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A simulation study of the spent nuclear fuel cask condition evaluation using high energy X-ray computed tomography

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ABSTRACT

The dry cask storage time could be much longer (> 60 years) for the spent nuclear fuels before final disposition in the United States. The casks have multiple internal components that are designed to provide structural integrity during storage and, in some cases, during transportation. The long-term internal stability of the internals and spent fuel and their cladding is important to maintain the sub-criticality of the fissile materials in the casks. In this study, we propose to develop a high-energy X-ray CT system to examine the integrity of casks and their inner components. With careful system design and advanced image reconstruction techniques, we estimate that a sub-centimeter spatial resolution can be achieved through the simulation study. A complete three-dimension "anatomical" picture of the cask and its inner components can be obtained with a reasonable scanning time.

1. Introduction

As the Yucca Mountain repository project was canceled in 2012, the United States currently does not have a designated disposal site for spent nuclear fuel (SNF). The nation, therefore, faces the prospect of much longer times (> 60 years) of dry cask storage for the spent fuels before final disposition [1]. Starting in 1985, dry casks for SNF have been in use to meet the shortage of wet storage facilities. By the end of 2014, there were more than 1500 dry casks in use [1].

There are many types and designs of SNF casks and containers currently in storage in the United States at various nuclear power plant sites. Designs of the dry casks are divided into two major types: welded canister-based systems and direct-loaded casks. The direct-loaded casks do not require a transfer cask to be moved to a storage site. In these systems, the SNF assemblies are placed in a basket that is an integral part of the storage cask, which is typically sealed using a bolted lid with redundant seals. In contrast, in the canister-based systems, the SNF assemblies are placed in a thin-walled (typically 12.5 mm or 0.5 in. thick) stainless or carbon steel cylindrical canister that is sealed with an inner and an outer welded lid. The canister is placed in either a cylindrical concrete and steel overpack or a concrete vault-type storage module. The storage module or overpack protects the canister against external natural phenomena and man-made events. The overpack or module is closed with a bolted lid or door. The canisters are typically designed to be dual-purpose; they can be stored or transported if they are placed in suitable storage or a transportation overpack.

The inventory of spent fuel in these casks is large and with varying burn-up rates and out-of-reactor times. The casks have multiple internal components that are designed to provide structural integrity during storage and, in some cases, during transportation. The long-term internal stability of the internals and spent fuel and their cladding is important to maintain the sub-criticality of the fissile materials in the casks. Sensors and visual/photographic inspection are currently in use where aging effects (such as cracks) can be examined at a reasonable scale on concrete or metal components. The technology becomes limited when the internal layered and inaccessible components with different materials and varying gaps between the layers are encountered.

This challenging problem could be solved by using the X-ray computed tomography (CT) technique. Since its introduction in 1973 [2], X-ray CT has established itself as a primary diagnostic imaging modality in the medical field. It is estimated that more than 80 million CT examinations were performed in 2007 in the U.S. [3], up from 3 million in 1980 [4]. X-ray CT is also used extensively in industrial NDE tasks, such as part verification, void, crack, and defect detection, etc. [5–7]. To tackle this challenging problem, we propose to develop a high-energy X-ray CT system to examine the integrity of casks and their inner components. The high-energy X-ray CT system is composed of an X-ray source from a 6 MV linear accelerator (Linac) and a detection system which can simultaneously rotate around the cask. With careful system design

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and advanced image reconstruction techniques, which will be illustrated in following sections, we estimate that a sub-centimeter spatial resolution can be achieved. A complete three-dimension (3D) "anatomical" picture of the cask and its inner components can be obtained.

2. Method

2.1. Overall concept

The overall concept is shown in Fig. 1. A high-energy X-ray CT system is configured by combining an X-ray transmission imaging system and a rotation system. The X-ray transmission imaging system includes an external high-energy X-ray source, a post-object collimator, a scintillator-based detector array, and a data acquisition system (DAS). A basic requirement of a tomographic measurement is the ability to record the X-ray photons at a large number of positions around the cask. At each positon, the detector array is used for collecting information about the X-ray photon flux. Here, the tomographic measurement is performed at a selected axial level of the cask. The cask is stationary and the X-ray source and detector array move around the cask a full 360 degrees, with a positioning instrument. Here, we propose to construct a fan-beam CT system, rather than a cone-beam CT (CBCT) system, for the following reasons: (1) CBCT requires a large 2D detector, which is much more expensive than a linear array detector; (2) Image artifacts caused by scatter are more severe in CBCT; and (3) Exact image reconstruction algorithms for CBCT are not mature [8–11].

2.2. Energy selection

The design of the X-ray CT system is motivated by the fact that a high-energy X-ray can penetrate a cask and form a radiographic image. Although fast neutrons penetrate a metal cask and its inner components more easily than high-energy X-rays do, nuclear fission caused by fast and thermalized neutrons make them unsuitable for this task. High-energy X-rays can also cause photonuclear reactions, such as (γ, n) and fission reactions, if the energy is above 6 MeV except for very light materials [12,13]. Therefore, we should limit our X-ray energy at a level below 6 MeV. Further analysis indicates that uranium and plutonium, which are the major elements in SNF, have the lowest mass attenuation coefficients at 4 MeV. As shown in Fig. 2, the mass attenuation coefficients of uranium are very close to those of plutonium due to their similar atomic numbers. Iron and concrete have similar mass attenuation coefficients and are 1.3 times less than that of uranium at 4 MeV.

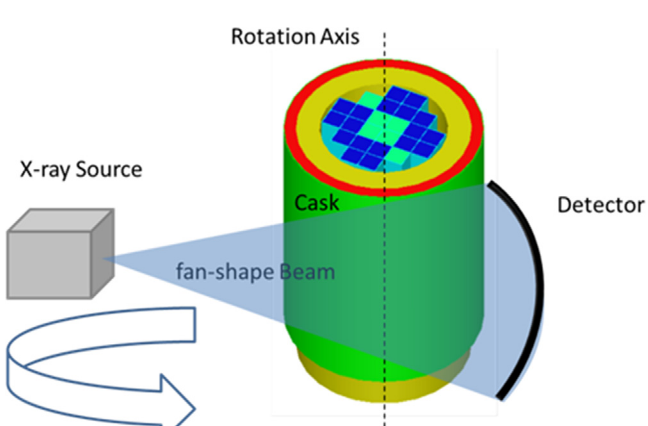

Fig. 1. Schematic drawing of the proposed CT system.

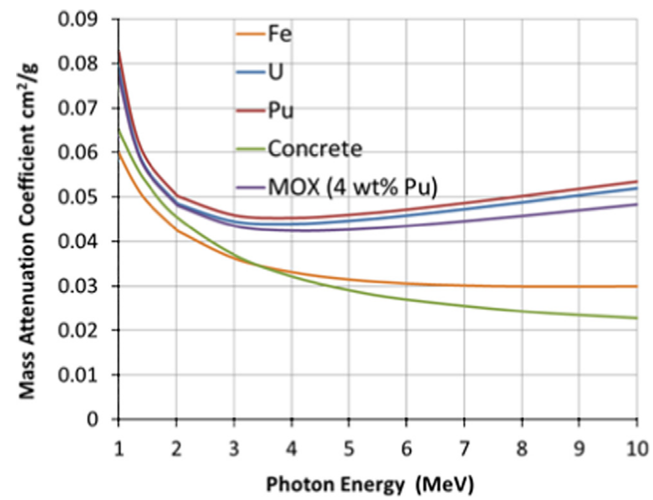

Fig. 2. Mass attenuation coefficients of several major elements in casks and spent fuel.

The major composition of SNF is a mix oxide of uranium-plutonium (MOX). Without loss of generality, the mass attenuation coefficients of a MOX fuel with 4 wt% plutonium are also plotted in Fig. 2. That figure shows that the mass attenuation coefficients of MOX are similar to those of uranium and plutonium.

To more accurately estimate optimum photon energy, the photon optical thickness, μx, (i.e., number of mean-free-paths) should be evaluated. The maximum optical thicknesses of the major materials should be calculated, including concrete, iron, and MOX fuel pellets. Total optical thickness can also be obtained by computing the sum of all individual optical thicknesses. Fig. 3 shows the photon optical thickness of two different cask designs: the canister based HI-STORM100 (Holtec International), and the non-canister based metal cask TN-24 (Areva-Transnuclear). As shown in Fig. 3, the total optical thicknesses are similar for these two different designs, as expected. The lowest optical thickness is around 5 MeV, but the values are very close to an energy range of 4–6 MeV.

2.3. CT scan and image reconstruction under ideal conditions

Once the optimum photon energy is determined, the feasibility of using a high-energy X-ray to generate an "anatomical" picture of the cask and its inner components was verified by a deterministic simulation based on the ray-tracing technique [14,15]. The X-rays is a Bremsstrahlung radiation from a Linac with a continuous energy spectrum. A 6 MV Linac produces more photons at 4 MeV than the number of photons at 6 MeV. Therefore, to simplify the simulation process, a CT scan of a cask phantom was simulated using a monoenergetic photon beam at 4 MeV. A phantom mimicking Areva-Transnucler's TN-24 metal cask was constructed numerically with the dimensions and materials specified in Table 1. Assuming that the fan angle of the X-ray beam and the detector array behind the cask are large enough to cover the whole cask, an ideal case was considered first while statistical noise and scattering are ignored. In the simulation, the source-to-object distance (SOD) is 1.9-m, and the source-to-detector distance (SDD) is 3.2-m, as shown in Fig. 4. The detector was modeled as an ideal detector with a pixel size of 1-mm which results in a spatial resolution of 0.6-mm at the isocenter if enough number of views per rotation was obtained.