DEMONSTRATING ONSITE SAFETY FOR RADIOACTIVE MATERIAL PACKAGING AND TRANSPORT SYSTEMS

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ABSTRACT

Packaging and transportation systems used to transfer radioactive materials and wastes onsite (e.g., within Site boundaries where public access is restricted and controlled) must provide an equivalent degree of safety to onsite workers, the general public, and the environment as would be achieved by meeting national standards. These standards are issued by the U.S. Department of Transportation (DOT) and the U.S. Nuclear Regulatory Commission (NRC) and are generally applied to shipments in intrastate and interstate commerce.

The U.S. Department of Energy, Richland Operations Office (RL), and its prime contractor, Fluor Hanford, are developing new performance-based and risk-based standards for the design and approval of these onsite packaging systems used within the 1,450 km^2 Site located in Washington State. The Hanford standards parallel national standards, but are tailored to fit the unique transport environment of the Hanford Site. The new system applies a graded approach to ensure high-risk and high-dose-consequence payloads are packaged and transported in packagings built with the necessary rigor to withstand normal and accident conditions, yet with enough flexibility to achieve operational efficiencies and cost savings. When package performance standards are not technically feasible or cost effective, a risk/dose consequence methodology is used to demonstrate equivalency to the national standards.

INTRODUCTION

The U.S. Department of Energy's (DOE) nuclear safety regulations located in 10 CFR 830 and DOE (1996) require onsite transportation safety. These rules and regulations require all onsite transfers of hazardous materials; substances and wastes, including radioactive materials and wastes; and nuclear materials be packaged and transported in a manner providing a level of safety equivalent to that achievable by meeting DOT and the NRC regulations. These regulations are specified in 49 CFR Subchapter C and 10 CFR 71, respectively.

Since the early 1970's, the DOE has had a formal transportation safety program. This program was managed primarily at the contractor level. Each prime contractor was responsible for maintaining a formal transportation safety program and implementing its unique methodology. As Site missions changed, two DOE organizations were established to manage the Site: RL and the DOE Office of River Protection (DOE-ORP). Each DOE organization contracts with prime contractors and subcontractors to fulfill specific mission needs. With the issuance of DOE Order 460.1A (DOE 1996) and more recently 10 CFR 830, DOE decided an integrated Sitewide transportation safety program was needed to ensure safety, improve efficiency, and minimize Site costs. As a consequence, in fiscal year 2001 RL, with concurrence of DOE-ORP, contracted Fluor Hanford to develop a Hanford Sitewide Transportation Safety Document (TSD).

To complete this task, two significant efforts were needed. The first was to develop a set of performance-based standards for the design, testing, and analysis of packagings to demonstrate equivalency to DOT and NRC standards. The second was to develop risk-based standards that could be applied to packagings where it is not practical to meet performance criteria; e.g. unique one-time onsite movements or to mitigate emergency situations. The following discussion summarizes Hanford's approach to meeting these performance- and risk-based standards.

APPROACH AND METHODOLOGY TO HANFORD PACKAGING PERFORMANCE STANDARDS

In accordance with DOE (1996), Hanford has developed performance standards for economical onsite packaging that provide an equivalent degree of safety to that provided by DOT regulatory packaging. The approach in providing an equivalent degree of safety is to develop standards for packaging and acceptable performance criteria for maintaining containment, shielding, and subcriticality under onsite conditions. In the development of these standards, the regulatory concept is used for ensuring packaging safety by establishing acceptable performance criteria for a defined set of requirements and performance tests. To ensure equivalency, the requirements and performance tests within the regulations are used. The methodology applied in developing these standards uses the regulatory performance criteria and amends the regulatory performance tests for onsite conditions to develop construction, performance, and evaluation requirements for onsite packaging. Development of these standards was also supplemented by the guidance documents developed by the NRC for packaging approval. As with all NRC packaging regulations and guidance documents, the fundamental concept applied in development of these standards is to establish standards of adequate protection, not absolute assurance.

Based on the regulations, the onsite packaging standards require the packaging to maintain containment, shielding, and subcriticality under the specified Hanford performance tests and requirements. The limiting onsite values for containment and shielding are identical to the requirements of 10 CFR 71.51 and 10 CFR 71.47. Also, subcriticality must be maintained under all onsite conditions. The Hanford performance tests and requirements for the most part are identical to the regulatory performance tests and requirements specified in 10 CFR 71 and are amended only for certain Hanford specific onsite conditions. A few examples of these modifications to the regulations are the environmental test condition temperatures, free-drop surface, and fire test conditions. Precedents for amendment of the regulations for specific onsite conditions are derived from 10 CFR 71.41 as long as equivalent safety to the regulations is demonstrated.

The environmental test condition temperatures specified for the Hanford Site are a high-temperature extreme of 46 °C and a low-temperature extreme of –33 °C. These environmental temperature extremes are based on Pacific Northwest National Laboratory climatological data summarized in Fadeff (1992).

In the case of free-drop heights, the heights specified in the regulations for both normal and accident conditions are retained for consistency with the regulations. However, because packages are restricted to transport over known routes and at restricted speeds, the free-drop surface for the performance test is amended from the regulations. In lieu of the hard unyielding free-drop surface defined in the regulation, the onsite packaging performance test free-drop surface is defined as the Central Waste Complex storage pad. The Central Waste Complex pad is a 20.5 cm thick, 20.7 MPa concrete pad reinforced with No. 7 rebar on 30.5 cm centers. This free-drop surface is the most rigid structure encountered over normal transport routes for packages on the Hanford Site. Defining a real and relatively rigid surface as the performance test surface for free-drop evaluations allows engineering of onsite packages that are robust for transportation safety and less costly than regulatory packages. As an example, a large costly heavy shielded cask for transport of high-hazard contents can be engineered without impact absorbing devices. Such a cask would have sufficient robustness that the concrete surface would absorb most of the impact energy. In contrast, the lighter less robust and less costly packages will have performance requirements nearly identical to the regulations. The basis for this approach is that to a lightweight package the concrete surface would be a hard unyielding surface. In essence, by establishing this surface, the least costly, most numerous, and least robust packages transported on the Hanford Site are subjected to essentially regulatory performance test structural loadings while the costly, robust, and least numerous onsite packages can be designed and built at reduced costs by reductions in the performance test structural loadings.

The regulatory hypothetical accident condition performance fire test requirements specified in 10 CFR 71.73 stipulates the fire temperature (800 °C), duration (30 minutes), emissivity (0.9), and package absorptivity (0.8). The sequence of events leading up to the fire is specified and stipulates that no artificial cooling is applied and that the fire must cool naturally. For onsite, the fire accident performance test conditions are the regulatory conditions specified, except artificial cooling is applied after the 30-minute fire duration. The basis for establishing artificial cooling after 30 minutes is that on the Hanford Site there are dedicated Fire Fighting Units trained in fighting radioactive material fires. The maximum response time at any location on the Hanford Site to actively engage in extinguishing a fire is less than 30 minutes. Table 1 shows the specific differences between the national standards and the Hanford onsite performance standards.

Table 1, 10 CFR 71 vs. Hanford Onsite Performance Standards—Specific Differences

10 CFR 71	Hanford onsite performance standard
10 CFR 71 philosophy is safety must be engineered into the package	Engineered containers and controls that include the conveyance, reliance on trained operations and emergency personnel, procedural controls, and restricted public access can provide onsite safety
Normal conditions ambient high air temperature 38 °C with national average solar loads	Normal conditions ambient high air temperature 46 °C with Hanford solar loads
Normal condition ambient low air temperature -40 °C	Normal condition ambient low air temperature -33 °C
Package venting not authorized	Controlled venting allowed through nuclear filter
Free drop onto hard unyielding surface	Free drop onto 20.5 cm thick reinforced concrete
Dynamic crush	Crush impact of similar size and weight package
Puncture bar on hard unyielding surface	Puncture bar on Hanford-defined drop surface
Thermal test 800 °C for 30 minutes with theoretical emissivity of 0.9 and absorptivity of 0.8 with no active cooling	Thermal test 800 °C for 30 minutes with theoretical emissivity of 0.9 and absorptivity of 0.8 with active cooling after event

HANFORD NON-DOT EQUIVALENT PACKAGING STANDARDS (RISK-BASED)

If circumstances do not allow use of performance-based packaging (e.g. one-time shipments, emergency transfers to protect personnel or environment), risk-based standards are then used to demonstrate equivalent safety. Hanford's risk-based standards relate worker and public dose consequence to nationally accepted leak rates used as the design bases for certified packagings under NRC regulations. The following paragraphs summarize the risk-based standards and the rationale for this approach to provide equivalent safety.

APPROACH FOR RISK-BASED STANDARDS

The criticality and shielding requirements for a risk-based packaging are identical to the requirements for a performance-based packaging. However, risk-based packaging, by definition, does not maintain the same level of containment as DOT or equivalent performance packaging. The intake of radionuclides into the body, rather than the containment performance of the packaging, is used to determine whether the onsite transfer of risk-based packages meets a degree of safety equivalent to the regulations. Because of the controlled conditions during onsite shipments and large distances to the Site boundary, the assumption of DOT containment requirements that a member of the public is in the immediate vicinity of a package damaged in commerce does not apply. The maximally exposed member of the public is at least 300 m away from Site shipment routes in the 300 Area and at least 10 km away from a shipment route within the 200 Area central plateau. Therefore, depending on the area of shipment, and taking into account the dispersability of the payload, damage to the package after accident conditions, potential leak paths, and 99.5% worst-case meteorology, a release limit specific to that shipment may be calculated such that the intake of radioactive material by the maximally exposed member of the public is no greater than the intake associated with the DOT allowable release limits. Note that the calculated shipment-specific release limits are not considered an acceptable public exposure and are not to be treated as design acceptance criteria. Rather, they are meant to result in an intake that is equivalent to the intake used in the derivation of the DOT hazardous material regulations (HMR). Use of these limits shall not prevent the transportation operation from including design features to mitigate the release of material during accident conditions as much as practicable below these limits. The packaging is only the first line of defense in the transportation operation, and all other available administrative and engineering controls that reasonably reduce the frequency of an accidental release and/or the intake by the maximally exposed member of the public should be implemented as practicable, consistent with the principle of as low as reasonably achievable. The combination of the calculated shipment-specific release limits and the administrative and engineering controls designed to preclude and mitigate a release provides a degree of safety equivalent to the DOT HMR for onsite transfers of radioactive material packages.

BASIS FOR RISK-BASED STANDARDS

For shipments in commerce, 10 CFR 71.51 requires that certified Type B packages be designed, constructed, and prepared for shipment so that under the tests specified in 10 CFR 71.73, there would be no escape of radioactive material exceeding a total amount A_2 in one week. This leakage is taken to mean that no more than 1 A_2 per accident may be released rather than a continuous uniform release rate during the week the accident occurs. The intake of the release by the public, rather than the release itself, causes the exposure and must be controlled in order to show an equivalent degree of safety. For an accident on a public highway, the public could be in the immediate vicinity of the package. In the derivation of the allowable release during accident conditions, the release of 1 A_2 is based on the release of 10^{-3} to 10^{-2} A_2 as a respirable aerosol combined with a fractional uptake into the body of 10^{-4} to 10^{-3} of the respirable aerosol (IAEA 1990, p. 78) for a total intake of approximately 10^{-6} A_2. The release of 1 A_2 is defined such that the dose to a person in the vicinity of a transport package following an accident does not exceed the annual dose limit for radiation workers recommended by the International Commission on Radiological Protection, namely 5 rem (IAEA 1990, pp. 72 and 110).

The 10 CFR 71.51 also requires that certified Type B packages be designed, constructed, and prepared for shipment so that under the tests specified in 10 CFR 71.71, there would be no loss or dispersal or radioactive contents as demonstrated to a sensitivity of 10^{-6} A_2 per hour. It is possible that some risk-based packages fail only the DOT containment requirement for accident conditions; i.e., they may meet the DOT containment requirements for normal conditions. For risk-based packages that do not meet the containment requirements for normal conditions, the intake associated with a leaking package during normal conditions at the location of the maximally exposed member of the public shall not exceed the intake by a member of the public from a certified DOT package in the immediate vicinity of a package in commerce. In the derivation of the allowable release rate from Type B packages during normal conditions of transport (IAEA 1990, pp. 107-108), the release of 10^{-6} A_2 per hour is based on a member of the public spending 20% of working time (400 h/yr = 20% x 2000 h/yr) working around a leaking certified Type B package in an enclosed vehicle of 50 m^3 volume with 10 air changes per hour. Note that in commerce, the public includes those who work in transportation. This scenario results in a maximum public intake over the course of 1 year of 10^{-6} A_2 from a certified Type B package at the maximum release rate during normal conditions of transport.

A degree of safety equivalent to the DOT HMR can be shown by limiting the public intake of radioactive material from a risk-based package to 10^{-6} A_2 from both normal and accident conditions, which is the same intake on which the DOT containment limits are based.

During transportation, the accident scenarios severe enough to damage risk-based packages that potentially could occur are a collision or overturn resulting in an impact or a fire. Because arrays of packages are commonly transported onsite, the inertial crush of the front row of drums against the front of the conveyance by subsequent rows of drums is a potential accident scenario. However, crush is considered a subset of the impact scenario, and the data on airborne release fractions generally do not distinguish between inertial crush and other types of impact. Puncture is another accident scenario that potentially could occur during transportation; however, because the damage to the package from puncture is typically not as severe as from an impact at highway speeds, this scenario is not considered further.

For shipments on the Hanford Site, the dominant exposure pathway for the offsite receptor is by inhalation of released particulate material in an airborne plume carried downwind by atmospheric transport to the Site boundary. Other pathways are small in comparison, including the exposure by inhalation of airborne particulates resuspended after being deposited on the ground, external exposure by submersion within the airborne plume, external exposure from material from the plume deposited on the ground, and direct external photon exposure from the payload at the accident location. Exposure from consuming contaminated food or drinking contaminated water is not considered, because the primary determinant of exposure from the ingestion pathway is the effectiveness of public health measures (i.e., interdiction) rather than the severity of the accident itself.

The intake of airborne particulate material by inhalation depends on the airborne source term, meteorology, and the receptor’s breathing rate. The airborne source term is the amount of material that is released to the atmosphere that becomes airborne and is sufficiently small to be respirable. This is calculated using standard airborne release fractions and respirable fractions from DOE (2000), for various accident environments and material forms, and using damage ratios and leak path fractions estimated from a structural and thermal evaluation of the failure of the package after accident conditions.

Site-specific meteorology is used to determine the atmospheric concentration at the Site boundary. Wind speed, direction, frequency, and stability class data were collected at various onsite locations between 1983 and 1991 to establish joint frequency tables. Using the methodology in NRC (1983), and these joint frequency tables, values of c/Q’, which is a measure of the airborne concentration, are calculated with a 99.5% statistical confidence for various distances from a release at various locations onsite.

The breathing rate of the public receptor is the rate for the reference man during light activity from ICRP (1975) (20 L/min or 3.33×10^{-4} m^3/s), which normally applies during the 16 hours of the day when the man is assumed to be awake.

IAEA (1990) calculates intake as the product of three factors as discussed above: (1) the amount of material released from the package (limited to a maximum of 1 A_2 from a certified package); (2) the fraction of the amount released that is respirable aerosol (assumed to be in the range of 10^{-3} to 10^{-2}); and (3) the fraction of the respirable aerosol that is taken into the body (“uptake,” assumed to be in the range of 10^{-4} to 10^{-3}). At Hanford, values of the aerosol respirable fraction that apply to the particular material are used, and site-specific meteorology is used. As an example, for a material with an airborne release fraction of 10^{-3}, a respirable fraction of 10^{-1}, and a χ/Q of 6.38×10^{-3} s/m^3 at 300 m (corresponding to the nearest distance between a shipment within the 300 Area and the Site boundary), the amount that could be released that causes an intake of 10^{-6} A_2 is 4.71×10^3 A_2, as shown below.

$$\text{Release} = \frac{\text{Intake}}{\text{ARF x RF x} \div/\text{Q x BR}} = \frac{10^{-6}\ A_2}{10^{-3} \text{ x } 10^{-1} \text{ x } 6.38 \text{ x } 10^{-3}\ \text{s/m}^3 \text{ x } 3.33 \text{ x } 10^{-4}\ \text{m}^3/\text{s}} = 4.71 \text{ x } 10^3\ A_2$$

The values in Table 2 are derived using conservative assumptions to provide an example of the release limits that are calculated for various areas that result in an intake of 10^{-6} A_2 by the maximally exposed member of the public at the Hanford Site boundary. Actual limits will account for the physical form of the payload (which governs dispersibility) and the performance capability of the particular package. An intake of 10^{-6} A_2 is the same intake as from the maximum allowable release of 1 A_2 from a certified Type B package in an accident in commerce. Note that, in addition to meeting the limits in Table 2, the risk to the onsite worker must also be accepted by RL. This requirement, in effect, controls the frequency of a release.

Table 2. Example Limits Based on Equivalent Public Intake.

Release location	Release rate (A_2/h) normal transfer conditions	Release (A_2) accident conditions
300 Area	3.51×10^{-4}	4.71×10^{2}
200 Area	2.46×10^{-2}	1.71×10^{5}
100 K Area	9.65×10^{-3}	6.70×10^{4}
In commerce	1.00×10^{-6}	1.00×10^{0}

In addition to the release limits derived to result in an equivalent intake, administrative and engineered controls are a part of the onsite equivalent safety program. These limits restrict speeds and define transport routes, acceptable road and weather conditions, and other controls that minimize the potential for a serious accident.

In addition to showing equivalency to the DOT HMR, calculations of the dose to the onsite worker and the frequency of an accident are also performed. These calculations help determine if the risk to the onsite worker is acceptable. This determination is made by the RL, not the Site contractor. In addition to the dose from the damaged package and the frequency of a release, factors influencing this determination include the performance capability of the package during accident conditions, the scope of the shipment campaign, the preventative and mitigating features of the administrative and engineered controls, the availability (or lack thereof) of suitable certified or equivalent packages, and the consequence of nonshipment.

The dose to the onsite worker from an accident is calculated considering an impact or fire scenario as discussed above for the public intake calculation; however, in addition to the inhalation dose pathway, the external dose pathway from photons, beta particles, and neutrons is considered. Because the onsite receptor is not a fixed distance away from the conveyance as is a co-located worker from facilities, the worker is assumed to be the driver of the vehicle and remain at 3 m from the damaged package for a duration of 15 minutes. Because atmospheric transport at such close distances cannot be described by a χ/Q, the uptake by the onsite receptor is taken to be 10^{-4} of the released respirable aerosol, consistent with the IAEA (1990) approach described above. Dose conversion factors published by the U.S. Environmental Protection Agency (Eckerman 1988) are used to convert intake by inhalation to a 50-year effective dose equivalent commitment.

The frequency of an accidental release during transportation is based on an accident rate per mile; the conditional probabilities, given an accident, of encountering severe impact, puncture, crush, and fire environments; and the conditional probabilities of encountering accident conditions that are more severe than the particular package's failure thresholds. The package's failure thresholds for impact, puncture, crush, and fire environments are determined by a structural evaluation. Conditional probabilities of the occurrence of these environments, as well as the magnitudes of these environments, have been developed based primarily on data from NUREG/CR-6672 (Sprung et al. 2000).

CONCLUSIONS

Hanford's performance- and risk-based standards will ensure onsite transportation safety and will demonstrate that equivalent protection is provided to workers, the public, and the environment as would be achievable through compliance with national standards applied to shipments in commerce. Hanford's new TSD will implement these standards. It is currently scheduled for implementation in fiscal year 2002.

REFERENCES

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