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A Methodology for Estimating the Residual Contamination Contribution to the Source Term in a Spent-Fuel Transport Cask

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**A METHODOLOGY FOR ESTIMATING THE RESIDUAL CONTAMINATION CONTRIBUTION
TO THE SOURCE TERM IN A SPENT-FUEL TRANSPORT CASK***

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ABSTRACT

This report describes the ranges of the residual contamination that may build up in spent-fuel transport casks. These contamination ranges are calculated based on data taken from published reports and from previously unpublished data supplied by cask transporters. The data involve dose rate measurements, interior smear surveys, and analyses of water flushed out of cask cavities during decontamination operations. A methodology has been developed to estimate the effect of residual contamination on spent-fuel cask containment requirements. Factors in estimating the maximum permissible leak rates include the form of the residual contamination; possible release modes; internal gas-borne depletion; and the temperature, pressure, and vibration characteristics of the cask during transport under normal and accident conditions.

QUALITY ASSURANCE

This work was performed under a quality level of QL-3. The applicable level-three requirements of the Sandia National Laboratories' Transportation Systems Development Division Quality Assurance Program Plan were implemented for all phases of this activity.

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1.0 INTRODUCTION

1.1 Problem Description

Under normal and accident conditions of transport the containment requirements for spent-fuel transport casks are directly related to the source term. The source term is the amount of dispersible radioactive species within the cask that are available for release. In evaluating concentrations of radionuclides available for release, three sources of radioactivity have been identified:

1. radionuclides contained within the individual fuel rods that make up the fuel assemblies;
2. activated corrosion products and, possibly, fission products adhering to the surface of the spent fuel rods, referred to as CRUD; and
3. radioactive contaminants that build up on the cask internal surfaces as a result of previous loading and transport operations, referred to as cask residual contamination.

The contribution of each of these sources to the total source term can differ significantly. It is important to evaluate each of these sources and to quantify the potential contribution from each to the dispersed activity available for release from the cask. The purpose of this source analysis is to evaluate item 3 listed above, i.e., the contribution of cask residual contamination to the source term that is present in a shipment of spent nuclear fuel transported under normal and accident conditions.

1.2 Task Objective

The purpose of this analysis is to identify the radioactivity associated with residual contamination on internal cask and basket surfaces and to estimate its contribution to the total radioactive source term. No information is available on the concentration of alpha-emitting species, such as uranium or plutonium, in the residual contamination. However, the presence of such spent-fuel material would have been indicated by significantly high ^{137}Cs activity. The predominant source of gamma activity has been found to be ^{60}Co , and the quantity of alpha emitters present is considered to be negligible. Therefore, all calculations are performed attributing all measured activity to ^{60}Co . Cask containment requirements as defined by maximum permissible leak rates under normal and accident conditions, L_N and L_A , are calculated; these deposits are the only source of radioactivity considered. Factors include the chemical, radiological, and physical properties of the contaminants; particulate characteristics; loading under normal and accident conditions that render particles airborne; and diffusional deposition and gravitational settling of the particulates during transport from their point of origin to a breach in the cask containment barrier.

1.3 Issues

In a source-term methodology release credit is based on the material, physical, and chemical properties of the contents that tend to limit or inhibit radionuclide release. An approach in which no credit is taken generally results in a leak-tight design basis.

While previous containment analyses for shipping casks have used both leak-tight and source-term approaches, the recent practice of both designers and regulators has been to require the cask to be leak tight. This evolution to a leak-tight criterion primarily has resulted from the lack of a standardized source-term characterization methodology that might have addressed specific properties of cask contents.

The development of a complete source-term methodology must consider the independent contributions of each of the three sources listed in Chapter 1.1. Preliminary assessments of the CRUD and fuel contributions have been performed and documented [SA91a,91b]. The object of this analysis is to estimate the potential contribution of residual contamination as well as to determine the necessity of applying a source-term method to this source of radionuclides. Available data are reviewed and a method is developed to estimate the total residual contaminant activity that has built up in a cask during prior spent-fuel transport.

1.4 Background

The containment function of a transport cask is provided by the cask containment boundary, including one or more closure lids, bolting, hardware, and seals associated with the cavity closure and other containment penetrations. The containment function of the cask contents is produced by all characteristics of those contents that impede the movement of radionuclides to the external environment. In essence, there are a series of barriers to release from a cask, and the actual magnitude of the releasable activity is considerably lower than the total activity of the contents. A source-term approach applies release credit to those material characteristics that impede the release of material by determining the degree of barrier resistance to release provided by a given characteristic.

The containment requirements for radioactive material in transport casks are defined by regulations of the U. S. Nuclear Regulatory Commission (NRC) and the International Atomic Energy Agency (IAEA) [US75] [IA85,87]. Both NRC and IAEA regulations allow a source-term approach in containment evaluations. The U.S. Code of Federal Regulations, Title 10, Part 71 [US90], requires that irradiated nuclear reactor fuel must be transported in shipping casks which are "designed, constructed, and prepared for shipment so that... [under specified normal conditions of transport]... there would be no loss or dispersal of radioactive contents, as demonstrated to a sensitivity of $10^{-6}A_2$ per hour, no significant increase in external radiation levels, and no substantial reduction in the effectiveness of the packaging; and... [under specified hypothetical accident conditions]... there would be no escape of krypton-85 exceeding 10,000 curies in one week, no escape of other radioactive material exceeding a total amount of A_2 in one week, and no external radiation dose rate exceeding one rem per hour at one meter from the external surface of

the (shipping cask)" [US90]. The quantity A_2 is an assigned quantity of activity of each particular radionuclide that limits potential biological hazard to a specific level if released. Values of A_2 (e.g., $A_2 = 7$ Ci for ^{60}Co ; $A_2 = 10$ Ci for ^{137}Cs) are tabulated in Appendix A of 10 CFR 71.

Procedures generally acceptable to the NRC for assessing compliance with these provisions have been identified in "Regulatory Guide 7.4" [US75]. This guide, in turn, endorses the containment and leak test procedures that are specified in American National Standards for Radioactive Materials Leakage Tests on Packages for Shipment, N14.5, produced by the American National Standards Institute (ANSI) [AN87]. The ANSI standard permits time-integrated values for both R_N and R_A ; i.e., if $r_i(t)$ represents the instantaneous release rate under the appropriate conditions and $i = N$ or A , then the requirements become the following:

for normal conditions

$$R_N = \int_0^{\tau} r_N(t) dt \leq 10^{-6} A_2 \quad , \quad (1-1)$$

where

$$\tau = 1 \text{ hr},$$

and for accident conditions

$$R_A = \int_0^{\tau} r_A(t) dt \leq A_2 \quad , \quad (1-2)$$

where

$$\tau = 1 \text{ week}.$$

Compliance with these release limits may be demonstrated by direct measurement. If this is not practical, the ANSI standard provides an alternate method for demonstrating containment adequacy that is derived from the definitions of R_N and R_A . This alternate approach relates gas leak rates, L_i (cm^3/s), to the appropriate activity release rates, R_i , through the expression

$$L_i = R_i / C_i \quad , \quad (1-3)$$

where $i = N$ or A , and C_i represents the suspended radioactivity (in Ci/cm^3 in the shipping cask medium) that could escape from the containment system.

To account for differences in cask media (e.g., air, helium, nitrogen, water, etc.) and different sets of pressure and temperature conditions, the ANSI standard further defines a reference air leak rate, L_R , which is expressed in $\text{std cm}^3/\text{s}$ [AN87]. The standard conditions of dry air at absolute atmospheric pressure and 25°C are used to define all leak rates. If the estimated value of L_R is greater than or equal to $10 \text{ std cm}^3/\text{s}$, the ANSI standard exempts the package from leak testing. Otherwise, the

fabricated package must be shown to have adequate containment before its initial use, after a shakedown period (normally after the first three uses), and annually thereafter. Demonstration that the fabricated package is in compliance with 10 CFR 71 requires that the assembly must be shown to release material at rates less than or equal to R_N and R_A for transport under normal and accident conditions, respectively, or that the reference air leak rates are less than or equal to L_R . When the calculated value of L_R is less than or equal to 10^{-7} std cm³/s for either normal or accident conditions, it is only necessary to demonstrate that the leak rate does not exceed 10^{-7} std cm³/s.

The emphasis in the ANSI standard is on measuring and correlating leak rates. Little guidance is given regarding the determination of the activity concentrations of C_N and C_A . When C_N and C_A cannot be definitively established, the leak-tight design criteria are required.

As previously stated, the activity concentration or source term, C_i , available in a loaded spent-fuel shipping cask consists of radionuclides that can be released from three sources: (1) any residual activity on internal cask cavity surfaces resulting from loading and/or previous shipment operations; (2) fission and activation-product activity associated with radioactive material deposited on the surfaces of fuel assemblies, or CRUD; and (3) the fission and activation product radionuclides contained within the individual rods comprising the spent-fuel assemblies. These individual sources are additive, as illustrated by Equation (1-4):

$$C_i = C_{RC_i} + C_{CR_i} + C_{F_i} \quad (1-4)$$

where

- C_{RC} = residual contaminants contribution
- C_{CR} = CRUD contribution
- C_F = fuel contribution
- $i = N$ for normal transport conditions
- $i = A$ for accident conditions of transport.

Each of these three distinct sources have differing concentrations, physical and chemical forms, barriers which impede release, and release mechanisms.

Figure 1 illustrates the effect of the activity concentration, C_i , available for release from the cask on cask containment requirements of transport under normal and accident conditions. The diagonal lines represent technical limit lines based on constants R_N and R_A for various combinations of L_i on the vertical axis, and C_i on the horizontal axis. These lines are essentially constant risk lines corresponding to the lower limits of unacceptable regions above or to the right of each line. Limiting leak rates, L_N and L_A , are plotted for constants R_N and R_A , and varying specific source densities in the cavity of a cask, C_N and C_A , are given in A₂/cm³. The leak-tight criterion shown in the horizontal line is

Figure 1. Limiting Average Leak Rates Versus Activity Concentration

bounding for concentrations exceeding $C_N = 3 \times 10^{-3} \text{ A}_2/\text{cm}^3$ and $C_A = 17 \text{ A}_2/\text{cm}^3$. For smaller concentrations, the ANSI standards permits average gas leak rates below the sloping line [AN87].

1.5 Technical Approach

Residual contaminants can produce radiological consequences in the environment external to a cask only if radionuclides are first deposited on the cask surfaces, then released to the cask cavity, and subsequently released from the cask to the external environment. The first phase is governed by the deposition and surface release characteristics of the products involved, while the second phase is governed by the characteristics of both the material released to the cask cavity and the pathway through the cask to the external environment. For this analysis the pathway through the cask must limit releases to the R_N and R_A values for normal and accident conditions, respectively. This corresponds to definitive containment limits in terms of limiting leak rates, L_i , given by Equation (1-3).

A realistic estimate of L_i requires the development of a more mechanistic description of contaminant release mechanisms and transport behavior in the cask. The concentration of residual contaminant radionuclides available for release, C_i , is a function of the following:

1. the environmental conditions initiating the release, i.e., the normal and accident conditions of transport;
2. the total residual contaminant inventory, which is a function of the cask's operational history;
3. the physical, chemical, and radioactive characteristics of the residual contaminants contained in the cask;
4. the contaminant spallation fraction and the particle size distribution of dispersed contaminant products;
5. the cask design features such as cavity dimensions and configuration, and pathways for release of radioactive products from the surfaces of cask cavity, basket, and other internal features; and
6. the mass-transport characteristics of the contaminant products released to the cask cavity.

For this analysis the first variable listed above, initiating environmental conditions, is defined by the regulatory requirements for transport under normal and accident conditions. As noted above, these conditions represent prescriptive performance requirements. The response of particulate contaminants to these conditions must be determined, which, in turn, depends largely on the cask response.

The total contaminant inventory in the spent-fuel cask is a function of the cask's operational history, the amount of CRUD removed during normal handling, and the amount of CRUD that spalls during normal transport. Parameters involved include the fuel types carried, pressurized water

reactor (PWR) or boiling water reactor (BWR), the initial enrichment, fuel burnup, and the decay time (age) since the fuel's discharge from an operating nuclear reactor. The operational procedures pertaining to the cask, such as decontamination method used and frequency, also strongly affect the residual contaminant buildup on cask surfaces.

The physical and chemical characteristics of the contaminants prior to transport will significantly influence their response to the transport environment. The physical, chemical, and radiological characteristics of the contaminant products contained in the cask affect not only the releasability of particular species, but also the radiological implications of specific products, as characterized by the A_2 values assigned to each. Releasability is a qualitative measure of the ease with which a particular species can be dislodged and transported to a cask release point under varying pressure, under temperature-driving force, or during impact.

The cask and contaminant configuration is a multibarrier confinement and containment system. For a release to occur, radionuclides contained on internal cask surfaces must first be in a dispersible condition. Second, a driving force is necessary to initiate and maintain radionuclide transport. Third, some form of barrier release pathway must exist or be initiated.

The fault tree in Figure 2 traces the potential consequences of an initiating event. Radioactive material released to the cask cavity can occur as a result of one of four different mechanisms. Each mechanism, in turn, is instigated by a particular initiating event brought about by some environmental condition. The physical mechanisms that can cause release of residual contaminant radionuclides from cavity surfaces are the following:

- impact dislodgment and mobilization,
- thermal dry-out and suspension,
- diffusion of vaporized contaminant products from cavity surfaces, or
- leaching of soluble contaminant products from cavity surfaces in contact with water.

Each of the above release mechanisms can be investigated further by using fault-tree logic to identify subevents and parameters that may influence the initiation and maintenance of each mechanism. The fault tree in Figure 3 describes the sequence of events involved in an impact release of products from cavity surfaces. The release of radioactive material occurs as a result of mechanical disruption and subsequent mobilization of the material. As a result of the impact, small particles, referred to as fines, may be generated with a size and mass distribution such that some particles are transported to the cask cavity by gravity, diffusion, or pressure gradients. Depending on temperature, cavity venting could also release volatile species contained in the contaminants.

Both the release mode and release threshold for adherent contaminants depend on initial conditions such as location, thickness, adhesive properties, and the loading condition experienced by the cask.

Figure 2. Release Scenarios Affecting the Residual Contaminant Source Term in a Spent-Fuel Transport Cask

Figure 3. Factors Affecting the Release of Radionuclides From Cavity Surfaces During Mechanical Impact Conditions

The contaminant mass may exhibit ductile or brittle behavior, and release may occur as a result of crack initiation at high-stress locations followed by shearing at product/wall interfaces. The response behavior depends on a number of initial condition variables such as cavity temperature, operational history, cask orientation, and the particle sizes that are generated. The loading conditions that affect the contaminants depend on the cask design, i.e., the way in which the cask responds to the impact event and the process by which the forces involved are transferred through the cask to internal cask surfaces. The loads can range from severe impact conditions over short-time durations to long-duration, time-varying accelerations experienced during normal transport.

Dry-out and release could occur in a thermally severe environment. As the cask surfaces are heated by either excessive internal heat generation or as a result of an external heat source such as a fire, any moisture contained in residual contaminants could be released as steam, carrying with it particulate matter. Volatile products could also be released as gas vapor. The sequence and governing conditions for thermally driven releases are illustrated in Figure 4. As in the impact case, failure criteria determine the threshold condition that must be reached for a release to occur. These failure criteria are dependent on initial contaminant conditions and the product of the cask response in relation to input conditions on internal cask surfaces. The heat load of the cask can range from the extreme accident conditions of fire to the normal heat load during shipment that, in turn, depend on ambient conditions, internal heat generation rates, and the heat-transfer design of the cask.

Leaching of contaminants by water or steam is another mechanism for release. Its importance for future transport activities in the U.S. is much lower than for previous activities because future shipments are expected to require a dry, inert gas atmosphere in cask cavities. Figure 5 illustrates the events and processes required for leaching to occur. Water may be present as a result of operational error before shipment or may be contained in water-logged fuel. Water may also result from gross containment failure during transport. In the event of a high heat input, sufficiently water-logged fuel could generate and release steam into the cavity. Direct contact between water or steam and residual contaminants can result in contact leaching of radionuclide products that can then be carried directly throughout the cask cavity in the event of gross water in-leakage. As illustrated in Figure 5, the leaching release mechanism is relevant only to severe accident conditions that could result in gross water in-leakage. The gross loading errors or other preshipment errors that would be a prerequisite to this leaching release mechanism are classified under accident, not normal, conditions.

Radionuclides contained in surface contaminants could also be released by a diffusion process. The events and conditions necessary for diffusion to occur are illustrated in Figure 6. The likelihood of diffusion occurring increases with temperature.

Following a release of contaminants from cavity surfaces, the mass-transport characteristics of the released material govern its dispersal pathway through the cask cavity to a containment release point.

Figure 4. Factors Affecting the Release of Radionuclides From Cavity Surfaces During Severe Thermal Conditions

Figure 5. Factors Required for Leaching Release of Radionuclides From Cavity Surfaces

Figure 6. Factors Required for Diffusion Release of Radionuclides From Cavity Surfaces

The internal movement of the material occurs under the influence of gradients in temperature, pressure, and possibly, concentration. Factors and conditions that influence this dispersion and release scenario are illustrated in Figure 7.

The size of released particles must also be considered. To reach the external environment through a containment leak pathway, radioactive gases and particles must diffuse through the cavity gas. For particles, diffusive deposition and gravitational settling processes may significantly reduce the particle source term exiting the containment. The attenuation capabilities of these processes depend on the aerosol residence time, particle-size distributions, and the fuel and cask designs. Cask design parameters that are influential include the total surface area in the cask cavity, the cask orientation and the gravitational settling area described by that orientation, and the gas-void volume of the cask and fuel.

1.6 Summary and Analysis Sequence

This analysis also describes the development of a data base and a physical model that represents the release mechanisms and material characteristics which affect the scenarios discussed above. A literature search was first conducted that found little published data useful in estimating the amount of internal residual contamination in casks. Subsequently, a survey of cask owners and users was conducted that requested the following information, where available:

1. What data, reports, or studies are currently available regarding the buildup of residual contamination in spent-fuel shipping casks?
2. What quantities of radioactivity (in curies) are typically deposited on the internal surfaces of casks, including baskets, structural members, or other cask parts during operations?
3. Can the peak and average values of radioactivity on internal cask surfaces be quantified as functions of the cask type and the operating history of the cask?
4. What is the radionuclide composition of the residual contamination?
5. What is the chemical composition of the residual contamination?

In response to this survey, data that is useful for establishing a residual contamination data base has been provided by Battelle Memorial Institute and Duke Power Company. Both data groups are from previously unpublished information generated in the course of a number of spent-fuel transport operations.

Chapter 2.0 summarizes the results of analyses performed to evaluate and quantify the extent of residual contamination on internal cask and basket surfaces. Chapter 3.0 describes a methodology developed for determining the maximum permissible leak rates for residual contamination, which is based on an assumed particle-size distribution and three mechanisms which tend to deplete airborne concentrations of aerosols inside the cask cavity. This methodology is used to evaluate release scenarios

Figure 7. Factors Affecting the Releasable Source Term in a Spent-Fuel Shipping Cask

for representative cask and fuel geometries, including PWR and BWR cases. Where necessary, conservative estimates are used when actual values of the pertinent material parameters are unavailable. Chapter 4.0 summarizes the results of this analysis effort and includes conclusions and recommendations. Mathematical aspects of the models are provided in Appendix I. The previously unpublished data provided by Battelle and Duke Power are presented in Appendix II.

2.0 DATA BASE FOR CASK RESIDUAL CONTAMINATION

2.1 Description of Data

The types of cask residual contamination data that were available included measurements of gamma radiation levels (mR/hr) along the length of the cask cavity and results from smear surveys of the cask cavity. The smears were usually performed to determine the radionuclide composition of the removable contamination. Additional data regarding the cask residual contamination involved gamma-spectroscopic analysis of flush water. (The flush-water samples were usually taken from the final flushing operation to meet the procedural requirements of the cask owners.) However, flush-water samples from casks generally do not provide a representative analysis of radionuclide composition because some of the radionuclides such as ^{137}Cs are in a chemical form that is more soluble than other radionuclides such as ^{60}Co .

2.1.1 Battelle Data

Battelle Columbus Laboratories provided 13 sets of cask residual contamination measurements [BD88]. All but one set of data were for NLI 1/2 casks; the other set of measurements was on a NAC-1, Serial D cask. The gamma radiation field in the cask cavities was measured at specific axial locations along the center line of the cask. Occasionally, the measurements were taken with the cask basket removed from the cavity. In other cases the basket was in place and the radiation probe was lowered into the center of the square cavity of the basket. A β - γ detector that was suspended by a cable yielded direct readings of radiation in mR/hr or R/hr. In some cases the composition of the contamination was determined by a smear survey, and in others, by flush-water analysis. While these two methods provided different compositions for the residual contamination, generally the primary source of radioactivity was ^{60}Co . The smear data indicated that the contribution of radioactivity from ^{60}Co was in the range of 70 to 80 percent. All measured dose rates were attributed to cobalt in the shipping documents.

2.1.2 Duke Power Data

Seven different sets of data were provided by Duke Power Company's McGuire Nuclear Station [DP88]. Six of these data sets were obtained from one TN-8L cask, and the seventh was obtained on an NLI 1/2 cask. In the TN-8L cask, radiation measurements were performed in 2-ft segments along the surface of each of the three fuel-element cavities in the cask. The radiation probe was lowered at a corner, approximately 1 cm from the surface of the cavity. The measurements supposedly represented radiation levels at contact; however, only the highest reading for each segment was reported. Conservatively, this was considered to be a uniform measurement for the entire 2-ft segment. The composition of the internal contamination was obtained by smear survey and gamma spectroscopy of the smears. Using these measurements, the internal contamination activity for each of the three element cavities was obtained and the residual contamination level for the entire cask was determined by summing the contamination levels in

each of the three fuel-element cavities. A more detailed description of the calculational method is presented below and in Appendix I. All data used in the calculations are presented in Appendix II.

2.2 Contamination Properties

Very little published information is available on the physical characteristics of residual contamination. No data are available on particle size, adherence, or spallation characteristics of the contamination observed on internal cask surfaces. Observations of the residual contamination by visual inspection of the cask cavity have produced descriptions that ranged from a dry, coated surface to an oily, dark slurry at the bottom of the cask [LD88].

Occasionally, a cloud of CRUD has been observed emanating from the surface of an assembly when removed from a cask cavity underwater [RH87]. Presumably, the internal cask contamination consists of the same cloud of CRUD released from the assembly. The physical characteristics of the residual contamination were not quantified during any of these observations. No experimental information is available regarding the contamination mobility or the fraction of the contamination that tends to become gas-borne and is available for release from a cask. In general, highly-contaminated internal cask surfaces do tend to produce some local spreading of contamination, whereas casks with relatively low residual contamination levels have been handled many times without the spread of contamination [CA89]. Lower levels of contamination appear to produce very little or limited amounts of gas-borne activity.

2.3 Calculation of Cask Residual Contamination Levels

Calculations have been performed to determine the approximate residual contamination level in casks based on the data provided by Battelle and Duke Power Company. Three separate models have been developed to establish a range within which the total activity could be bounded. In all three models, the cask is divided into discrete regions corresponding to a specific radiation measurement. The interdependence between measurements in the different regions is considered in the calculation of cask residual contamination activity for each region.

2.3.1 Cask Description

The cask cavity of the NLI cask is 4.6 m long and has a cylindrical inner surface with a radius of 17.1 cm. Inside the cask a 22.2-cm-square metal basket extends to the length of the cask, as illustrated in Figure 8. Calculations represent the basket as being constructed of 0.635-cm-thick steel and the contamination as either on the inner surface of the basket or on the inner surface of the cask.

The TN-8L cask cavity is 4.3 m long and has three 23.0-cm-square cavities, as illustrated in Figure 9. No removable basket is associated with this cask, and calculations represent the three assembly cavities as being perfectly shielded from each other.

BASKET INSERTED
INTO CYLINDRICAL
OPENING IN CASK

LEAD
SHIELDING

Figure 8. NLI 1/2 and NAC Transport Cask Model

Figure 9. TN-8L Transport Cask Model

2.3.2 Models

Three models have been developed to determine the range of activity in the NLI 1/2 casks. All activity has been attributed to ^{60}Co , although the data show that 20 to 30 percent or more of the activity may come from other isotopes. This tends to overestimate the amount of residual contamination available for release since the other isotopes have less energetic emissions, and, therefore, smaller mR/Ci conversion values. The models are:

1. The shielded cask model assumes all contamination is located on the inner surface of the cask. Attenuation of measured radiation by the basket structure is also incorporated into this model. The shielded cask model provides the highest residual contamination estimate because it assumes that there is shielding between the residual contamination and the detector.
2. The nonshielded cask model assumes all contamination is located on the inner surface of the cask. The basket is not present; i.e., no credit is taken for attenuation of radiation by the basket.
3. The nonshielded basket model assumes all contamination is located on the inner surface of the basket.

All three models separate the cask into a number of axial regions equal to the number of detector measurements available. Each region is assumed to have a constant surface activity density. The activity density is expressed in curies per square centimeter (Ci/cm^2).

The three models are then evaluated using a coupled method in which each detector location receives contributions from every region within the cask. The upper regions and the bottom region are treated as cylindrical and disc sources, respectively. The equations used for each of the models and the results of their application to the Battelle and Duke cask contaminant data are given in Appendix I.

The TN-8L cask was evaluated using only the second model listed above which assumed all contamination was on the inner cask surfaces.

2.4 Results

The results of the surface activity calculations are provided in Tables 1 and 2 for the NLI 1/2 and TN-8L casks, respectively. The results for each model are provided and compared in Appendix I.

2.5 Discussion of Data and Calculations

2.5.1 Applicability of the Data

An extensive search for cask residual contamination information resulted in only the two sets of data described above. Thus our conclusions regarding the potential magnitude of residual contamination in a spent-fuel cask are based on very limited data. However, it is likely that the available data represent typical service conditions.

Table 1

Contamination Activity Levels for NLI and
NAC Casks Calculated Using the Shielded Model

<u>Cask</u>	<u>Date</u>	<u>Shielded Cask Activity (Ci)</u>
NLI 1/2 SR# 5382	09/25/82	1.64E-01
NLI 1/2 SR# 5382	10/05/82	1.74E-02
NLI 1/2 SR# 5382-585	04/25/86	7.06E-02
NLI 1/2 SR# 5382-585	06/09/86	7.11E-02
NLI 1/2 SR# 5461	12/20/82	1.08E-02
NLI 1/2 SR# 5461	03/27/83	5.91E-04
NLI 1/2 SR# 5461	07/03/85	5.58E-01
NLI 1/2 SR# 5461	11/01/85	1.76E-02
NLI 1/2 SR# 5461	04/29/86	2.74E-02
NLI 1/2 SR# 5462-4	11/17/85	7.31E-03
NLI 1/2 SR# 5462-4	04/24/86	4.91E-02
NLI 1/2 SR# 5462	04/26/86	2.04E-02
NAC 1D	07/02/81	4.28E-01

Table 2

Contamination Activity Levels for the TN-8L Cask

<u>Cask</u>	<u>Date</u>	<u>Element 1 Activity (Ci)</u>	<u>Element 2 Activity (Ci)</u>	<u>Element 3 Activity (Ci)</u>	<u>Total (Ci)</u>
TN-8L	09/11/86	3.47E-02	4.84E-02	5.16E-02	1.35E-01
TN-8L	10/28/86	1.71E-01	1.57E-01	1.54E-01	4.83E-01
TN-8L	02/08/87	3.28E-01	1.59E-01	3.17E-01	8.04E-01
TN-8L	03/19/87	1.47E-01	3.62E-01	6.02E-01	1.11E+00
TN-8L	07/27/87	2.00E-01	1.51E-01	1.22E-01	4.73E-01
TN-8L	02/24/88	4.62E-03	1.79E-02	5.20E-03	2.77E-02

The Battelle NLI cask data was obtained from an operational period of approximately 5 years involving four separate casks. A variety of fuel shipments were performed in each cask over this time period. The burnup of transported fuel ranged from 10,000 to 50,000 MWD/MTU. The cask contents ranged from whole spent-fuel assemblies to a small number of loose fuel rods, and some of the contents included breached fuel. Note that during this operational period the casks were subjected to different handling operations and conditions at different facilities.

To understand the potential effects of these parameters on expected residual contamination levels, the operational history of one NLI 1/2, Serial No. 5461 cask has been examined in detail. The residual contamination data available for this cask spanned a period greater than 3 years. During this time the cask was involved in at least 14 spent-fuel transport operations from various facilities. Review of the residual contamination estimates for five of these shipments indicates that residual contamination levels did not necessarily increase with continuous cask use, even when the cavity was not decontaminated between shipments.

In comparison, the data on TN-8L casks involved a single campaign of five fuel shipments, each involving three PWR fuel assemblies. These data indicate that residual contamination levels increased during the first four shipments, followed by a significant reduction during the fifth shipment. The reason for this reduction is unknown. The sixth and final set of data was obtained after decontamination operations were performed in preparation for the return of the cask to the owner. The decontamination operation reduced the internal residual contamination level by approximately a factor of 15, indicating that periodic decontamination operations may be quite effective for reducing residual contamination levels in a cask.

2.5.2 Calculations and Uncertainties

The residual contamination estimates obtained from both data sets are subject to significant uncertainties. The assumption that the contamination is homogeneous and uniformly distributed on individual regions of the cask may be somewhat conservative. Moreover, the vertical position of the radiation detector within the cask cavities during the measurements was not certain. This uncertainty of the detector position is particularly significant for the bottom region where the contamination was found to be highest. A difference of a few inches in the detector position near the bottom can change the results significantly. For the Battelle NLI cask data, a maximum uncertainty of 6 in. has been deemed credible. An uncertainty estimate could not be made for the TN-8L data, but based on conversations with Duke Power personnel, it is likely that the uncertainty in the detector position is several inches.

Several calculations have been carried out for NLI casks by varying the assumed position of the detector near the bottom of the cask up to 6 inches to determine the sensitivities of the calculated activity density to the detector location. The total calculated activity density varies by a factor of 3 for the largest difference in the assumed detector position. Similar calculations for the upper region produced no significant change in the estimated activity. For the TN-8L cask, the assumed detector position near the bottom of the cask cannot be varied more than 2 in. without

resulting in nonphysical results, i.e., negative activity. This estimated 2-in. uncertainty for the detector position in the bottom region also results in an activity change by a factor of 3. Thus the calculated surface activities in the cask may have at least a factor-of-3 uncertainty.

3.0 CALCULATION OF RESIDUAL CONTAMINANT CONTAINMENT REQUIREMENTS

3.1 Method for Determining Containment Requirements

Equation (1-3) relates the postulated gas leak rate, L_i , to the maximum permitted activity release rate, R_i , provided that the concentration, C_i , of gas-borne material in the cask is homogeneously dispersed. A conservative upper bound on L_i may therefore be established by determining possible maximum values of the gas-borne activity concentration for each isotope associated with the residual contaminants. For 5-yr or older fuel, this activity is largely composed of ^{60}Co (see Chapter 2.1.1).

The maximum possible gas-borne activity concentration is that which results from dispersal of all residual surface contaminants regardless of the release mechanism involved. A more realistic estimate of L_i is possible, provided that the fraction of the residual contaminant which can become gas-borne and the particle size distribution of this fraction are known. If these are known, it is possible to calculate the effects of diffusive particle deposition, settling, and leakage loss on the activity concentration, which then becomes a function of time. For this analysis the particles are considered to be monodispersed. The time-dependent concentration is given by

$$\begin{aligned} dC_i/dt &= -(A_T D'/V + A_s v_s/V + L_i/V)C_i \quad , \\ &= -\beta C_i \quad , \end{aligned} \quad (3-1)$$

where

$C_i = C_i(t)$ = instantaneous surface activity suspended in the cask cavity gas volume (in Ci/m^3), $i = \text{N}$ for normal, A for accident conditions

A_T = total surface area of the cask cavity, including the fuel and basket (m^2)

A_s = settling area inside the cask cavity, including the fuel and basket (m^2)

V = void volume of the cask (m^3)

L_i = gas leak rate (assumed to be constant) (m^3/s)

D' = diffusive plate-out velocity of particles (m/s)

v_s = settling velocity of particles (m/s).

Sandoval et al. describe the derivation of this equation and its generalization to polydispersed aerosols [SA91a]. Equation (1-3) can be generalized for constant gas leak rates to

$$L_i = \bar{R}_i / \bar{C}_i \quad , \quad (3-2)$$

where C_i is the time-averaged activity concentration during the release period, τ , of interest (1 hr for normal transport, 1 week for accidents). The value of C_i , in turn, can be related to initial conditions, $C(t = 0)$, by

$$\bar{C}_i = \langle F(\tau) \rangle d_{p,o} C_i(t=0) \quad , \quad (3-3)$$

where $\langle F(\tau) \rangle d_{p,o}$ is the value of $F(\tau)$ averaged over the mass distribution of the estimated instantaneously dispersed residual contaminant activity, and

$$F(\tau) = \frac{1 - e^{-\beta\tau}}{\beta\tau} \quad (3-4)$$

is the corresponding factor for monodispersed particles of size d_p , averaged over the time interval τ .

3.2 Particle Size Distribution

To use the above equations, the particle size distribution of the residual contaminant that dislodges or spalls from interior cask surfaces must be known. For this analysis all the contaminant that dislodges is assumed to do so instantaneously regardless of the initiating event (impact or thermal). Unfortunately, neither the spallation fraction nor the particle size distribution of released contaminants have ever been measured.

In a companion report on the source-term contribution from CRUD on fuel assemblies [SA91a], the lack of data on CRUD spallation fractions led to the conservative assumption that all CRUD spalls. An analogous assumption will be made here: The release fraction for residual contamination is considered to be 1.0 for all release mechanisms. This is consistent with the view that residual contamination is derived largely from CRUD that has spalled from fuel assemblies. If material originates by spallation, it can spall again. However, the low levels of residual contamination observed indicate that either (1) the CRUD spallation fraction is typically much less than 1.0, or (2) the CRUD activity density on the assemblies is generally very small.

If residual contamination results largely from CRUD that has spalled from fuel assemblies during transport, the associated particle size distribution should be similar to that which is associated with the CRUD. Changes in this distribution are only possible if coalescence occurs on the cask surfaces or diminution occurs as a result of scrubbing operations. Coalescence on cask surfaces is possible only at higher-than-expected surface concentrations; diminution is equally unlikely. CRUD particles are already small [SA91a] and the shear forces at a particle's surface that result from wash-down operations are insufficient to provide the force needed to fracture a particle.

Sandoval et al. provide the containment particle size distribution for CRUD on fuel assemblies used in this analysis [SA91a]. This distribution is lognormal with a number median diameter of $3.0 \mu\text{m}$ and a logarithmic

standard deviation of 1.87 μm . The distribution is based on measurements of CRUD on a segment of Quad City (BWR) fuel, the only known measurements of a CRUD particle size distribution on a fuel rod surface. The uncertainty involved in generalizing those measurements to the inventories of both BWR and PWR fuel is recognized, and further measurements are clearly needed to reduce both this uncertainty and those associated with its use for estimating the residual contamination source term. A qualitative comparison of the residual contaminant source term with the CRUD source term is nevertheless independent of that uncertainty.

3.3 Calculations

The calculations of maximum permissible leak rates given here closely follow those for CRUD on fuel assemblies that were provided by Sandoval et al. [SA91a]. The values of the factor $\langle F(\tau) \rangle d_{p,o}$ in Equation (3-3) for the NLI 1/2, TN-8L, and NAC casks are provided below. This factor, together with the maximum permissible activity release rates (R_i), yield the desired maximum permissible leak rates, L_i .

The value of $\langle F(\tau) \rangle d_{p,o}$ is given in Table 3 for normal transport ($\tau = 1$ hr) and for accidents ($\tau = 1$ week). In this table, V is the void volume of the cask (m^3), A_T is the total surface area in the cask cavity [including basket and fuel rods (m^2)], and A_{sh} and A_{sv} are horizontal and vertical orientation settling areas (including fuel rods).

To allow for the possibility of unusual cask orientations under accident conditions, both horizontal and vertical cases are addressed. For normal transport conditions, only the horizontal case is treated. The results apply to the over-the-road portion of a transport operation and do not cover crane transfers or other vertical situations that might occur at a source or destination facility. In those situations, larger average concentrations may result and the permissible leak rates are smaller.

Table 3 gives values for $\langle F(\tau) \rangle d_{p,o}$ for both PWR and BWR assemblies in transport in a given cask. These values differ because the void volume and interior surface areas of a loaded cask depend on its contents. In the calculations of maximum permissible leak rates, the larger value of $\langle F(\tau) \rangle d_{p,o}$ has been used as the more conservative choice for NLI and NAC casks because these casks are used for both kinds of fuel. For the TN-8L cask that is used only for PWR shipments, the value of the factor is uniquely determined.

Combining Equations (3-2) and (3-3) yields

$$L_i = R_i / [\langle F(\tau) \rangle d_{p,o} C_i(t = 0)] \quad ,$$

$$L_i = R_i / [\langle F(\tau) \rangle d_{p,o} I_s / V] \quad .$$

The term I_s is the inventory (in Curies) of the residual contamination that dislodges. For the following, all residual contamination is assumed to spall instantaneously. In this case, I_s corresponds to the values in Tables 1, 2, and 3 (i.e., the residual contamination levels that have been deduced from radiation measurements of the cask interiors). In these tables, the residual contamination radioactivity is assumed to

Table 3

Release Reduction Factor for NLI 1/2 and TN-8L Casks

Cask Type	Fuel Type	No.	V(m ³)	A _T (m ²)	A _{sh} (m ²)	A _{sv} (m ²)	Normal Factor	Horizontal Accident Factor	Vertical Accident Factor
1. NLI 1/2	PWR	1	.155	39.0	12.3	0.272	7.9x10 ⁻⁴	4.7x10 ⁻⁶	2.0x10 ⁻⁴
2. NLI 1/2	BWR	2	.129	26.7	8.43	0.272	9.6x10 ⁻⁴	5.7x10 ⁻⁶	1.7x10 ⁻⁴
3. TN-8L	PWR	3	.151	113.7	35.1	0.471	8.3x10 ⁻⁴	5.0x10 ⁻⁶	3.5x10 ⁻⁴
4. NAC-1/NFS4	PWR	1	.257	39.5	12.3	0.277	1.3x10 ⁻³	7.8x10 ⁻⁶	3.3x10 ⁻⁴
5. NAC-1/NFS4	BWR	2	.268	27.2	8.43	0.277	2.0x10 ⁻³	1.2x10 ⁻⁵	3.5x10 ⁻⁴

V = void volume of loaded cask.

A_T = total surface area of cask cavity, including fuel rods.A_{sh} = total settling area of cask cavity, including fuel rods, for cask in horizontal position**.A_{sv} = total settling area of cask cavity, including fuel rods, for cask in vertical position**.

No. = number of assemblies that can be transported in the cask.

*TN-8L has three compartments; values given are per compartment.

**Baskets were excluded in the sample calculations for lack of data.

result entirely from ^{60}Co . The maximum permitted release rates for this isotope are $R_i = 7 \times 10^{-6}$ Ci in 1 hr for normal transport conditions and $R_i = 7$ Ci in 1 week for accident conditions [US90].

The resulting containment requirements in terms of maximum permissible leak rates are shown in Table 4 for normal transport and for each of the cask activity measurements available in the data base. The smallest value, $0.318 \text{ cm}^3/\text{s}$, is several orders of magnitude larger than the leak rate that corresponds to the leak-tight design basis (10^{-7} std cm^3/s). A sample calculation is provided below.

As shown in Table I-1 of Appendix I, the shielded cask model produced a residual contamination estimate of 0.558 Ci for the NLI 1/2, Serial No. 5461 cask on July 3, 1985. During the next transport operation we assume this cask carried a BWR assembly and all the cask residual contamination spilled after a shock resulting from some normally occurring road hazard. Table 3 shows the cask void volume and release reduction factor to be 0.129 and 9.6×10^{-4} , respectively. Because the composition of the contamination is uncertain but known to be mostly ^{60}Co , $A_2 = 7$ Ci. Applying Equation (3-3),

$$L_i = \frac{(7 \text{ Ci}/A_2) \times (10^{-6} A_2/\text{hr}) \times (0.129 \text{ m}^3) \times (10^6 \text{ cm}^3/\text{m}^3)}{(0.558 \text{ Ci}) \times (9.6 \times 10^{-4}) \times (3.6 \times 10^3 \text{ s/hr})}$$

This yields

$$L_i = 0.47 \text{ cm}^3/\text{s}$$

Maximum permissible leak rates for the less restrictive accident conditions were also calculated. In both horizontal and vertical orientations the resulting permissible rates are in excess of $10 \text{ cm}^3/\text{s}$, which implies that leaks larger than those encompassed in our modeling assumptions would still be small enough to release less than the value of A_2 of contamination in a week.

Table 4

Maximum Permissible Leak Rates* by Cask Type--Normal Transport

<u>Cask</u>	<u>Date</u>	<u>Shielded Cask Activity (Ci)</u>	<u>Maximum Permissible Leak Rate (cm³/s)</u>
NLI 1/2 SR# 5382	09/25/82	1.64E-01	1.594
NLI 1/2 SR# 5382	10/5/82	1.74E-02	15.000
NLI 1/2 SR# 5382-585	04/25/86	7.06E-02	3.710
NLI 1/2 SR# 5382-585	06/9/86	7.11E-02	3.680
NLI 1/2 SR# 5461	12/20/82	1.08E-02	24.200
NLI 1/2 SR# 5461	03/27/83	5.91E-04	443.000
NLI 1/2 SR# 5461	07/3/85	5.58E-01	0.469
NLI 1/2 SR# 5461	11/1/85	1.76E-02	14.800
NLI 1/2 SR# 5461	04/29/86	2.74E-02	9.530
NLI 1/2 SR# 5462-4	11/17/85	7.31E-03	35.800
NLI 1/2 SR# 5462-4	04/24/86	4.91E-02	5.310
NLI 1/2 SR# 5462-5	04/26/86	2.04E-02	12.800
NAC 1D	07/2/81	4.28E-01	0.612
TN-8L	09/11/86	1.31E-01	2.700
TN-8L	10/28/86	4.83E-01	0.732
TN-8L	02/8/87	8.04E-01	0.439
TN-8L	03/19/87	1.11E+00	0.318
TN-8L	07/27/87	4.73E-01	0.745
TN-8L	02/24/88	2.77E-02	12.800

*Based on the A₂ value of ⁶⁰Co.

4.0 SUMMARY

A methodology has been developed for determining the activity source-term concentrations C_N and C_A in a spent-fuel transport cask associated with possible residual contamination on cask-cavity surfaces. This methodology accounts for particle characteristics (such as particle size distribution) of the activity concentration inside the cask cavity and for particle deposition due to diffusion and gravitational settling onto surfaces inside the cask cavity. (Particles in the expected size range, 1 to 10 μm , adhere strongly to surfaces to which they become attached, so resuspension is not considered.) The determination of the activity release to the cask cavity accounts for transport under both normal and accident conditions. The data used for determining potential levels of residual contaminant activity are based on actual cask shipments.

The results of the calculations can be summarized as follows:

1. For the prescribed regulatory accident conditions [US90], the maximum permissible leak rates associated with residual contaminants are likely to be well in excess of 10 $\text{std cm}^3/\text{s}$.
2. Measurement uncertainties present in the data that has been used limit the precision of the results to at least a factor of 3.
3. Assumptions used in our calculations that may tend to underestimate the amount of residual contamination activity available for release include the following:
 - Negligible resuspension. The initiating events in normal transport occur less frequently than once per hour, and the adhesion of settling particles is not affected by surface vibration.
 - Particle Size Distribution. Cask containment requirements, defined in terms of maximum permissible leak rates, are greatly affected by the particle size distribution of released material. The effect on maximum permissible leak rates could be a factor of 100 to 1,000, depending on cask design, and particle size.
4. Conservative assumptions that tend to overestimate the amount of residual contamination available for release are the following:
 - A spallation fraction of 1.0 was used for both normal and accident conditions of transport (shock, vibration, impact, and thermal).
 - The assumption that contaminant spallation caused by impact, shock, or vibration occurs instantaneously (rather than at a constant rate over the release period) tends to overestimate the release.

- The influence of radiation scattering on the dose rate data has not been addressed in calculating the residual contaminant burden.
- While all activity was attributed to ^{60}Co , the data show 20 to 30 percent or more of the activity may come from other isotopes, some of which have less energetic emissions and, therefore, smaller mR/Ci conversion values.

5.0 REFERENCES

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APPENDIX I
EQUATIONS USED FOR CALCULATIONS

APPENDIX I

EQUATIONS USED FOR CALCULATIONS

Each of the three models used in this analysis -- the shielded cask, nonshielded cask, and nonshielded basket -- involves a system of coupled linear equations that is solved for the activity density which contaminates surfaces in the individual cask regions. The models are coupled in that each detector collects radiation emitted from every region within the cask. The models are integrated with respect to each detector point, which results in a matrix equation of the form

$$\Phi = A \cdot S ,$$

in which Φ is the set of detector readings written as a column vector and A is the matrix of coefficients determined by the integrations. This equation is solved for set S of surface activity densities using conventional numerical techniques. Each element of S represents the average residual contamination in Ci/cm^2 present on a separate segment of the contaminated interior surface. The total residual contamination in the cask is calculated by summing the products of each region's activity density and its corresponding area.

The elements of matrix A are determined by the following: the model that is used; the dimensions of the cask or basket cavity; and for the shielded cask model, the degree of attenuation provided by the basket for radiation contamination from the interior surface of the cask cavity. The matrix elements for the shielded model for NAC and NLI casks and the nonshielded model for the TN-8L cask are derived in this Appendix. The nonshielded basket model only applies to NAC and NLI casks and can be derived from the shielded cask model as a special case.

Shielded Cask Model for NAC and NLI Casks

This model represents all contamination to be on the inner surface of the cask; no contamination is on the basket surface. As shown in Figure I-1, the model represents the basket as a cylindrical shield of outer and inner radii, r_1 and r_2 , respectively. The basket is centered on the axis of the cask with a cavity radius R and interior length h . The linear attenuation coefficient for the basket material is denoted by μ . Scattering from the cask or basket is not included; this tends to overestimate the residual contamination.

In this case an on-axis dosimeter can be expected to have a reading Φ given by

$$\Phi(d) = \int_0^R \frac{e^{-\mu t \sec \phi} \sigma(0) 2\pi r dr}{4\pi(r^2 + d^2)} + \int_0^h \frac{e^{-\mu t \csc \theta} \sigma(z) 2\pi R dz}{4\pi(R^2 + (z-d)^2)} .$$

The on-axis dosimeter is calibrated in Ci/cm^2 and located at distance d from the bottom and in a cask with surface activity density $\sigma(z)$ on the

Figure I-1. Coordinate Systems for Modeling Residual Contamination in NAC and NLI Casks

cask walls and activity $\sigma(0)$ on its base. The first integration provides the contribution from contamination on the base of the cask cavity, while the second integration treats contamination on the walls. The slant thickness through the basket is represented through the base by

$$t_{\text{sec}\phi} = (r_2 - r_1) \sqrt{1 + (r/d)^2}$$

and through the wall, by

$$t_{\text{csc}\theta} = (r_2 - r_1) \sqrt{1 + ((z-d)/R)^2} .$$

To obtain the matrix notation for the system of equations that determines the source activity, the first integral is denoted by $\sigma(0)F_0(d)$. Moreover, because the wall activity is constant for each cask region, the second integral reduces to a sum over the regions, with the j th contribution denoted as $\sigma_j F_j(d)$, where

$$F_0(d) = \int_0^R \frac{e^{-\mu t_{\text{sec}\phi}}}{4\pi(r^2 + d^2)} 2\pi r dr ,$$

$$F_j(d) = \int_{z_{j-1}}^{z_j} \frac{e^{-\mu t_{\text{csc}\theta}}}{4\pi(R^2 + (z-d)^2)} 2\pi R dz .$$

In practice, the F integrals are evaluated by Gaussian quadrature. The experimentally measured values of Φ , which are at locations that are distances d_i from the base, can be determined in terms of these quantities:

$$\Phi(d_i) = \sum_{j=0}^N F_j(d_i) \sigma_j .$$

This is the component form of the original matrix equation, where the i, j element of the A matrix with $F_j(d_i)$ and the j th entry for the S matrix with σ_j are identified.

Nonshielded Basket Model for NAC and NLI Casks

This model is similar to the shielded cask model because the dosimeter is on-axis but differs from it because nothing shields the dosimeter from the residual contamination. All residual contamination is considered to be on the inner surface of the basket. For modeling purposes, the basket is again replaced by a circular cylinder of inner radius r_1 , and μ is zero. In this case the F integrals can be performed explicitly with the following results:

$$F_0(d) = \frac{1}{2} \ln \sqrt{1 + (r_1/d)^2} ,$$

and

$$F_j(d) = \frac{1}{2} \tan^{-1} \left(\frac{z_j - d}{r_1} \right) - \frac{1}{2} \tan^{-1} \left(\frac{z_{j-1} - d}{r_1} \right) .$$

Nonshielded Cask Model for the TN-8L Cask

This model treats each cask cavity as a square opening in the cask body of overall length h and with sides of length w (see Figure I-2). There is no basket; therefore, there is no shielding to consider and μ is 0. The F integrals are performed over the floor and walls of the cask cavity. For a detector located at x_D, y_D , and d , the value of F_0 is given by

$$F_0(d) = \frac{1}{4\pi} \int_0^w \frac{\tan^{-1} \left(\frac{w - y_D}{c} \right) - \tan^{-1} \left(\frac{y_D}{c} \right)}{c} dx ,$$

where

$$c^2 = (x - x_D)^2 + d^2 .$$

Each of the F_j integrals involves four such terms, one from each of the side walls in the j th region. Performing the integrals in the z direction first yields the following:

$$\begin{aligned} F_j(d) = & \frac{1}{4\pi} \int_0^w \frac{\tan^{-1} \left((z_j - d)/c_1 \right) - \tan^{-1} \left((z_{j-1} - d)/c_1 \right)}{c_1} dx \\ & + \frac{1}{4\pi} \int_0^w \frac{\tan^{-1} \left((z_j - d)/c_2 \right) - \tan^{-1} \left((z_{j-1} - d)/c_2 \right)}{c_2} dx \\ & + \frac{1}{4\pi} \int_0^w \frac{\tan^{-1} \left((z_j - d)/c_3 \right) - \tan^{-1} \left((z_{j-1} - d)/c_3 \right)}{c_3} dy \\ & + \frac{1}{4\pi} \int_0^w \frac{\tan^{-1} \left((z_j - d)/c_4 \right) - \tan^{-1} \left((z_{j-1} - d)/c_4 \right)}{c_4} dy , \end{aligned}$$

where

$$c_1^2 = (x - x_D)^2 + y_D^2 ,$$

$$c_2^2 = (x - x_D)^2 + (w - y_D)^2 ,$$

$$c_3^2 = (y - y_D)^2 + x_D^2 ,$$

Figure I-2. Coordinate System for a TN-8L Cavity

$$c_4^2 = (y - y_D)^2 + (w - w_D)^2 \quad .$$

Sample Calculations

The results of the calculations for the NLI casks are shown in Table I-1. As expected, the nonshielded basket model provides lower values while the shielded cask model provides higher values for cask activity. Table I-2 shows the corresponding results for the TN-8L cask, where only the unshielded cask model is used because of features in the design.

Table I-1
Contamination Activity Levels for NLI and NAC Casks

<u>Cask</u>	<u>Date</u>	<u>Nonshielded Basket Activity (Ci)</u>	<u>Nonshielded Cask Activity (Ci)</u>	<u>Shielded Cask Activity (Ci)</u>
NLI 1/2 SR# 5382	09/25/82	6.92E-02	9.91E-02	1.64E-01
NLI 1/2 SR# 5382	10/05/82	7.76E-03	1.08E-02	1.74E-02
NLI 1/2 SR# 5382-585	04/25/86	3.08E-02	4.29E-02	7.06E-02
NLI 1/2 SR# 5382-585	06/09/86	3.12E-02	4.34E-02	7.11E-02
NLI 1/2 SR# 5461	12/20/82	5.11E-03	7.01E-03	1.08E-02
NLI 1/2 SR# 5461	03/27/83	2.53E-04	3.56E-04	5.91E-04
NLI 1/7 SR# 5461	07/03/85	2.24E-01	3.25E-01	5.58E-01
NLI 1/2 SR# 5461	11/01/85	7.35E-03	1.04E-02	1.76E-02
NLI 1/2 SR# 5462-5	04/26/86	8.68E-03	1.22E-02	2.04E-02
NLI 1/2 SR# 5461	04/29/86	1.20E-02	1.67E-02	2.74E-02
NLI 1/2 SR# 5462-4	11/17/85	3.12E-03	4.37E-03	7.31E-03
NLI 1/2 SR# 5462-4	04/24/86	1.98E-02	2.84E-02	4.91E-02
NAC 1D	07/02/81	2.88E-01	3.14E-01	4.28E-01

Table I-2
Contamination Activity Levels for the TN-8L Cask

<u>Cask</u>	<u>Date</u>	<u>Element 1 Activity (Ci)</u>	<u>Element 2 Activity (Ci)</u>	<u>Element 3 Activity (Ci)</u>	<u>TOTAL (Ci)</u>
TN-8L	09/11/86	3.47E-02	4.84E-02	5.16E-02	1.35E-01
TN-8L	10/28/86	1.71E-01	1.57E-01	1.54E-01	4.83E-01
TN-8L	02/08/87	3.28E-01	1.59E-01	3.17E-01	8.04E-01
TN-8L	03/19/87	1.47E-01	3.62E-01	6.02E-01	1.11E+00
TN-8L	07/27/87	2.00E-01	1.51E-01	1.22E-01	4.73E-01
TN-8L	02/24/88	4.62E-03	1.79E-02	5.20E-03	2.77E-02

APPENDIX II

CASK CONTAMINATION DATA USED IN ACTIVITY CALCULATIONS

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement A

Cask Serial No.: NLI 1/2 Serial #5382

Date: 09/25/82

Data Source - Battelle Columbus Shipping Documents

Recorded Data:

Radiation Levels (mR/hr)

<u>Location</u>	<u>Cask Cavity</u>
Top	500
2'	400
4'	200
6'	200
8'	250
10'	250 (center)
12'	350
14'	600
15'	5r
3' from bottom	1r

All measurements taken at the central axis.

Contamination Composition: Primarily ^{60}Co ; range - 50-80 percent.

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement B

Cask Serial No.: NAC ID

Date: 07/02/81

Data Source - Battelle Columbus Shipping Documents

Recorded Data:

Radiation Levels (mR/hr)

<u>Location</u>	<u>Cask Cavity</u>	<u>Liner</u>
Top	60	
1'	100	400 (basket)
3'	100	700
5'	45	450
7'	45	350
9'	50	380
11'	70	425
12'	70	800
Bottom	300	225

All measurements taken at the central axis.

Contamination Composition: Primarily ^{60}Co ; range - 50-80 percent.

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement C

Cask Serial No.: NLI 1/2 Serial #5461

Date: 12/20/82

Data Source - Battelle Columbus Shipping Documents

Recorded Data:

<u>Radiation Levels (mR/hr)</u>	
<u>Location</u>	<u>Cask Cavity</u>
Top	3
3'	4
6'	4
9'	15 (center)
14'	85
15'	250

All measurements taken at the central axis.

Contamination Composition: Primarily ^{60}Co ; range - 50-80 percent.

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement D

Cask Serial No.: NLI 1/2 Serial #5382

Date: 10/05/82

Data Source - Battelle Columbus Shipping Documents

Recorded Data:

<u>Radiation Levels (mR/hr)</u>	
<u>Location</u>	<u>Cask Cavity</u>
Top	30
2'	65
4'	30
6'	18
8'	45 (center)
10'	35
12'	45
14'	80
15'	300

All measurements taken at the central axis.

Contamination Composition: Primarily ^{60}Co ; range - 50-80 percent.

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement E

Cask Serial No.: NLI 1/2 Serial #5382-585

Date: 06/09/86

Data Source - Battelle Columbus Shipping Documents

Recorded Data:

<u>Radiation Levels (mR/hr)</u>	
<u>Location</u>	<u>Cask Cavity</u>
Top	45
3'	200
6'	175
9'	230
12'	250
Bottom	400

All measurements taken at the central axis.

Contamination Composition: Primarily ^{60}Co ; range - 50-80 percent.

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement F

Cask Serial No.: NLI 1/2 Serial #5382-585

Date: 04/25/86

Data Source - Battelle Columbus Shipping Documents

Recorded Data:

Radiation Levels (mR/hr)

<u>Location</u>	<u>Cask Cavity</u>
Top	60
3'	125
6'	175
9'	250
12'	250
Bottom	600

All measurements taken at the central axis.

Contamination Composition: Primarily ^{60}Co ; range - 50-80 percent.

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement G

Cask Serial No.: NLI 1/2 Serial #5462-5

Date: 04/26/86

Data Source - Battelle Columbus Shipping Documents

Recorded Data:

Radiation Levels (mR/hr)

<u>Location</u>	<u>Cask Cavity</u>
Top	10
3'	40
6'	30
9'	55
12'	75
Bottom	400

All measurements taken at the central axis.

Contamination Composition: Primarily ^{60}Co ; range - 50-80 percent.

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement H

Cask Serial No.: NLI 1/2 Serial #5461

Date: 07/03/85

Data Source - Battelle Columbus Shipping Documents

Recorded Data:

<u>Radiation Levels (mR/hr)</u>	
<u>Location</u>	<u>Cask Cavity</u>
Top	150
2'	170
4'	220
6'	280
8'	450
10'	2,000
12'	20,000

All measurements taken at the central axis.

Contamination Composition: Primarily ^{60}Co ; range - 50-80 percent.

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement I

Cask Serial No.: NLI 1/2 Serial #5462-4

Date: 11/17/85

Data Source - Battelle Columbus Shipping Documents

Recorded Data:

Radiation Levels (mR/hr)

<u>Location</u>	<u>Cask Cavity</u>
-----------------	--------------------

Top	6
3'	20
6'	15
9'	20
12'	20
Bottom	125

All measurements taken at the central axis.

Contamination Composition: Primarily ^{60}Co ; range - 50-80 percent.

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement J

Cask Serial No.: NLI 1/2 Serial #5462-4

Date: 04/24/86

Data Source - Battelle Columbus Shipping Documents

Recorded Data:

Radiation Levels (mR/hr)

<u>Location</u>	<u>Cask Cavity</u>
Top	25
3'	60
6'	45
9'	65
12'	150
Bottom	2,000

All measurements taken at the central axis.

Contamination Composition: Primarily ^{60}Co ; range - 50-80 percent.

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement K

Cask Serial No.: NLI 1/2 Serial #5461

Date: 03/27/83

Data Source - Battelle Columbus Shipping Documents

Recorded Data:

<u>Radiation Levels (mR/hr)</u>	
<u>Location</u>	<u>Cask Cavity</u>
Top	0.5
2'	0.9
4'	1.25
6'	1.4
8'	1.4
10'	1.5
12'	2.05
Bottom	10.0

All measurements taken at the central axis.

Contamination Composition: Primarily ^{60}Co ; range - 50-80 percent.

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement L

Cask Serial No.: NLI 1/2 Serial #5461

Date: 11/01/85

Data Source - Battelle Columbus Shipping Documents

Recorded Data:

<u>Radiation Levels (mR/hr)</u>	
<u>Location</u>	<u>Cask Cavity</u>
Top	17
3'	60
6'	24
9'	25
12'	45
Bottom	450

All measurements taken at the central axis.

Contamination Composition: Primarily ^{60}Co ; range - 50-80 percent.

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement M

Cask Serial No.: NLI 1/2 Serial #5461

Date: 04/29/86

Data Source - Battelle Columbus Shipping Documents

Recorded Data:

Radiation Levels (mR/hr)

<u>Location</u>	<u>Cask Cavity</u>
Top	25
3'	125
6'	50
9'	55
12'	90
Bottom	175

All measurements taken at the central axis.

Contamination Composition: Primarily ^{60}Co ; range - 50-80 percent.

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement N

Distance	Element #		
	1	2	3
1 ft.	12	15	20
3 ft.	12	15	20
5 ft.	16	20	20
7 ft.	15	30	30
9 ft.	30	40	40
11 ft.	70	150	80
13 ft.	4000	5000	6000

TN-8L RADIATION SURVEY RESULTS (9/11/86)

Highest Contact Reading in Two-Foot Intervals
(all readings in mR/hr)

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement 0

Distance	Element #		
	1	2	3
1 ft.	30	100	70
2 ft.	30	45	30
4 ft.	30	60	45
6 ft.	40	60	50
8 ft.	65	75	70
10 ft.	125	125	110
12 ft.	450	500	350
Bottom	20,000	18,000	18,000

TN-8L RADIATION SURVEY RESULTS (10/28/86)

Highest Contact Reading in Two-Foot Intervals
(all readings in mR/hr)

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement P

Distance	Element #		
	1	2	3
1 ft.	90	55	80
3 ft.	85	40	60
5 ft.	125	45	90
7 ft.	200	65	150
9 ft.	500	130	350
11 ft.	2000	500	1500
13 ft.	2000	500	1500
Bottom	35,000	18,000	35,000

TN-8L RADIATION SURVEY RESULTS (02/08/87)

Highest Contact Reading in Two-Foot Intervals
(all readings in mR/hr)

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement Q

Distance	Element #		
	1	2	3
1 ft.	45	85	130
3 ft.	30	50	85
5 ft.	30	65	125
7 ft.	45	100	175
9 ft.	95	180	300
11 ft.	225	425	700
13 ft.	1800	4000	6500
Bottom	17,000	60,000	100,000

TN-8L RADIATION SURVEY RESULTS (03/19/87)

Highest Contact Reading in Two-Foot Intervals
(all readings in mR/hr)

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement R

Distance	Element #		
	1	2	3
1 ft.	50	50	60
3 ft.	40	40	50
5 ft.	50	50	50
7 ft.	70	55	70
9 ft.	110	90	100
11 ft.	400	200	250
13 ft.	5000	4000	3000
Bottom	20,000	15,000	12,000

TN-8L RADIATION SURVEY RESULTS (07/27/87)

Highest Contact Reading in Two-Foot Intervals
(all readings in mR/hr)

RESIDUAL CONTAMINATION
CASK DATA SHEET

Measurement S

Distance	Element #		
	1	2	3
1 ft.	5	5	5
3 ft.	10	10	5
5 ft.	5	15	5
7 ft.	5	10	10
9 ft.	5	30	30
11 ft.	10	30	30
13 ft.	20	700	50
Bottom	500	1500	500

TN-8L RADIATION SURVEY RESULTS (02/24/88)

Highest Contact Reading in Two-Foot Intervals
(all readings in mR/hr)

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