An Estimate of the Contribution of Spent Fuel Products to the Releasable Source Term in Spent Fuel Transport Casks*

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INTRODUCTION

The radioactive source terms pertinent to spent fuel transport cask safety assessments are of three distinct origins; residual contamination within the cask due to previous transport and handling operations, "crud" deposited on the fuel rods in the course of reactor operation, and the radioactive material contained within the rods. Although the last source overwhelms the others in terms of inventory, its release into the cask, and thence into the biosphere, requires the breach of an additional release barrier, viz., the fuel rod cladding. Hence an evaluation of the fuel source term is complicated by the need to address the likelihood of fuel cladding failure during transport.

A comprehensive methodology is being developed to accurately describe fuel rod response to severe impacts which includes the extent of release of radioactive material in the event of fuel cladding failure. The analysis model allows for the various levels of interaction that could occur, namely, between the cask basket and assemblies, between assemblies, and between rods. Using as-transported conditions and material properties of spent fuel, analyses have been conducted for various levels of geometric modeling details, including multi- assemblies, single assemblies, and single rod configurations.

For cask design purposes, the maximum impact loading on the fuel rods that need be considered is that resulting from 0.3 meter and 9 meter drops of the loaded cask onto an unyielding target. If it is assumed that the cask body is infinitely rigid, energy absorption is limited only to the impact limiters of the cask, providing a conservative estimate of the deceleration forces imparted by the cask to its contents.

Thermal response analyses have been conducted to estimate fuel rod cladding temperatures that might be experienced under the regulatory normal and accident transport conditions (10CFR71). These analyses indicate that, for both normal and accident conditions of transport, and for a cask designed to limit peak cladding

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** A United States Department of Energy Facility temperatures to 380°C, the peak fuel temperature of a PWR fuel assembly is well below the 725°C temperature required for cladding burst rupture to occur (Burian 1985). For typical fuel decay of at least 5 years, the regulatory thermal transient is not of sufficient duration for the fuel to reach very high temperatures, thus cladding failure as a result of elevated temperature is not considered a likely failure mode. Analyses have also been made of effects due to shock and vibration experienced during both road and rail transport; the resulting stresses appear to be inconsequential based on historical bounding shock and frequency data.

The extent of radionuclide release following cladding breach depends primarily on the inventory in the fuel void region. The gap inventories that are developed during the course of fuel irradiation can be estimated using the methodology provided by the American National Standard ANSI/ANS-5.4-1982. In the event of fuel cladding failure, most of the inventory of gases will be released within the cask, almost instantaneously, along with some fraction of volatile species. Experiments (Lorenz 1979) indicate that about 85 mg of the fuel, in the form of fines, is entrained by the escaping gases. These particulates are of the same radionuclide composition as the bulk material, but may contain elevated levels of cesium if the gap inventory of cesium is large. Gross failure of the fuel rod, should it occur, may result in additional fuel fines production and release, but in either case significant attenuation of the aerosol concentration in the cask can occur, depending upon the residence time of the aerosol in the cask compared with its rate of escape from the cask into the environment.

FUEL ROD MECHANICAL RESPONSE

Side Drop Model

Under side drop loading, the primary deformation mode is rod-on-rod stacking with support provided by the basket and cask along the length of the assembly . This deformation mode can be simulated by a longitudinal slice model of the assembly. This 2 dimensional approximation of the assembly under side drop loading is conservative, since it neglects the out-of-plane stiffness of the spacer grids which confine the fuel rods and increases the assembly's in-plane stiffness.

The side drop computational model consists of a row of rods in the assembly made up of segmented beam elements, rigid end plates, spacer grid spring elements, and rod-to-rod contact elements along the length of the rod between the spacer grids. The fuel rods are modeled with Euler beam elements with large displacement and plastic deformation capabilities. The stiffness properties of the rods are based on the fuel rod cladding and neglect the contribution of the fuel pellets. A nonlinear spring element was developed from separate detailed analyses of the spacer grids isolated from the assemblies, and then included in the assembly models. This spring element models the highly non-linear force transfer mechanism between the spacer grids and fuel rods.

The side drop assembly model is analyzed using a dynamic time marching procedure. The free drop condition is simulated with an initial velocity (44 ft/sec for a 30 foot drop) input to all components of the structural model. The momentum due to this initial velocity is reacted by a retarding force equal to the mass of the assemblies times the cask rigid body deceleration time history. The deceleration history is based on the geometric and material properties of the cask impact limiters . The retarding force is applied to all of the assembly-basket support points.

End Drop Model

The fuel assembly response under end drop loading can be modeled with a single rod since the primary load path is essentially the same for all rods in the assembly. Under end drop loading, the primary load path is axially along the length of the fuel rods. Thus, if all rods are assumed to have the same deformation pattern, a single rod model can be used to define the assembly end drop response. This assumption is conservative since rod-to-rod interaction caused by variations in deformation patterns among rods will reduce (rather than increase) the maximum rod lateral deformations which govern peak cladding strains.

Lateral constraints on the fuel assembly play a critical role in determining fuel rod response since typical cask drop loading conditions exceed the lateral buckling strength of individual fuel rods. Unrestricted lateral displacements between spacer grids, which are associated with open-frame basket design, will significantly increase the peak fuel rod response. Cellular basket designs, on the other hand, provide continuous lateral constraints along the length of the assembly which result in much reduced lateral displacements.

The end drop computational model consists of: a single fuel rod made up of multiple beam elements, spacer grid spring elements, and lateral constraint springs along the length of the rod between the spacer grids. The nonlinear spacer grid springs are similar to those described in the previous section, however the single rod spacer grid spring element is based on the deformation pattern of the rod within the assembly. Thus the spacer grid spring element describes the force-deformation relationship of the single rod from initial displacement through contact with the basket support. An assumed initial bowing of the single rod model is included to permit the possibility of fuel rod buckling. The bowing profile is conservatively defined with the maximum plausible lateral offset in the lowest buckling mode shape of the rod.

Corner Drop/Slap Down Model

The corner drop response is divided into separate events: (1) initial impact, and (2) slap down. Initial impact is defined as the deceleration loading corresponding to the crushing of the cask impact limiter at its initial impact location. The initial impact response is largest for cask drop angles close to the end drop condition. After the initial impact phase has brought the cask to rest in the upright position, a secondary impact or slap down event will occur if the cask's center of mass is positioned outside the impact "footprint". The slap down event is most critical when the drop angle is very small (the cask is nearly in its side drop configuration).

Failure Criteria and Failure Modes

Cladding failure can occur by one of two failure mechanisms: ductile tearing due to excessive strain, and material fracture at a pre-existing crack. The failure criteria measures that govern both of these failure mechanisms are, respectively, the material ductility, ε_f, and the fracture toughness, K_{IC}.

Data in the form of distributions are available for both of these quantities (Bauer et al., 1977;Mills 1985). The ε_f distribution is a function of a ductility parameter called biaxiality ratio which, for fuel cladding, is the ratio of hoop stress to axial stress; the lower this ratio the higher the ductility exhibited by the material. These curves can be used directly to estimate the failure probability if the strains and stresses are known from a deterministic response analysis.

The two failure mechanisms discussed above are characteristic of the three cladding failure modes that could occur. These are:

> Transverse Tearing: Rupture initiated at the cladding outer surface as the result of strain exceeding the ductility limit. This failure mode is governed by the ε_f criterion.
>
> Longitudinal Tearing: Cladding fracture initiating from a pellet-cladding interaction (PCI) crack. This failure mode is governed by the K_{IC} criterion.
>
> Rod Breakage: Crack extension of a transverse tear to full rod breakage. This failure mode is governed by the K_{IC} criterion.

Figure 1 illustrates these three failure modes. A pin hole or narrow transverse crack is associated with stretching of the cladding material past its ductility limit. Large tensile strains can occur in the fuel rods when they bend, adjacent to, and around the assembly spacer grids and end plates. The dominant sources of cladding fractures are PCI part-wall cracks (Tasooji et. al., 1984). Pinch loads caused by rod-to-rod interaction under side drop loading are the primary driving forces for longitudinal fracture. Rod breakage can occur if the transverse crack caused by ductile tearing propagates circumferentially and causes complete or partial separation.

Maximum locations for stress/strain and pinch forces were determined for the rods; a probabilistic evaluation of failure was then performed which considered statistical variation in the ductile rupture strain and brittle fracture toughness of the material, and the size, location, orientation and frequency of part-wall cracks (viz. PCI induced cracks)

RELEASE OF RADIOACTIVE MATERIALS

Upon failure of the fuel rod cladding, radiotoxic materials are released by three different processes: expansion of fission and fill gases in the interconnected void volume within the fuel rod; subliming of volatile species which are then purged with the gaseous material or later diffuse from the cladding; and entrainment of fuel fines with the other material exiting the cladding. Only the material that resides within the interconnected voids (gap fraction) within the fuel rods is available for release. The model for gaseous fission product escape permits complete release of the gaseous component of the gap fraction, but only a fraction of the volatile species, whose value is temperature dependent. Observations of the behavior of fines released from overheated fuel, indicate about 10% of the ejected fines remain airborne sufficiently long to be available for release from the cask (Lorentz, 1979).

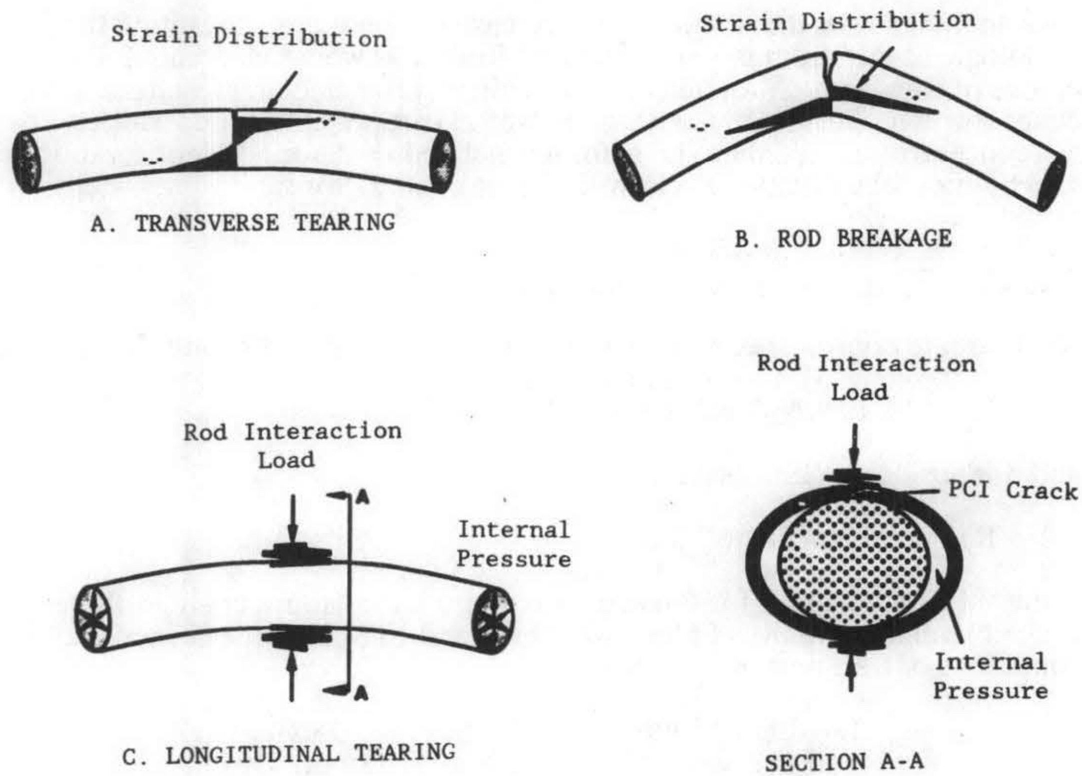

Figure 1. Fuel Rod Failure Modes

RESULTS AND DISCUSSION

The fuel response code FREY and the finite element code ABAQUS were used to evaluate the dynamic fuel response models. Probability distributions for PCI cracks and their depth, together with data on the variation of ductile rupture strain and brittle fracture toughness for cladding material, enabled determination of the probability of failure per rod per event for the different environments shown in Table 1. The corner drop angles illustrated are those resulting in maximum fuel rod stress for the particular height. Other angles were also evaluated.

The consequences of cladding failure depend on the fuel's irradiation and decay history. Estimates of the inventory for a 15x15 PWR fuel assembly irradiation history were conducted using the ORIGEN2 computational routine (Croff 1983). The gap fraction of ^{85}Kr was calculated using the methodology described in the standard ANSI/ANS-5.4-1982 (ANSI 1982). The corresponding gap fractions for ^{134}Cs and ^{137}Cs were assumed to be identical to that of ^{85}Kr. The gap fraction for ^{3}H was conservatively assumed to be 0.5.

All of the ^{85}Kr and ^{3}H in the fuel-cladding gap region and plenum were assumed to be released at the time of cladding failure, along with 85 mg (.003%) of the fuel as fuel fines. In addition to the cesium (and krypton) contained in the fuel fines, volatile cesium species which are purged from the gap regions were estimated using a model developed for cesium release from overheated fuel (Lorenz 1979).

This analysis shows that the actinides, released as fuel fines, constitute the main radiologic hazard from material released from rods whose claddings fail in the course of transport. Also, failure of a single fuel rod cladding results in a concentration of 0.161 A_2 Ci/m^3 in the typical truck cask volume. This constitutes the concentration C_i (where i = N for normal and i = A for accident conditions) which relates the release rate R_i with the leak rate L_i for safety assessment purposes,

$$L_i = R_i/C_i. \tag{1}$$

Release rate criteria specified in 10 CFR 71 are, for normal conditions of transport,

$$R_N = 1 \times 10^{-6}\, A_2\, C_i/h, \tag{2}$$

and, for accident conditions,

$$R_A = A_2 \text{ Ci/week}. \tag{3}$$

If the value cited above for C_i is employed in the rod failure analysis, these criteria yield containment limits of 1.73×10^{-3} cm^3/s and 10.3/cm^3/s for normal and accident conditions of transport, respectively.

TABLE 1. Failure Probabilities for a 15 x 15 PWR Fuel Assembly in a Generic Transport Cask

Assembly Loading Condition	Failure Probability Per Rod Per Event Longitudinal Slit	Pinhole Rupture	Rod Breakage
30 ft. End Drop	1×10^{-9}	7×10^{-6}	8×10^{-7}
30 ft. Corner Drop (84° Drop Angle)	4×10^{-9}	9×10^{-6}	1×10^{-6}
30 ft. Corner Drop (2° Drop Angle)	5×10^{-5}	1×10^{-4}	2×10^{-5}
30 ft. Side Drop	4×10^{-5}	2×10^{-4}	5×10^{-5}
1 ft. Corner Drop (60° Drop Angle)	1×10^{-5}	1×10^{-5}	2×10^{-7}
Fire[a]	1×10^{-11}	-	-

[a]Based upon a partial incipient crack in the cladding with a probability of 1×10^{-4}.

CONCLUSIONS

1. The phenomena involved in determining the source term in spent fuel transport casks can be modeled reasonably accurately on the basis of existing analytical capabilities, material properties data and operational history information.

However, some important data are lacking and therefore major compensating assumptions have to be made which affect the results in crucial ways. These assumptions are now being investigated through sensitivity analyses to prioritize future data development needs.

2. An assumption of massive fuel rod failures for the containment design of spent fuel transport cask is very conservative. The likely failure frequency appears to be smaller by several orders of magnitude.

3. PWR fuel appears to be more vulnerable to rupture during transport than BWR fuel under the conditions examined. The smaller BWR fuel rod diameters are mostly responsible for this condition. Rod failure due to initial PCI cracks are more probable for PWR fuel than BWR fuel, although BWR fuel is the more vulnerable of the two fuel systems to PCI failures while in the reactor.

4. The fuel fines, rather than the gaseous or volatile species, dominate the potentially releasable source term. However, the basis for the calculations of the radionuclides contained in the fuel fines that could be purged with the gases in the event of cladding breach is supported by a very limited amount of data.

5. The effects of a regulatory fire, as an isolated event, on the fuel failure probability appears to be negligible.

6. PCI incipient failures (partial cracks) emerge as the most prominent initial condition that affects rod failure probabilities.

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