COMPARISON OF CALCULATED TO MEASURED DOSE RATES FOR THE

REA-2023 AND CASTOR-1C BWR STORAGE CASKS

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ABSTRACT

A number of casks have been designed and several have been built for the storage of spent nuclear fuel rods. As part of the comprehensive demonstration test programs, spent fuel has been loaded into the REA-2023 and Castor-1C casks and radiation dose rates measured. Major differences between the casks are discussed. Point kernel and discrete ordinates methods were used to predict radiation dose rates on the surface of the two casks. The QAD-CG code was used for primary gamma-ray calculations. The DOT-4 code was used for neutron and secondary gamma-ray calculations.

Calculated dose rates agree reasonably well with the measurements. Calculated neutron dose rates for the REA-2023 cask range from good agreement to a factor of four high. The calculated gamma-ray dose rates range from a factor of two high to a factor of four low. Calculated neutron dose rates for the Castor-1C cask range from a factor of two to a factor of four high. The calculated gamma-ray dose rates are a factor of two high. The sensitivity of the dose rates to the details of the calculation is discussed, and the importance of various assumptions made for the calculations is evaluated.

INTRODUCTION

Radiation dose rates have been measured on the surface of the REA-2023 and the Castor-1C dry storage casks loaded with spent nuclear fuel assemblies. Shielding analyses were made with the QAD-CG [1,2] and DOT-4 [3] codes in order to predict the dose rates on the cask surfaces prior to the test data being made available for comparisons. The calculated dose rates were compared with the measured dose rates to evaluate the shielding codes.

Test data were taken with the REA-2023 cask containing 52 BWR spent fuel assemblies [4] as a task in the U.S. Department of Energy's Commercial Spent Fuel Management Program. The cask uses lead as the gamma-ray shielding material and a water/ethylene glycol mixture as the neutron shielding material. The shielding calculations were made prior to the test data being taken.

In a program conducted in Germany, test data were taken with the Castor-1C cask containing 16 BWR spent fuel assemblies. The cask is made of cast iron and has neutron shielding material added. The test data were not available for comparison until the calculations were completed.

CASK DESCRIPTIONS

REA-2023 Cask

The REA-2023 cask has a cylindrical shape with a cylindrical cavity. The primary gamma-ray shield is lead. The structural material is stainless steel which also provides gamma-ray shielding. The neutron shield is attached to the outside surface of the cask body. It consists of a mixture of water and ethylene glycol. On the ends of the cask, lead and stainless steel serve as the neutron shield since there is no hydrogenous material in these locations.

The cavity of the cask contains stainless steel tubes - one per assembly. It is designed to hold 52 BWR assemblies or 28 PWR assemblies (without consolidation). The cavity also contains copper to enhance conduction of heat to the surface.

The cask was loaded with 52 BWR spent fuel assemblies from the Cooper Station. The assembly exposures ranged from 25,344 MWD/MTU to 28,048 MWD/MTU. The time interval between reactor discharge and the start of performance tests was 863 days for 36 assemblies and 1259 days for 16 assemblies.

Castor-1C Cask

The Castor-1C cask is made of cast iron and has a square shape with rounded corners. The iron serves as the shielding for gamma-rays. Neutrons are shielded with polyethylene. Moderator tubes are contained within the cask body in the radial direction and moderator disks are located in the axial directions. Axial fins are located on the surface of the cask to aid in dissipating the heat to the atmosphere.

The cavity of the cask is square with rounded corners. It contains plates of stainless steel configured to form locations for the fuel assemblies on a square array. It is designed to hold 16 BWR assemblies.

The cask was loaded with 16 spent fuel assemblies from the Wuergassen Station. The assembly exposures ranged from 27,200 MWD/MTU to 28,500 MWD/MTU. The elapsed time between reactor discharge and start of performance testing was 434 days.

ANALYTICAL METHODS

Codes and Libraries

The QAD-CG code was used to calculate primary gamma-ray dose rates on the surface of each cask. Gamma-ray penetrations through various shielding configurations are calculated using the point-kernel method. Combinatorial geometry subroutines permit accurate descriptions of the casks. From the distances through the shielding regions and the attenuating characteristics of the shielding materials, geometric attenuation and material attenuation are determined.

The DOT-4 code was used to calculate neutron and secondary gamma-ray dose rates on the surface of each cask. Neutron and photon particle fluxes are calculated using the method of discrete ordinates to solve the Boltzmann transport equation. Each cask was modeled with R-Z geometry. The DLC-85 coupled neutron/photon library [5] with P-3 cross sections was used for the analyses. The neutron cross sections are represented in 22 energy groups and the photon cross sections are represented in 21 energy groups.

Cask Models

Detailed cask models were made for the QAD-CG calculations. Within each fuel assembly, the fuel rods were homogenized with the space between the rods. The end fitting, plenum, tie plate, and handle regions were also homogenized. These regions were represented explicitly in the models. The cooling fins on the Castor-1C cask were not modeled because the dose rates were measured in the valley between the fins.

The cask models made for the DOT-4 calculations were more approximate because of the code geometry restriction. In the cavity, the fuel assemblies were homogenized with the structural material of the basket. The polyethylene neutron moderator tubes in the Castor-1C cask were homogenized with iron into an annulus. The surface of the Castor-1C cask was cylindricized. The neutron shield on the REA-2023 cask is compartmentalized, so there is a possibility that the lowest compartment is not full of moderator material. The assumption was made that it was empty.

Neutron and photon source terms for the fuel were based on ORIGEN2 [6] calculations. The values are given in Table I. Spatial distribution of the source terms was determined using reactor operating data and reactor core-follow-analyses.

TABLE I

Source Terms for the Fuel

Source Type	REA-2023	Castor-1C
Neutron, n/sec	1.85 +9	8.41 +8
Gamma-Ray, photons/sec. above 1 MeV	2.17 +15	1.63 +15

In addition to the gamma rays from the fuel, there were gamma rays produced in the stainless steel and Inconel structural materials because of the presence of cobalt. During irradiation, neutron captures by Co-59 produce Co-60 which has a half-life of 5.272 years. Each Co-60 decay results in two photons, one with an energy of 1.332 MeV and the other with an energy of 1.173 MeV. The Co-60 activity was calculated with XSDRN [7] by modeling the fuel and the regions above and below the fuel as slab regions. The photon source terms were calculated from the activations taking into account decay during irradiation and during the time from discharge to start of cask performance tests. Values of the source terms are given in Table II. Axial distribution of the source terms was also based on the XSDRN calculations.

TABLE II

Photon Source Terms Due to Co-59 Activations

Region	Source, photons/sec REA-2023	Castor-1C
End Fitting	6.19 +13	1.02 +13
Plenum	2.14 +14	1.59 +14
Tie Plate	4.07 +13	6.18 +13
Handle	1.24 +13	1.46 +13

PREDICTIONS COMPARED TO MEASUREMENTS

Neutron Dose Rates

Calculated dose rates on the top, side, and bottom of the REA-2023 cask are compared to test data in Figs. 1-3. Calculated dose rates agree quite well with GE data directly above the fuel, but are a factor of 2 higher than the PNL data. At the edge of the cask, calculated dose rates are in good agreement with the PNL data, but are a factor of 4 lower than the GE data.

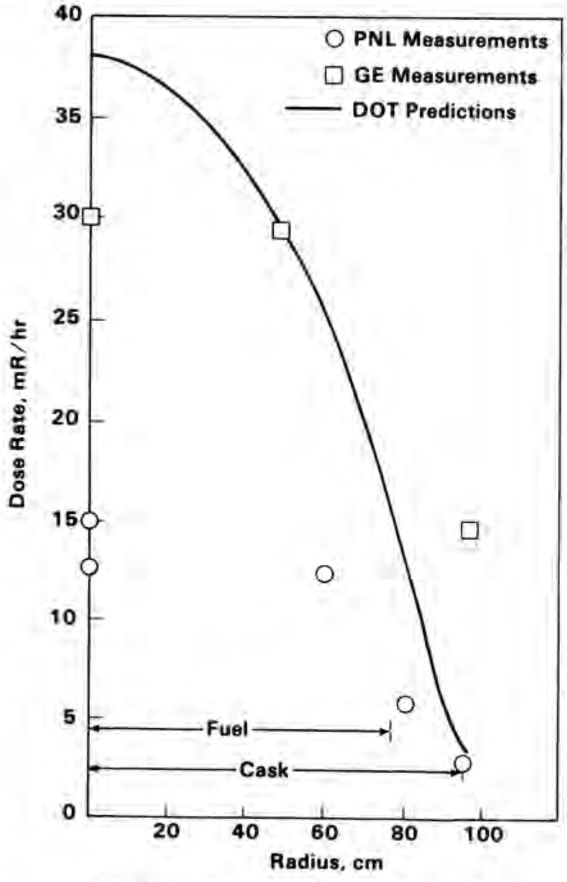

Fig. 1. Neutron Dose Rates on Top of the REA-2023 Cask

On the side of the REA-2023 cask, the dose rate peaks just above and just below the neutron shield. The calculated dose-rate peaks are a factor of 3 higher than the test data. Over the length of the neutron shield, the calculated dose rates are slightly lower than the data. The dose-rate peak at a height of 40 cm validates the assumption that there is no neutron shielding material in the bottom compartment.

On the bottom of the REA-2023 cask, the calculated dose rates are a factor of 4 higher than the test data. The bottom center of the cask is the position of maximum dose rate.

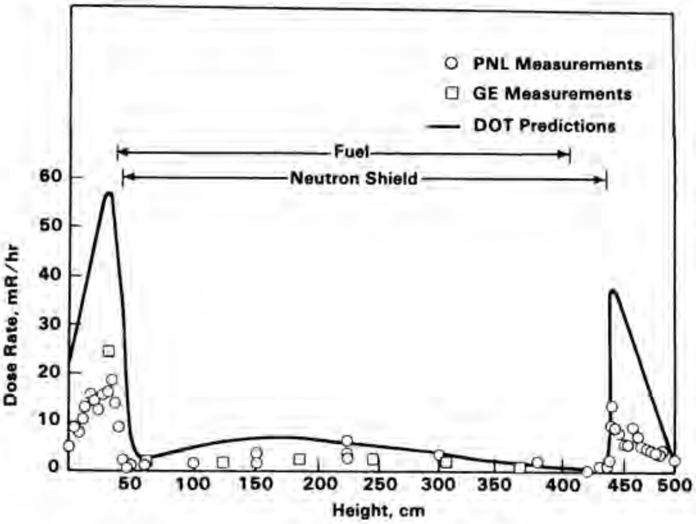

Fig. 2. Neutron Dose Rates on Side of the REA-2023 Cask

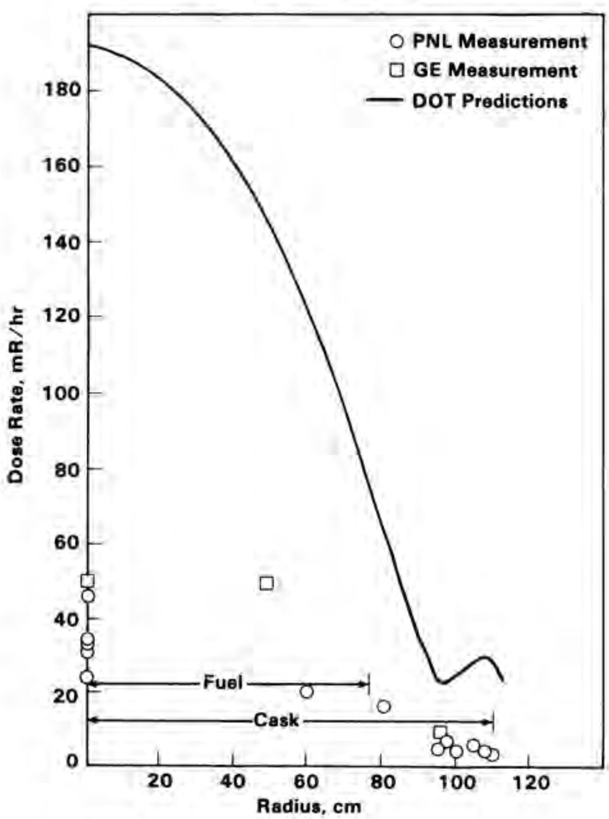

Fig. 3. Neutron Dose Rates on Bottom of the REA-2023 Cask

Calculated dose rates on the side of the Castor-1C cask are compared to test data in Fig. 4. Calculated values are a factor of 4 higher than measured values. This is consistent with the comparisons made for the REA-2023 cask where there is no neutron shield. However, it is inconsistent for the side of the REA-2023 cask where there is a neutron shield. The geometrical approximation made in modelling the Castor-1C cask may be cause for significant discrepancy between calculated and measured dose rates.

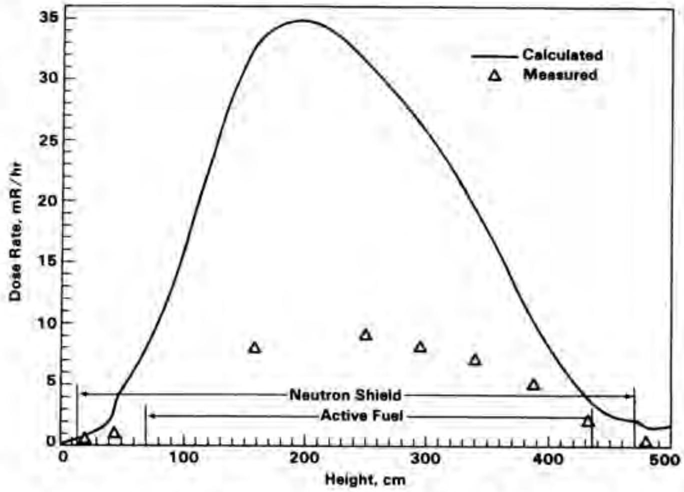

Fig. 4. Comparisons of Predicted and Measured Neutron Dose Rates on Side of the Castor-1C Cask

Gamma-Ray Dose Rates

Calculated dose rates on the top, side, and bottom of the REA-2023 cask are compared to test data in Figs. 5-7. The dose rates shown in Fig. 5 are directly above the fuel assemblies on the cask lid. The calculated values agree with the measured values for the edge assemblies, but are 50-70 percent high for the internal assemblies. The overall comparisons for the top of the cask are shown on Fig. 6. The dose-rate peak at 80 cm radius, just beyond the lead shield in the cask lid, is underpredicted by a factor of 4.

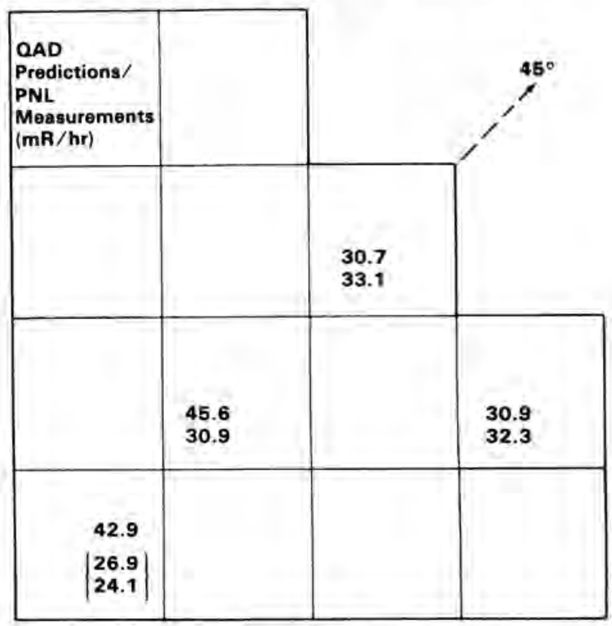

Fig. 5. Gamma-Ray Dose Rates (mR/hr) on Top of the REA-2023 Cask

On the side of the REA-2023 cask, the dose rate peaks above and below the neutron shield. The peaks are underpredicted by a factor of 2 to 3. The underpredicted dose-rate peaks could be due to too low of a Co-59 content assumed for the end fitting.

plenum, tie plate, and/or handle of each fuel assembly. Along the neutron shield the dose rates are overpredicted by 40 percent. About 60 percent of the calculated dose rate on the neutron shield is due to secondary gamma rays.

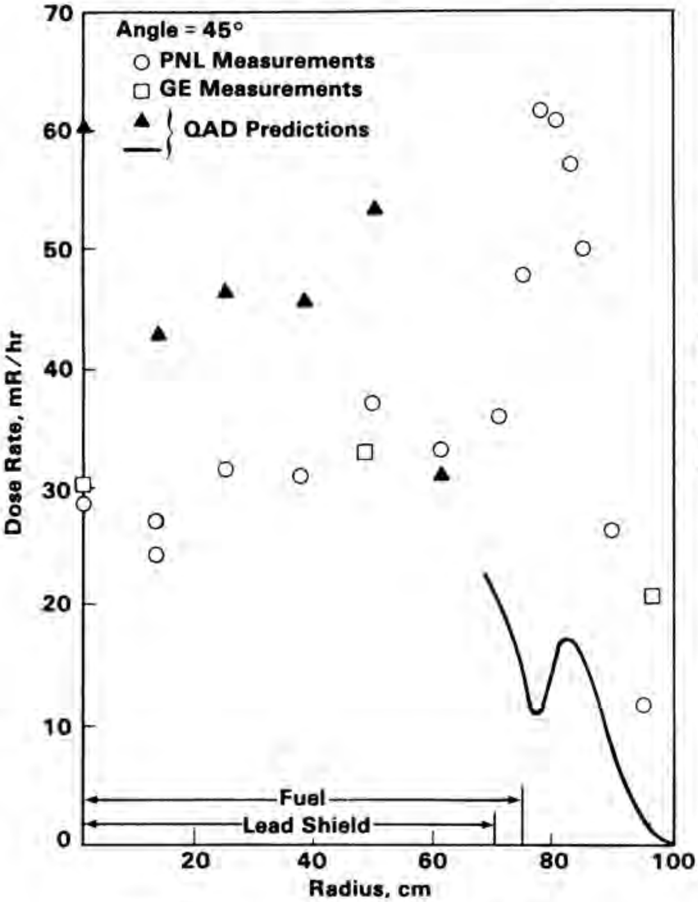

Fig. 6. Gamma-Ray Dose Rates on Top of the REA-2023 Cask

On the bottom of the REA-2023 cask, calculated dose rates were compared to test data for radii of 0.0 and 61.1 cm. The calculated centerline dose rate of 72 mR/hr. agrees with measured values of 70 and 68 mR/hr. At a radius of 61.1 cm the calculated dose rate of 37 mR/hr. is a factor of 2 lower than the measured values.

Calculated dose rates on the side of the Castor-1C cask are compared to test data on Fig. 8. The calculated values are a factor of 2 higher than the measured values. There is no significant contribution to the dose rate from secondary gamma-rays.

CONCLUSIONS

The QAD-CG code gave satisfactory overall agreement with gamma-ray radiation dose rates measured on the REA-2023 cask. However, the dose-rate peaks were underpredicted. This is a limitation of the point-kernel method. On the Castor-1C cask the QAD code was conservative; i.e., it overpredicted the dose rates.

A major contribution to the gamma-ray dose rate on the top and bottom of the cask is the decay of Co-60. Thus, the Co-59 content in the end fitting, plenum, tie plate, and handle needs to be known accurately if the source term is to be calculated. In addition, activation of the Co-59 needs to be calculated accurately.

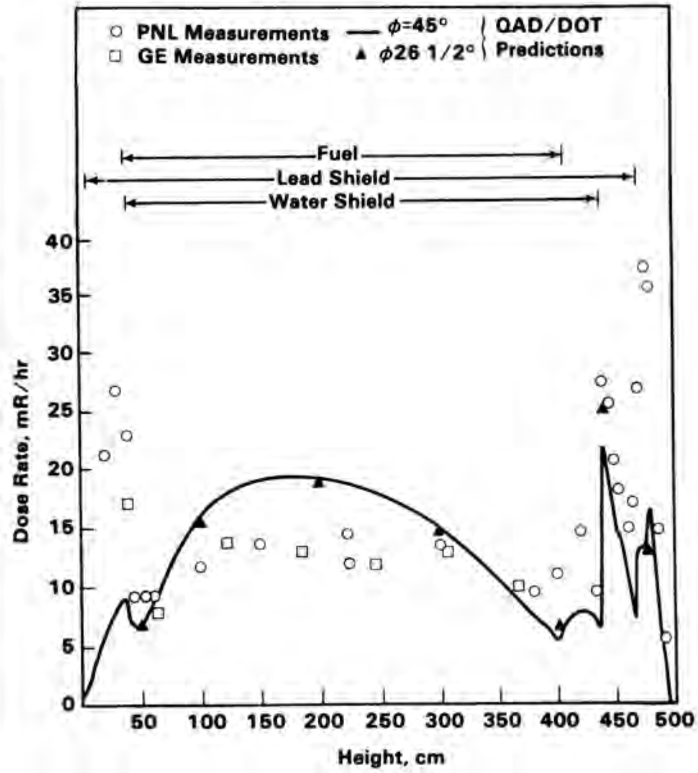

Fig. 7. Gamma-Ray Dose Rates on Side of the REA-2023 Cask

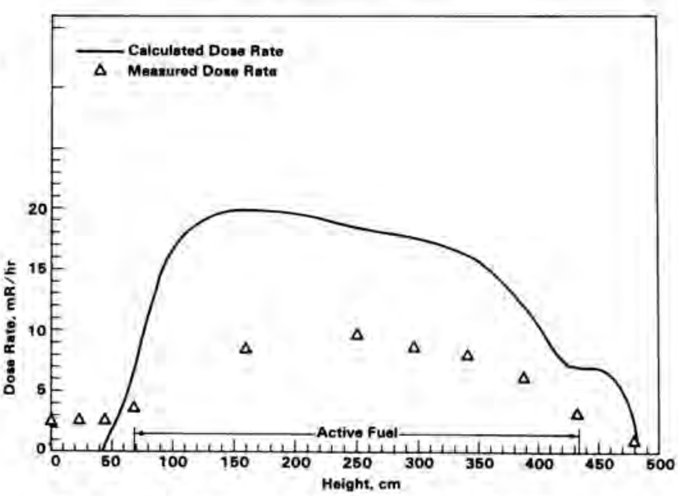

Fig. 8. Comparison of Predicted to Measured Gamma-Ray Dose Rates on the Castor-IC Cask

The contribution to the dose rate from secondary gamma-rays can be significant. The neutron shield is the outer-most part of the REA-2023 cask, so some of the secondary gamma-rays are not shielded. Secondary gamma-rays did not contribute significantly to the dose rates on the Castor-1C cask and the top and bottom of the REA-2023 cask.

The DOT-4 code is conservative in predicting neutron radiation dose rates on the cask surfaces. Calculated values are a factor of 2 to 4 higher than measured values. The high values could be due to the neutron source strength being too high. Measurements of the neutron source strength should be made in order to validate the ORIGEN2 calculation.

The QAD-CG and DOT-4 codes should be evaluated/benchmarked on other casks. Cask designs are quite complex, so there may be characteristics in other casks which were not important for the REA-2023 and Castor-1C casks.

An independent check on methodologies could be made with a Monte Carlo calculation. Both the REA-2023 cask and the Castor-1C casks should be analyzed with a Monte Carlo code.

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