A Regulatory Perspective on the Response Function Method for Determining Allowable Content of a Radioactive Materials Transportation Package or Storage Cask – 15023

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ABSTRACT

In order to simplify shielding design, there has been an increasingly use of a so-called dose rate response function method for determining the allowable contents in radioactive materials (including spent fuel) transportation package and spent fuel storage cask designs. In essence, this approach uses a pre-calculated dose rate at a given location outside the storage cask or transportation package for a given source inside the cask. It assumes that there is a one-to-one relationship between a source inside the cask and the dose rate outside the cask, i.e., a dose rate response function of a source. Thus, the allowable content is obtained by simply dividing the targeted dose rate by the response function. This method converts the complex particle transport problem into a simple arithmetic calculation. If used correctly and prudently, this approach can greatly simplify the shielding design of casks. However, the use of this method must demonstrate the validity of the assumption, that is, the nuclear physics property of the media through which the particle transverses must be similar to that used in computing the response function. Because of the assumptions and approximations, either implicitly or explicitly, made in the models for dose rate response functions, to assure safety the users should also consider the errors in the models and the bias and uncertainties associated with the code used to calculate the response function. This paper reviewed the advantages and some of the major potential pitfalls of this method from the regulatory perspective.

INTRODUCTION

Part 71 and Part 72 of Title 10 Code of Federal Regulations [1, 2] establish safety performance requirements for radioactive materials transportation and spent fuel storage systems respectively. The vendors of these systems must demonstrate compliance with respective regulations in order to be licensed for use or certified for compliance with the regulation. One of the critical design requirements of these types of systems is radiation shielding. A spent fuel storage cask or radioactive materials, including spent fuel, transportation package design must demonstrate compliance with dose rate limit requirements of respective regulations.

Typically, shielding design of a radioactive materials transportation package or spent fuel storage cask system would first determine the intended bounding content and estimated shielding requirements. The designer then performs a shielding analysis with the content and the selected shielding materials and geometric dimensions of the shielding structure. However, it is in general fairly complicated to complete a shielding design even for people who have significant experience in shielding material selection and shielding structure design. It may take several iterations to achieve the desired system shielding performance [3]. Sometimes, complex and costly mockups may become necessary to confirm the design. It is particularly challenging for systems for which the contents are complex in terms of source term geometric form and energy distribution characteristics, source region material composition, shielding materials composition and geometric distribution. This is particularly true for spent fuel storage cask and general radioactive materials (including spent fuel and great than class C wastes [4]) transportation package designs because the activities and energy spectrum of the sources in the contents typically vary significantly and the vendors also desire to design casks or packaging systems that would allow for

contents of various forms and sometimes the characteristics of the source terms can only be determined at the time of waste characterization.

In addition, for sources generated by neutron irradiation, such as spent nuclear fuel, general nuclear waste, the source terms in general depend on several factors, including irradiation exposure, burnup, cooling time that are difficult to define the sources in one set of values for all contents. A combination of various exposure and cooling time may give the same source strength. Although it is possible to use a bounding source for those types of contents, using a bounding source in the shielding design sometimes can be too restrictive and overly penalizing. Therefore, it is desirable to use a more flexible approach to determine the contents. The response function approach provides a solution to this problem.

In order to simplify the shielding design process, a so-called response method has been used in the spent fuel storage and radioactive materials (including spent fuel) transportation package designs. This approach first calculates the dose rate at a given location outside the cask or package for a given source with a specific energy spectrum and uniformly distributed inside the cavity of a package or a cell of spent fuel basket of a spent fuel storage or transportation cask. It then uses the pre-calculated normalized dose rate to determine how much content with these specific nuclear characteristics can be loaded into the cask for a desired dose rate limit. The implicit assumption is that there is a one-to-one relationship between a source inside the cask and the dose rate outside the cask, i.e., a dose rate response function of a source for a given system design. With this approach, the allowable content is obtained by simply dividing the targeted dose rate by the response function. This method converts the complex particle transport problem into a simple arithmetic calculation. However, there is a fundamental assumption that the media through which the particles transverse are the same as what were used in determining the dose response function developed in the forward calculation. The users of this method must demonstrate the validity of the assumption, i.e., the nuclear physics property of the media through which the particle transverses must be sufficient similar to what was used in computing the response function in terms of the macroscopic cross sections for each region. Also, the users of this method should consider the errors in the response functions that will be propagated when used to determine the allowable contents. In summary, if used correctly and prudently, this method can greatly simplify shielding design of general waste and spent fuel storage casks transportation packages. The following sections review the advantages and some of the potential pitfalls of this method and a discussion on the need for forward confirmatory calculation from the regulatory perspective.

A BRIEF DESCRIPTION OF THE RESPONSE FUNCTION METHOD

The dose rate at a detector location is the product of the flux or fluence of a particular particle type and a particular flux-to-dose-rate conversion factor. Once a flux-to-dose rate conversion factor is determined, the remaining task of a shielding question is to determine the flux or fluence of the particle at the detector location. For a system with a given shielding design, the dose rate received at a detector location is dependent on the shielding capability of the system and the spatial distribution, material composition, and energy characteristics of the source. For a given a volume source of volume V centered at the origin of the reference system, the dose rate at location R(x, y, z) can be determined as:

$$DR = \int^V \left(\int_0^{Emax} \varphi(R,E) D(E) dE \right) dv \tag{1}$$

Where:

        DR is the dose rate of the detector at location R,
        $\varphi(R, E)$ is the flux of the specific particles at location R with energy E
        $D(E)$ is the flux to dose rate conversion factor for particle at energy E, and
        V is the volume of the source term.

Equation (1) holds true as long as the source and the shielding materials and their respective geometry remain the same. Based on this relationship, for a uniformly distributed source with a fixed shielding structure the allowable content can be determined as:

$$Q = \frac{DRL}{DR} \qquad (2)$$

Where Q is the total allowable quantity of radioactive materials in a package or cask that meets a specific dose rate limit DRL.

As a practical approach, these two equations can also be applied to a source with discrete energy spectrum or grouped energy distribution as long as the particles in the energy interval of each group are weighted correctly against the energy distribution. With equation (2), for a package containing uniformly distributed source in a homogenous media, the allowable quantity of a payload with can be determined with pre-calculated response function using equation (1).

FUNDAMENTAL ASSUMPTIONS OF THE RESPONSE FUNCTION METHOD

As can be observed from equations (1) and (2), the response function method consists of two steps. The first step is to make a forward calculation of the particle transport problem for a source, $S(R', E')$, as a function of energy and space. The second step is to use the response function calculated in the first step to determine the allowable quantity of content. The first step is to find a solution for a system with given source and shielding design. However, for all practical purposes, solving any practical shielding problem with a space and energy dependent source, such as general radioactive waste or spent fuel, and thick shields, such as spent fuel storage/transportation system or general waste transportation package, requires solution of deep penetration problem and large computation resource with carefully designed solution technique or a combination of various schemes. For example, a typical Monte Carlo method model of a deep penetration problem often requires use variance reduction techniques to obtain a reliable result within a reasonable computer time and computational power [5]. Sometimes, a pre-calculated adjoint function is applied in order to obtain a reliable solution with reasonable computation time. However, finding the adjoint function of complex shielding problem requires solution of the transport equation using some kind of deterministic method. The Monaco/Mavric code [6], for example, uses S_N method to determine the adjoint function first and uses Monte Carlo method to solve the actual particle transport equation.

In addition, some users further break down the energy into small intervals and treat all particles in each energy interval as with the same energy. This further approximation makes the response function calculation more manageable because computing the response function for particles with a single energy would typically help convergence speed and alleviate the difficulties in determining the biasing scheme that is typically used in Monte Carl method models. In addition, this energy discretization also makes the application of the response function more flexible because the users can use the energy groups that are appropriate for the sources that are characterized by the energy distribution of the contents that need to be stored or transported.

The fundamental representation of the particle transport is the linear Boltzmann equation [7, 8, 9]. A shielding problem is typically to find solution of solution of the steady state Boltzmann equation. For a non-steady state problem, such as neutron transport problem in a system containing fissile materials, it is typical to convert the non-fixed source problem in two steps, solving the eigenvalue problem of the system first and then use an adjusted source to account for neutron multiplication during transport. This strategy can also be used for the response function method.

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As pointed out earlier, to use the response function method, the users would have to find the fluence or flux of the particles at the locations of interest. For a given source distribution, to obtain the fluence or flux at location r, one can solve the following integral form of the Boltzmann equation for a fixed-source problem that is defined by the following integral Boltzmann equation:

$$\phi(r,\Omega,E) = \int_0^\infty dR\, e^{-\int_0^R dR' \Sigma_t(r-R'\Omega,E)} \left[S(r-R\Omega,\Omega,E) \right.$$

$$\left. + \int d\Omega' \int dE' \Sigma_s(\overset{\vee}{r}-R\Omega,\Omega'\to\Omega,E'\to E)\phi(\overset{\vee}{r}-R\Omega,\Omega',E')\right] \tag{3}$$

Where:

$\phi(r,E,\Omega) = $ Angular flux

$e^{-\int_0^R dR\,\Sigma_t(r-R'\Omega,E)} = $ Probability of no collision between r - RΩ and r

$S(r-R'\Omega,\Omega,E) = $ External source by position, direction, and energy

$\Sigma_s(r-R'\Omega,\Omega'\to\Omega,E'\to E) = $ Scattering cross section by position, directions, and energies

$\int_0^\infty dE' \int_{4\pi}^\infty d\Omega' \Sigma_s(r-R'\Omega,\Omega'\to\Omega,E'\to E)\phi(r-R'\Omega,E',\Omega') = $ Source of scattered particles

by position, direction, and energy

For photon shielding problem, the term, $S(r − R'\Omega, \Omega, E)$, in equation (3) represents the energy and geometry dependent source distribution. For neutron transport problem in a media that contain fissile materials, the source term, $S(r − R'\Omega, \Omega, E)$, must include potential neutron multiplication. However, when performing shielding calculation, it is common to treat the system as non-fissile in solving the transport equation but account for the subcritical multiplication by modifying the source term as:

$$S^* = S/\left(\frac{1}{1-k_{eff}}\right) \tag{4}$$

Where S^* is the actual source adjusted with subcritical neutron multiplication factor k_{eff} and S is the neutrons produced by fixed sources.

THE REGULATORY PERSPECTIVE ON THE RESPONSE FUNCTION METHOD

The motivation of using the so-called response function method is to simplify the shielding design and provide greater flexibility for the cask design by allowing the users to determine the proper quantity of content for specific materials to be stored or transported. However, it can be observed from the integral Boltzmann equation as shown in equation (2) that the transport of particles in a medium depends on the scattering and absorption of the medium. The response function is therefore fundamentally dependent on the geometric arrangement of the shielding materials and the geometric distributions and the nuclear and physical properties of the source and content materials. To obtain a reliable response function, the users must assure that the model used for computing the response functions is truly representing the system, including the source and content material geometric distribution. Consequently, the calculated response function may be valid only for a specific system which consists of a specific shielding design and content. As such, the safety analysis for the potential content is expected to include a clear justification for the similarity of the nuclear and physical property of content in comparison with what was used in the models

for computing the system response function. For example, a response function calculated using a material density for contents that are general radioactive wastes should consider the material density and the nuclide composition of the materials. For gamma shielding design, the users may also need to consider the z value of the material that. These are the dominating factors of shielding because these properties are principally affecting the particle transport and hence the dose rate at the given detector location.

Various methods can been used to solve the Boltzmann particle transport equation. Solution method of the Boltzmann equation is beyond the scope of this discussion. However, of importance are the assumptions used in the solutions, the approximations inherited the solution method, inherited errors resulting from approximation of the problem and various computation methods. These assumptions and assumptions used in the method for solving the Boltzmann equation dictate the applicability of the calculated response function values and the associated errors in the response function values. The users should be aware that although it provides a way with great convenience, the response function method also has potential shortfalls if not used correctly because it can produce non-conservative results for allowable contents. The follows are the three major categories of errors that could potentially be introduced in using the response function method for determining the allowable contents.

1. The bias and uncertainties of the method and/or computer code used to determine the response function,

2. The assumptions and approximations used in computing the response function,

3. The differences between the actual content what were assumed and in the nuclear and chemical property of the media through which the particles transverse,

4. Propagation and amplification of errors introduced in the modeling and computational method.

From the regulatory perspective, the ultimate goal is to assure the safety of the system, either a storage cask or a transportation package. All of those factors will affect the applicability and accuracy of the results of application of this method. The users of the response function method for determining the allowable contents are expected to consider the impacts of these factors in its calculation of the response function and demonstrate:

1. The nuclear properties and geometric distribution of media through which the particle transverse, including the content and the shielding materials, are essentially same to what were assumed in models used to compute the response function.

2. Proper considerations of the errors inherited in the computation of the response function values, and

3. Proper consideration of error propagation in using the response functions in determining the allowable content.

For the first consideration, it is important to note that the response function is calculated based on a certain assumptions of the source material and shielding material property, including material composition and density. For most of the cases, the geometric dimensions of the shielding materials and geometric distribution, including the geometric shape and dimensions are not of concern because these parameters in response function models are typically the dimensions and geometric structure of the actual shielding design. The main concern is whether the material properties used in the response function are appropriate for the contents for which the allowable quantity is to be determined using the response function. As can be observed from equation (3) and (4), particle transport primarily depends on the macroscopic cross section of the source and the shielding materials for non-point source shielding system. The calculated response function is therefore valid only for the specific material composition and geometric distribution. For example, it has been demonstrated, in comparison with using actual spent fuel

material composition, that using fresh fuel assumption in spent fuel transportation package shielding calculation will underestimate the dose rate at all locations outside a package as prescribed by 10 CFR 71.47, i.e., on the projected surface from flatbed track edge, 1 meter from the projected surface from flatbed track edge, and 2 meters from projected surface from flatbed track edge for an exclusive use package. Consequently, using the response function computed with fresh fuel assumption will produce a non-conservative result for the allowable content.

With respect to potential bias and errors inherited in the solution methodology of the particle transport equation, all solution methods currently used in shielding calculations use approximations of some sort. For examples, computer codes implementing the S_N method include approximation of geometric dimensions and particle energy because they use discrete representation of system geometry and particle energy and Monte Carlo method code uses statistical approach that includes a statistical uncertainty in the result.

Finally, the users should include consideration of error propagation in the determining the allowable content. For example, a 10% underestimate and bias in the response function will produce more than 11% overestimate of the allowable content and a 20% overestimate will produce an overestimate of the allowable content by 25%. From these examples, it is obvious that non-conservative results could be introduced when without proper consideration of the errors introduced by the bias and approximation in calculating the response function.

In summary, the users of the response function method for determining the allowable contents are expected to take into the assumptions and approximations, and the errors introduced in modeling of the system and the choice of method for calculating the allowable content. Rather than using the results of the forward shielding analyses, i.e., the response function directly, the users are expected to modify the results to include bias, uncertainties, and errors introduced by various assumptions as shown in equation 5.

$$DRM = DR + \delta m + \delta M \qquad (5)$$

The users can then use the adjusted dose rate per unit source, *DRM*, to calculate the maximum allowable content for the specific cask or packaging design.

$$Q = DRL/DRM \qquad (6)$$

The fundamental assumption of this method is that there is a fixed one-to-one relationship between the dose rate and the particle type, energy, and location regardless of the medium the particle transverses. Although this approach may provide acceptable results if the material composition in the package is similar to that used in the model for the response function calculations. However, this one-to-one relationship is no longer valid if there is a significant change in material composition of the medium through which the particle transverses.

In addition, it is recognized that there exist inherited errors and biases of this approach. The users should include proper considerations of these errors and biases in the calculated response function. Omission of the errors and biases may produce results in non-conservative allowable contents.

Finally, in order to assure that the calculated response function is reliable and accurate, i.e., there is no misrepresentation of the content and the shielding design, the users of the response function method is expected to perform forward shielding calculations for a few selected representative cases to confirm the reliability and accuracy of the calculated response function values that are to be used to determine the allowable contents.

CONCLUSIONS

The response method derived from a forward shielding calculation a dose rate per particle at a specific energy. The allowable amount of radioactive materials content per cask is then determined via dividing the regulatory dose rate limits by the dose response function value. Although this approach greatly simplifies the shielding design calculations and provide a convenient way for the users to determine the maximum allowable contents that meet the respective regulatory requirements, the use of this approach must pay a close attention to the fundamental assumption that is the actual material compositions of the content and shielding materials are identical to what were used in the dose rate response function. In addition, the errors in commutating the dose rate response function will be prorogated when the response function value is used in determining the allowable contents. The storage cask or transportation package designer must take into consideration of potential amplification of the errors when determining the allowable contents. In general, a forward calculation for a cask with bounding payload should be made to confirm that the content determined by the response function method is correct and reliable. An appropriate safety margin should be specified together with the response function values when provided as part of the operating procedures that include determination of the allowable content.

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