated 19 January 2005:

- Attachment 1: Clarification to Responses to the RAI. The clarification is
  referenced to the RAI comment to which it pertains.

- Attachment 2: Revised Appendix 4.10.2. In clarifying our RAI response,
  we determined that additional changes to Appendix 4.10.2 were needed.
  Please substitute the enclosed copy for the one originally submitted under
  Duratek document E&L-014-05.

- Attachment 3: Revised Appendix 4.10.2.5 In clarifying our RAI response,
  we determined that additional changes to Appendix 4.10.2.5 were needed.
  Please substitute the enclosed copy for the one originally submitted under
  Duratek document E&L-014-05.

- Attachment 4: Addition to Chapter 5. We have added an appendix to
  Chapter 5 to discuss the external radiation levels from the transport of
  INEEL waste.

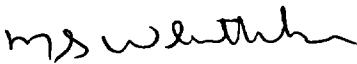Also enclosed are the following referenced documents:
1. "Methodology to Determine Radioisotope Contents in RH TRU
   Waste Drums from Irradiated Fuel Examination at ANL-E",
   INEEL/EXT-02-00169

2. "Expected Dose-Reduction Factors from Argonne National Laboratory-East Remote-Handled Waste in a 30-gal Drum Overpack", EDF-4365
3. "Dose Rate Outside Transport Cask 10-160B from Neutrons Generated in RH TRU Waste from ANL-E", ICP/EXT-05-00875
4. A. Zerwekh, "Gas Generation from Radiolytic Attack of TRU-Contaminated Hydrogenous Waste", LA-7674-MS

Should you or members of your staff have questions about the submittal, please contact Mark Whittaker at (803) 758-1898.

Sincerely,

So^r Patrick L. Paquin
General Manager – Engineering and Licensing

Attachments and Enclosures: As stated

Clarification to RAI Responses

A. Revised response to RAI comment 4.10.2 A-4

    (Note: Text changed to more closely match language in Appendix 4.10.2,
    Attachmnt A.6.0. Text **highlighted bold** to reflect change in original text)

    1. **Determine maximum allowable decay limit (Q) using alpha and beta dose-
        dependent G values and** non-dose-dependent G value for gamma radiation. (ID
        325B: Q=0.206 W, Appendix 4.10.2.5, Table 10-1)

    2. **Determine decay heat limit that excludes the gamma radiation contribution
        (Q_{allow}) as a function of the maximum allowable hydrogen gas generation
        rate (C_g) and bounding G value for the content code** using equation in Step 2.
        This limit will be lower value than the limit using dose-dependent G values.

    Maximum allowable hydrogen gas generation limit = 3.28e-8 mol/s (Appendix
    4.10.2.5, Table 10-1)

    Bounding G value: 5.61 molecules/100 eV (Appendix 4.10.2.5, Table 10-3)

    $$Q_{allow} = 3.28e\text{-}8(6.023e23)(1.602e\text{-}19)/(5.61/100 \text{ eV}) = 0.0564 \text{ W}$$

    3. The ratio (Q_{allow}/Q) **is less** than unity. Q_{allow}/Q = 0.0564/0.206 = 0.274

    4. By multiplying the **actual decay heat for the** waste drum by the ratio calculated
        in Step 3, a conservative value of the effective decay heat to use in determining
        whether the dose-dependent criterion (0.012 W-yr) has been met.

        If **actual decay heat** for waste drum = 4.85e-3 W, $Q_{watt\cdot yr}$ = 0.274 (4.85e-3 W) =
        1.33e-3 W

    5. Multiply the weighted decay heat value calculated in Step 4 by the total elapsed
        time that the waste has been irradiated. If this value is greater than 0.012 W-yr,
        then decay heat limit determined with dose-dependent G values can be used to
        determine the shippability of the waste.

        For drums described by ID 325B, minimum drum age is 9 years

        $$Q_{watt\cdot yr} * N = 1.33e\text{-}3(9) = 0.012 \text{ W-yr}$$

B. Clarification to response to RAI comment 4.10.2.5-7

    The 7.5-gallon waste cans are not considered to be sealed containers
    because holes were drilled in the sides of the cans to allow a cable to be
    attached to enable the waste cans to be moved by robotic arm (Reference
    12.1, Appendix 4.10.2.5). The fiberboard bag spreader, which is situated
    between the waste cans and the PVC bag, is open on top and serves only
    as a means of support for the innermost PVC bag as the waste cans are
    placed in the waste drum. Neither the waste cans nor the fiberboard bag
    spreaders inside the innermost PVC bag are considered confinement
    layers. Hydrogen release rate from openings in the waste cans via gas

diffusion will be significantly greater than the hydrogen release rate from the innermost sealed PVC bag surrounding the waste cans. As a result of the greater resistance to hydrogen release being the PVC bag, the hydrogen concentration inside the bag will be uniform. Thus, the innermost PVC bag is the first actual confinement layer to the waste.

It is also assumed that the site will adhere to all requirements pertaining to the waste contents, including proposed requirements in Section 4 of Appendix 4.10.2: "Sealed containers greater than four liters in volume that do not have a known, measured, or calculated hydrogen release rate or resistance are prohibited."

Hydrogen diffusion rates through heat sealed plastic bags are estimated as described in Appendix 4.10.2.5, Section 10.3. Thus, it is assumed in calculating the hydrogen generation rate and decay heat limits that there are no sealed containers greater than four liters inside the waste cans.

The waste packaging configuration figure and text clarifying the confinement layers will be added to Appendix 4.10.2.5.

C. Clarification of the release rate equation on page 4.10.2.5-9

The equation described in the Appendix 4.10.2.5 is identical to equation references in Appendix 6.13 of the CH-TRU Payload Appendices. However, different symbols are used to represent the equation parameters.
In order to obtain more clarity in Appendix 4.10.2.5, the following will be inserted after "where"
    RR   release rate of hydrogen (mole H_2/s/mole fraction H_2)

D. Clarification of response to RAI comment 4.10.2.5-13

In Appendix 3.2 (CH-TRU Payload Appendices), the equation for the effective G value, G_{eff}, is

$$G_{eff} = \sum_M (F_P \times F_M) \times G_M$$

where
F_P fraction of energy emerging from the particles
F_M fraction of energy absorbed by material M
G_M maximum G value for material M

For beta and gamma radiation, the fraction of energy emitted from source particles is unity. The fraction of emitted alpha radiation from a source particle can be affected by self-shielding depending on particle size. However, since the maximum effective G-value associated with alpha

radiation was determined experimentally (Appendix 3.3, CH-TRU Payload Appendices), this value already accounts for any self-shielding of alpha radiation.

The effective G-values in Table 10.3 assume that 100% of radiation is absorbed by the waste material. For alpha and beta radiation, the fraction of absorbed energy is unity. However, only a fraction of gamma energy will be absorbed in the package and the waste. The absorbed gamma energy is a function of energy, waste density, material type, and geometry. The gamma energy absorbed by the waste is a function of the gamma emission strength, the quantity of gamma ray energy that is absorbed by collision with a waste particle, and the number of particles which interact with the gamma ray. Therefore, gamma energy absorption increases with increasing waste density. For a given waste density, a larger container will contain more particles, and therefore a higher percentage of the gamma ray energy would be absorbed than in a smaller container.

The fraction of absorbed gamma radiation is calculated in RadCalc and used in the equation above to determine the true effective G value for waste exposed to gamma radiation. RadCalc uses curve fits obtained from Flaherty et al. (Appendix 4.10.2, Reference 12.7) and recalculated using the Monte Carlo N-Particle (MCNP) transport code (Appendix 4.10.2, Reference 12.8) for ten containers, for obtaining the absorbed gamma dose. A 6- by 6-foot liner with a volume equal to the CNS cask is used to represent the payload container in the RadCalc input file as the RadCalc database does not include the CNS cask.

E. Clarification of discussion of decay heat and minimum drum age included in response to RAI comment 4.10.2.5-13

Decay heat alone does not allow the determination of total dose for a waste container. The decay heat and the time history of the container are evaluated individually at the time of shipment to determine the dose value applicable to the container. The dose on the waste (expressed in units of watt-year) is defined as the product of the container decay heat and elapsed time from waste generation to compliance evaluation. The evaluation of the dose is performed on a container-by-container basis. Specifically, the elapsed time (in years) between the date of container closure and the date of decay heat compliance evaluation is calculated. The dose is calculated as the elapsed time multiplied by the reported decay heat of the container (in watts).

The 0.012 watt-year criterion is specifically to determine when it is appropriate to assume G value of 1.09 for solid organic waste instead of a value of 5.61 (Appendix 4.10.2.5, Table 10-3). In the case of Zerwekh, the limit data presented in the report indicates that this assumption is valid. In a number of test cylinders, the amount of Pu-238 was identified to be 62 or 31 milligrams (mg). The time for

the waste matrix in the cylinder to reach a total dose of 0.012 W-yr is 123 and 247 days, respectively. The inspection of the graphs plotting experimental G values versus elapsed test time indicates that for most organic waste matrices, experimental G values are similar to or less than 1.09 at elapsed time when the total dose equals 0.012 W-yr.

The assertion by the reviewer that the rate of change in the G value over a specifically long period of time (approximately two years) is a valid basis for requiring a minimum drum or waste age is not correct. The data of Zerwekh indicate that the G value in test cylinders is at or below 1.09 at the time when a total dose of 0.012 W-yr was achieved in the test cylinder while also decreasing by approximately 50% over a two-year period. The Zerwekh data validates the conclusion of the Matrix Depletion Study (Appendix 3.3, CH-TRU Payload Appendices) on which the watt-year criterion was established and provides no basis for justifying a minimum drum age requirement in addition to the existing watt-year criterion.

Appendix 4.10.2

TRU Waste Payload Control

1.0 INTRODUCTION

The purpose of this appendix is to identify the requirements for the control of remote handled transuranic (RH-TRU) and contact-handled transuranic (CH-TRU) waste, as defined by the U.S. Department of Energy (DOE) (Reference 12.1), as payload for transport in the CNS 10-160B cask.

The payload parameters that are controlled in order to ensure safe transport of the TRU waste in the CNS 10-160B cask are as follows:

- Restrictions on the physical and chemical form of CH-TRU and RH-TRU waste.

- Restrictions on payload materials to ensure chemical compatibility among all constituents in a particular CNS 10-160B cask (including the parts of the cask that might be affected by the payload).

- Restrictions on the maximum pressure in the CNS 10-160B cask during a 60-day transport period. (As a conservative analysis, the maximum pressure calculations are performed for a period of one year. Attachment C discusses the transport period.)

- Restrictions on the amount of potentially flammable gases that might be present or generated in the payload during a 60-day transport period.

- Restrictions on the layers of confinement for RH-TRU and CH-TRU waste materials in the waste containers packaged in the cask.

- Restrictions on the fissile material content for the cask.

- Restrictions on the hydrogen generation rates or the decay heat for the waste containers packaged in the cask.

- Restrictions on the weight for the loaded cask.

The methods for determining or measuring each restricted parameter, the factors influencing the parameter values, and the methods used by each shipping site for demonstrating compliance, are provided in the site-specific sub tier appendices.

This appendix also includes the following as attachments:

- Description of the use of dose-dependent G values for TRU wastes (Attachment A)
- Chemical compatibility analysis for the TRU waste content codes (Attachment B).
- Shipping period for TRU waste in the CNS 10-160B cask (Attachment C)

2.0 PURPOSE

2.1 Payload Parameters

The purpose of this appendix is to describe the payload requirements for RH-TRU and CH-TRU waste for transport in the CNS 10-160B cask. Detailed descriptions of the site compliance methods associated with these requirements shall be provided in the site-specific sub tier appendices. Any and all assumptions used in the site compliance methods will be specified in the site-specific sub tier appendices.

Sub tier appendices will be added, as necessary, to incorporate additional site-specific waste content codes that may be identified in the future. These appendices shall be submitted to the U.S. Nuclear Regulatory Commission (NRC) for review and approval, with shipments under additional codes authorized only after NRC approval.

Section 2.2 describes some typical methods of compliance available to show compliance with the individual payload parameter requirements. Section 3.0 describes the relationship between payload parameters and the classification of RH-TRU and CH-TRU materials into CNS 10-160B cask payload content codes. Sections 4.0 through 11.0 discuss each payload parameter requirements for the CNS 10-160B cask.

The payload parameters addressed in this document include:

- Physical form
- Chemical form and chemical properties
- Chemical compatibility
- Gas distribution and pressure buildup
- Payload container and contents configuration
- Isotopic characterization and fissile content
- Decay heat and hydrogen generation rates
- Weight.

2.2 Methods of Compliance

This section describes some typical methods that may be used to determine compliance with each payload parameter requirement and the controls imposed on the use of each method. Each shipping site shall select and implement a single compliance method, or a combination of methods, to ensure that the payload is compliant with each requirement and is qualified for shipment. These methods shall be documented in the site-specific sub tier appendices associated with this appendix.

A summary of typical methods of compliance that may be used for the 10-160B cask payload control is provided in the following sections.

2.2.1 Visual Examination

Visual examination at the time of waste generation may be used to qualify waste for transport. The operator(s) of a waste generating area shall visually examine the physical form of the waste according to site/equipment-specific procedures and remove all prohibited waste forms prior to its placement in the payload container. Observation of the waste generation process by an independent operator may be used as an independent verification of the compliance of the waste prior to closure of the payload container.

2.2.2 Visual Inspection

Visual inspection may be used to evaluate compliance with specific restrictions (e.g., visual inspection of payload container type, number of filters, etc.).

2.2.3 Radiography

Radiography may be used as an independent verification to qualify waste for transport. Radiography may be used to nondestructively examine the physical form of the waste, and to verify the absence of prohibited waste forms, after the payload container is closed.

2.2.4 Process Knowledge (Records and Database Information)

Process knowledge (PK) (also referred to as acceptable knowledge for the purposes of this document) refers to applying knowledge of the waste in light of the materials or processes used to generate the waste. PK is detailed information on the waste obtained from existing published or documented waste analysis data or studies conducted on wastes generated by processes similar to that which generated the waste. PK may include information on the physical, chemical, and radiological properties of the materials associated with the waste generation process(es), the fate of those materials during and subsequent to the process, and associated administrative controls. PK commonly includes detailed information on the waste obtained from existing waste analysis data, review of waste generating process(es), or detailed information relative to the properties of the waste that are known due to site-specific or process-specific factors (e.g., material accountability and tracking systems or waste management databases may supply information on waste isotopic composition or quantity of radionuclides, among other waste attributes). PK sources may include information collected by one or more of the compliance methods described in Sections 2.2.1 through 2.2.7.

Information obtained from existing site records and/or databases or knowledge of process may be used as a basis for reporting the absence of prohibited waste forms within waste containers. PK may also be used to show compliance with the physical and chemical form requirements and the payload container and contents requirements.

2.2.5 Administrative and Procurement Controls

Site-specific administrative and procurement controls may be used to show that the payload container contents are monitored and controlled, and to demonstrate the absence of prohibited items within waste containers.

2.2.6 Sampling Programs

Sampling programs may be used as an independent verification of compliance.

2.2.7 Measurement

Direct measurement or evaluation based on analysis using the direct measurement may be used to qualify waste (e.g., direct measurement of the weight or analysis of assay data to determine decay heat).

3.0 TRU WASTE PAYLOAD FOR CNS 10-160B CASK

RH-TRU and CH-TRU waste is classified into content codes, which give a description of the RH-TRU and CH-TRU waste material in terms of processes generating the waste, the packaging methods used in the waste container(s), and the generating site. Content codes for the RH-TRU and CH-TRU waste to be shipped from each site are provided in the site-specific sub tier appendices to this appendix. Each content code provides a listing of all the payload parameters, their corresponding limits and restrictions, and the methods used by the site to meet these limits.

4.0 PHYSICAL FORM REQUIREMENTS

The physical form of waste comprising the CNS 10-160B cask payload is restricted to solid or solidified materials in secondary containers. The total volume of residual liquid in a secondary container is restricted to less than 1% by volume. A secondary container is any container placed inside the primary

container, the CNS 10-160B cask. Secondary containers must be shored to prevent movement during accident conditions. Sharp or heavy objects in the waste shall be blocked, braced, or suitably packaged as necessary to provide puncture protection for the payload containers packaging these objects. Sealed containers greater than four liters in volume that do not have a known, measured, or calculated hydrogen release rate or resistance are prohibited.

5.0 CHEMICAL FORM AND CHEMICAL PROPERTIES

The chemical constituents allowed in a given content code determine the chemical properties of the waste. Specific requirements regarding the chemical form of the waste are as follows:

- Explosives, nonradioactive pyrophorics, compressed gases, and corrosives are prohibited.

- Pyrophoric radionuclides may be present only in residual amounts less than 1 weight percent.

- The total amount of potentially flammable volatile organic compounds (VOCs) present in the headspace of a secondary container is restricted to 500 parts per million (ppm).

6.0 CHEMICAL COMPATIBILITY

Each content code has an associated chemical list based on PK information. Chemical constituents in a payload container assigned to a given content code shall conform to these chemical lists (included in each site-specific sub tier appendix). Chemicals or materials that are not listed are allowed in trace amounts (quantities less than one weight percent) in a payload container provided that the total quantity of trace chemicals or materials is restricted to less than five weight percent.

Chemical compatibility of the waste within itself and with the packaging shall ensure that chemical processes would not occur that might pose a threat to safe transport of the payload in the 10-160B Cask. The basis for evaluating the chemical compatibility shall be the U.S. Environmental Protection Agency (EPA) document, "A Method for Determining the Compatibility of Hazardous Wastes" (Reference 12.2). This method provides a systematic means of analyzing the chemical compatibility of specific combinations of chemical compounds and materials. Any incompatibilities between the payload and the packaging shall be evaluated separately if not covered by the EPA method.

As described in Attachment B to this appendix, the EPA method classifies individual chemical compounds, identified in the list of allowable chemicals and materials, into chemical groups and identifies the potential adverse reactions resulting from incompatible combinations of the groups. Attachment B presents the methodology and results for the chemical compatibility analyses performed on the list of allowable chemicals and materials associated with the TRU waste content codes expected to be shipped in the 10-160B Cask.

Chemicals and materials included on the content code chemical lists (in concentrations greater than one weight percent) shall be a subset of the list of allowable materials identified in Table B-1 of Attachment B to this appendix to demonstrate compliance with the compatibility requirement. The results of the compatibility analyses show that these content codes can be transported without any incompatibilities.

7.0 GAS DISTRIBUTION AND PRESSURE BUILDUP

Gas distribution and pressure buildup during transport of TRU waste in the CNS 10-160B cask payload are restricted to the following limits:

- The gases generated in the payload must be controlled to prevent the occurrence of potentially flammable concentrations of gases within the payload confinement layers and the void volume of the inner vessel (IV) cavity. Specifically, hydrogen concentrations within the payload confinement layers are limited to 5 percent by volume during a maximum 60-day shipping period (see Attachment C).

- The gases generated in the payload and released into the IV cavity must be controlled to maintain the pressure within the IV cavity below the acceptable packaging design limit of 31.2 pounds per square inch gauge (psig).

The primary mechanism for gas generation during TRU waste transportation in the CNS 10-160B cask is by radiolysis of the waste materials. Gas generation from other mechanisms such as chemical, thermal, or biological activity is expected to be insignificant for the TRU waste payload. As discussed in Section 6.0, the chemicals and materials in the TRU waste are compatible and inert, and the restrictions of the materials that can be present in each content code precludes the occurrence of chemical reactions that can produce excessive gas. Gas generation from biological activity is expected to be insignificant given the transportation time, the nature of the waste (solid or solidified), and the environment of the payload (lack of nutrients, lack of water content, etc.). The temperatures of the payload, given the decay heat limits applicable, are expected to be below the normal usage range for the payload materials, resulting in very little potential for gas generation due to thermal decomposition.

8.0 PAYLOAD CONTAINER AND CONTENTS CONFIGURATION

Thirty-gallon and 55-gallon secondary containers may be used as payload containers in the CNS 10-160B. The available volume of the cask cavity limits the number of payload containers that may be shipped at one time. In the case of 55-gallon drums, a maximum number of ten drums can be loaded into the 10-160B cask. Payload containers must have at least one filter vent. Filter vents shall be legibly marked to ensure both (1) identification of the supplier and (2) date of manufacture, lot number, or unique serial number. Typically, for purposes of radiological safety, TRU waste in the payload container may be packaged in one or more layers of confinement (plastic bags). Bags are closed with a twist and tape, fold and tape or heat-sealed closure. Heat-sealed bags may have a filter vent or be unvented.

Any drum or rigid polymer liner present inside a payload container shall have a filter vent or an opening that is equivalent to or larger than a 0.3-inch diameter hole before the container is transported in the CNS 10-160B.

9.0 ISOTOPIC CHARACTERIZATION AND FISSILE CONTENT

9.1 Requirements

The CNS 10-160B cask payload allows fissile materials, provided the mass limits of Title 10, Code of Federal Regulations, Section 71.15 (10 CFR 71.15) are not exceeded. Plutonium content must not exceed 0.74 TBq (20 curies) per cask.

Compliance with the isotopic characterization and fissile content requirements involves the following steps:

- Determination of isotopic composition
- Determination of the quantity of radionuclides
- Calculation of the fissile mass and comparison with 10 CFR 71.15 limits
- Calculation of plutonium content and comparison with 20 curie limit.

9.1.1 Isotopic Composition

The isotopic composition of the waste may be determined from direct measurements taken on the product material during the processing or post-process certification at each site, analysis of the waste, or from existing records and PK. The isotopic composition of the waste need not be determined by direct analysis or measurement of the waste unless PK is not available.

9.1.2 Quantity of Radionuclides

The quantity of the radionuclides in each payload container shall be estimated by either PK or direct measurement of the individual payload container, a summation of assay results from individual packages in a payload container, or a direct measurement on a representative sample of a waste stream (such as solidified inorganics). An assay refers to one of several radiation measurement techniques that determine the quantity of nuclear material in TRU wastes. Assay instruments detect and quantify the primary radiation (alpha, gamma, neutron) emanating from specific radionuclides, or a secondary radiation emitted from neutron interrogation techniques. The measured quantity of radiation is then used to calculate the quantity of other radionuclides. That calculation requires knowledge of the isotopic composition of the waste. Combinations of gamma spectroscopy and neutron measurements are often needed to calculate the quantity of nonfissile radionuclides.

9.1.3 Calculation of Fissile Mass

The calculation of the fissile mass shall be performed to meet the requirements of 10 CFR 71.15.

9.1.4 Calculation of Plutonium Curies

The total plutonium (all plutonium isotopes) activity (curies) for each payload container shall be determined as described above and summed for the entire payload to demonstrate compliance with the 20 curie limit.

10.0 DECAY HEAT AND HYDROGEN GAS GENERATION RATES

10.1 Requirements

The hydrogen gas concentration shall not exceed five percent by volume in all void volumes within the CNS 10-160B cask payload during a 60-day shipping period (see Attachment C). Payload containers of different content codes with different bounding G values and resistances may be assembled together as a payload, provided the decay heat limit and hydrogen gas generation rate limit for all payload containers within the payload is conservatively assumed to be the same as that of the payload container with the lowest decay heat limit and hydrogen gas generation rate limit.

10.2 Methodology of Ensuring Compliance with Flammable Gas Concentration Limits

As stated in Section 7, chemical, biological, and thermal gas generation mechanisms are expected to be insignificant in the CNS 10-160B cask. In addition, potentially flammable VOCs are restricted to 500 ppm in the headspace of the CNS 10-160B cask secondary containers (Section 5). Therefore, the only flammable gas of concern for transportation purposes is hydrogen. The concentration of hydrogen within any void volume in a layer of confinement of the payload or in the cask IV has been evaluated during a 60-day shipping period (see Attachment C).

Each content code shall have a unique and completely defined packaging configuration. Modeling the movement of hydrogen from the waste material to the payload voids, using the release rates of hydrogen through the various confinement layers, defines the relationship between generation rate and void concentration. This modeling allows determination of the maximum allowable hydrogen generation rate for a given content code to meet the 5% concentration limit. Based on hydrogen gas generation potential, quantified by hydrogen gas generation G values, the gas concentration limit can be converted to a decay heat limit. The maximum allowable hydrogen generation rates and decay heat limits for each site-specific content code shall be determined and reported in the site-specific payload compliance appendix (sub tier to this appendix). The modeling methodology for determining the hydrogen gas generation rate limit and the decay heat limit shall be presented in each site-specific payload compliance appendix. Conservative assumptions may be used in site-specific subtier appendices to introduce an additional margin of safety.

Parameters that govern the maximum allowable hydrogen generation rates and maximum allowable decay heat limits are listed below:

- Waste packaging configuration (i.e., the number and type of confinement layers).

- Release rates of hydrogen from each of these confinement layers.

- Void volume in the cask IV available for gas accumulation.

- Operating temperature and pressure for the payload in the 10-160B cask IV during the shipping period.

- Duration of the shipping period (see Attachment C).

- Hydrogen generation rates quantified by the G value of a waste material (the number of molecules of hydrogen produced per 100 eV of energy absorbed) (see Attachment A for description of dose-dependent G values and the Matrix Depletion Program).

10.3 Determination of Maximum Allowable Hydrogen Generation Rate

The modeling for determination of the maximum allowable generation rates is described below.

10.3.1 Input Parameters

The model parameters that must be quantified include the following:

Waste Packaging Configuration and Release Rates:
Packaging configurations are content code specific and will be documented in the sub-tier appendices. The bags, any rigid container with an opening or filter vent, and the drum filter vent all provide some resistance to the release of hydrogen from the container.

Pressure: The pressure is assumed to be isobaric and equal to one atmosphere. The mole fraction of hydrogen in each void volume would be smaller if pressurization is considered and would result in a greater maximum allowable hydrogen gas generation rate. Furthermore, the amount of hydrogen gas generated during a 60-day shipping period would be negligible compared to the quantity of air initially present at the time of sealing the CNS 10-160B cask.

Temperature: The system temperature increases and decreases as the result of diurnal and seasonal variations in the environment (i.e, weather, solar radiation). Heat released from the radioactive components in the waste can also contribute to thermal input in the system.

The input parameters that can be described as a function of temperature are the release rate across the different confinement layers in the payload containers and the hydrogen G values for the waste streams. The resistance to the release of hydrogen is a function of temperature as documented in Appendix 3.6.12 of the TRUPACT-II SAR (Reference 12.3). The resistance generally decreases with increasing temperature and increases with decreasing temperature. The release rates across each confinement layer shall be defined at a specified temperature. The specified temperature shall be defined in terms of the expected operating temperature range. Since the release rates decrease with decreasing temperature, the use of the minimum expected operating temperature to calculate the lowest release rate will provide the maximum margin of safety when calculating the hydrogen gas generation rate or decay heat limit. Theoretically, the G value for a waste stream increases with increasing temperature (Reference 12.3). The G values at room temperature (i.e., 70°F) will be adjusted to the maximum expected operating temperature using the Arrhenius equation, unless it is demonstrated that the G values for the waste streams are not a function of temperature. The G values adjusted to reflect the maximum expected operating temperature would provide the maximum margin of safety in the calculated hydrogen gas generation rate or decay heat limits.

These are the important input parameters for determining the maximum allowable hydrogen generation rate limit. Other assumptions used in the mathematical analysis are included in Section 10.3.2.

10.3.2 Mathematical Analysis For Determining the Maximum Allowable Hydrogen Gas Generation Rates

At steady state, the flow rate of hydrogen across each of the confinement layers is equal to the same value and to the hydrogen generation rate. The maximum hydrogen concentration in a payload container with filter vents is reached at steady state. That is, a filter vented container with a hydrogen generation source has increasing concentrations of hydrogen with time until steady state conditions are reached. For the purpose of these calculations, it has been assumed that all payload containers are at steady state at the start of transport.

Once the drums are sealed inside the CNS 10-160B cask IV, concentrations of hydrogen in the different layers increase due to the accumulation of hydrogen in the IV cavity. Some of the hydrogen generated during the transport period would accumulate in the payload containers, with the remainder being released into the cavity. For the purpose of these calculations, the mole fraction of hydrogen in a bag layer is set equal to the steady state value plus the mole fraction of hydrogen that has accumulated in the cavity. The IV cavity mole fraction of hydrogen is obtained by assuming that all of the hydrogen generated is released into the IV cavity. The maximum hydrogen concentration in the innermost layer is then limited to less than or equal to five (5) volume percent at the end of the shipping period by suitably choosing the gas generation rates. The maximum number of moles of hydrogen which can accumulate in the IV cavity is:

$$N_{gen} = (CG)(n_{gen})(t)$$

Where:

N_{gen}	=	total moles of hydrogen generated
CG	=	hydrogen gas generation rate per innermost layer of confinement (moles/sec)
n_{gen}	=	number of hydrogen generators (payload containers) in the CNS 10-160B cask

t = shipping period duration, s

The maximum mole fraction of hydrogen in the CNS 10-160B IV cavity is then equal to:

$$X_{fh} = (N_{gen}/N_{tg}) = \{N_{gen}/[P(V_{void})/RT]\}$$

Where:

X_{fh} = maximum mole fraction of hydrogen in the CNS 10-160B IV cavity
N_{tg} = total moles of gas inside the CNS 10-160B IV cavity
P = pressure inside the CNS 10-160B, assumed to be constant at 1 atm (760 mm Hg), because the amount of gas generated is much less than the total amount of air originally in the cavity
V_{void} = void volume inside the CNS 10-160B IV cavity (liters)
R = gas constant = 62.361 mm Hg-liter/mole-K
T = absolute temperature of air in the CNS 10-160B IV cavity at the time of closure = 70°F = 294K

The gas generation rate per innermost confinement layer that will yield a maximum hydrogen concentration of five (5) volume percent is then computed as the following:

$$X_{inner} = X_{fh} + (CG)(R_{eff})$$

Where:

X_{inner} = mole fraction of hydrogen in innermost confinement layer (a value of 0.05 has been used for this parameter since this is the maximum permissible concentration)
R_{eff} = the effective resistance to the release of hydrogen (sec/mole)

The effective resistance is computed by summing the individual confinement layer resistances. The resistance of a layer is equal to the reciprocal of the release rate from that layer. After substituting the first two equations into the third for X_{inner} and solving for the gas generation rate the following results:

$$CG = (X_{inner})/\{R_{eff} + [(t)(n_{gen})/N_{tg}]\}$$

where all terms are as defined previously.

10.4 Determination of Maximum Allowable Decay Limits for Content Codes

The maximum allowable decay heat limit for the CH-TRU waste content codes will be calculated assuming 100% deposition of the emitted energy into the waste within the drum. Specifically, the decay heat limit is calculated from the hydrogen gas generation rate and effective G-Value through the following expression:

$$Q = [(CG)(N_A)/(G_{eff} \text{ molecules}/100eV)][1.602 \times 10^{-19} \text{ watt-sec/eV}]$$

Where:

CG = Hydrogen gas generation rate per innermost confinement layer in one drum (mol/sec).
Q = decay heat per innermost confinement layer (watts)

N_A = Avogadro's number = 6.023×10^{23} molecules/mole
G_{eff} = G (hydrogen gas) = effective G value for flammable gas (molecules of hydrogen formed/100 electron volts [eV] emitted energy).

The maximum allowable decay heat limits for the RH-TRU waste content codes will be determined using the RadCalc Software (Reference 12.4). The current version of RadCalc is a Windows-compatible software program with applications in the packaging and transportation of radioactive materials. Its primary function is to calculate the generation of hydrogen gas by radiolytic production in the waste matrix of radioactive wastes. It contains a robust algorithm that determines the daughter products of selected radionuclides. The various functions in RadCalc can be used separately or together. The procedure is outlined below.

The first step in the evaluation of decay heat limits involves determining the activities of the radionuclides and daughters and the associated hydrogen gas generation rate at the time of sealing based on an initial isotopic ratio for the waste. The generation of hydrogen gas by radiolysis is a function of the energy absorbed by the waste. The second step in the evaluation of decay heat limits involves iterating on the total activity (decay heat limit) given the activity fractions from step one until the allowable hydrogen gas generation rate is obtained.

10.4.1 Databases and Input Parameters Used For Calculation of Maximum Allowable Decay Heat Limits

10.4.1.1 Radionuclide Databases

RadCalc uses radionuclide information, calculated gamma absorption fractions for selected container types, and G values to determine decay heat values. Radionuclide information is taken from FENDL/D-1.0 database (Reference 12.5). The following are a list of radionuclide parameters taken from FENDL/D-1.0 and the values they are used to calculate:

- Radionuclide half-lives are used in calculating specific activity

- Average heavy particle, beta-type radiation, and gamma radiation energies per disintegration are used in decay heat and hydrogen gas generation calculations

- Discrete gamma energies and abundances are used in hydrogen gas generation calculations.

RadCalc uses the ORIGEN2 (Reference 12.6) database for decay calculations. The decay algorithms calculate the activity of the user specified source and daughter products over a specified period of time and the total number of disintegrations accumulated over this same time interval for each radionuclide. Parameters relevant to these calculations include atomic mass, atomic number, and state. These parameters are used for radionuclide identification and conversions. The decay constant and the branching ratios for decay modes are also used in the decay algorithms.

10.4.1.2 Gamma Absorption Fraction Input Parameters

RadCalc uses the total energy emitted by heavy particle and beta-type decay in calculating the volume of hydrogen produced. However, only a percent of gamma energy will be absorbed in the package and the waste. The absorbed gamma energy is a function of energy, waste density, material type, and geometry. The gamma energy absorbed by the waste is a function of the gamma emission strength, the quantity of gamma ray energy that is absorbed by collision with a waste particle, and the number of particles which interact with the gamma ray. Therefore, gamma energy absorption increases with increasing waste

density. For a given waste density, a larger container will contain more particles, and therefore a higher percentage of the gamma ray energy would be absorbed than in a smaller container. The total cumulative absorbed dose for all nuclides and decay modes at time, t is evaluated as:

$$D_{total}(t) = \sum_{i=1}^{NR} A C_i / \&_i \ (0.82E_i^{\lor} + E_i^{\beta} + E_i^{\flat} + E_i^{x})[1 - \exp(-\&_i t)]$$

where,

$D_{total}(t)$	=	Total cumulative absorbed dose at time, t (rad)
A	=	A proportionality constant equal to 1.84×10^{10} rad gram MeV^{-1} yr^{-1} Ci^{-1}
C_i	=	The specific activity of the "i"th nuclide in Curies/gram of waste
$\&_i$	=	The decay constant of the "i"th radionuclide (yr^{-1})
NR	=	Number of radionuclides
$E_i^{\lor}$	=	$\lor$ energy in MeV of the "i"th radionuclide extracted from Flaherty et al. (Reference 12.11)
E_i^{β}	=	Average beta energy in MeV of the "i"th nuclide. The average beta energy is approximately one-third of the sum of the possible beta emissions multiplied by the relative abundance of each emission and were obtained from Flaherty et al. (Reference 12.7).
Eix	=	The absorbed secondary energy in MeV of the "i"th radionuclide. The secondary radiations result from the transition of a radionuclide from an excited state to the ground state and were obtained from Flaherty et al. (Reference 12.7).
Eiɔ	=	The absorbed gamma ray energy in MeV of the "i"th nuclide. The fraction of gamma energy that is absorbed by the waste is a function of the waste density and waste container geometry, and is evaluated for each radionuclide "i" as:

$$E_i^{\flat} = \Gamma_j \ n_{ij} \ f_{ij} \ E_{ij}^{\flat}$$

where,

Γ_j	=	the summation of the fractions of the gamma ray energies absorbed for all gamma emissions of the "i"th nuclide.
n_{ij}	=	the abundance of the "j"th gamma ray per decay of the "i"th nuclide
fij	=	the fraction of energy, of the "j"th gamma ray of the "i"th nuclide that is absorbed in the waste.
$E_{ij}^{\flat}$	=	the energy in MeV, of the "j"th gamma ray of the "i"th nuclide.

RadCalc uses curve fits obtained from Flaherty et al. (Reference 12.7) and recalculated using the Monte Carlo N-Particle (MCNP) transport code (Reference 12.8) for ten containers, for obtaining the absorbed gamma dose.

The CNS cask is not currently recognized by the RadCalc software. Therefore, another container with dimensions directly proportional to the cask was used in the calculations.

10.4.1.3 G Value Data

G values for TRU waste are content specific. G values are determined based on the bounding materials present in the payload. The G values at room temperature (i.e., 70°F) will be adjusted to the maximum expected operating temperature using the Arrhenius equation (unless data shows that the G values are

temperature independent) in order to introduce a greater margin of safety in the calculated hydrogen gas generation rate or decay heat limits. The use of temperature-dependent and or dose-dependent G values for authorized content codes is discussed in the individual site-specific sub tier appendices. The methodology associated with the determination of dose-dependent G values pursuant to the Matrix Depletion Program is further discussed in Attachment A of this Appendix.

10.4.2 Input Parameters

The input parameters for the RadCalc software can be placed in three groups: (1) container data, (2) waste data, and (3) source data.

10.4.2.1 Container Data

RadCalc requires as input the following parameters associated with the container for which the maximum allowable decay heat limit is being calculated:

Container Type - The payload container for the waste material
Container Dates - Date of generation, date of sealing, and shipping period
Package Void Volume - void volume of the payload container.

A 6- by 6-foot liner with a volume equal to the CNS cask is used to represent the payload container in the RadCalc input file as the RadCalc database does not include the CNS cask. The package void volume for a CNS 10-160B cask is 1938 liters as shown earlier.

10.4.2.2 Waste Data

RadCalc requires as input the following parameters associated with the waste for which the maximum allowable decay heat limit is being calculated:

Physical Form – liquid, solid, or gas
Waste Volume – volume of the waste, cm^3
Waste Mass – mass of the waste, g
G Value – G value of the waste, molecules per 100 eV

Liquids and gas wastes are prohibited in the CNS 10-160B cask. The volume of the waste is determined based on the maximum number of 55-gallon drums that can be placed in the 10-160B cask. The waste volume in one drum is assumed to be 217 liters per drum (the external volume of a 55-gallon waste drum) and 2170 liters for 10 drums of waste in the cask. The waste volume is used by RadCalc, along with the waste mass, to determine the volume of hydrogen generated in the cask. The mass of the waste is calculated based on the assumed bulk density of the waste. The volume of hydrogen generated is a function of container waste density and geometry (Reference 12.7). The most conservative estimate of the volume of hydrogen (greatest volume) would occur at the highest possible bulk density of the waste. Appropriate density values for the RH-TRU content codes are discussed in the individual site-specific sub-tier appendices.

10.4.2.3 Source Data

RadCalc requires as input the following parameters associated with the source for which the maximum allowable decay heat limit is being calculated:

Isotopic Composition - List of radionuclides present in the waste

Activity - Reported activities of the listed radionuclides in curies or Becquerel.

10.4.3 Procedure For Determining Maximum Allowable Decay Heat Limits

The necessary inputs are provided to the code prior to initiating a run. A time period of 60 days is conservatively assumed between date of beginning of decay and date of analysis to reflect the shipping period. The model is run with the initial isotopic composition and activity and the corresponding hydrogen gas generation rate is obtained. It is compared with the maximum allowable hydrogen gas generation rate as obtained from Section 10.3, and the scaling factor is obtained by dividing the maximum allowable hydrogen gas generation rate by the RadCalc obtained rate. The isotopic composition is scaled by this differential factor. This is done on the basis of the assumption that the maximum decay heat occurs at the time of maximum activity that will result in the maximum hydrogen gas generation rate. |
The associated decay heat value will be the maximum decay heat limit as the decay heat limit shares a direct relationship with the hydrogen gas generation rate, independent of time.

10.5 Methodology for Compliance with Payload Assembly Requirements

Prior to shipping, the Transportation Certification Official at the shipping site (TCO) shall ensure that the CNS 10-160B Cask payload consists of payload containers belonging to the same or equivalent content code. In the event that payload containers of different content codes with different bounding G values and resistances are assembled together in the CNS 10-160B Cask, the TCO shall ensure that the decay heat and hydrogen gas generation rate for all payload containers within the payload are less than or equal to the limits associated with the payload container with the lowest decay heat limit and hydrogen gas generation rate limit.

11.0 WEIGHT

The weight limit for the contents of the loaded cask is 14,500 pounds.

12.0 REFERENCES

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Attachment A

Use of Dose-Dependent G Values for TRU Wastes

A.1.0 BACKGROUND

This attachment describes controlled studies and experiments that quantify the reduction in the rate of hydrogen gas generation (G value) over time based on the total dose received by the target matrix. Over time and with constant exposure to radiation, hydrogen is removed from the hydrogenous waste or packaging material (the matrix), thus decreasing the number of hydrogen bonds available for further radiolytic breakdown (the matrix is depleted). Therefore, when the alpha-generating source is dispersed in the target matrix, it will affect only that portion of the target material that is present in a small spherical volume surrounding the source particle. As the amount of available hydrogen is reduced over time, the effective G value decreases with increasing dose toward a value that is defined as the "dose-dependent G value." This phenomenon of matrix depletion has been studied and observed in previous studies (see Appendix 3.3 of the CH-TRU Payload Appendices [Reference A.7.1]). A formal study was recently undertaken to quantify dose-dependent G values under strictly controlled conditions and evaluate their applicability to transuranic (TRU) wastes (Reference A.7.2). This appendix summarizes the results of this study and derives dose-dependent G values for TRU waste materials, as applicable.

A.2.0 OVERVIEW OF THE MATRIX DEPLETION PROGRAM

The Matrix Depletion Program (MDP), established as a joint venture by the U.S. Department of Energy (DOE) National TRU Waste Program and the DOE Mixed Waste Focus Area, is comprised of the following elements:

1. Laboratory experiments for the assessment of effective G values as a function of dose for matrices expected in contact-handled (CH)-TRU wastes (polyethylene, polyvinyl chloride, cellulose, etc.), as well as an assessment of the impact of other variables (isotope, temperature, etc.) on the dose-dependent G values.

2. Measurements of effective G values and hydrogen concentrations in real waste and comparisons with dose-dependent G values.

3. Analysis to calculate effective G values from fundamental nuclear and molecular mechanisms.

A total of 60 one-liter test cylinders containing the simulated TRU waste materials were used, with two replicates for each test. Solid waste matrices (plastics and cellulose) were prepared by sprinkling the radioactive isotope powders over the matrix, folding the matrix over the contaminated surfaces, securing them, and placing them in test cylinders. Solidified waste matrices (cement) were mixed with a solution of dissolved plutonium oxide, water, and sodium hydroxide to adjust the pH. The test cylinders were connected to measurement devices that facilitated sampling of generated gases and quantifying the gas generation over time. The entire test apparatus was controlled by a personal computer through LABVIEW software.

All activities of the MDP were performed under a documented quality assurance (QA) program that specified the performance-based QA/quality control requirements for all aspects of the program (Reference A.7.3). The experiments under the MDP were designed using an U.S. Environmental Protection Agency established procedure to formulate data quality objectives. QA objectives for the MDP were defined in terms of precision, accuracy, representativeness, completeness, and comparability. All data were validated and verified pursuant to the performance objectives of the program. The MDP was run for a duration of approximately three years.

A.3.0 RESULTS AND CONCLUSIONS FROM THE MDP

Results from the MDP are described in detail in the MDP final report (Reference A.7.2) and are summarized in Table A-1 in terms of the dose-dependent G values for each matrix tested.

For all matrices, these dose-dependent G values were achieved within a maximum dose of 0.006 watt*year (product of watts times years). For example, for a waste container with a watt loading of 0.1 watt, the dose-dependent G value shown in Table A-1 would be reached after 0.06 years or 22 days. The lower the watt loading, the longer it would take for the watt*year criteria to be satisfied and the dose-dependent G value to be applicable.

Table A-1. Experimental Dose-Dependent G Values					
Matrix	Current Waste Material Type G Value	Number of Observations	Mean	Standard Deviation	95% Upper Tolerance Limit
Cement	1.3	202	0.25	0.18	0.58
Dry Cellulose	3.4	302	0.27	0.18	0.59
Polyethylene	3.4	186	0.23	0.22	0.64
Polyvinyl Chloride	3.4	99	0.14	0.19	0.50
Wet Cellulose	3.4	276	0.44	0.36	1.09

Source: Reference A.7.1.

The following conclusions can be drawn from the results of the MDP:

• Increasing dose (product of the decay heat loading and elapsed time) decreases the effective G value for hydrogen due to depletion of the matrix in the vicinity of the alpha-emitting radioactive source particle. The lower G value, called the "dose-dependent G value," is applicable after a dose of 0.006 watt*years.

• As with initial G values, the dose-dependent G values are a function of the waste matrix.

• Dose-dependent G values for wet cellulosics were higher than those for dry cellulosics because of the presence of water.

• The dose-dependent G values were independent of temperature based on testing performed at room temperature and at 140°F.

• Experiments performed with different particle sizes show that while initial G values could be higher for smaller particle sizes, the dose-dependent G values for all particle sizes tested are bounded by the values shown in Table A-1.

• Previous experiments that included agitation of cylinders similar to those used in the MDP indicated that agitation did not affect dose-dependent G values (See Section A.4.0).

• Isotopic composition did not have a significant impact on the dose-dependent G values based on experiments performed with two different isotopes of Pu (^{238}Pu and ^{239}Pu).

Data from actual CH-TRU waste containers at the Rocky Flats Environmental Technology Site and the Idaho National Engineering and Environmental Laboratory show that even when compared to the mean dose-dependent G values from the matrix depletion experiments, G values from real waste containers are lower. Theoretical analysis, using nuclear and molecular level mechanisms, also shows that hydrogen generation from radiolysis and matrix depletion is consistent with the experimental results from the MDP.

A.4.0 EFFECTS OF AGITATION ON DOSE-DEPENDENT G VALUES

The effects of agitation on dose-dependent G values have been evaluated by previous studies at both the laboratory-scale and drum-scale levels, and agitation has been found to have no impact on dose-dependent gas generation rates. Agitation could occur under transportation conditions but, as shown below, does not cause redistribution of the radionuclides to a nondepleted portion of the waste matrix and therefore does not cause an increase in the dose-dependent G values as shown in this section.

The earliest study of the effects of agitation on gas generation rates was performed by Zerwekh at the Los Alamos National Laboratory (LANL) in the late 1970s (Reference A.7.4). Zerwekh prepared an experimental array of 300-cm^3 stainless steel pressure cylinders, each loaded with 52.5 grams of a single or a combination of TRU waste matrix materials. Materials tested included cellulosics, polyethylene (PE) (low-density) bags, PE (high-density) drum liner material, and other typical TRU waste material. Net gas G values as a function of elapsed time were derived for each of the test cylinders and showed the characteristic decrease in G value with dose. Thorough mechanical shaking of two of the cylinders on two different occasions did not affect the rate of gas generation (Reference A.7.4).

In a second study, researchers at LANL retrieved six drums of ^{238}Pu contaminated waste from storage to study gas generation (Reference A.7.5). The wastes were contained in 30-gallon drums and consisted of either mixed cellulosic wastes or mixed combustible wastes. The drums ranged in age from four to ten years. Two of the drums containing mixed combustible wastes were tumbled end over end in a drum tumbler for four hours (Reference A.7.5). The researchers also reported G values for three drums of newly generated waste that were previously characterized. All six retrieved drums had measured G values that were lower than those measured for newly generated drums. The researchers concluded that the retrieved drums' effective hydrogen G values corroborate the matrix depletion observed for the laboratory-scale experiments in Reference A.7.4. Also, because of the vigorous nature of the agitation experienced by two of the four-year-old drums, the researchers concluded that radionuclide redistribution does not occur under transportation conditions (Reference A.7.5).

More recently, experiments on alpha radiolysis were conducted at LANL by Smith et al. (Reference A.7.6) to determine radionuclide loading limits for safe on-site storage of containers at LANL. Simulated TRU waste matrices in the form of cellulose (cheesecloth and computer paper) and PE (bottle and bag material forms) were contaminated with pre-weighed amounts of ^{238}PuO$_2$ powder. The first PE experiment (referred to as PE test cylinder 1) used a PE bottle to allow any potential later redistribution of the radionuclide particles to fresh matrix surfaces. The radionuclide powder was poured into the bottle, which was sealed and gently rolled to allow contamination of the sides of the bottle. The bottle was returned to an upright position and the lid was punctured with an approximately 0.5-inch diameter hole to allow free movement of generated gas from the bottle to the test canister. It was noted that the ^{238}PuO$_2$ powder adhered to the walls of the bottle and very little, if any, collected at the bottom. The remaining five test sample matrices were prepared by uniformly sprinkling the powder across a letter-sized sheet of the waste matrix, folding the sheet in toward the center from each end, and finally rolling each sheet into a cylindrical shape of about 2 by 4 inches. The six test matrices were placed inside six cylindrical, 2.06 liter stainless steel sealed canisters. Gas samples were extracted periodically and analyzed by mass spectrometry.

The first test canister for each waste material was subjected to vigorous dropping, rolling several times, and shaking on day 188 to simulate drum handling and transportation that could result in redistribution of the $^{238}PuO_2$ to fresh nondepleted portions of the waste matrix. Any agitation effects were expected to be most pronounced for the test canister containing the PE bottle in PE test cylinder 1, because some aggregation of the powder at the bottom of the bottle was expected. However, no change in the effective hydrogen G value was observed for either the cellulose or PE test canisters.

In summary, three separate studies have investigated the ability of agitation to redistribute radionuclide particles to nondepleted surfaces of TRU waste matrices. All three studies conclusively showed that the dose-dependent G values are not impacted by agitation during transportation. Application of dose-dependent effective G values is discussed in Section A.5.0.

A.5.0 APPLICATION OF DOSE-DEPENDENT G VALUES TO CH- and RH-TRU WASTES

Application to CH-TRU dose-dependent G values, based on the results of the MDP, are applicable to solid organic and solid inorganic CH-TRU waste material types. Solidified organic and inorganic solid wastes will be governed by the initial G values under all conditions because the solidified, aqueous nature of these waste forms, in theory, precludes observation of matrix depletion (as the matrix near the Pu is depleted, water can move to replace the depleted matrix). The watt*year criteria used to apply dose-dependent G values is twice the highest value recorded in the experiments. The dose-dependent G values chosen for the TRU waste materials are the 95% upper tolerance limit values shown in Table A-1. The application of dose-dependent G values to the waste types is as follows:

- Solid Inorganic Waste: Dose-dependent G value (H_2) for containers meeting a watt*year criteria of 0.012 is governed by assuming polyethylene as the packaging material, with a G value (H_2) of 0.64.

- Solid Organic Waste: Dose-dependent G value for containers meeting a watt*year criteria of 0.012 is governed by wet cellulosic materials in the waste, with a G value (H_2) of 1.09.

As can be seen from Table A-1, the above dose-dependent G values represent conservative values that are more than two times the mean value from the experiments.

The phenomenon of matrix depletion primarily stems from the nature of the waste matrix and the type of penetrating radiation; thus, if the waste matrix and radiation type are properly accounted for, G value results obtained for CH-TRU waste can be applicable to RH-TRU waste as well.

With respect to waste matrix, both CH- and RH-TRU waste are characterized by a large percentage of the materials shown in Table A-1. Thus, the required level of conservatism will be attained by assuming that the waste is comprised of the matrix with the greatest associated G value.

With respect to radiation type, both CH- and RH-TRU waste are characterized by large amounts of alpha and beta emitters; the primary difference between the two waste forms is the noticeable presence of gamma emitters in RH-TRU waste. Thus, while the G value for CH-TRU waste is dependent primarily on the emitted decay heat (since most or all of the alpha and beta radiation is absorbed by the waste matrix and contributes to hydrogen gas generation), the G value for RH-TRU waste is dependent on the actual fraction of the decay heat that is absorbed by the waste matrix.

Since the results of the MDP are applicable only to alpha and beta radiation, while gamma radiation effects were not quantified, G values for RH-TRU waste can be separated into those for alpha, beta, and gamma radiation and treated accordingly. Thus, RH-TRU waste G values for alpha and beta radiation can be treated as being dose-dependent and the lower "dose-dependent G value" used after a dose of

0.012 watt*years (twice the highest value recorded in the experiments), while G values for gamma radiation can conservatively be treated as not being dose-dependent and the initial G value used.

A.6.0 COMPLIANCE WITH WATT*YEAR CRITERIA

For RH-TRU waste, content codes using dose-dependent G values to obtain maximum allowable decay heat limits are required to comply with the watt*year criteria of 0.012 watt*years. Demonstration of compliance with the 0.012 watt*year criteria is carried out as follows:

1. Determine maximum allowable decay heat (Q) using the α and β dose-dependent G values and non-dose-dependent G values for γ radiation.

2. Determine decay heat limit that excludes the gamma radiation contribution (Q_{allow}) as a function of the maximum allowable hydrogen gas generation rate (Cg) and bounding G value for the content code as:

$$Q_{allow} = \frac{Cg \ * \ N_A \ * \ 1.602(10)^{-19} \ watt\text{-}sec/eV}{G}$$

where,

Cg   =   Maximum allowable hydrogen gas generation rate limit obtained using the methodology described in site-specific sub tier appendices.

G   =   Bounding G value (molecules of hydrogen formed/100 electron volts [eV] emitted energy)

N_A =   Avogadro's number (6.023×10^{23} molecules/mole).

3. Determine the Q_{allow}/Q ratio, which represents the minimum fraction of the total container decay heat that excludes the gamma radiation contribution.

4. Calculate the decay heat value for a container ($Q_{watt*yr}$) for watt*year compliance as:

$$Q_{watt*yr} = \frac{Q_{allow}}{Q} * Q_{actual}$$

where, Q_{actual}, is the actual decay heat value for the container.

5. The watt*year for the payload is calculated as $Q_{watt*yr}$ times the elapsed time, and this value is compared to the 0.012 watt*year limit. The elapsed time is the time elapsed between the time of generation of the payload and the time of sealing of the payload.

A.7.0 REFERENCES

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Attachment B

Chemical Compatibility of
TRU Waste Content Codes

B.1.0 INTRODUCTION

This attachment describes the method used for demonstrating chemical compatibility in a given payload container, within a given waste stream/content code, and among content codes for the CNS-10-160B Cask payload. The chemical compatibility analyses cover normal conditions of transport as well as hypothetical accident conditions.

B.2.0 METHODOLOGY FOR CHEMICAL COMPATIBILITY ANALYSES

The chemical compatibility analysis was performed using the methods described in the EPA document "A Method for Determining the Compatibility of Hazardous Wastes" (Reference B.3.1).

Waste streams/content codes are classified as potentially chemically "incompatible" if the potential exists for any of the following reactions:

- explosion
- heat generation
- gas generation (flammable gases)
- pressure build up (nonflammable gases)
- toxic by-product generation
- fire
- violent polymerization
- solubilization of toxic substances.

Note: Solubilization of toxic substances and toxic byproduct generation are not directly a concern for transportation of waste in the CNS 10-160B Cask payload but have been included for completeness.

Each generator and storage site has produced a comprehensive list of chemicals present in an approved content code. These chemical components are determined by examining the process technology, and by comprehensive analyses of the process knowledge. Under this system, all chemical inputs into the system are accounted for, even though all of these components may not be a final part of the waste. For example, generator sites might include both acids and bases in their lists, even though the two groups have been neutralized prior to placement in a payload container.

A list of chemicals/materials that may be present in TRU waste in concentrations greater than or equal to 1 percent by weight was compiled based on process knowledge from the potential waste shipping sites, as shown in Table B-1. The chemical compatibility analyses for the CNS 10-160B Cask payload are then based on this table.

Although Table B-1 only identifies chemicals/materials in TRU waste in concentrations greater than or equal to 1 percent by weight, interactions involving compounds present in trace quantities (<1 percent by weight) do not pose an incompatibility problem for the following reasons:

- Most trace chemicals reported by the sites are in concentrations well below the trace limit of 1 weight percent.

- The trace chemicals are usually dispersed in the waste, which further dilutes concentrations of these materials.

- Total trace chemicals within a payload container are limited to less than 5 weight percent.

Table B-1
Table of Allowable Materials for TRU Waste[a]

Absorbent polymers, organic
Absorbents/adsorbents (e.g., Celite®, diatomaceous earth, diatomite, Florco®, Oil-Dri®, perlite, vermiculite)
Acids (inorganic and organic)
Alcohols (e.g., butanol, ethanol, isopropanol, methanol)
Alumina cement
Aquaset® products (for aqueous solutions)
Aqueous sludges or solutions
Asbestos
Ash (e.g., ash bottoms, fly ash, soot)
Asphalt
Bakelite® b
Batteries, dry (e.g., flashlight)
Caustics
Cellulose (e.g., Benelex®, cotton Conwed®, paper, rags, rayon, wood)
Cellulose acetate butyrate
Cellulose propionate
Ceramics (e.g., molds and crucibles)
Chlorinated polyether
Clays (e.g., bentonite)
Concrete
Detergent, solid (e.g., emulsifiers, surfactants)
Envirostone® (no organic emulsifiers allowed)
Esters (e.g., ethyl acetate, polyethylene glycol ester)
Ethers (e.g., ethyl ether)
Fiberglass (inorganic and organic)
Filter media (inorganic and organic)
Firebrick
Glass (e.g., borosilicate glass, labware, leaded glass, Raschig rings)
Graphite (e.g., molds and crucibles)
Greases, commercial brands
Grit
Halogenated organics (e.g., bromoform; carbon tetrachloride; chlorobenzene; chloroform; 1,1-dichloroethane; 1,2-dichloroethane; 1,1-dichloroethylene; cis-1,2-dichloroethylene; methylene chloride; 1,1,2,2-tetrachloroethane; tetrachloroethylene; 1,1,1-trichloroethane; 1,1,2-trichloroethane; trichloroethylene; 1,1,2-trichloro-1,2,2-trifluoroethane)
Heel (e.g., ash heel; soot heel; firebrick heel; sand, slag, and crucible heel)
Hydrocarbons, aliphatic (e.g., cyclohexane, n-paraffin hydrocarbons)
Hydrocarbons, aromatic (e.g., benzene; ethyl benzene; toluene; 1,2,4-trimethylbenzene; 1,3,5-trimethylbenzene; xylene)
Insulation (inorganic and organic)
Ketones (e.g., acetone, methyl ethyl ketone, methyl isobutyl ketone)
Leaded rubber (e.g., gloves, aprons, sheet material)
Leather
Magnesia cement (e.g., Ramcote® cement)
Magnesium alloy
Metal hydroxides
Metal oxides (e.g., slag)

Table B-1
Table of Allowable Materials for TRU Waste[a]
(Continued)

Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)
Nitrates (e.g., ammonium nitrate, sodium nitrate)
Oil (e.g., petroleum, mineral)
Organophosphates (e.g., tributyl phosphate, dibutyl phosphate, monobutyl phosphite)
Paint, dry (e.g., floor/wall paint, ALARA)
Petroset® products (for aqueous solutions)
Plastics [e.g., polycarbonate, polyethylene, polymethyl methacrylate (Plexiglas®, Lucite®), polysulfone, polytetrafluoroethylene (Teflon®), polyvinyl acetate, polyvinyl chloride (PVC), polyvinylidene chloride (saran)]
Polyamides (nylon)
Polychlorotrifluoroethylene (e.g., Kel-F®)
Polyesters (e.g., Dacron®, Mylar®)
Polyethylene glycol (e.g., Carbowax®)
Polyimides
Polyphenyl methacrylate
Polypropylene (e.g., Ful-Flo® filters)
Polyurethane
Polyvinyl alcohol
Portland cement
Resins (e.g., aniline-formaldehyde, melamine-formaldehyde, organic resins, phenol-formaldehyde, phenolic resins, urea-formaldehyde)
Rubber, natural or synthetic [e.g., chlorosulfonated polyethylene (Hypalon®), ethylene-propylene rubber, EPDM, polybutadiene, polychloroprene (neoprene), polyisobutylene, polyisoprene, polystyrene, rubber hydrochloride (pliofilm®)]
Salts (e.g., calcium chloride, calcium fluoride, sodium chloride)
Sand/soil (inorganic and organic)
Trioctyl phosphine oxide
Water
Waxes, commercial brands
Other inorganic materials

[a]Other chemicals or materials not identified in this table are allowed provided that they meet the requirements for trace constituents (less than one weight percent of the payload container individually; less than five weight percent of the payload container combined). All materials in the final waste form must be inert (nonreactive), be in a nonreactive form, or have been rendered nonreactive.

[b]Bakelite is a trademark for materials that can be composed of several different polymers, including polyethylene, polypropylene, epoxy, phenolic, polystyrene, phenoxy, perylene, polysulfone, ethylene copolymers, ABS, acrylics, and vinyl resins and compounds.

- Trace chemicals that might be incompatible with materials/chemicals in concentrations greater than or equal to 1 percent by weight would have reacted during the waste generating process prior to placement in payload containers.

- The waste is either solidified and immobilized (solidified materials) or present in bulk form as a solid (solid materials). In almost all cases, any possible reactions take place before the waste is generated in its final form.

Potential incompatibilities between the allowable materials/compounds listed in Table B-1 have been analyzed for the CNS 10-160B payload. The analysis assigned EPA chemical reactivity group numbers and names to each allowable material. The reactivity group numbers were assigned based on information provided in Reference B.3.1. If the allowable material (or chemical) is a non-reactive inorganic material (not covered under the EPA reactivity group numbers), it was assigned a reactivity group number of "0" to reflect a complete analysis for all allowable materials (materials assigned a reactivity group number of "0" do not present a compatibility concern). The compiled list of allowable materials and assigned reactivity group numbers is provided in Attachment 1.0.

The list of allowable materials and assigned reactivity group numbers was sorted by reactivity group number and then condensed to form a list of the represented reactivity groups (Attachment 2.0).

Using the list of represented reactivity groups, a hazardous waste compatibility chart was generated. The chart, which is provided in Attachment 3.0, is a reduced version of the hazardous waste compatibility chart presented in Reference B.3.1. The chart summarizes the potential types of reactions possible between each of the reactivity groups represented in the list of allowable materials. The reaction codes and consequences of the reactions are specified for each combination of two reactivity groups.

Using the waste compatibility chart, a list of potential chemical incompatibilities in the TRU waste was generated. The list, which is presented in Attachment 4.0, also presents assessments of whether or not the reaction associated with each of the potential chemical incompatibilities will or will not occur. The results of the assessments indicated that no chemical incompatibilities will occur. Therefore, by precluding all potential incompatibilities, the chemicals/materials identified in Table B-1 are determined to be compatible for the CNS 10-160B Cask payload.

Chemical lists provided for site-specific TRU waste content codes identified for shipment in the CNS 10-160B Cask are a subset of Table B-1. Chemical incompatibilities therefore do not exist in and across these content codes. Only content codes with chemical lists that have been evaluated by this process and determined to be compatible shall be approved for shipment in the CNS 10-160B Cask.

B.3.0 REFERENCES

B.3.1 Hatayama, H. K., Chen, J.J., de Vera, E.R., Stephens, R.D., Storm, D.L., "A Method for Determining the Compatibility of Hazardous Wastes," EPA-600/2-80-076, EPA, Cincinnati, Ohio, 1980.

Attachment 1.0

Lists of Allowable Materials and
Associated Reactivity Groups

Lists of Allowable Materials and Associated Reactivity Groups

Allowable Chemical/Material[a]	Reactivity Group[b]	
	Name	Number[c]
Absorbent polymers, organic	Combustible and flammable materials, miscellaneous	101
Absorbents/adsorbents (e.g., Celite®, diatomaceous earth, diatomite, Florco®, Oil-Dri®, perlite, vermiculite)	Other solidification materials and absorbents/adsorbents	0
Acids, inorganic	Acids, Mineral, Non-oxidizing	1
Acids, inorganic	Acids, Mineral, Oxidizing	2
Acids, organic	Acids, organic	3
Alcohols (e.g., butanol, ethanol, isopropanol, methanol)	Alcohols and Glycols	4
Alumina cement	Water reactive substance	107
Aquaset® products (for aqueous solutions)	Other solidification materials and absorbents/adsorbents	0
Aqueous sludges or solutions	Other solidification materials and absorbents/adsorbents	0
Asbestos	Other Inorganics (non-reactive)	0
Ash (e.g., ash bottoms, fly ash, soot)	Other Inorganics (non-reactive)	0
Asphalt	Combustible and flammable materials, miscellaneous	101
Bakelite®	Combustible and flammable materials, miscellaneous	101
Batteries, dry (e.g., flashlight)	Metals, alkali and alkaline earth, elemental and alloys	21
Caustics	Caustics	10
Cellulose (e.g., Benelex®, cotton Conwed®, paper, rags, rayon, wood)	Combustible and flammable materials, miscellaneous	101
Cellulose acetate butyrate	Polymerizable compounds	103
Cellulose propionate	Polymerizable compounds	103
Ceramics (e.g., molds and crucibles)	Other Inorganics (non-reactive)	0
Chlorinated polyether	Ethers	14
Clays (e.g., bentonite)	Other Inorganics (non-reactive)	0
Concrete	Other solidification materials and absorbents/adsorbents	0
Detergent, solid (e.g., emulsifiers, surfactants)	Esters	13
Detergent, solid (e.g., emulsifiers, surfactants)	Hydrocarbons, aromatic	16
Detergent, solid (e.g., emulsifiers, surfactants)	Hydrocarbons, aliphatic, unsaturated	28
Detergent, solid (e.g., emulsifiers, surfactants)	Organophosphates, phosphothioates, and phosphodithioates	32
Envirostone® (no organic emulsifiers allowed)	Other solidification materials and absorbents/adsorbents	0
Esters (e.g., ethyl acetate, polyethylene glycol ester)	Esters	13
Ethers (e.g., ethyl ether)	Ethers	14
Fiberglass, inorganic	Other Inorganics (non-reactive)	0
Fiberglass, organic	Combustible and flammable materials, miscellaneous	101
Filter media, inorganic	Other Inorganics (non-reactive)	0
Filter media, organic	Combustible and flammable materials, miscellaneous	101
Firebrick	Other Inorganics (non-reactive)	0

Lists of Allowable Materials and Associated Reactivity Groups

Allowable Chemical/Material[a]	Reactivity Group[b] Name	Number[c]
Glass (e.g., borosilicate glass, labware, leaded glass, Raschig rings)	Other Inorganics (non-reactive)	0
Graphite (e.g., molds and crucibles)	Other Inorganics (non-reactive)	0
Greases, commercial brands	Combustible and flammable materials, miscellaneous	101
Grit	Other Inorganics (non-reactive)	0
Halogenated organics (e.g., bromoform; carbon tetrachloride; chlorobenzene; chloroform; 1,1-dichloroethane; 1,2-dichloroethane; 1,1-dichloroethylene; cis-1,2-dichloroethylene; methylene chloride; 1,1,2,2-tetrachloroethane; tetrachloroethylene; 1,1,1-trichloroethane; 1,1,2-trichloroethane; trichloroethylene; 1,1,2-trichloro-1,2,2-trifluoroethane)	Halogenated Organics	17
Heel (e.g., ash heel; soot heel; firebrick heel; sand, slag, and crucible heel)	Other Inorganics (non-reactive)	0
Hydrocarbons, aliphatic (e.g., cyclohexane, n-paraffin hydrocarbons)	Hydrocarbon, aliphatic, unsaturated	28
Hydrocarbons, aliphatic (e.g., cyclohexane, n-paraffin hydrocarbons)	Hydrocarbon, aliphatic, saturated	29
Hydrocarbons, aromatic (e.g., benzene; ethyl benzene; toluene; 1,2,4-trimethylbenzene; 1,3,5-trimethylbenzene; xylene)	Hydrocarbons, aromatic	16
Insulation, inorganic	Other Inorganics (non-reactive)	0
Insulation, organic	Combustible and flammable materials, miscellaneous	101
Ketones (e.g., acetone, methyl ethyl ketone, methyl isobutyl ketone)	Ketones	19
Leaded rubber (e.g., gloves, aprons, sheet material)	Metals, Other elemental, and alloy, as sheets, rods, moldings, vapors, or sponges	23
Leaded rubber (e.g., gloves, aprons, sheet material)	Metals and metal compounds, toxic	24
Leaded rubber (e.g., gloves, aprons, sheet material)	Combustible and flammable materials, miscellaneous	101
Leather	Combustible and flammable materials, miscellaneous	101
Magnesia cement (e.g., Ramcote® cement)	Water reactive substance	107
Magnesium alloy	Metals, Other elemental, and alloy, as sheets, rods, moldings, vapors, or sponges	23
Metal hydroxides	Other Inorganics (non-reactive)	0
Metal oxides (e.g., slag)	Other Inorganics (non-reactive)	0
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Metals, alkali and alkaline earth, elemental	21
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Metals, Other elemental and alloy in the form of powders, vapors, or sponges	22
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Metals, Other elemental, and alloy, as sheets, rods, moldings, vapors, or sponges	23

Lists of Allowable Materials and Associated Reactivity Groups

Allowable Chemical/Material[a]	Reactivity Group[b]	
	Name	Number[c]
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Metals and metal compounds, toxic	24
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Reducing agents, strong	105
Nitrates (e.g., ammonium nitrate, sodium nitrate)	Oxidizing Agents, Strong	104
Oil (e.g., petroleum, mineral)	Combustible and flammable materials, miscellaneous	101
Organophosphates (e.g., tributyl phosphate, dibutyl phosphate, monobutyl phosphite)	Organophosphates, phosphothioates, and phosphodithioates	32
Paint, dry (e.g., floor/wall paint, ALARA)	Combustible and flammable materials, miscellaneous	101
Petroset® products (for aqueous solutions)	Other solidification materials and absorbents/adsorbents	0
Plastics [e.g., polycarbonate, polyethylene, polymethyl methacrylate (Plexiglas®, Lucite®), polysulfone, polytetrafluoroethylene (Teflon®), polyvinyl acetate, polyvinyl chloride (PVC), polyvinylidene chloride (saran)]	Combustible and flammable materials, miscellaneous	101
Polyamides (nylon)	Amides	6
Polyamides (nylon)	Combustible and flammable materials, miscellaneous	101
Polychlorotrifluoroethylene (e.g., Kel-F®)	Combustible and flammable materials, miscellaneous	101
Polyesters (e.g., Dacron®, Mylar®)	Esters	13
Polyesters (e.g., Dacron®, Mylar®)	Combustible and flammable materials, miscellaneous	101
Polyethylene glycol (e.g., Carbowax®)	Alcohols and Glycols	4
Polyethylene glycol (e.g., Carbowax®)	Combustible and flammable materials, miscellaneous	101
Polyimides	Hydrocarbons, aromatic	16
Polyphenyl methacrylate	Combustible and flammable materials, miscellaneous	101
Polypropylene (e.g., Ful-Flo® filters)	Combustible and flammable materials, miscellaneous	101
Polyurethane	Combustible and flammable materials, miscellaneous	101
Polyvinyl alcohol	Alcohols and Glycols	4
Portland cement	Caustics	10
Portland cement	Water reactive substance	107
Resins (e.g., aniline-formaldehyde, melamine-formaldehyde, organic resins, phenol-formaldehyde, phenolic resins, urea-formaldehyde)	Aldehydes	5
Resins (e.g., aniline-formaldehyde, melamine-formaldehyde, organic resins, phenol-formaldehyde, phenolic resins, urea-formaldehyde)	Phenols and Creosols	31
Rubber, natural or synthetic [e.g., chlorosulfonated polyethylene (Hypalon®), ethylene-propylene rubber, EPDM, polybutadiene, polychloroprene (neoprene), polyisobutylene, polyisoprene, polystyrene, rubber hydrochloride (pliofilm®)]	Combustible and flammable materials, miscellaneous	101

Lists of Allowable Materials and Associated Reactivity Groups		
Allowable Chemical/Material[a]	**Reactivity Group[b]**	
	Name	**Number[c]**
Salts (e.g., calcium chloride, calcium fluoride, sodium chloride)	Other Inorganics (non-reactive)	0
Salts (e.g., calcium chloride, calcium fluoride, sodium chloride)	Fluorides, inorganic	15
Sand/soil, inorganic	Other Inorganics (non-reactive)	0
Sand/soil, organic	Combustible and flammable materials, miscellaneous	101
Trioctyl phosphine oxide	Organophosphates, phosphothioates, and phosphodithioates	32
Water	Water and Mixtures containing water	106
Waxes, commercial brands	Combustible and flammable materials, miscellaneous	101
Other inorganic materials	Other Inorganics (non-reactive)	0

[a]Chemicals in *bold italic* have been assigned to more than one reactivity group.
[b]Reactivity group from Hatayama, H.K., J. J. Chen, E.R. deVera, R.D. Stephens, and D.L. Storm, "A Method for Determining the Compatibility of Hazardous Wastes," EPA-600/2-80-076, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980.
[c]Non-reactive inorganic materials or chemicals are assigned a reactivity group number of "0."

Attachment 2.0

Lists of Unique Reactivity Group Numbers in Lists of
Allowable Materials

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List of Unique Reactivity Group Numbers in
Lists of Allowable Materials

Allowable Chemical/Material[a]	Reactivity Group[b]	
	Name	Number
Absorbents/adsorbents (e.g., Celite®, diatomaceous earth, diatomite, Florco®, Oil-Dri®, perlite, vermiculite)	Other solidification materials and absorbents/adsorbents	0
Acids, inorganic	Acids, Mineral, Non-oxidizing	1
Acids, inorganic	Acids, Mineral, Oxidizing	2
Acids, solid, organic	Acids, Organic	3
Polyethylene glycol (e.g., Carbowax®)	Alcohols and Glycols	4
Resins (e.g., aniline-formaldehyde, melamine-formaldehyde, organic resins, phenol-formaldehyde, phenolic resins, urea-formaldehyde)	Aldehydes	5
Polyamides (nylon)	Amides	6
Portland cement	Caustics	10
Esters (e.g., ethyl acetate, polyethylene glycol ester)	Esters	13
Ethers (e.g., ethyl ether)	Ethers	14
Salts (e.g., calcium chloride, calcium fluoride, sodium chloride)	Fluorides, inorganic	15
Hydrocarbons, aromatic (e.g., benzene; ethyl benzene; toluene; 1,2,4-trimethylbenzene; 1,3,5-trimethylbenzene; xylene)	Hydrocarbons, aromatic	16
Halogenated organics (e.g., bromoform; carbon tetrachloride; chlorobenzene; chloroform; 1,1-dichloroethane; 1,2-dichloroethane; 1,1-dichloroethylene; cis-1,2-dichloroethylene; methylene chloride; 1,1,2,2-tetrachloroethane; tetrachloroethylene; 1,1,1-trichloroethane; 1,1,2-trichloroethane; trichloroethylene; 1,1,2-trichloro-1,2,2-trifluoroethane)	Halogenated Organics	17
Ketones (e.g., acetone, methyl ethyl ketone, methyl isobutyl ketone)	Ketones	19
Batteries, dry (e.g., flashlight)	Metals, alkali and alkaline earth, elemental and alloys	21
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Metals, Other elemental and alloy in the form of powders, vapors, or sponges	22
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Metals, Other elemental, and alloy, as sheets, rods, moldings, vapors, or sponges	23
Leaded rubber (e.g., gloves, aprons, sheet material)	Metals and metal compounds, toxic	24
Hydrocarbons, aliphatic (e.g., cyclohexane, n-paraffin hydrocarbons)	Hydrocarbon, aliphatic, unsaturated	28
Hydrocarbons, aliphatic (e.g., cyclohexane, n-paraffin hydrocarbons)	Hydrocarbon, aliphatic, saturated	29
Resins (e.g., aniline-formaldehyde, melamine-formaldehyde, organic resins, phenol-formaldehyde, phenolic resins, urea-formaldehyde)	Phenols and Creosols	31
Organophosphates (e.g., tributyl phosphate, dibutyl phosphate, monobutyl phosphite)	Organophosphates, phosphothioates, and phosphodithioates	32

List of Unique Reactivity Group Numbers in Lists of Allowable Materials		
Allowable Chemical/Material[a]	Reactivity Group[b]	
	Name	Number
Asphalt	Combustible and flammable materials, miscellaneous	101
Cellulose acetate butyrate	Polymerizable compounds	103
Nitrates (e.g., ammonium nitrate, sodium nitrate)	Oxidizing Agents, Strong	104
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Reducing agents, strong	105
Aqueous solutions/water	Water and Mixtures containing water	106
Portland cement	Water reactive substances	107

[a]Chemicals in *bold italic* have been assigned to more than one reactivity group.
[b]Reactivity group from Hatayama, H.K., J.J. Chen, E.R. deVera, R.D. Stephens, and D.L. Storm, "A Method for Determining the Compatibility of Hazardous Wastes," EPA-600/2-80-076, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980.

Attachment 3.0

Waste Chemical Compatibility Chart

Hazardous Waste Chemical Compatibility Chart

Reactivity Code / Consequence

Reactivity Code	Consequence
E	Explosion
F	Fire
G	Innocuous and Non-Flammable Gas Generation
GF	Flammable Gas Generation
GT	Toxic Gas Generation
H	Heat Generation
P	Violent Polymerization
S	Solubilization of Toxic Substance

Source: Hatayama, H.K., J.J. Chen, E.R. deVera, R.D. Stephens, and D.L.Strom, "A Method for Determining the Compatibility of Hazardous Wastes" EPA-600/2-80-076, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980

Group No.	Reactivity Group Name	1	2	3	4	5	6	10	13	14	15	16	17	19	21	22	23	24	28	29	31	32	101	103	104	105	106	107
1	Acids, Mineral, Non-Oxidizing	1																										
2	Acids, Mineral, Oxidizing		2																									
3	Acids, Organic	G, H		3																								
4	Alcohols and Glycols	H	H, F	H, P	4																							
5	Aldehydes	H, P	H, F	H, P		5																						
6	Amides	H	H, GT				6																					
10	Caustics	H	H	H		H		10																				
13	Esters	H	H, F					H	13																			
14	Ethers	H	H, F							14																		
15	Fluorides, Inorganic	GT	GT	GT							15																	
16	Hydrocarbons, Aromatic		H, F									16																
17	Halogenated Organics	H, GT	H, GT, P						H, GF				17															
19	Ketones	H	H, F						H					19														
21	Metals, Alkali and Alkaline Earth, Elemental	GF, H, F	GF, H, F	GF, H, F	GF, H, F	GF, H, F	GF, H	GF, H	GF, H						21													
22	Metals, Other Elemental Alloys as Powders, Vapors, or Sponges	GF, H, F	GF, H, F	GF				GF, H					H, E			22												
23	Metals, Other Elemental Alloys as Sheets, Rods, Moldings, Etc.	GF, H, F	GF, H, F										H, F				23											
24	Metals and Metal Compounds, Toxic	S	S	S			S	S										24										
28	Hydrocarbons, Aliphatic, Unsaturated	H	H, F			H							H, E						28									
29	Hydrocarbons, Aliphatic, Saturated		H, F																	29								
31	Phenols and Cresols	H	H, F											GF, H							31							
32	Organophosphates, Phosphothioates, Phosphodithioates	GT, H	GT, H					H, E						H								32						
101	Combustible and Flammable Materials, Miscellaneous	H, G	GT, H, F										H, G, F										101					
103	Polymerizable Compounds	P, H	P, H	P, H			P, H						P, H	P, H	P, H	P, H					P, H			103				
104	Oxidizing Agents, Strong	GT, H		GT, H	H, F	H, F	GT, H, F		H, F	H, F		H, F	GT, H	H, F	H, F, E	H, F, E	H, F		H, F	H, F	H, F	GT, H, F	H, G, F	GT, H, F	104			
105	Reducing Agents, Strong	GF, H	GT, H, F	GF, H	GF, H, F	GF, H, F	GF, H		H, F				H, E	GF, H							GF, H	GF, GT	GF, H	GF, H, P	H, F, E	105		
106	Water and Mixtures Containing Water	H	H												GF, H	GF, H		S								GF, GT	106	
107	Water Reactive Substances	E	X	T	R	E	M	A	C	T	I	V	!	D	O		N		M	I	!	!	!					107
Reactivity Group No.		1	2	3	4	5	6	10	13	14	15	16	17	19	21	22	23	24	28	29	31	32	101	103	104	105	106	107

Attachment 4.0

Potential Chemical Incompatibilities

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
1	4	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	5	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	5	Violent Polymerization	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	6	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	10	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; Bases/caustic materials are neutralized and solidified/immobilized prior to shipping
1	13	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	14	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	15	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	17	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	17	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	19	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	21	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	21	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	21	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	22	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	22	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	22	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	23	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	23	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	23	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	24	Solubilization of Toxic Substances	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping. Additionally, any solubilization of toxic substances will not affect transportation of wastes.
1	28	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		**Reaction Result (A x B)**	**Explanation of Potential Incompatibility**
Group A	**Group B**		
1	31	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	32	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	32	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	101	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	101	Innocuous and Non-Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	103	Violent Polymerization	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	103	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	104	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
1	104	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
1	105	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
1	105	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
1	106	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume
1	107	Highly Reactive	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
2	3	Innocuous and Non-Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	3	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	4	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	4	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
2	5	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	5	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	6	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	6	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	10	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; Bases/caustic materials are neutralized and solidified/immobilized prior to shipping
2	13	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	13	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	14	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	14	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	15	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	16	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	16	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	17	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	17	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	17	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	19	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	19	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	21	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	21	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	21	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	22	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	22	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	22	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		**Reaction Result (A x B)**	**Explanation of Potential Incompatibility**
Group A	**Group B**		
2	23	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	23	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	23	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	24	Solubilization of Toxic Substances	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping. Additionally, any solubilization of toxic substances will not affect transportation of wastes.
2	28	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	28	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	29	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	29	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	31	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	31	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	32	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	32	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	101	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	101	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	101	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	103	Violent Polymerization	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	103	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	105	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
2	105	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
2	105	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
2	106	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		**Reaction Result (A x B)**	**Explanation of Potential Incompatibility**
Group A	**Group B**		
2	107	Highly Reactive	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
3	4	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	4	Violent Polymerization	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	5	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	5	Violent Polymerization	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	10	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; Bases/caustic materials are neutralized and solidified/immobilized prior to shipping
3	15	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	21	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	21	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	21	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	22	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	24	Solubilization of Toxic Substances	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping. Additionally, any solubilization of toxic substances will not affect transportation of wastes.
3	103	Violent Polymerization	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	103	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	104	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
3	104	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
3	105	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.

Potential Chemical Incompatibilities

Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
3	105	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
3	107	Highly Reactive	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
4	21	Flammable Gas Generation	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping
4	21	Heat Generation	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping
4	21	Fire	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping
4	104	Heat Generation	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
4	104	Fire	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
4	105	Heat Generation	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
4	105	Flammable Gas Generation	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
4	105	Fire	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
4	107	Highly Reactive	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
5	10	Heat Generation	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping; bases/caustic materials are neutralized and solidified/immobilized prior to shipping
5	21	Flammable Gas Generation	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping

Potential Chemical Incompatibilities

Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
5	21	Heat Generation	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping
5	21	Fire	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping
5	28	Heat Generation	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping
5	104	Heat Generation	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
5	104	Fire	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
5	105	Heat Generation	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
5	105	Flammable Gas Generation	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
5	105	Fire	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
5	107	Highly Reactive	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
6	17	Heat Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping
6	17	Toxic Gas Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping
6	21	Flammable Gas Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping
6	21	Heat Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping
6	24	Solubilization of Toxic Substances	Reaction will not occur – Amides are solidified/immobilized prior to shipping. Additionally, any solubilization of toxic substances will not affect transportation of wastes.
6	104	Heat Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
6	104	Fire	Reaction will not occur – Amides are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		**Reaction Result (A x B)**	**Explanation of Potential Incompatibility**
Group A	**Group B**		
6	104	Toxic Gas Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
6	105	Heat Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
6	105	Flammable Gas Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
6	107	Highly Reactive	Reaction will not occur – Amides are solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
10	13	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	17	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	19	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	21	Flammable Gas Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	21	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	22	Flammable Gas Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	22	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	23	Flammable Gas Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	23	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	24	Solubilization of Toxic Substances	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping; Additionally, any solubilization of toxic substances will not affect transportation of wastes.
10	32	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	32	Explosion	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	103	Violent Polymerization	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	103	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping

Potential Chemical Incompatibilities

Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	**Group B**		
10	107	Highly Reactive	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
13	21	Flammable Gas Generation	Reaction will not occur – Esters are solidified/immobilized prior to shipping
13	21	Heat Generation	Reaction will not occur – Esters are solidified/immobilized prior to shipping
13	104	Heat Generation	Reaction will not occur – Esters are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
13	104	Fire	Reaction will not occur – Esters are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
13	105	Heat Generation	Reaction will not occur – Esters are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
13	105	Fire	Reaction will not occur – Esters are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
13	107	Highly Reactive	Reaction will not occur – Esters are solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
14	104	Heat Generation	Reaction will not occur – Ethers are solidified / immobilized prior to shipping. Oxidizing agents are reacted prior to being placed in the waste/shipped.
14	104	Fire	Reaction will not occur – Ethers are solidified / immobilized prior to shipping. Oxidizing agents are reacted prior to being placed in the waste/shipped.
14	107	Highly Reactive	Reaction will not occur – Ethers are solidified / immobilized prior to shipping. Free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
15	107	Highly Reactive	Reaction will not occur – Salts are reacted during use and processing; Free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
16	104	Heat Generation	Reaction will not occur – Aromatic hydrocarbons are solidified/immobilized prior to shipping. Oxidizing agents are reacted prior to being placed in the waste/shipped.
16	104	Fire	Reaction will not occur – Aromatic hydrocarbons are solidified/immobilized prior to shipping. Oxidizing agents are reacted prior to being placed in the waste/shipped.
16	107	Highly Reactive	Reaction will not occur – Aromatic hydrocarbons are solidified/immobilized prior to shipping. Free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
17	21	Heat Generation	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping
17	21	Explosion	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping
17	22	Heat Generation	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping
17	22	Explosion	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping
17	23	Heat Generation	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping
17	23	Fire	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping
17	104	Heat Generation	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
17	104	Toxic Gas Generation	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
17	105	Heat Generation	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
17	105	Explosion	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
17	107	Highly Reactive	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
19	21	Flammable Gas Generation	Reaction will not occur – Ketones are solidified/immobilized prior to shipping
19	21	Heat Generation	Reaction will not occur – Ketones are solidified/immobilized prior to shipping
19	104	Heat Generation	Reaction will not occur –Ketones are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
19	104	Fire	Reaction will not occur –Ketones are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
19	105	Flammable Gas Generation	Reaction will not occur –Ketones are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
19	105	Heat Generation	Reaction will not occur –Ketones are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
19	107	Highly Reactive	Reaction will not occur – Ketones are solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
21	31	Flammable Gas Generation	Reaction will not occur – Phenols and Creosols are solidified/immobilized prior to shipping; metals are typically in oxide form
21	31	Heat Generation	Reaction will not occur – Phenols and Creosols are solidified/immobilized prior to shipping; metals are typically in oxide form
21	32	Heat Generation	Reaction will not occur – Organophosphates are solidified/immobilized prior to shipping; metals are typically in oxide form
21	101	Heat Generation	Reaction will not occur – Combustible materials are dry; free liquid content is limited to less than 1% of waste volume; metals are typically in oxide form
21	101	Innocuous and Non-Flammable Gas Generation	Reaction will not occur – Combustible materials are dry; free liquid content is limited to less than 1% of waste volume; metals are typically in oxide form

Potential Chemical Incompatibilities

Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
21	101	Fire	Reaction will not occur – Combustible materials are dry; free liquid content is limited to less than 1% of waste volume; metals are typically in oxide form
21	103	Violent Polymerization	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; metals are typically in oxide form
21	103	Heat Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; metals are typically in oxide form
21	104	Heat Generation	Reaction will not occur –Oxidizing agents are reacted prior to being placed in the waste/shipped; metals are typically in oxide form
21	104	Fire	Reaction will not occur –Oxidizing agents are reacted prior to being placed in the waste/shipped; metals are typically in oxide form
21	104	Explosion	Reaction will not occur –Oxidizing agents are reacted prior to being placed in the waste/shipped; metals are typically in oxide form
21	106	Flammable Gas Generation	Reaction will not occur – Free liquids are limited to less than 1% of waste volume; metals are typically in oxide form.
21	106	Heat Generation	Reaction will not occur – Free liquids are limited to less than 1% of waste volume; metals are typically in oxide form.
21	107	Highly Reactive	Reaction will not occur – Metals are typically in oxide form; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
22	28	Heat Generation	Reaction will not occur – Unsaturated aliphatic hydrocarbons are solidified/immobilized prior to shipping
22	28	Explosion	Reaction will not occur – Unsaturated aliphatic hydrocarbons are solidified/immobilized prior to shipping
22	103	Violent Polymerization	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping
22	103	Heat Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping
22	104	Heat Generation	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped
22	104	Fire	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped
22	104	Explosion	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped
22	106	Flammable Gas Generation	Reaction will not occur – Free liquids are limited to less than 1% of waste volume; water reactive metals are reacted prior to shipping
22	106	Heat Generation	Reaction will not occur – Free liquids are limited to less than 1% of waste volume; water reactive metals are reacted prior to shipping

Potential Chemical Incompatibilities

Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
22	107	Highly Reactive	Reaction will not occur –Water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
23	103	Violent Polymerization	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping
23	103	Heat Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping
23	104	Heat Generation	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped
23	104	Fire	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped
23	107	Highly Reactive	Reaction will not occur –Water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
24	103	Violent Polymerization	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping
24	103	Heat Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping
24	106	Solubilization of Toxic Substances	Reaction will not occur – Free liquid content is limited to less than 1% of waste volume; Additionally, any solubilization of toxic substances will not affect transportation of wastes.
24	107	Highly Reactive	Reaction will not occur – Water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
28	104	Heat Generation	Reaction will not occur – Unsaturated aliphatic hydrocarbons are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
28	104	Fire	Reaction will not occur – Unsaturated aliphatic hydrocarbons are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
28	107	Highly Reactive	Reaction will not occur – Unsaturated aliphatic hydrocarbons are immobilized/solidified prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.

Potential Chemical Incompatibilities

Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
29	104	Heat Generation	Reaction will not occur – Saturated aliphatic hydrocarbons are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
29	104	Fire	Reaction will not occur – Saturated aliphatic hydrocarbons are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
29	107	Highly Reactive	Reaction will not occur – Saturated aliphatic hydrocarbons are immobilized/solidified prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
31	103	Violent Polymerization	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; phenols and creosols are immobilized/solidified prior to shipping
31	103	Heat Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; phenols and creosols are immobilized/solidified prior to shipping
31	104	Heat Generation	Reaction will not occur – Phenols and creosols are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
31	104	Fire	Reaction will not occur – Phenols and creosols are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
31	105	Flammable Gas Generation	Reaction will not occur – Phenols and creosols are immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
31	105	Heat Generation	Reaction will not occur – Phenols and creosols are immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
31	107	Highly Reactive	Reaction will not occur – Phenols and creosols are immobilized/solidified prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
32	104	Heat Generation	Reaction will not occur – Organophosphates are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
32	104	Fire	Reaction will not occur – Organophosphates are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped

Potential Chemical Incompatibilities

Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
32	104	Toxic Gas Generation	Reaction will not occur – Organophosphates are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
32	105	Toxic Gas Generation	Reaction will not occur – Organophosphates are immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
32	105	Flammable Gas Generation	Reaction will not occur – Organophosphates are immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
32	105	Heat Generation	Reaction will not occur – Organophosphates are immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
32	107	Highly Reactive	Reaction will not occur – Organophosphates are immobilized/solidified prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
101	104	Heat Generation	Reaction will not occur – Combustible materials are dry; oxidizing agents are reacted prior to being placed in the waste/shipped
101	104	Fire	Reaction will not occur – Combustible materials are dry; oxidizing agents are reacted prior to being placed in the waste/shipped
101	104	Innocuous and Non-Flammable Gas Generation	Reaction will not occur – Combustible materials are dry; oxidizing agents are reacted prior to being placed in the waste/shipped
101	105	Flammable Gas Generation	Reaction will not occur – Combustible materials are dry; reducing agents are reacted prior to being placed in the waste/shipped
101	105	Heat Generation	Reaction will not occur – Combustible materials are dry; reducing agents are reacted prior to being placed in the waste/shipped
101	107	Highly Reactive	Reaction will not occur – Combustible materials are dry; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
103	104	Heat Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped

Potential Chemical Incompatibilities

Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
103	104	Fire	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
103	104	Toxic Gas Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
103	105	Heat Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
103	105	Violent Polymerization	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
103	105	Flammable Gas Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
103	107	Highly Reactive	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
104	105	Heat Generation	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped; reducing agents are reacted prior to being placed in the waste/shipped
104	105	Fire	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped; reducing agents are reacted prior to being placed in the waste/shipped
104	105	Explosion	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped; reducing agents are reacted prior to being placed in the waste/shipped
104	107	Highly Reactive	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
105	106	Flammable Gas Generation	Reaction will not occur – Reducing agents are reacted prior to being placed in the waste/shipped; free liquid content is limited to less than 1% of waste volume
105	106	Toxic Gas Generation	Reaction will not occur – Reducing agents are reacted prior to being placed in the waste/shipped; free liquid content is limited to less than 1% of waste volume

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
105	107	Highly Reactive	Reaction will not occur – Reducing agents are reacted prior to being placed in the waste/shipped; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
106	107	Highly Reactive	Reaction will not occur – Free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.

Attachment C

Shipping Period for TRU Waste in the 10-160B Cask

C.1.0 INTRODUCTION

This Attachment presents the basis for the shipping period for TRU wastes from the time of cask closure until cask opening. This shipping period is used in the analysis of the gas generation in the 10-160B cask.

The 10-160B cask may be used to ship TRU waste from generator sites to the Waste Isolation Pilot Plant (WIPP) for disposal or between sites (e.g., from the Battelle West Jefferson, OH site to the U.S. Department of Energy [DOE] Hanford, WA site) for interim storage. While the shipments are in transit, a satellite tracking system will be operational to monitor progress and provide direct communication between the driver and the transport dispatcher.

C.2.0 EXPECTED SHIPPING PERIOD

The expected shipping period is the amount of time from the sealing of the cask at the loading facility until the opening of the cask at the unloading facility. It consists of: the time from cask sealing to the release of the transport unit from the loading facility, the expected transit time, and the time from arrival at the unloading facility until the cask is opened. For assessing the expected shipping period, it will be assumed that there are no delays.

C.2.1 Loading

The loading process from cask sealing to unit release includes health physics surveys, installing the upper impact limiter, and vehicle inspections. The time from cask sealing until the unit is released for travel has been accomplished in less than four (4) hours. To be conservative, a one-day (24 hour) duration will be assumed.

C.2.2 Transit

The longest route of prospective intersite shipments is from Savannah River, SC to Hanford, approximately 2800 miles. Shipments to WIPP are encompassed by this distance. All TRU shipments will be made with two drivers. Using two drivers, on an appropriate rotational schedule, the truck can travel for twenty-four (24) hours per day for up to seven days. Assuming an average speed of 45 mph, which includes time for vehicle inspections, fueling, meals, and driver relief, the duration of a 2800 mile trip is expected to be 62 hours. Again, to be conservative, the transit duration will be assumed to be three days (72 hours).

C.2.3 Unloading

The unloading process includes receipt survey and security checks, positioning of the trailer in the TRU waste unloading area, removal of the cask from the trailer to a transfer cart, positioning of the cask in the cask unloading room, and removal of the lid. This process has been accomplished in less than eight (8) hours. Again, to be conservative, the unloading duration will be assumed to be one day (24 hours).

C.2.4 Total

The total expected shipping period, with no delays, is less than 75 hours. For the purpose of this analysis, a conservative period of 5 days (120 hours) will be assumed.

C.3.0 SHIPPING DELAYS

The maximum shipping time will be assumed to be the sum of the expected shipping time and the time for delays which could extend the shipping time. These delays are: loading delays; transit delays due to weather or road closures, shipping vehicle accidents, mechanical delays, or driver illness; and unloading delays. Each of these delays are assessed below.

C.3.1 Loading Delays

There are a number of situations that could extend the time between cask sealing and truck release. These include: loading preceding a holiday weekend, problems with a leak test, and handling equipment failure. Both the leak test problem and the handling equipment failure should be resolvable by replacing or obtaining temporary equipment. Each of these situations is unlikely to cause more than a two day delay. The holiday weekend could cause a delay of three days, i.e., from Friday afternoon until Tuesday. It is very unlikely that more than two of the three loading delays could occur on the same shipment, so a total of five days seems a reasonably conservative assessment for a loading delay.

C.3.2 Transit Delays

Transit delays due to weather, e.g., a road closed due to snow, are unlikely to cause a delay of more than five days. A road closure due to a vehicle accident or a roadway or bridge failure would result in re-routing which could add up to two days to the transit time. A transit time delay due to weather or road closure will be assumed to be five days.

Transit delays due to an accident with the truck could cause a lengthy delay. Response time for notification and to take immediate corrective action is assumed to be one day. (The use of the on-board satellite communication system will facilitate an early response.) Accident mitigation may require transferring the cask to a different trailer using cranes and other heavy equipment. Mitigation is assumed to take five days for a total accident delay of six days.

Mechanical problems with the truck or trailer could also cause multi-day delays. Significant failures may require a replacement tractor or trailer. An appropriate response to a mechanical failure is assumed to take four days.

Driver illness could also cause transit delays. If a driver it too ill to continue, a replacement driver will be brought in. A two day delay is assessed for bringing in a replacement driver.

C.3.3 Unloading Delay

An unloading delay will occur if the truck arrives just before a holiday weekend. This could result in a four day delay. Additionally, a delay due to unloading equipment failure could occur. Repair of such equipment should not require more than four days. The unloading delay will be conservatively assumed to be five days. If an unanticipated situation occurs that would result in a much longer delay, the cask can be vented.

C.3.4 Total Delay

The total delay, i.e., the sum of the delay times for each of the delay types, is 27 days. This assumes that each type of delay occurs on the same shipment.

C.4.0 MAXIMUM SHIPPING PERIOD

The maximum shipping period, as the sum of the expected shipping period and the total delay, is 32 days. This period assumes that each of the possible shipping delays occurs on the same shipment, a very unlikely occurrence. Further, for additional conservatism, the assumed maximum will be nearly doubled to 60 days. Thus, a 60 day shipping period will be the maximum used in analysis of gas generation in the sealed cask. A shorter, site-specific shipping period may be developed and included in the site-specific sub tier appendix, which contains the waste content codes for the site, that is submitted to the NRC for approval. This site-specific shipping period may be used in the gas generation analysis for the site's waste.

Appendix 4.10.2.5

Compliance Methodology for TRU Waste From
Idaho National Engineering and Environmental Laboratory (INEEL)
Idaho Falls, ID

1.0 INTRODUCTION

This appendix presents the methods used to qualify approximately 620 drums of remote-handled (RH) transuranic (TRU) waste stored at Idaho National Engineering and Environmental Laboratory (INEEL) as payload for transport in the CNS 10-160B cask. The methods for determining each restricted parameter, the factors influencing the parameter values, and the methods used by INEEL for demonstrating compliance, are provided in the following sections. This appendix also includes the following as attachment:

- Content codes ID 322A, 322B, 325A and 325B (Attachment A)
- Chemical lists for content codes ID 322A, 322B, 325A and 325B (Attachment A).

2.0 PURPOSE

The purpose of this appendix is to describe the methods used to qualify the RH-TRU waste stored at INEEL prior to transport in the CNS 10-160B cask and is based on the format and requirements for TRU waste identified in Appendix 4.10.2 of the CNS 10-160B cask Safety Analysis Report (SAR). Acceptable methods and process knowledge applicable to content codes ID 322A, 322B, 325A, and ID 325B are described in this appendix. Process knowledge (PK) (also referred to as acceptable knowledge (AK) for the purposes of this document) refers to applying knowledge of the waste in light of the materials or processes used to generate the waste.

Section 3.0 describes the TRU waste payload. Sections 4.0 through 11.0 discuss each payload parameter and the methods employed to demonstrate compliance with the CNS 10-160B cask payload requirements.

3.0 TRU WASTE PAYLOAD FOR CNS 10-160B CASK

The content codes for the RH-TRU waste stored at INEEL (ID 322A and 322B - Solid Inorganic Waste and ID 325A and 325B - Solid Organic Waste) are provided in Attachment A. These content codes apply to approximately 620 30-gallon drums of waste at the INEEL from the destructive and non-destructive examination of radiological materials such as fuel pins, reactor structural materials, and targets in the Argonne National Laboratory-East (ANL-E) Alpha Gamma Hot Cell Facility (AGHCF) between 1971 and 1995.

Complete documentation packages along with quality assurance and quality control records are generated for all payload containers as summarized in this appendix. TRU waste shipped from the INEEL will comply with all transportation requirements using the following methods:

- Formally documented AK of the processes generating the waste, including data packages generated for payload containers that document the contents and properties of the waste in the container including the absence of prohibited items and compliance with packaging requirements

- Measurement of required parameters to ensure compliance with limits.

4.0 PHYSICAL FORM

4.1 Requirements

The physical form of waste comprising the CNS 10-160B cask payload is restricted to solid or solidified materials in secondary containers. The total volume of residual liquid in a secondary container is

restricted to less than 1% by volume. Secondary containers must be shored to prevent movement during accident conditions. Sharp or heavy objects in the waste shall be blocked, braced, or suitably packaged as necessary to provide puncture protection for the payload containers packaging these objects. Sealed containers (e.g., rigid plastic containers, plastic bags, metal containers) greater than four liters in volume that do not have a known, measured, or calculated hydrogen release rate or resistance are prohibited.

4.2 Methods of Compliance and Verification

Compliance with the physical form requirements will be determined using AK (i.e., records and data base information). AK documentation for drums containing waste described by content codes ID 322A, 322B, 325A, and ID 325B (Reference 12.1) indicates that the physical form requirements have been met. Liquid chemicals were neutralized, if necessary, and absorbed resulting in no free liquid. Waste packaging records show that sharp and heavy objects have been packaged to provide puncture protection equivalent to Type A packaging requirements and there are no pressurized containers in the waste. The calculated hydrogen release rate for heat-sealed confinement layers greater than four liters in volume that may be present in the payload container is listed in Section 10 of this appendix.

5.0 CHEMICAL FORM AND CHEMICAL PROPERTIES

5.1 Requirements

The chemical properties of the waste are determined by the chemical constituents allowed in a given content code. Specific requirements regarding the chemical form of the waste are as :

- Explosives, nonradioactive pyrophorics, compressed gases, and corrosives are prohibited.

- Pyrophoric radionuclides may be present only in residual amounts less than 1 weight percent.

- The total amount of potentially flammable volatile organic compounds (VOCs) present in the headspace of a secondary container is restricted to 500 parts per million.

5.2 Methods of Compliance and Verification

PK documentation (Reference 12.1) details the compliance with the chemical form and chemical property restrictions. Explosives, pyrophorics, and compressed gases including aerosol cans were prohibited from RH-TRU waste containers. Sodium and sodium potassium (NaK) metal were rendered safe by controlled reaction with ethanol or butanol. The resulting product was absorbed on pelletized clay and evaporated to dryness prior to disposal. All potentially corrosive liquid chemicals were neutralized and absorbed prior to packaging; therefore, the waste would not be considered corrosive. All organic liquids were evaporated to dryness before packaging. The chemical lists for content codes ID 322A, 322B, 325A and ID 325B are presented in Attachment A.

6.0 CHEMICAL COMPATIBILITY

6.1 Requirements

Each content code has an associated chemical list (Attachment A) based on AK information. Chemical constituents in a payload container assigned to a given content code shall conform to these approved chemical lists. Chemicals and materials that are not listed are allowed in trace amounts (quantities less than one weight percent) in a payload container provided that the total quantity of trace chemicals or materials is restricted to less than five weight percent. Chemical compatibility of a waste with its packaging ensures that chemical reactions will not occur that might pose a threat to the safe transport of a payload in the CNS 10-160B cask.

6.2 Methods of Compliance and Verification

Attachment B of Appendix 4.10.2 presents the methodology and results for the chemical compatibility analyses performed for the list of allowable chemicals and materials associated with the TRU waste content codes expected to be shipped in the CNS 10-160B cask. The results of these chemical compatibility analyses show that these content codes can be transported without any incompatibilities. The chemicals present in ID 322A, 322B, 325A, and ID 325B conform to the list of allowable materials in Attachment B of Appendix 4.10.2. Therefore, the waste meets the chemical compatibility requirements.

7.0 GAS DISTRIBUTION AND PRESSURE BUILDUP

7.1 Requirements

Gas distribution and pressure buildup during transportation of TRU waste in the CNS 10-160B cask payload are restricted to the following limits:

- The gases generated in the payload must be controlled to prevent the occurrence of potentially flammable concentrations of gases within the payload confinement layers and the void volume of the inner vessel (IV) cavity. Specifically, the hydrogen concentrations within the payload confinement layers are limited to five percent by volume during the shipping period (see Attachment C of Appendix 4.10.2 of the CNS 10-160B SAR).

- The gas generated in the payload and released into the IV cavity must be controlled to maintain the pressure within the IV cavity below the acceptable packaging design limit of 31.2 pounds per square inch (psig).

7.2 Methods of Compliance and Verification

Compliance with the CNS 10-160B cask design pressure limit for each content code described in Attachment A is analyzed by assuming all gases generated are released into the IV cavity and by including the contributions from thermal expansion of gases and vapor pressure of atmospheric water. The maximum effective total gas G value is described by that of cellulose and is evaluated at the maximum operating temperature of 168°F using the Arrhenius equation given the room temperature G value and an activation energy is 2.1 kcal/gmol (Reference 12.2, Appendix 3.1). Table 7-1 shows that the pressure increase during a period of 365 days is below the design pressure limit of 31.2 psig for all content codes listed in Attachment A. Compliance with the restrictions on flammable gas concentration is discussed in Section 10.0.

Table 7-1 Maximum Pressure Increase In Cask IV Over 365-Day Shipping Period

Content Code	No Matrix Depletion[a]			Matrix Depletion[b]		
	Geff, molecules per 100eV	Decay Heat Limit per Cask (W)[c]	ΔPtot (psig)	Geff, molecules per 100eV	Decay Heat Limit per Cask (W)[c]	ΔPtot (psig)
ID 322A	17.86	3.26e-1	12.2	14.19	1.17e-0	19.9
ID 322B	17.86	1.81e-0	31.1	14.19	2.28e-0	31.1
ID 325A	17.86	6.48e-2	8.9	14.19	2.35e-1	10.5
ID 325B	17.86	5.94e-1	15.7	14.19	2.06e-0	28.9

a. Geff @ 70°F: 10.2 molecules per 100 eV; Activation Energy: 2.1 kcal/mol (Ref. 12.2, Appx 3.2)
b. Geff @ 70°F: 8.1 molecules per 100 eV; Activation Energy: 2.1 kcal/mol (Ref. 12.2, Appx 3.2)
c. Ten waste drums per cask.

8.0 PAYLOAD CONTAINER AND CONTENTS CONFIGURATION

8.1 Requirements

Thirty-gallon and 55-gallon secondary containers may be used as payload containers in the CNS 10-160B cask. Secondary containers must be shored to prevent movement during accident conditions. The available volume of the cask cavity limits the number of payload containers that may be shipped at one time. Up to ten 30-gallon or 55-gallon drums of TRU waste may be packaged in the cask. Payload containers and any sealed container liners greater than four liters in volume used to package waste inside the containers must have at least one filter vent with a minimum allowable hydrogen diffusivity listed in Table 8.1. A rigid polyethylene liner, if present in a payload container, shall have an opening that is equivalent to or larger than a 0.3-inch diameter hole (or equivalent filter vent) before the container is transported in the CNS 10-160B. The typical waste packaging configuration is shown below.
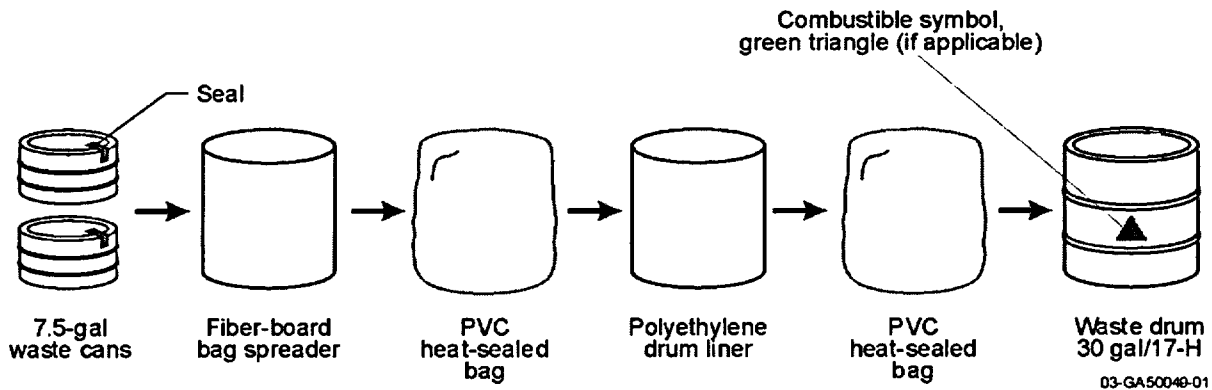
The 7.5-gallon waste cans are not sealed containers because holes were drilled in the sides of the cans to allow a cable to be attached (Reference 12.1, Appendix 4.10.2.5). The fiberboard bag spreader, which is situated between the waste cans and the PVC bag, is open on top. Neither the waste cans nor the fiberboard bag spreader inside the innermost PVC bag are considered confinement layers.

Sealed bags are closed with a twist-and-tape, fold-and-tape, or heat-sealed closure. Heat-sealed bags may have a filter vent or be unvented.

Table 8-1 Minimum Filter Vent Specifications

Container Filter Type	Minimum Flow Rate (mL/min air, STP, inch water)[a]	Efficiency (percent)	Hydrogen Diffusivity @ 25°C (mol/s/mol fraction)

Drum	35	99.9b	3.70e-6
Bag	35	---b	1.075e-5

a. Filters tested at a different pressure (other than 1 in water) shall have a proportional flow rate (Reference 12.3 , CH-TRAMPAC, Table 2.5-1).

b. Filters installed in payload containers that are overpacked in a drum are exempt from the efficiency requirement (Reference 12.3 , CH-TRAMPAC, Table 2.5-1).

8.2 Methods of Compliance and Verification

Compliance with the payload container and contents configuration requirements is determined by visual examination, process knowledge, and through procurement records. The methods used to determine the compliance of filter vents with the performance-based requirements of flow rate, efficiency, and hydrogen diffusivity shall be directed by procedures under a quality assurance program. Filter vents shall be legibly marked to ensure identification of the supplier as well as the date of manufacture, lot number, or unique serial number.

9.0 ISOTOPIC CHARACTERIZATION AND FISSILE CONTENT

9.1 Requirements

The CNS 10-160B cask payload allows fissile materials, provided the mass limits of Title 10, Code of Federal Regulations, Section 71.15 (10 CFR 71.15) are not exceeded. Plutonium content that exceeds 0.74 TBq (20 curies) per cask must be in solid form.

9.2 Methods of Compliance and Verification

Compliance with the isotopic characterization and fissile content requirements involves the following steps:
- Determination of the isotopic composition
- Determination of the quantity of radionuclides
- Calculation of the fissile mass and comparison with 10 CFR 71.15 limits
- Calculations of plutonium content and comparison with 20-curie limit.

9.2.1 Isotopic composition

The isotopic composition of the waste may be determined from direct measurements taken on the product material during processing or post-process certification at each site, analysis of the waste, or from existing records and AK. The isotopic composition of the waste need not be determined by direct analysis or measurement of the waste unless AK is not available.

9.2.2 Quantity of Radionuclides

The quantity of the radionuclides in each payload container shall be estimated by either AK or direct measurement of the individual payload containers, a summation of assay results from individual packages in a payload container, or a direct measurement on a representative sample of the quantity of nuclear material in TRU wastes. Assay instruments detect and quantify the primary radiation (alpha, gamma, and or neutron) emanating from specific radionuclides, or a secondary radiation emitted from neutron interrogation techniques. The measured quantity of radiation is then used to calculate the quantity of other radionuclides. That calculation requires knowledge of the isotopic composition of the waste. Combinations of gamma spectroscopy and neutron measurements are often needed to calculate the quantity of nonfissile radionuclides.

9.2.3 Calculation of Fissile Mass

The calculation of the fissile mass shall be performed to meet the requirements of 10 CFR 71.15.

9.2.4 Calculation of Plutonium Curies

The total plutonium (all plutonium isotopes) activity (curies) for each payload container shall be determined as described above, summed for the entire payload and compared with the 20-curie waste form limit.

10. DECAY HEAT AND HYDROGEN GAS GENERATION RATES

10.1 Requirements

The hydrogen gas concentration shall not exceed 5% by volume in all void volumes within the CNS 10-160B cask payload during the 60-day shipping period. Payload containers of different content codes with different bounding G values and resistances may be assembled together as a payload, provided the decay heat limit and hydrogen gas generation rate limit for all payload containers within the payload is conservatively assumed to be the same as that of the payload container with the lowest decay heat limit and hydrogen gas generation rate limit.

10.2 Methodology of Ensuring Compliance with Flammable Gas Limits

As stated in Section 7.2 of Appendix 4.10.2, chemical, biological, and thermal gas generation mechanisms are considered to be insignificant in the CNS 10-160 cask. In addition, as shown in Section 5.1 of Appendix 4.10.2, potentially flammable VOCs are restricted to no more than 500 ppm in the headspace of the CNS 10-160B cask secondary containers. Therefore, the only flammable gas of concern for transportation purposes is hydrogen. The hydrogen concentration within the void volumes of the payload confinement layers or the cask IV has been evaluated for a specified shipping period.

Attachment A of this appendix provides the TRU waste content codes for the INEEL RH TRU that are included in the authorized payload for the CNS 10-160B cask. Each content code has a unique and completely defined packaging configuration. The movement of hydrogen from the waste material and across waste confinement layers to the payload voids can be modeled to determine the maximum allowable hydrogen gas generation rate to ensure the 5% by volume concentration is not exceeded in any of the void volumes inside the waste drums or CNS 10-160B cask. Based on the hydrogen gas generation potential of the waste, quantified by hydrogen gas generation G values, the hydrogen gas generation limit can be expressed as an equivalent decay heat limit. The shippability of a waste drum regarding flammable gases can be determined by comparing its decay heat to the content code-specific decay heat limit listed in Table 10-1. If the decay heat limit is exceeded, the hydrogen gas generation rate in the waste drum can be calculated based on measured hydrogen concentration in the waste drum or a container in which the waste drum is placed, as detailed in Section 10.5.

Table 10-1 Maximum allowable hydrogen gas generation rates and decay heat limits.

Content Code	Hydrogen Gas Generation Rate Limit per Drum (mol/s)	Hydrogen Gas Generation Rate Limit per Cask (mol/s)	Decay Heat Limit per Drum, W (Dose ≤ 0.012 W-yr)	Decay Heat Limit per Cask,W (Dose ≤ 0.012 W-yr)	Decay Heat Limit per Drum, W (Dose > 0.012 W-yr)	Decay Heat Limit per Cask,W (Dose > 0.012 W-yr)
ID 322A	3.61e-9	3.61e-8	3.26e-2	3.26e-1	1.17e-1	1.17e-0
ID 322B	3.28e-8	3.28e-7	2.97e-1	1.81e-0	1.02e-0	2.28e-0
ID 325A	3.61e-9	3.61e-8	6.48e-3	6.48e-2	2.35e-2	2.35e-1
ID 325B	3.28e-8	3.28e-7	5.94e-2	5.94e-1	2.06e-1	2.06e-0

10.3 Determination of Maximum Allowable Hydrogen Generation Rates

The modeling methodology for determining the maximum allowable hydrogen gas generation rate limits is presented in this section. Parameters that impact the maximum allowable hydrogen gas generation rate limit are:

- Waste packaging configuration (i.e., the number and type of confinement layers)

- Release rates of hydrogen from each confinement layer
- Void volume in the cask IV available for gas accumulation
- Operating temperature and pressure for the payload in the 10-160B cask IV during the shipping period
- Duration of the shipping period

Waste Packaging Configuration:

ID 322A, ID 325A: The waste is packaged in two 7.5-gallon metal cans, a fiber drum pouch spreader, an inner polyvinyl chloride (PVC) pouch, a polyethylene drum liner, an outer PVC pouch, and a 17H 30-gallon drum with a high-efficiency particulate air (HEPA) filter vent or an opening in the drum lid. The PVC pouches are heat-sealed.

ID 322B, ID 325B: The waste is packaged in two 7.5-gallon metal cans, a fiber drum pouch spreader, an inner PVC pouch with a HEPA filter vent, a polyethylene drum liner, an outer PVC pouch with a HEPA filter vent, and a 17H 30-gallon drum with a HEPA filter vent or an opening in the drum lid.

Two shipping scenarios are considered:
1. The 30-gallon waste drums are placed directly in the 10-160B cask.
2. Each 30-gallon drum is placed directly in a 55-gallon drum with a filter vent installed on each drum. Ten drums will then be placed into the CNS 10-160B cask.

In defining the hydrogen gas generation limits, the second shipping scenario bounds the first scenario; thus, this waste packaging configuration is used to define the maximum allowable hydrogen generation rates.

Release Rates from Confinement Layers:

The hydrogen release rate across a heat-sealed polymer bag (RR) is a function of hydrogen permeability, ρ, across the PVC bag, the permeable surface area (Ap), bag thickness (xp), and gas concentration at standard temperature and pressure (STP) (Reference 12.2, Appendix 6.13). Specifically,

$$RR = \frac{\rho A_p P_g}{x_p} \frac{mole}{22,400 cm^3 (STP)}$$

where

RR	release rate of hydrogen (mole H_2/s/mole fraction H_2
ρ	hydrogen permeability, cm3(STP) cm-1 (cm Hg)-1 s-1
Ap	permeable surface area, cm2
Pg	gas pressure, cm Hg
xp	bag thickness, cm

The temperature dependence of gas permeability across a polymer can be defined by an Arrhenius equation:

$$\rho = \rho_0 \exp\left(\frac{-E_a}{RT}\right)$$

where Ea is the activation energy (kcal) associated with gas permeability, R is the gas constant defined as 1.987e-3 kcal/(mol K), and T is absolute gas temperature (K). For a hydrogen permeability for polyvinyl chloride of 3.6e-10 cm3(STP) cm-1 (cm Hg)-1 s-1 at 77°F (298.2 K) (Reference 12.2, Appendix 6.13)

with an activation energy of 1.9 kcal/mole, the constant $\rho 0$ can be defined to 8.89e-9 cm3 (STP) cm-1 (cm Hg)-1 s-1. The effect of temperature of the hydrogen release rate is demonstrated below.

Void Volume in the 10-160B cask IV: The minimum void volume in the cask when filled with the maximum number of ten (10) 55-gallon waste drums is estimated to be 1,938 L (Appendix 4.10.2.3 of CNS 10-160B SAR).

Permeable Surface Area and Thickness of PVC Confinement Layers: The minimum permeable surface area inside the 30-gallon waste drum was calculated based on the waste drum configuration described in Reference 12.1. The permeable surface area of a PVC confinement layer is defined by its minimum height and diameter. The maximum outside diameters of the 7.5-gallon steels cans and polyethylene drum liner is 15 in (38.1 cm) and 18 in (45.7 cm), respectively. The 30-gallon drum has a useable height of 28 in (71.1 cm). The diameters of the inner and outer PVC confinement layers are assumed to be 16 in (40.6 cm) and 17 cm (43.2 cm), respectively. Because of the presence of a fiberboard pouch spreader and polyethylene liner, the heights of the inner and outer PVC confinement layers are assumed to be 26 in (66.0 cm) and 27 in (68.6 cm), respectively. The dimensions of the inner confinement layer, assumed to be that of a cylinder, are used to define the surface of both PVC confinement layers. The surface area along the side and top of the cylinder defined the total surface area. The permeable area of each PVC layer was calculated to be 9,700 cm2 and its thickness is 20 mils (0.0508 cm).

Pressure: The pressure is assumed to be isobaric and equal to one atmosphere. The mole fraction of hydrogen in each void volume would be smaller if pressurization is considered and would result in a greater maximum allowable hydrogen gas generation rate. Furthermore, the amount of hydrogen gas generated during the shipping would be negligible compared to the quantity of air initially present at the time of closure of the 10-160B cask.

Temperature: In order to account for effect of temperature on gas permeability across a PVC confinement layer, an average gas permeability is defined over the operating temperature range. The maximum and minimum operating temperatures in the 10-160B cask have been assumed to be 168°F (348.7 K) and -40°F (233.2 K), respectively. In order to provide an additional margin of safety, an average hydrogen permeability, ρavg, was determined over the lower temperature range of 77°F (298.2 K) and -40°F (233.2 K).

$$\rho_{avg} = \frac{\int_{233.2K}^{298.2K} \rho_0 \exp\left(\frac{-E_a}{RT}\right) dT}{\int_{233.2K}^{298.2K} dT}$$

The average hydrogen permeability equals 2.46e-10 cm3 (STP) cm-1 (cm Hg)-1 s-1, which is equivalent to maintaining a constant temperature of 20°F (266.5 K).

Temperature-corrected hydrogen diffusivity values across filter vents (D*) used on drums and in heat-sealed bags were calculated at 20°F (266.5 K). The gas diffusivity across a filter vent at an absolute temperature T2 can be defined in terms of the hydrogen diffusivity across the same filter vent at a known absolute temperature T1(Reference 12.2, Appendix 6.9)

$$D_{T_2}^* = D_{T_1}^* \left(\frac{T_2}{T_1} \right)^{1.75}$$

The release rates across confinement layers used in the analysis are listed in Table 10-2.

Table 10-2. Hydrogen Release Rates Across Confinement Layers

Content Codes	Confinement Layer	Release Rate (mol/s/mol fraction)	
		T = 266.5 K	T = 298.2 K
ID 322A ID 325A	55-gal Drum Filter Vent	3.04e-6	3.70e-6
	30-gal Drum Filter Vent	3.04e-6	3.70e-6
	Each Heat-Sealed Bag	1.59e-7	2.33e-7
ID 322B ID 325B	55-gal Drum Filter Vent	3.04e-6	3.70e-6
	30-gal Drum Filter Vent	3.04e-6	3.70e-6
	Each Heat-Sealed Bag w/Filter Vent	8.99e-6	1.10e-5

10.4 Determination of Maximum Allowable Decay Heat Limits

The maximum allowable decay heat limits for content codes ID 322A, ID 322B, ID 325A, and ID 325B were calculated using the modeling methodology described in Section 10.4 of Appendix 4.10.2 and the content-code specific G values described below.

The gas-generation potential of a waste stream depends on the waste composition as well as the type of radiation that strikes the waste material. The radiation-specific effective G-values for each waste stream are calculated based on the maximum G-value for organic waste and the relative fraction of organic waste in the waste stream (Reference 12.2, Appendix 3.2). Waste streams designated to contain inorganic (noncombustible) or organic (combustible) solid waste contain at least 80% of the designated material (Reference 12.1). In calculating a G value for drums containing organic waste (ID 325A and ID 325B) , the drums are conservatively assumed to contain 100% combustible, hydrogenous material. Drums containing inorganic waste (ID 322A and ID 322B), the drums are assumed to contain a maximum of 20% hydrogenous material.

For waste drums in which the total dose has not exceed 0.012 W-yr, the maximum G value is based on cellulose and is determined at the maximum temperature (168°F) described by an Arrhenius equation (Reference 12.2, Appendix 3.1). Its G value at room temperature is 3.2 molecules per 100 eV with an activation energy of 2.1 kcal/mol. The maximum G value associated with solid organic waste is that of wet cellulose, which at room temperature is 1.09 molecules per 100 eV. Since matrix-depleted G values show no variation with temperature (Appendix 4.10.2, Attachment A), no temperature correction of these G values are made. Effective G values used to calculate decay heat limits are summarized in Table 10-3.

Table 10-3. Effective G-values by radiation type and content code.

	Content Code			
	ID 325A, ID 325B		**ID 322A, ID 322B**	
Radiation Type	**No Matrix Depletion**	**Matrix Depletion**	**No Matrix Depletion**	**Matrix Depletion**
Alpha	5.61	1.09	1.12	0.22
Beta	5.61	1.09	1.12	0.22
Gamma	5.61	5.61	1.12	1.12

G-value units: molecules per 100eV absorbed energy

10.5 Methodology for Compliance with Payload Assembly Requirements

10.5.1. Gas Generation Test Methodology

A waste drum in which its decay heat exceeds the maximum allowable decay heat limit can be shipped if the hydrogen gas generation in the waste drum can be demonstrated to be less than the maximum allowable hydrogen generation limit listed in Table 10-1 of this appendix. During the interim between drum retrieval and drum shipment, gas sample can be collected directly from the waste drum or from the container in which the vented waste drum is packaged. The measured hydrogen concentration can be related to the generation rate in the waste drum. Material balance equations are defined for different sampling scenarios from: (1) a vented 30-gallon waste drum; (2) a vented 55-gallon waste drum; or (3) a vented overpack container.

Direct Measurement of Hydrogen in Waste Drum

Vented waste drums in storage for over nine years are assumed to be at steady state. If a gas sample is collected directly from a waste drum, the gas generation rate is assumed to equal the hydrogen release rate across the filter vent:

$$C_g = X_{HS,H_2} D^*_{H_2}$$

where

C_g hydrogen gas generation rate, mol/s

$X_{HS,H2}$ hydrogen mole fraction in drum headspace

D^*_{H2} hydrogen diffusivity of drum filter vent, mol/s/mol fraction

The actual hydrogen concentration in a previously unvented waste drum asymptotically approaches its steady-state value with increasing vent time. If the hydrogen concentration from a newly vented drum is greater than the steady-state concentration, it will result in a higher (more conservative) calculated hydrogen gas generation rate.

Waste Drum Inside a Vented Waste Container

In cases where a vented waste drum (wd) is placed in a vented waste container (wc), a gas sample can be collected from the waste container headspace. The hydrogen concentration in the waste container headspace is determined by solving the following material balance equations:

$$\frac{dX_{wd}}{dt} = \frac{C_g}{N_{wd}} - \frac{RR^*_{wd}}{N_{wd}} \left(X_{wd} - X_{wc} \right)$$

$$\frac{dX_{wc}}{dt} = \frac{RR^*_{wd}}{N_{wc}}\left(X_{wd} - X_{wc}\right) - \frac{RR^*_{wc}}{N_{wc}}X_{wc}$$

where

X	hydrogen mole fraction in the innermost confinement layer of waste drum (wd) or container (wc)
RR*	hydrogen release rate across all confinement layers in waste drum or container
N	total moles gas in waste drum (wd) or container (wc)

In the case of the waste drum, there are multiple confinement layers defined by the heat-sealed bags and drum filter vent. The hydrogen release rate across multiple confinement layers is defined as the inverse of the sum of the effective hydrogen resistance , Reff, across each confinement layer.

$$RR^* = \left[\sum_i R_{eff,i}\right]^{-1}$$

In the waste container, the hydrogen release rate is defined solely by that of its filter vent, which is the inverse of the hydrogen diffusivity across the filter vent. The total moles, N, in any volume (V) is defined by the ideal gas law:

$$N = \frac{PV}{RT}$$

where

P'	gas pressure, atm
V	gas volume, liter (L)
R'	gas constant = 0.08206 atm l/(mol K)

The two differential equations above are identical in form to differential equations describing flammable gas generation in a container with two void volumes (Reference 12.2, Appendix 3.10). The analytical solution for these equations are described by Equations (5) through (9) in Reference 12.2, Appendix 3.10 and can be used to define the solutions to the differential equations. The resulting solution defines the relationship between the measured hydrogen concentration in the waste container at time t and the hydrogen gas generation rate. The value of hydrogen gas generation rate in the waste drum can be iterated in the equation defining hydrogen concentration in the waste container headspace until the calculated hydrogen concentration equals the measured value in the waste container headspace.

The initial hydrogen concentration in the waste container, Xwc(0), is zero. It is assumed that the vented waste drum is at steady state when placed inside the waste container. In this case, the initial hydrogen concentration in the waste drum is defined as:

$$X_{wd}(0) = \frac{C_g}{RR^*_{wd}}$$

The steady-state case bounds the situation when the hydrogen concentration in the newly vented waste drum may exceed its steady-state concentration. In this case, the hydrogen release rate will be greater than that in the steady-state case. This means hydrogen accumulation in the waste container headspace will occur more quickly, resulting in a calculated hydrogen generate rate greater than would be calculated in the case of the waste drum at steady state.

Waste Drum Inside Two Waste Containers
In the case where a waste drum is placed inside two consecutive vented waste containers, a gas sample can be collected from the headspace of the outer vented waste container. The material balance equations that describe hydrogen accumulation in the waste drum (wd), an inner waste container (iwc), and an outer waste container (owc), respectively, are:

$$\frac{dX_{wd}}{dt} = \frac{C_g}{N_{wd}} - \frac{RR^*_{wd}}{N_{wd}}(X_{wd} - X_{iwc})$$

$$\frac{dX_{iwc}}{dt} = \frac{RR^*_{wd}}{N_{iwc}}(X_{wd} - X_{iwc}) - \frac{RR^*_{iwc}}{N_{iwc}}(X_{iwc} - X_{owc})$$

$$\frac{dX_{owc}}{dt} = \frac{RR^*_{iwc}}{N_{owc}}(X_{iwc} - X_{owc}) - \frac{RR^*_{owc}}{N_{owc}}X_{owc}$$

At time zero, the waste drum is assumed to have been at steady state when placed inside the waste containers; therefore, Xwd(0) = Cg/RR*wd. The initial values, Xiwc(0) and Xowc(0) equal zero. At time t, the hydrogen concentration in the outer waste container headspace, Xowc, is measured.

The three differential equations above are identical in form to differential equations describing flammable gas generation for a container with three void volumes (Reference 12.2, Appendix 3.10). The analytical solution for these equations are described by Equations (16) through (34) in Reference 12.2 (Appendix 3.10) and can be used to determine the hydrogen gas generation rate based on the measured hydrogen concentration in the outer waste container headspace at time t. The value of hydrogen gas generation rate can be iterated in the equation defining hydrogen concentration in the outer waste container headspace until the calculated hydrogen concentration equals the measured value.

It is assumed that the vented waste drum is at steady state when placed inside the two waste containers. In this case, the initial hydrogen concentration in the waste drum is defined by same equation as in the case of waste in one waste container. As in the case of a waste drum inside one waste container, the steady state case bounds the situation when the hydrogen concentration in the newly vented waste drum may exceed its steady-state concentration.

11.0 WEIGHT

11.1 Requirements

The weight limit for the contents of the loaded cask is 14,500 pounds.

11.2 Methods of Compliance and Verification

The INEEL shall weigh each payload container and contents on a calibrated scale to determine the total weight of the payload container. Based on the total measured weight of the individual payload containers and the payload carriage, INEEL shall calculate total assembly weight and evaluate compliance with maximum contents weight limit.

12.0 REFERENCES

12.1   IT Corporation, "AK Documentation Report for INEEL-Stored Remote-Handled Transuranic Waste from Argonne National Laboratory-East," Revision 0, July 2003, IT Corporation, Albuquerque, New Mexico.

12.2   U. S. Department of Energy (DOE), CH-TRU Payload Appendices, Current Revision, U.S. Department of Energy Carlsbad Field Office, Carlsbad, New Mexico.

12.3   U. S. Department of Energy (DOE), Contact-Handled Transuranic Waste Authorized Methods for Payload Control (CH-TRAMPAC), Current Revision, U.S. Department of Energy Carlsbad Field Office, Carlsbad, New Mexico.

Attachment A

Transuranic Content Codes and Chemical Lists
for Idaho National Engineering and Environmental Laboratory

CONTENT CODE: ID 322A, ID 322B

CONTENT DESCRIPTION: Solid Inorganic Waste

WASTE DESCRIPTION: This waste consists primarily of a variety of inorganic debris.

GENERATING SOURCES: This waste is generated at the Argonne National Laboratory-East (ANL-E) Alpha Gamma Hot Cell Facility (AGHCF) between November 1971 and November 1995 during the processing of irradiated and unirradiated fuel pins from various reactor programs at ANL-W [Experimental Breeder Reactor-II (EBR-II)] and other U.S. Department of Energy (DOE) reactors, such as the New Production Reactor at the Savannah River Site (SRS). The AGHCF is a hot cell complex that includes office space, shielded gloveboxes, a hot cell under nitrogen atmosphere with work stations for remote manipulation of materials, and a Decontamination/Repair Area (DRA).

WASTE FORM: The waste consists of ferrous metals, including carbon and stainless steel and cast iron; nonferrous metals, including aluminum, brass, bronze, copper, lead, and tin; glass bottles, tubing, beakers, and plates; ceramic firebrick; porcelain (insulators); quartz; Vycor; boron nitride; and "passivated chemicals" absorbed in clay. Waste was contaminated primarily with fissile materials, MFP, and activation products. The predominant radionuclides are: Pu-239, Pu-240, Pu-241, Am-241, U-235, U-238, Cs-137, Ba-137m, Sr-90, Y-90, Co-60, and Fe-55.

WASTE PACKAGING:
ID 322A: The waste is packaged in two 7.5-gallon metal cans, a fiber drum pouch spreader, an inner PVC pouch, a polyethylene drum liner, an outer PVC pouch, and a 17H 30-gallon drum with a filter vent or an opening in the drum lid. The PVC pouches are heat-sealed. The inner PVC pouch is placed inside a rigid polyethylene liner without a lid. The liner and its contents are then heat-sealed inside the outer PVC pouch.

ID 322B: The waste is packaged in two 7.5-gallon metal cans, a fiber drum pouch spreader, an inner PVC pouch with a HEPA filter vent, a polyethylene drum liner, an outer PVC pouch with a filter vent, and a 17H 30-gallon drum with a filter vent or an opening in the drum lid. The inner PVC pouch is placed inside a rigid polyethylene liner without a lid. The liner and its contents are then heat-sealed inside the outer PVC pouch.

In addition, the 30-gallon drum may be placed within a vented 55-gallon waste drum.

METHODS FOR DETERMINATION OF ISOTOPIC CHARACTERIZATION: The isotopic composition of the waste is determined from process loss calculations and fission product calculations and was recorded on the associated forms or in data management systems. Therefore, the isotopic composition of the waste need not be determined by direct analysis or measurement of the waste unless process information is not available.

FREE LIQUIDS: Liquid waste is prohibited in the drums except for residual amounts in well-drained containers. The total volume of residual liquid in a payload container shall be less than 1 volume percent of the payload container. Waste packaging procedures ensure that free liquids are less than 1 volume percent of the payload container.

EXPLOSIVE/COMPRESSED GASES: Explosives and compressed gases in the payload containers are prohibited by waste packaging procedures.

PYROPHORICS: Sodium and NaK were passivated with alcohol and the alcohol absorbed into pelletized clay and evaporated. Other pyrophorics such as Zircalloy were sorted to segregate from WIPP waste containers.

CORROSIVES: Corrosives are prohibited in the payload container. Etchant solutions were neutralized and absorbed in pelletized clay rendering the solution noncorrosive prior to being a part of the waste. The physical form of the waste and the waste generating procedures ensure that the waste is in a nonreactive form.

CHEMICAL COMPATIBILITY: A chemical compatibility study has been performed on this content code, and all waste is chemically compatible for materials in greater than trace (>1% by weight) quantities.

ADDITIONAL CRITERIA: The sum of the hydrogen diffusivity of all drum filter vents per drum lid (30-gallon or 55-gallon), if present, is equal to or greater than 3.70e-06 mol/s/mol fraction at 25°C. The drum lid opening, if present, has an equivalent diameter equal to or greater than 0.3 in. Each bag filter vent, if present, has a minimum hydrogen diffusivity of 1.075e-05 mol/s/mol fraction at 25°C.

MAXIMUM ALLOWABLE HYDROGEN GENERATION RATES - OPTION 1: For ID 322A, the maximum allowable hydrogen generation rate limit is 3.61E-09 moles per second per drum and 3.61E-08 moles per second per CNS 10-160B cask. For ID 322B, the maximum allowable hydrogen generation rate limit is 3.28E-08 moles per second per drum and 3.28E-07 moles per second per CNS 10-160B cask.

MAXIMUM ALLOWABLE DECAY HEAT LIMIT - OPTION 2: For ID 322A, the maximum allowable decay heat limit is 3.26e-02 watts per drum and 3.26e-01 watts per CNS 10-160B cask if the total dose is less than or equal to 0.012 watt-yr and 1.17e-01 watts per drum and 1.17 watts per CNS 10-160B cask if the total dose is greater than 0.012 watt-yr. For ID 322B, the maximum allowable decay heat limit is 2.97e-01 watts per drum and 1.81 watts per CNS 10-160B cask if the total dose is less than or equal to 0.012 watt-yr and 1.02 watts per drum and 2.28 watts per CNS 10-160B cask if the total dose is greater than 0.012 watt-yr.

IDAHO NATIONAL ENGINEERING AND ENVIRONMENTAL LABORATORY CONTENT
CODE ID 322A
SOLID INORGANIC WASTE
MATERIALS AND CHEMICALS >1%

Aluminum
boron nitride
Brass
brick
Ceramic firebrick
Clay, pelletized
concrete
Ferrous metals (including carbon and stainless steels, cast iron)
Glass
HEPA FILTERS
Nonferrous metals (including aluminum, barium, brass, bronze, cadmium, chromium, copper, lead, mercury, selenium, and tin)
Organic debris ($\leq$ 20 volume %)
porcelain
quartz
STEEL
Vycor

MATERIALS AND CHEMICALS <1%

Toluene

4.10.2.5-A-4

CONTENT CODE: ID 325A, ID 325B

CONTENT DESCRIPTION: Solid Organic Waste

WASTE DESCRIPTION: This waste consists primarily of a variety of combustible debris.

GENERATING SOURCES: This waste is generated at the Argonne National Laboratory-East (ANL-E) Alpha Gamma Hot Cell Facility (AGHCF) between November 1971 and November 1995 during the processing of irradiated and unirradiated fuel pins from various reactor programs at ANL-W [Experimental Breeder Reactor-II (EBR-II)] and other U.S. Department of Energy (DOE) reactors, such as the New Production Reactor at the Savannah River Site (SRS). The AGHCF is a hot cell complex that includes office space, shielded gloveboxes, a hot cell under nitrogen atmosphere with workstations for remote manipulation of materials, and a Decontamination/Repair Area (DRA).

WASTE FORM: The waste consists of neoprene gloves and O-rings, polyethylene and polypropylene bottles; plastic tubing (including PVC, polyethylene, rubber, and styrene butadiene); PVC, polyurethane, and polyethylene bagging pouches; silicone and Teflon O-rings; paper products; cotton and synthetic rags; polyethylene and PVC sheeting; wood products (including masonite); neoprene, koroseal, and rubber gaskets; and a variety of plastics and cellulosics. Waste was contaminated primarily with fissile materials, mixed fission products (MFP), and activation products. The predominant radionuclides are: plutonium (Pu)-239, Pu-240, Pu-241, americium (Am)-241, uranium (U)-235, U-238, cesium (Cs)-137, barium (Ba)-137m, strontium (Sr)-90, yttrium (Y)-90, cobalt (Co)-60, and iron (Fe)-55.

WASTE PACKAGING:

ID 325A: The waste is packaged in two 7.5-gallon metal cans, a fiber drum pouch spreader, an inner PVC pouch, a polyethylene drum liner, an outer PVC pouch, and a 17H 30-gallon drum with a filter vent or an opening in the drum lid. The PVC pouches are heat-sealed. The inner PVC pouch is placed inside a rigid polyethylene liner without a lid. The liner and its contents are then heat-sealed inside the outer PVC pouch.

ID 325B: The waste is packaged in two 7.5-gallon metal cans, a fiber drum pouch spreader, an inner PVC pouch with a HEPA filter vent, a polyethylene drum liner, an outer PVC pouch with a filter vent, and a 17H 30-gallon drum with a filter vent or an opening in the drum lid. The inner PVC pouch is placed inside a rigid polyethylene liner without a lid. The liner and its contents are then heat-sealed inside the outer PVC pouch.

In addition, the 30-gallon drum may be placed within a vented 55-gallon waste drum.

METHODS FOR DETERMINATION OF ISOTOPIC CHARACTERIZATION: The isotopic composition of the waste is determined from process loss calculations and fission product calculations and was recorded on the associated forms or in data management systems. Therefore, the isotopic composition of the waste need not be determined by direct analysis or measurement of the waste unless process information is not available.

FREE LIQUIDS: Liquid waste is prohibited in the drums except for residual amounts in well-drained containers. The total volume of residual liquid in a payload container shall be less than 1 volume percent of the payload container. Waste packaging procedures ensure that free liquids are less than 1 volume percent of the payload container.

EXPLOSIVE/COMPRESSED GASES: Explosives and compressed gases in the payload containers are prohibited by waste packaging procedures.

PYROPHORICS: Sodium and NaK were passivated with alcohol and the alcohol absorbed into pelletized clay and evaporated. Other pyrophorics such as Zircalloy were sorted to segregate from WIPP waste containers.

CORROSIVES: Corrosives are prohibited in the payload container. Etchant solutions were neutralized and absorbed in pelletized clay rendering the solution noncorrosive prior to being a part of the waste. The physical form of the waste and the waste generating procedures ensure that the waste is in a noncreative form.

CHEMICAL COMPATIBILITY: A chemical compatibility study has been performed on this content code, and all waste is chemically compatible for materials in greater than trace (>1% by weight) quantities.

ADDITIONAL CRITERIA: The sum of the hydrogen diffusivity of all drum filter vents per drum lid (30-gallon or 55-gallon), if present, is equal to or greater than 3.70e-06 mol/s/mol fraction at 25°C. The drum lid opening, if present, has an equivalent diameter equal to or greater than 0.3 in. Each bag filter vent, if present, has a minimum hydrogen diffusivity of 1.075e-05 mol/s/mol fraction.

MAXIMUM ALLOWABLE HYDROGEN GENERATION RATES - OPTION 1: For ID 325A, the maximum allowable hydrogen generation rate limit is 3.61E-09 moles per second per drum and 3.61E-08 moles per second per CNS 10-160B cask. For ID 325B, the maximum allowable hydrogen generation rate limit is 3.28E-08 moles per second per drum and 3.28E-07 moles per second per CNS 10-160B cask.

MAXIMUM ALLOWABLE DECAY HEAT LIMIT - OPTION 2: For ID 325A, the maximum allowable decay heat limit is 6.48e-03 watts per drum and 6.48e-02 watts per CNS 10-160B cask if the total dose is less than or equal to 0.012 watt-yr and 2.35e-02 watts per drum and 2.35e-01 watts per CNS 10-160B cask if the total dose is greater than 0.012 watt-yr. For ID 325B, the maximum allowable decay heat limit is 5.94e-02 watts per drum and 5.94e-01 watts per CNS 10-160B cask if the total dose is less than or equal to 0.012 watt-yr and 2.06e-01 watts per drum and 2.06 watts per CNS 10-160B cask if the total dose is greater than 0.012 watt-yr.

**IDAHO NATIONAL ENGINEERING AND ENVIRONMENTAL LABORATORY CONTENT
CODE ID 325A
SOLID ORGANIC WASTE
MATERIALS AND CHEMICALS >1%**

cellulosics
clay, pelletized
Cotton
inorganic debris (including power cords, $\leq$ 20 volume %)
koroseal
Neoprene
plastic
polyethylene
polypropylene
PVC
Polyurethane
Paper
rubber
Silicone
styrene butadiene
synthetic rags
Teflon
wood (including masonite)

MATERIALS AND CHEMICALS <1%

Toluene

5.6 Appendices

Appendix 5.6.1

Shielding Evaluation of TRU Waste From
Idaho National Engineering and Environmental Laboratory (INEEL)
Idaho Falls, ID

1. Introduction

This appendix presents the shielding evaluation of RH-TRU wastes produced by Argonne National Laboratory-East (ANL-E) stored at the Idaho National Engineering and Environmental Laboratory (INEEL). The ANL-E RH-TRU waste was generated at the Alpha Gamma Hot Cell Facility during the destructive examination of experimental fuel elements. The INEEL currently has approximately 620 30-gallon drums of ANL-E RH-TRU waste in storage.

A typical drum of ANL-E waste is a 30-gallon drum containing a high-density polyethylene drum liner, a paper liner, two polyvinyl chloride (PVC) bags, two polyethylene discs, and two 7.5-gallon pails containing the waste.

2. Description of Shielding Design

2.1. Design Features
    See Section 5.1.2

2.2. Maximum Radiation Levels

Table A-1   Summary Table of External Radiation Levels

Normal Conditions of Transport	Package Surface mSv/h (mrem/h)			2 Meters from Vehicle mSv/h (mrem/h)
Radiation	Top	Side	Bottom	Side
Gamma	0.0027(0.27)	0.018(1.8)	0.0027(0.27)	0.0016(0.16)
Neutron	2E-6(2E-4)	5E-6(5E-4)	2E-6(2E-4)	7E-7(7E-5)
Total	0.0027(0.27)	0.018(1.8)	0.0027(0.27)	0.0016(0.16)
10 CFR 71.47 Limit[1]	2 (200)	2 (200)	2 (200)	0.1(10)

1. INEEL RH-TRU waste is shipped "exclusive use"

Hypothetical Accident Conditions	1 Meter from Package Surface mSv/h (mrem/h)		
Radiation	Top	Side	Bottom
Gamma	0.0043(0.43)	0.0025(0.25)	0.0043(0.43)
Neutron	8E-7(8E-5)	1E-6(1E-4)	8E-7(8E-5)
Total	0.0043(0.43)	0.0025(0.25)	0.0043(0.43)
10 CFR 71.51(a)(2) Limit	10 (1000)	10 (1000)	10 (1000)

These values are the area averaged axial and radial surface detector results for the SCALE default surface detectors. Values for segmented surfaces, which may give higher values than the surface averages, are presented in Section 5.4. The location of the surface detectors is shown in Figure A-1, below.

Figure A-1   SCALE Default Surface Detectors

AXIAL

RADIUS = RCAV   FOR 1a
= RCAV + 100 FOR 2a
· 100 FOR 3a
= RCAV + 100 FOR 4a

RADIAL DETECTORS

HEIGHT = 2 x (HFUE)   FOR 1b
= 2 x (HFUE + 100) FOR 2b
= 2 x (HFUE + 100) FOR 3b
= 2 x (HFUE + 100) FOR 4b

CASK
MIDPLANE
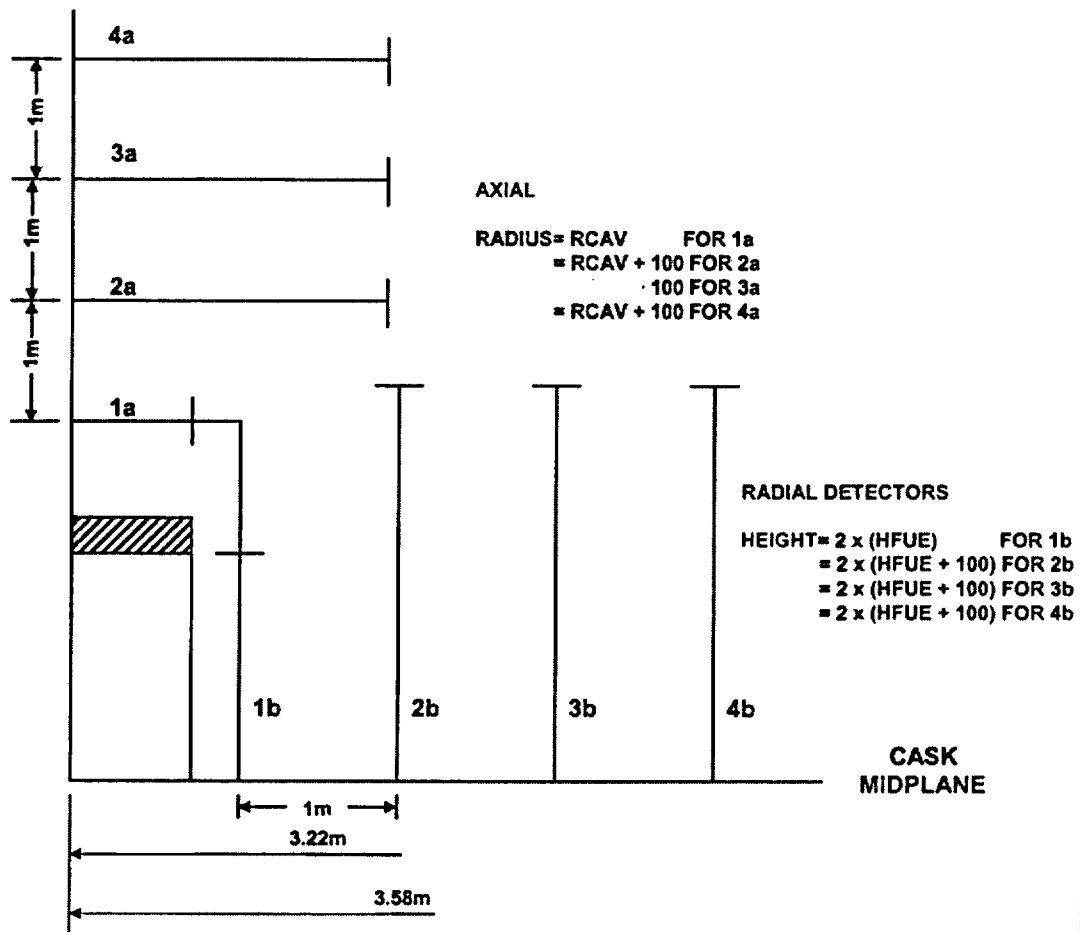
3. Source Specification

The radionuclide content of the INEEL RH-TRU waste is taken from Appendix A of reference 1. The expected activity (Ci) and uncertainty (one-sigma) is given by isotope for a batch of ten drums. The activity used in the estimate of external radiation levels is the expected plus 3 sigma. Activities by isotope (expected value, uncertainty (1 sigma), and expected plus 3 sigma) are given in Table A-2. As noted in Ref. 1, activation products make up less than 0.12% of the total activity in the fuel elements, nearly all from Fe-55 and Co-60. To conservatively estimate the gamma source term, Co-60 activity equal to 0.12% of the total of the other isotopes was included as expected activity.

Table A-2   Radionuclide Content for 10 Drums of RH-TRU

Isotope	Expected (Ci)	1 Sigma (Ci)	E + 3 Sigma (Ci)
Am-241	0.195	0.0856	4.52E-01
Ba-137m	2.18E+00	1.82E-01	2.73E+00
Co-60	1.54E-02	3.32E-03	2.54E-02
Cs-137	2.32E+00	1.93E-01	2.90E+00
Pu-238	0.0488	0.0272	1.30E-01
Pu-239	0.238	0.00783	2.61E-01
Pu-240	0.148	0.00444	1.61E-01
Pu-241	4.44E+00	1.87E+00	1.01E+01
Pu-242	3.88E-05	1.04E-05	7.00E-05
Sr-90	1.63E+00	1.97E-01	2.22E+00
U-233	3.28E-08	1.55E-08	7.93E-08
U-234	4.41E-04	1.30E-04	8.31E-04
U-238	2.75E-06	4.22E-08	2.88E-06
Y-90	1.63E+00	1.97E-01	2.22E+00

3.1. Gamma Source

The gamma source is shown in Table A-3, below. The values in the table are determined by listing the photons for each photon producing radionuclide in the 10 drum source from Table A-2. Photons with energies less than 0.1 MeV are neglected in the dose rate calculation, as they will not contribute to the dose rate at the cask exterior.

Table A-3   Individual Photon Characteristics
INEEL728-737

Photon Number	Nuclide	Energy (MeV)	Probability per decay	Equivalent curies	Photons per second	MeV per second
1	BA-137	.00447	.0103810	2.834e-002	1.049e+009	4.687e+006
2	PU-238	.01360	.1157500	1.505e-002	5.568e+008	7.572e+006
3	PU-239	.01360	.0441410	1.152e-002	4.263e+008	5.797e+006
4	PU-240	.01360	.1101200	1.773e-002	6.560e+008	8.921e+006
5	AM-241	.01390	.4270000	1.930e-001	7.141e+009	9.926e+007
6	AM-241	.02635	.0240000	1.085e-002	4.014e+008	1.057e+007
7	BA-137m	.03182	.0207030	5.652e-002	2.091e+009	6.654e+007
8	BA-137m	.03219	.0381970	1.043e-001	3.858e+009	1.242e+008
9	AM-241	.03320	.0010600	4.791e-004	1.773e+007	5.886e+005
10	BA-137m	.03640	.0139000	3.795e-002	1.404e+009	5.111e+007
11	PU-240	.05433	.0005247	8.447e-005	3.125e+006	1.698e+005
12	PU-238	.05530	.0004731	6.150e-005	2.276e+006	1.258e+005
13	AM-241	.05954	.3590000	1.623e-001	6.004e+009	3.575e+008
14	AM-241	.06923	.0017932	8.105e-004	2.999e+007	2.076e+006

15	PU-239	.11291	.0004758	1.242e-004	4.595e+006	5.188e+005
16	BA-137m	.66165	.8998000	2.456e+000	9.089e+010	6.014e+010
17	Co-60	.69382	.0001631	4.143e-006	1.533e+005	1.064e+005
18	Co-60	1.17320	1.0000000	2.540e-002	9.398e+008	1.103e+009
19	Co-60	1.33250	1.0000000	2.540e-002	9.398e+008	1.252e+009

3.2 Neutron Source

Neutrons are potentially produced in the INEEL waste from three mechanisms, spontaneous fission, α,n reactions, and induced fission. Induced fission was determined to not be a significant contributor for the INEEL waste. The neutron source term from the combination of these mechanisms, normalized to 1 gram of Pu-239, is shown in Table A-4.

**Table A-4   Neutron Source Term
INEEL728-737, per gram Pu-239**

Mechanism	Energy (MeV)	Neutrons per second
Spontaneous Fission	1.3	179.58
α,n reactions	4.8	112.15

From "Dose Rate Outside Transport Cask 10-160B from Neutrons Generated in RH TRU Waste from ANL-E",ICP/EXT-05-00875, (Ref. 5)

4. Shielding Model

4.1. Configuration of Source and Shielding

4.1.1. Normal Conditions of Transport

The INEEL waste, under normal transport conditions, is modeled as a annular volume in the10-160B cask cavity. The annulus has the inner (6.6") and outer (24.8") radius and height (58") of a circular array of 5 30-gallon drums stacked two high. The mass of the waste and the 10 30-gallon drums, as well as the radioactive contents, are assumed to be uniformly distributed throughout the volume of the annulus. The mass of the 7.5-gallon cans, the polyethylene liner, and PVC bags are conservatively not included. The walls of the 10-160B cask, 1.125" inner and 2" outer steel walls with a 1.875" lead layer between, are modeled as cylindrical shells around the waste cylinder. The base and lid of the cask is a 5.5" steel plate. Impact limiters are mounted on the top and bottom of the cask, as shown on page 1-5. The outer surface of the impact limiter is 21" above the lid or below the base. This geometry is shown in Figure A-2. Interms of shielding, the cask top and bottom are the same so only one end is modeled. Doses are evaluated at contact with the cask side and at contact with the top and bottom of the impact limiter, and at 2m from the cask trailer.

Figure A-2   NCT Cask Model

INEEL NCT

LEGEND
VOID
MATERIAL 1
MATERIAL 2
MATERIAL 3
MATERIAL 4
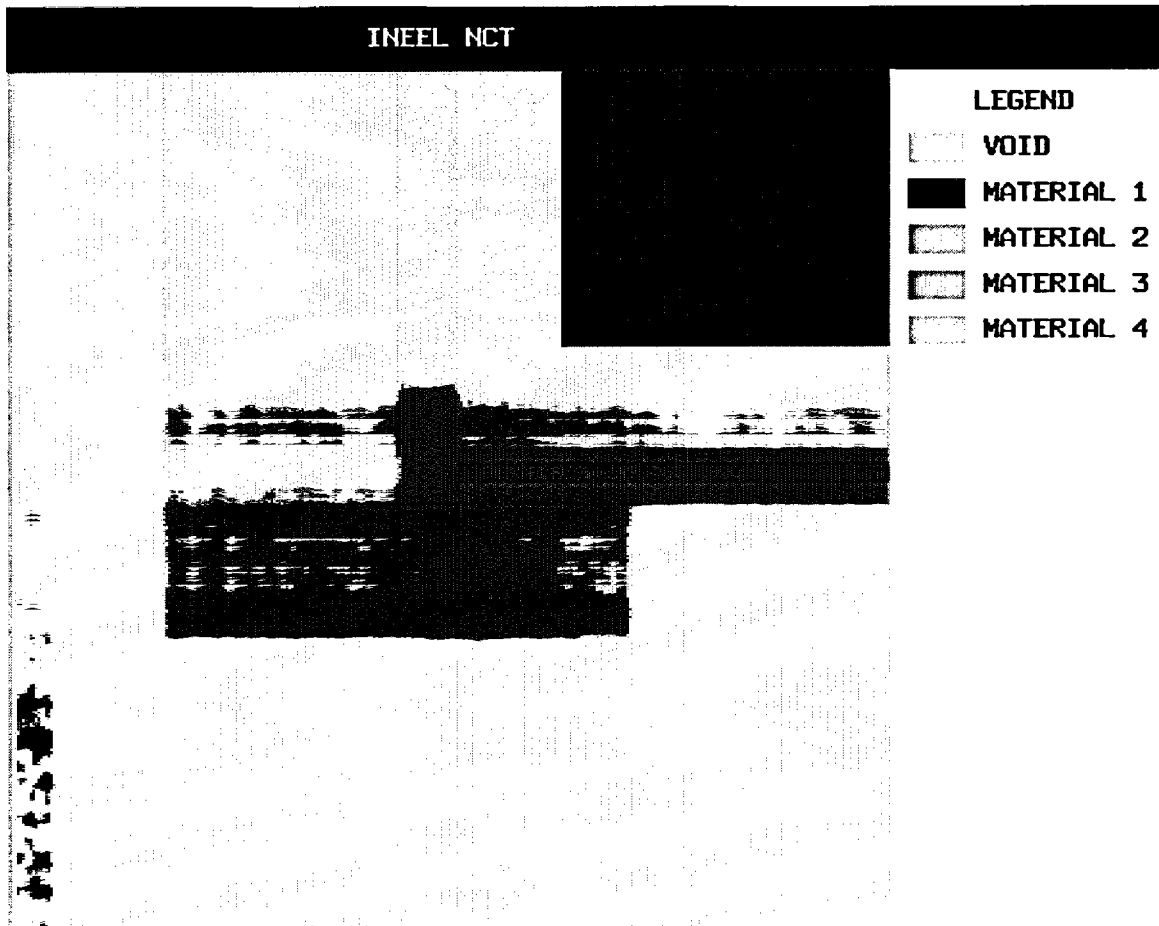
Material 1= waste   Material 2 = carbon steel   Material 3 = lead
Material 4 = air

4.1.2   Hypothetical Accident Conditions

The INEEL waste, after the 30' drop of the hypothetical accident conditions, is assumed to compress into a disc with a density 10 times the density of the waste as packaged. The waste disc is assumed to rest against the cask bottom at the intersection of the base and the side, as shown in Figure A-3. The lead slump resulting from the 30' drop (< 0.02") discussed in Section 5.4.3, does not significantly affect the dose. Doses are determined at 1 m from the side and the base.

Figure A-3   HAC Cask Model
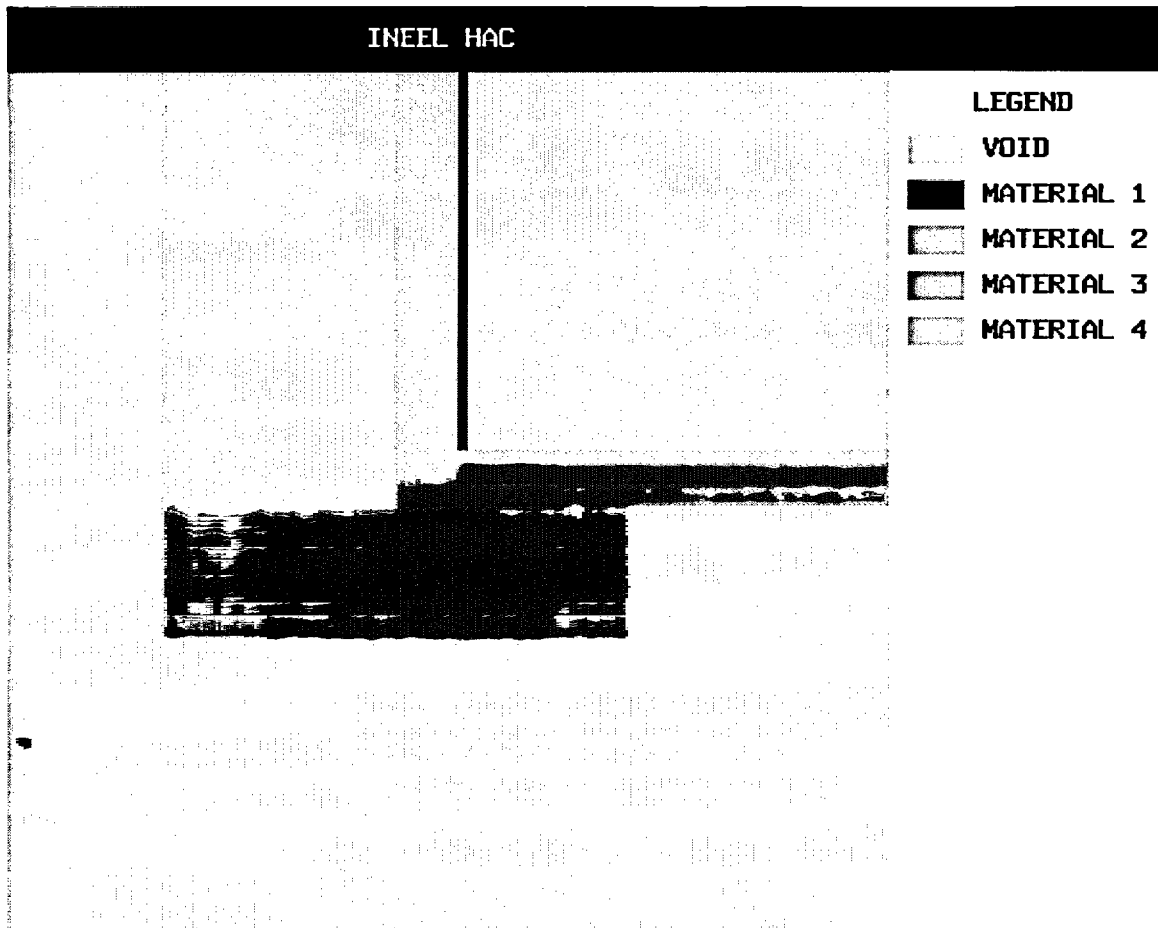
Material 1= waste   Material 2 = carbon steel   Material 3 = lead
Material 4 = air

4.2   Material Properties
The waste composition used in the shielding evaluation is taken from INEEL report EDF-4365 (Ref. 2). This report gives compositions for three waste matrices. The lowest density matrix, i.e., combustible waste, was used to maximize the calculated dose rates. The waste in a ten drum array (15 gallons per drum) was combined with ten 30-gallon drums and homogenized over the volume of the annulus to give the material composition for the waste source term used in the NCT calculations. The waste matrix density was increased by a factor of 10 to give the source used in the HAC calculations.

Table A-5   Material Properties

Material	Composition	Density (g/cm^3)
Combustible Waste (NCT)	See Table 3 of Ref. 2	0.197
30-gallon drum	Steel	7.86
Homogenized Waste (NCT)	Combustible Waste plus steel	0.137
Cask inner wall	Steel	7.86
Cask outer wall	Steel	7.86
Cask shield layer	Lead	11.34
Homogenized Waste (HAC)	See Table 3 of Ref. 2	1.37

5. Shielding Evaluation

5.1. Methods

The gamma and neutron dose rates were calculated using SCALE, Module SAS4 (Ref.3), using the geometry described in Section 4. The dose locations are the default radial and axial detector locations in SAS4 (IGO=1).

5.2. Input and Output Data

Two representative SCALE input files and dose rate outputs are provided as Attachments 1 and 2. The input file lists the inputs that define the source dimensions, shield dimensions, materials and density, and source spectrum.

5.3. Flux-to-Dose-Rate Conversion

The flux to exposure rate conversion factors are listed in Table A-6 and Table A-7 (Ref. 4). These are the default conversion factors in SCALE.

Table A-6   Gamma-Ray-Flux-To-Dose-Rate Conversion Factors

Photon Energy-E (MeV)	$DF_\gamma(E)$ Rem/hr/(photons/cm^2-s)
0.01	3.96-06
0.03	5.82-07
0.05	2.90-07
0.07	2.58-07
0.1	2.83-07
0.15	3.79-07
0.2	5.01-07
0.25	6.31-07

0.3	7.59-07
0.35	8.78-07
0.4	9.85-07
0.45	1.08-06
0.5	1.17-06
0.55	1.27-06
0.6	1.36-06
0.65	1.44-06
0.7	1.52-06
0.8	1.68-06
1.0	1.98-06
1.4	2.51-06
1.8	2.99-06
2.2	3.42-06
2.6	3.82-06
2.8	4.01-06
3.25	4.41-06
3.75	4.83-06
4.25	5.23-06
4.75	5.60-06
5.0	5.80-06
5.25	6.01-06
5.75	6.37-06
6.25	6.74-06
6.75	7.11-06
7.5	7.66-06
9.0	8.77-06
11.0	1.03-05
13.0	1.18-05
15.0	1.33-05

Table A-7   Neutron Flux-To-Dose-Rate Conversion Factors And Mean Quality Factors (QF)

Neutron Energy-E (MeV)	$\overline{QF}$*	$DF_n(E)$ (rem/hr) (n/cm^2-s)
2.5-08#	2	3.67-06
1.0-07	2	3.67-06
1.0-06	2	4.46-06
10.-05	2	4.54-06
1.0-04	2	4.18-06
1.0-03	2	3.76-06
1.0-02	2.5	3.56-06
1.0-01	7.5	2.17-05

5.0-01	11	9.26-05
1.0	11	1.32-04
2.5	9	1.25-04
5.0	8	1.56-04
7.0	7	1.47-04
10.0	6.5	1.47-04
14.0	75	2.08-04
20.0	8	2.27-04

*Maximum value of QF in a 30-cm phantom.
#Read as 2.5×10^{-8}

5.4. External Radiation Levels

The SCALE model used to determine external radiation levels uses surface detectors to calculate the dose rates at various distances from the cask surface either radially or axially. The default surface detectors are located as shown in Figure A-1. The values shown in Section 2.2 are the averages over these surface detectors. As Section 2.2 shows, the neutron dose rate is not significant and, thus, will be ignored in the discussion of the local maximum values. The surface detectors were segmented into 10 spatial segments and 4 azimuthial segments to identify local maximum values. Table A-8 contains the local maximum gamma dose rates found for each of the four cases, i.e., NCT radial, NCT axial, HAC radial, and HAC axial. These values were identified in the model output by finding the highest value in a spatial segment and then the highest azimuthial segment value for that spatial segment for each of the surface detectors. These local maximum values are consistent with but slightly higher than the surface average values in Table A-1.

Table A-8   Local Maximum External Radiation Levels

Normal Conditions of Transport	Package Surface mSv/h (mrem/h)			2 Meters from Vehicle mSv/h (mrem/h)
Radiation	Top	Side	Bottom	Side
Gamma	0.0046(0.46)	0.028(2.8)	0.0046(0.46)	0.0027(0.27)
10 CFR 71.47 Limit[1]	2 (200)	2 (200)	2 (200)	0.1(10)

1. INEEL RH-TRU waste is shipped "exclusive use"

Hypothetical Accident Conditions	1 Meter from Package Surface mSv/h (mrem/h)		
Radiation	Top	Side	Bottom
Gamma	0.011(1.1)	0.0038(0.38)	0.011(1.1)
10 CFR 71.51(a)(2) Limit	10 (1000)	10 (1000)	10 (1000)

5.5. Maximum Drum Contents

As expected, the dose rate at 2m from the side of the vehicle is the most restrictive, i.e., has the smallest ratio of value to limit. To maintain a reasonable margin, the cask contents should not exceed the expected+3 sigma values of Table A-2 by more than a factor of thirty (30).

6. References

6.1. P. Kuan and R. Bhatt, "Methodology to Determine Radioisotope Contents in RH TRU Waste Drums for Irradiated Fuel Examination at ANL-E", INEEL/EXT-02-00169, Revision 0, Sept. 2003

6.2. C. Hoffman, "Expected Dose-Reduction Factors from Argonne National Laboratory-East Remote-Handled Waste in a 30-gal Drum Overpack", EDF-4365, February 2004

6.3. SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations, NUREG/CR-0200, Rev.6 (ORNL/NUREG/CSD-2/R6), Vols. I, II, III, May 2000

6.4. ANSI/ANS 6.1.1-1977, "Neutron and Gamma-Ray Flux-to-Dose-Rate Factors."

6.5. R. Bhatt, "Dose Rate Outside Transport Cask 10-160B from Neutrons Generated in RH TRU Waste from ANL-E", ICP/EXT-05-00875, April 2005

10-160b
HAC
Neutron

```
'Input generated by Espn 89 Compiled on 06-07-2002
=sas4      parm=size=500000
10-160B
27n-18couple  infhommedium
 arbmhacwst 1.37 7 0 0 0 26000 51.87 6012 28.32 17000 4.63 1001 3.93
 7014 0.82 8016 7.72 9019 2.71 1 1 293 end
 carbonsteel 2 1 293 end
 lead 3 1 293 end
 arbmair 0.0011 2 0 0 0 7014 82 8016 18 4 1 293 end
end comp
 idr=1 ity=1 izm=4 isn=8 irf=9029 ifs=0 mhw=1 frd=86.35 szf=1   end
 74 97.8 111.9 165.2    end
 4 0 2 4    end
xend
 ran=000000000003 tim=1 nst=100 nmt=400 nit=100 nco=4 ist=0 ipr=0 iso=1
 nod=0 sfa=292 igo=0 inb=0 ine=0 mfu=4 isp=0 ipf=0 isd=4 nda=1000   end
 soe 0 112.1 0 0 179.58 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 end
 sds 10 4 10 4 10 4 10 4 end
gend
ineel tru
 fue 95.28 97.7 end
fend
 inn 2 89.2 99.8 end
 rsl 3 94 97.8 end
 our 2 99.08 111.9 end
 asl 2 89.2 106.8 end
 imp 4 129.5 165.2 58.6 end
 hol 2 end
 cav 4 86.4 97.8 end
cend
end
```

* * * * surface detectors results (rem/h)* * * *

detector locations: axial

surface #	height	zrmin	zrmax	intzr	intam	dose rate	fsd	# of hits
1	165.200	0.000	86.400	10	4	7.616E-08	0.033	2502
2	265.200	0.000	186.400	10	4	1.861E-08	0.029	2930
3	365.200	0.000	186.400	10	4	1.075E-08	0.033	1853
4	465.200	0.000	186.400	10	4	6.479E-09	0.044	1176

- - - - tallies of spatial segments on each surface - - - -

tallies of spatial segments on surface # 1

segment #	mid point	dose rate	fsd	# of hits
1	4.32	1.721E-07	0.256	50
2	12.96	9.806E-08	0.135	92
3	21.60	1.004E-07	0.105	154
4	30.24	7.649E-08	0.093	195
5	38.88	1.013E-07	0.085	296
6	47.52	9.594E-08	0.071	357

7	56.16	8.673E-08	0.069	349
8	64.80	6.742E-08	0.087	345
9	73.44	5.805E-08	0.077	320
10	82.08	5.360E-08	0.074	344

tallies of spatial segments on surface # 2

segment #	mid point	dose rate	fsd	# of hits
1	9.32	4.745E-08	0.196	74
2	27.96	3.003E-08	0.116	155
3	46.60	2.960E-08	0.092	285
4	65.24	2.825E-08	0.067	358
5	83.88	2.351E-08	0.076	358
6	102.52	2.114E-08	0.072	373
7	121.16	1.745E-08	0.077	358
8	139.80	1.594E-08	0.065	358
9	158.44	1.323E-08	0.080	308
10	177.08	1.275E-08	0.079	303

tallies of spatial segments on surface # 3

segment #	mid point	dose rate	fsd	# of hits
1	9.32	1.026E-08	0.307	20
2	27.96	1.386E-08	0.160	79
3	46.60	1.669E-08	0.123	141
4	65.24	1.346E-08	0.113	188
5	83.88	1.117E-08	0.105	187
6	102.52	1.108E-08	0.099	220
7	121.16	1.085E-08	0.094	247
8	139.80	1.107E-08	0.090	276
9	158.44	8.824E-09	0.094	243
10	177.08	8.733E-09	0.080	252

tallies of spatial segments on surface # 4

segment #	mid point	dose rate	fsd	# of hits
1	9.32	7.209E-09	0.344	16
2	27.96	6.386E-09	0.288	32
3	46.60	9.695E-09	0.130	87
4	65.24	7.347E-09	0.140	108
5	83.88	7.440E-09	0.134	130
6	102.52	7.279E-09	0.113	143
7	121.16	6.046E-09	0.125	138
8	139.80	6.017E-09	0.116	152
9	158.44	6.303E-09	0.097	197
10	177.08	5.189E-09	0.116	173

- - - - tallies of azimuthal segments - - - -

tallies of azimuthal segments on surface # 1

azimuthal segmt. #	mid point	spatial segment 1			spatial segment 2			spatial segment 3			spatial segment 4		
		dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits
1	45.00	2.538E-07	0.528	20	9.710E-08	0.248	24	1.079E-07	0.243	37	1.022E-07	0.155	64
2	135.00	7.142E-08	0.507	7	7.025E-08	0.351	16	1.158E-07	0.208	48	7.023E-08	0.209	48
3	225.00	1.088E-07	0.346	11	7.784E-08	0.288	18	6.449E-08	0.239	26	5.859E-08	0.185	38
4	315.00	2.545E-07	0.437	12	1.471E-07	0.271	34	1.137E-07	0.200	43	7.495E-08	0.239	45

azimuthal	mid	spatial segment 5	spatial segment 6	spatial segment 7	spatial segment 8

segmt. #	point	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits
1	45.00	8.712E-08	0.150	71	7.980E-08	0.150	80	8.830E-08	0.134	97	5.939E-08	0.174	80
2	135.00	1.090E-07	0.202	74	9.783E-08	0.135	90	8.369E-08	0.147	90	6.883E-08	0.155	84
3	225.00	1.120E-07	0.162	74	8.387E-08	0.138	87	9.554E-08	0.137	80	6.590E-08	0.149	78
4	315.00	9.725E-08	0.138	77	1.223E-07	0.144	100	7.939E-08	0.169	82	7.558E-08	0.143	103

azimuthal mid		spatial segment 9			spatial segment 10		
segmt. #	point	dose rate	fsd	hits	dose rate	fsd	hits
1	45.00	5.469E-08	0.136	78	6.219E-08	0.137	95
2	135.00	6.450E-08	0.148	74	5.837E-08	0.157	84
3	225.00	6.221E-08	0.164	87	4.368E-08	0.164	71
4	315.00	5.082E-08	0.134	81	5.017E-08	0.150	94

tallies of azimuthal segments on surface # 2

azimuthal mid		spatial segment 1			spatial segment 2			spatial segment 3			spatial segment 4		
segmt. #	point	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits
1	45.00	7.609E-08	0.289	28	4.045E-08	0.189	49	3.304E-08	0.170	79	3.072E-08	0.164	94
2	135.00	2.349E-08	0.461	11	2.848E-08	0.311	33	2.072E-08	0.196	59	2.663E-08	0.139	89
3	225.00	3.336E-08	0.283	18	2.084E-08	0.209	35	3.082E-08	0.164	64	2.799E-08	0.160	82
4	315.00	5.686E-08	0.444	17	3.036E-08	0.296	38	3.380E-08	0.172	83	2.765E-08	0.141	93

azimuthal mid		spatial segment 5			spatial segment 6			spatial segment 7			spatial segment 8		
segmt. #	point	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits
1	45.00	2.743E-08	0.131	92	2.255E-08	0.156	103	1.709E-08	0.137	85	1.725E-08	0.122	98
2	135.00	2.071E-08	0.134	89	2.360E-08	0.174	87	1.778E-08	0.149	95	1.591E-08	0.131	88
3	225.00	1.961E-08	0.152	77	1.910E-08	0.135	87	1.876E-08	0.124	97	1.610E-08	0.134	92
4	315.00	2.631E-08	0.125	100	1.931E-08	0.152	96	1.616E-08	0.136	81	1.451E-08	0.134	80

azimuthal mid		spatial segment 9			spatial segment 10		
segmt. #	point	dose rate	fsd	hits	dose rate	fsd	hits
1	45.00	1.323E-08	0.151	75	1.254E-08	0.157	75
2	135.00	1.418E-08	0.142	77	1.258E-08	0.141	73
3	225.00	1.051E-08	0.154	66	1.132E-08	0.162	72
4	315.00	1.498E-08	0.148	90	1.457E-08	0.162	83

tallies of azimuthal segments on surface # 3

azimuthal mid		spatial segment 1			spatial segment 2			spatial segment 3			spatial segment 4		
segmt. #	point	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits
1	45.00	9.533E-09	0.696	3	1.940E-08	0.264	28	2.120E-08	0.280	46	1.432E-08	0.181	48
2	135.00	1.903E-08	0.442	7	9.822E-09	0.307	16	1.032E-08	0.275	25	1.549E-08	0.186	48
3	225.00	8.431E-09	0.806	5	6.730E-09	0.328	14	1.819E-08	0.219	34	1.058E-08	0.236	44
4	315.00	4.034E-09	0.772	5	1.948E-08	0.338	21	1.706E-08	0.218	36	1.347E-08	0.234	48

azimuthal mid		spatial segment 5			spatial segment 6			spatial segment 7			spatial segment 8		
segmt. #	point	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits
1	45.00	1.089E-08	0.210	46	1.308E-08	0.186	61	9.847E-09	0.195	61	1.359E-08	0.179	81
2	135.00	1.147E-08	0.250	48	9.952E-09	0.182	53	9.664E-09	0.181	55	9.615E-09	0.205	62
3	225.00	1.222E-08	0.191	49	9.282E-09	0.193	43	9.956E-09	0.177	58	1.188E-08	0.149	71
4	315.00	1.012E-08	0.243	44	1.203E-08	0.199	63	1.395E-08	0.191	73	9.178E-09	0.160	62

azimuthal mid		spatial segment 9			spatial segment 10		
segmt. #	point	dose rate	fsd	hits	dose rate	fsd	hits
1	45.00	8.404E-09	0.160	66	1.120E-08	0.138	71
2	135.00	9.273E-09	0.161	62	7.250E-09	0.163	56

```
3   225.00   1.091E-08 0.171   67   7.939E-09 0.157   63
4   315.00   6.707E-09 0.197   48   8.539E-09 0.169   62
```

tallies of azimuthal segments on surface # 4

azimuthal	mid	spatial segment 1			spatial segment 2			spatial segment 3			spatial segment 4		
segmt. #	point	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits
1	45.00	7.530E-09	0.724	4	8.079E-09	0.470	10	1.009E-08	0.253	31	8.340E-09	0.271	32
2	135.00	5.361E-09	0.741	2	1.909E-09	0.570	4	8.107E-09	0.273	17	6.064E-09	0.298	23
3	225.00	5.759E-09	0.638	5	7.319E-09	0.733	6	1.224E-08	0.271	21	7.472E-09	0.260	27
4	315.00	1.019E-08	0.662	5	8.238E-09	0.398	12	8.349E-09	0.322	18	7.514E-09	0.273	26

azimuthal	mid	spatial segment 5			spatial segment 6			spatial segment 7			spatial segment 8		
segmt. #	point	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits
1	45.00	1.045E-08	0.295	38	7.118E-09	0.223	32	5.243E-09	0.214	32	3.587E-09	0.271	33
2	135.00	5.516E-09	0.260	25	5.192E-09	0.289	26	7.206E-09	0.202	43	4.364E-09	0.230	29
3	225.00	7.379E-09	0.211	40	8.353E-09	0.218	42	4.293E-09	0.410	20	8.372E-09	0.194	44
4	315.00	6.413E-09	0.265	27	8.451E-09	0.230	43	7.443E-09	0.262	43	7.744E-09	0.239	46

azimuthal	mid	spatial segment 9			spatial segment 10		
segmt. #	point	dose rate	fsd	hits	dose rate	fsd	hits
1	45.00	6.666E-09	0.188	52	6.293E-09	0.240	52
2	135.00	6.188E-09	0.202	47	4.539E-09	0.300	36
3	225.00	6.080E-09	0.187	49	4.146E-09	0.245	37
4	315.00	6.278E-09	0.185	49	5.779E-09	0.175	48

10-160b
NCT
Gamma

```
'Input generated by Espn 89 Compiled on 06-07-2002
=sas4      parm=size=500000
10-160B
27n-18couple  infhommedium
 arbmwst 0.137 7 0 0 0 26000 51.87 6012 28.32 17000 4.63 1001 3.93 7014
 0.82 8016 7.72 9019 2.71 1 1 293 end
 carbonsteel 2 1 293 end
 lead 3 1 293 end
 arbmair 0.0011 2 0 0 0 7014 82 8016 18 4 1 293 end
end comp
 idr=0 ity=2 izm=5 isn=8 irf=9504 ifs=0 mhw=1 frd=62.9 szf=1   end
 62.9 86.36 89.2 94 99.08    end
 1 4 2 3 2    end
xend
 ran=000000000003 tim=5 nst=5000 nmt=15000 nit=100 nco=4 ist=0 ipr=0
 iso=0 nod=0 sfa=8.78e+10 igo=1 inb=0 ine=0 mfu=1 isp=0 ipf=0 isd=4
 nda=1000   end
 soe 0 112.1 0 0 179.58 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 121.1 429 0 24840 0 0 0 1 0 0 end
 sds 10 4 10 4 10 4 10 4 end
gend
ineel tru
 fu1 0.01 0.02 74 74.1 end
 fu2 16.7 62.9 74 74.1 end
fend
 inn 2 89.2 99.8 end
 rs1 3 94 97.8 end
 our 2 99.08 111.9 end
 as1 2 89.2 106.8 end
 imp 4 129.5 165.2 58.6 end
 hol 2 end
 cav 4 86.4 97.8 end
cend
end
```

* * * * surface detectors results (rem/h)* * * *

detector locations: radial

surface #	radius	zrmin	zrmax	intzr	intam	dose rate	fsd	# of hits
1	99.100	0.000	74.000	10	4	1.685E-03	0.014	374995
2	199.100	0.000	174.000	10	4	3.595E-04	0.035	536674
3	322.000	0.000	174.000	10	4	1.599E-04	0.043	420865
4	358.000	0.000	174.000	10	4	1.316E-04	0.045	390639

- - - - tallies of spatial segments on each surface - - - -

tallies of spatial segments on surface # 1
segment #	mid point	dose rate	fsd	# of hits
1	3.70	2.270E-03	0.023	49654
2	11.10	2.170E-03	0.020	49667
3	18.50	2.424E-03	0.063	50308

4	25.90	2.235E-03	0.043	49450
5	33.30	1.988E-03	0.021	47612
6	40.70	2.008E-03	0.021	45665
7	48.10	1.970E-03	0.021	43789
8	55.50	1.782E-03	0.050	38850
9	62.90	0.000E+00	0.000	0
10	70.30	0.000E+00	0.000	0

tallies of spatial segments on surface # 2

segment #	mid point	dose rate	fsd	# of hits
1	8.70	5.457E-04	0.055	84567
2	26.10	4.865E-04	0.021	81598
3	43.50	4.800E-04	0.025	77101
4	60.90	4.424E-04	0.033	69028
5	78.30	4.528E-04	0.139	64364
6	95.70	3.451E-04	0.039	49580
7	113.10	2.696E-04	0.035	39155
8	130.50	2.265E-04	0.034	30320
9	147.90	1.892E-04	0.049	23239
10	165.30	1.575E-04	0.055	17722

tallies of spatial segments on surface # 3

segment #	mid point	dose rate	fsd	# of hits
1	8.70	1.993E-04	0.096	52724
2	26.10	1.809E-04	0.028	51339
3	43.50	1.712E-04	0.025	49951
4	60.90	1.756E-04	0.040	48286
5	78.30	1.635E-04	0.035	44777
6	95.70	1.504E-04	0.025	40843
7	113.10	1.711E-04	0.202	42071
8	130.50	1.480E-04	0.079	33826
9	147.90	1.252E-04	0.039	30330
10	165.30	1.139E-04	0.055	26718

tallies of spatial segments on surface # 4

segment #	mid point	dose rate	fsd	# of hits
1	8.70	1.574E-04	0.108	47033
2	26.10	1.464E-04	0.031	46014
3	43.50	1.380E-04	0.028	44790
4	60.90	1.446E-04	0.043	43860
5	78.30	1.316E-04	0.037	41342
6	95.70	1.230E-04	0.030	38037
7	113.10	1.470E-04	0.206	40385
8	130.50	1.118E-04	0.048	32584
9	147.90	1.114E-04	0.084	29711
10	165.30	1.044E-04	0.041	26883

- - - - tallies of azimuthal segments - - - -

tallies of azimuthal segments on surface # 1

azimuthal segmt. #	mid point	spatial segment 1 dose rate	fsd	hits	spatial segment 2 dose rate	fsd	hits	spatial segment 3 dose rate	fsd	hits	spatial segment 4 dose rate	fsd	hits
1	45.00	2.204E-03	0.038	12373	2.118E-03	0.033	12257	2.782E-03	0.201	12314	2.126E-03	0.050	12242
2	135.00	2.391E-03	0.057	12502	2.322E-03	0.049	12663	2.314E-03	0.081	12949	2.118E-03	0.036	12338
3	225.00	2.287E-03	0.039	12521	2.083E-03	0.030	12321	2.196E-03	0.035	12557	2.517E-03	0.141	12534

| 4 | 315.00 | 2.199E-03 0.054 12258 | 2.156E-03 0.045 12426 | 2.405E-03 0.053 12488 | 2.181E-03 0.038 12336 |

azimuthal segmt. #	mid point	spatial segment 5 dose rate fsd hits	spatial segment 6 dose rate fsd hits	spatial segment 7 dose rate fsd hits	spatial segment 8 dose rate fsd hits
1	45.00	2.061E-03 0.038 11806	2.017E-03 0.037 11213	2.016E-03 0.047 10714	1.935E-03 0.161 9936
2	135.00	1.895E-03 0.036 11843	2.073E-03 0.039 11392	1.922E-03 0.040 11070	1.745E-03 0.040 9707
3	225.00	1.984E-03 0.035 11934	1.871E-03 0.036 11533	2.058E-03 0.039 10970	1.897E-03 0.076 9584
4	315.00	2.013E-03 0.045 12029	2.072E-03 0.042 11527	1.884E-03 0.041 11035	1.552E-03 0.036 9623

azimuthal segmt. #	mid point	spatial segment 9 dose rate fsd hits	spatial segment 10 dose rate fsd hits
1	45.00	0.000E+00 0.000 0	0.000E+00 0.000 0
2	135.00	0.000E+00 0.000 0	0.000E+00 0.000 0
3	225.00	0.000E+00 0.000 0	0.000E+00 0.000 0
4	315.00	0.000E+00 0.000 0	0.000E+00 0.000 0

tallies of azimuthal segments on surface # 2

azimuthal segmt. #	mid point	spatial segment 1 dose rate fsd hits	spatial segment 2 dose rate fsd hits	spatial segment 3 dose rate fsd hits	spatial segment 4 dose rate fsd hits
1	45.00	6.385E-04 0.188 21279	5.173E-04 0.063 20322	5.098E-04 0.076 19391	4.661E-04 0.112 17275
2	135.00	5.025E-04 0.031 21098	4.815E-04 0.026 20562	4.744E-04 0.046 19484	4.241E-04 0.039 17047
3	225.00	5.107E-04 0.030 21000	4.655E-04 0.025 20244	4.668E-04 0.032 19234	4.629E-04 0.057 17278
4	315.00	5.313E-04 0.040 21190	4.819E-04 0.028 20470	4.691E-04 0.030 18992	4.163E-04 0.024 17428

azimuthal segmt. #	mid point	spatial segment 5 dose rate fsd hits	spatial segment 6 dose rate fsd hits	spatial segment 7 dose rate fsd hits	spatial segment 8 dose rate fsd hits
1	45.00	6.068E-04 0.396 19955	3.524E-04 0.101 12653	2.881E-04 0.101 9865	2.358E-04 0.097 7634
2	135.00	4.008E-04 0.041 14991	3.568E-04 0.047 12298	2.635E-04 0.046 9911	2.013E-04 0.036 7444
3	225.00	4.416E-04 0.150 14731	3.084E-04 0.028 12426	2.725E-04 0.073 9652	2.438E-04 0.061 7593
4	315.00	3.622E-04 0.025 14687	3.626E-04 0.097 12203	2.545E-04 0.032 9727	2.249E-04 0.035 7649

azimuthal segmt. #	mid point	spatial segment 9 dose rate fsd hits	spatial segment 10 dose rate fsd hits
1	45.00	1.795E-04 0.060 5800	1.820E-04 0.116 4439
2	135.00	1.901E-04 0.061 5902	1.616E-04 0.092 4328
3	225.00	1.870E-04 0.046 5760	1.384E-04 0.049 4482
4	315.00	2.001E-04 0.166 5777	1.481E-04 0.093 4473

tallies of azimuthal segments on surface # 3

azimuthal segmt. #	mid point	spatial segment 1 dose rate fsd hits	spatial segment 2 dose rate fsd hits	spatial segment 3 dose rate fsd hits	spatial segment 4 dose rate fsd hits
1	45.00	2.672E-04 0.278 13198	1.941E-04 0.092 12875	1.814E-04 0.065 12418	1.736E-04 0.110 11969
2	135.00	1.792E-04 0.044 13246	1.772E-04 0.039 12729	1.692E-04 0.035 12609	1.770E-04 0.068 12361
3	225.00	1.673E-04 0.037 13111	1.754E-04 0.040 12870	1.700E-04 0.034 12488	1.814E-04 0.080 11933
4	315.00	1.836E-04 0.064 13169	1.767E-04 0.037 12865	1.642E-04 0.034 12436	1.702E-04 0.041 12023

azimuthal segmt. #	mid point	spatial segment 5 dose rate fsd hits	spatial segment 6 dose rate fsd hits	spatial segment 7 dose rate fsd hits	spatial segment 8 dose rate fsd hits
1	45.00	1.738E-04 0.115 11294	1.580E-04 0.084 10408	2.762E-04 0.495 14124	1.405E-04 0.081 8536
2	135.00	1.524E-04 0.034 11186	1.537E-04 0.044 10125	1.350E-04 0.055 9363	1.413E-04 0.068 8439
3	225.00	1.710E-04 0.048 11107	1.402E-04 0.038 10032	1.404E-04 0.040 9349	1.673E-04 0.238 8451
4	315.00	1.569E-04 0.039 11190	1.498E-04 0.040 10278	1.328E-04 0.036 9235	1.426E-04 0.133 8400

azimuthal	mid	spatial segment 9	spatial segment 10

```
segmt. #  point   dose rate  fsd   hits   dose rate  fsd   hits
   1    45.00   1.160E-04 0.083  7547   1.150E-04 0.102  6737
   2   135.00   1.265E-04 0.077  7504   1.088E-04 0.043  6768
   3   225.00   1.345E-04 0.099  7548   1.062E-04 0.046  6645
   4   315.00   1.240E-04 0.044  7731   1.256E-04 0.163  6568
```

tallies of azimuthal segments on surface # 4

azimuthal mid		spatial segment 1			spatial segment 2			spatial segment 3			spatial segment 4		
segmt. #	point	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits
1	45.00	2.151E-04	0.309	11739	1.611E-04	0.088	11578	1.425E-04	0.084	11060	1.479E-04	0.106	10919
2	135.00	1.408E-04	0.044	11733	1.437E-04	0.043	11574	1.394E-04	0.040	11158	1.366E-04	0.071	11292
3	225.00	1.307E-04	0.037	11805	1.427E-04	0.038	11388	1.310E-04	0.038	11291	1.570E-04	0.079	10751
4	315.00	1.429E-04	0.070	11756	1.379E-04	0.041	11474	1.389E-04	0.038	11281	1.371E-04	0.043	10898

azimuthal mid		spatial segment 5			spatial segment 6			spatial segment 7			spatial segment 8		
segmt. #	point	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits	dose rate	fsd	hits
1	45.00	1.367E-04	0.117	10432	1.296E-04	0.092	9697	2.363E-04	0.515	13727	1.170E-04	0.086	8210
2	135.00	1.315E-04	0.039	10271	1.184E-04	0.042	9496	1.233E-04	0.054	8998	1.047E-04	0.050	8056
3	225.00	1.334E-04	0.048	10367	1.185E-04	0.046	9391	1.152E-04	0.039	8726	1.046E-04	0.038	8188
4	315.00	1.249E-04	0.044	10272	1.257E-04	0.043	9453	1.130E-04	0.040	8934	1.209E-04	0.139	8130

azimuthal mid		spatial segment 9			spatial segment 10		
segmt. #	point	dose rate	fsd	hits	dose rate	fsd	hits
1	45.00	1.092E-04	0.077	7532	9.977E-05	0.086	6698
2	135.00	1.008E-04	0.041	7424	1.064E-04	0.082	6669
3	225.00	1.349E-04	0.266	7257	1.160E-04	0.107	6824
4	315.00	1.008E-04	0.034	7498	9.553E-05	0.045	6692