Design and Construction of a High Energy X-Ray R&D Facility, and the Development and Optimization of Real Time Radioisotopic Characterization of Remote Handled Waste at MeV Energies.

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ABSTRACT

Real time radioscopy (RTR) is used extensively for the non-destructive examination (NDE) modality in the characterization of waste using x-ray energies of up to 450keV. The majority of contact handled waste in drums and boxes such as the standard waste box (SWB) and the B25 box, can be penetrated by x-rays at these energies. However, the shielding within remote handled (RH) waste packages, the high density of many waste matrices, and the large size of other waste packages containing both remote handled and contact handled waste, require x-rays at MeV energies, in order to penetrate the waste matrices to enable x-ray images to be made. To develop, optimize and validate the performance of high energy x-ray imaging systems, requires a shielded vault complete with remote handling equipment for the manipulation of the x-ray generating equipment, the imaging chain, and the surrogate waste being inspected. This paper describes the design and construction of a High Energy X-Ray, R&D facility, and the results of the initial program of work to optimize systems for the real time inspection of RH waste.

INTRODUCTION

Development of linear accelerators has been driven mainly by the large medical market, however, industrial linear accelerators have been available for many years and are a mature and reliable generator of x-rays at MeV energies. Consideration was given to the range of x-ray energies likely to be required for deployed characterization systems. Higher energies enable larger and more dense objects to be imaged, but require greater, more expensive shielding of the x-ray vault. To enable penetration of items of up to the equivalent of 350mm of steel (13.8 inches) a vault has been designed to safely accommodate x-ray energies of 9MeV.

The internal dimensions of the vault are 12m x 7.5m x 4.8m (40' x 25' x 16') high, making the vault large enough to enable a wide range of objects to be imaged, including items as large as a 6m x 2.4m x 2.4m (20' x 8' x 8') "sea-land" container. Heavy duty mechanical handling equipment, that is servo controlled for repeatability and positional accuracy, is required to enable the object being inspected, the linear accelerator and the imaging chain to be moved during the inspection process.

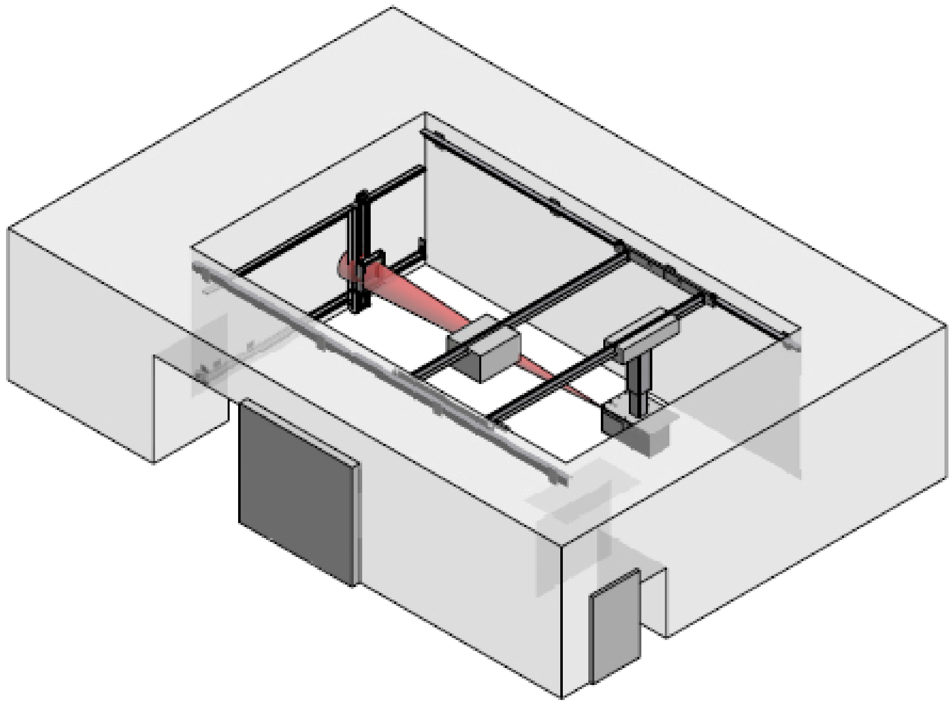

Fig 1. Isometric drawing of the high energy vault

HIGH ENERGY VAULT DESIGN AND BUILD

The high energy vault is required to be shielded to be fully compliant with ANSI.N43.3, and classified as an "exempt shielded" facility for x-ray energies up to 9MeV. High integrity safety interlocks, audible and visual alarms, and surveillance systems are also a requirement of this specification. The "exempt shielded" classification enables the team of operators, engineers and research scientists to have unrestricted working in the operations control room while high energy x-rays are being generated in the vault.

For x-ray energies of 9MeV, substantial wall shielding is needed. The wall that the x-ray beam is directed towards is termed the primary wall. In this case the shielding calculations determined that to meet the primary wall shielding requirements of ANSI.N43.3, an 3.45 m (11 feet 6 inches) thick wall of concrete, or concrete equivalent material was needed. The side and rear walls would not be subjected to the primary x-ray beam, but would be required to shield against secondary radiation and leakage radiation from the linear accelerator. The shielding calculations determined that these walls be 2.4 m (8 feet) of concrete, or concrete equivalent material.

All shield walls were constructed by casting 30.5 cm (12 inch) thick inner and outer walls, 2.85 m (9 feet 6 inches) apart for the primary wall, and 6 feet apart for the other walls, after which the cavity was filled with compacted gravel composite. The ceiling and floors were required to be constructed of 0.9 m (3 feet) thick concrete slab. Including the foundations, walls and ceilings, almost 535.2 m^3 (700 cubic yards) of 3000 psi (21 MPa) - test concrete were used. To support the total mass of the structure, the foundation structural design required that 42 steel "I-beams" be driven down over 30 m (100 feet) in depth to the bedrock.

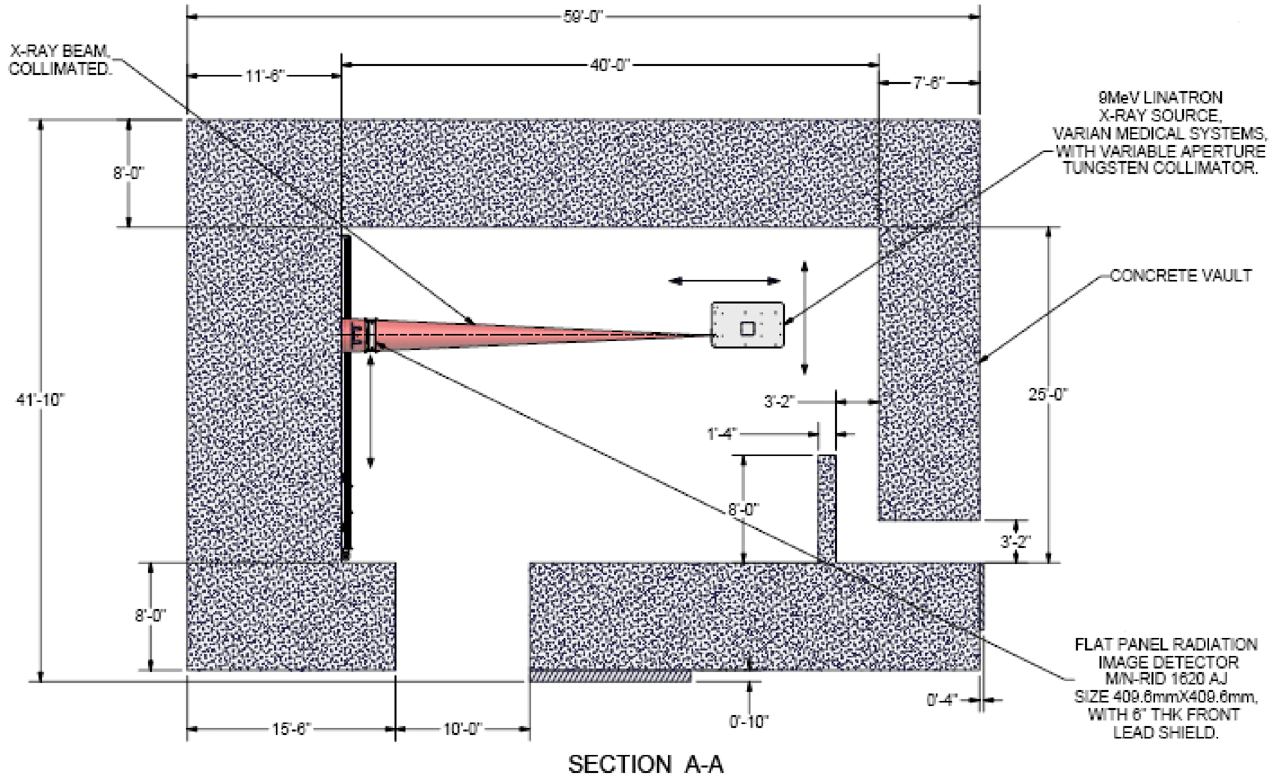

Fig 2. Plan view of the high energy vault

The entrance to the vault for the large items to be inspected is 3 m (10 feet) wide by 3 m (10 feet) high. A shield door of 3.6 m (12 feet) wide by 3.6 m (12 feet) high, set into a floor trench overlaps this opening on all four sides. The shield door comprises a 12 inch thick steel frame filled with lead blocks, and weighs almost 36 Mg (80,000lbs). A personnel entry door is situated in the rear wall and is shielded by a concrete "labyrinth" wall which reduces the thickness of the door. This door is 1.5 m (5 feet) wide by 2.1 m (7 feet) high, is 15 cm (6 inches) thick, constructed of a steel frame filled with lead blocks, and weighs almost 6.75 Mg (15,000lbs). Both doors are operated by electrical motors and have high integrity safety interlocks for protection of personnel and equipment when the doors are in motion. A separate high integrity interlock system will shut off and prevent x-ray generation as soon as either door starts to open.

DEVELOPMENT PLANS FOR X-RAY CHARACTERIZATION OF NUCLEAR WASTE

Nuclear waste characterization by x-ray has required a broad imaging performance to enable the identification of a range of prohibited items, including such requirements as the ability to identify a hole of 0.32 cm (1/8th inch) in a small aerosol canister, and the ability to see a moving liquid meniscus which indicates the presence of free liquid, in a waste matrix that can vary from low density materials such as paper and plastics, to high density materials such as steel plant items and tools. To achieve this at the higher x-ray energies requires the development of reliable imaging chains comprising detectors, signal processing electronics and image acquisition software. Not only are such imaging chains required to have a high special resolution and high contrast sensitivity at the higher energies, but also they must be capable of functioning in real time. It is the real time feature which enables the operator to see the moving liquid meniscus when a waste container is jogged.

The initial phase of the development program in the High Energy vault will assess the effectiveness of currently available high energy area detectors when they are operated in real time mode.

Imaging performance is also a function of x-ray photons which have passed straight through the object being inspected to the detector (the signal), and detected x-ray photons which are the result of secondary radiation from other sources (the noise). A configuration of techniques such as primary beam collimation to irradiate only the object being inspected, thus reducing or eliminating secondary radiation from objects such as the mechanical system, will be tested. Shielding of the detector and the detector "grids" will be evaluated. A detector "grid" is a device that attenuates x-ray photons other than those directly from the x-ray source as they enter the detector.

A more radical approach to the identification of liquids and other such materials is most likely to be achievable by the use of dual energy x-ray beams to automatically differentiate materials by density and atomic number (Z-number). Where current nuclear waste characterization systems use single-energy X-rays which contain only shape and relative density information about the contents of a container, dual energy technology employs dual-energy X-rays that provide information about not only the shape and relative densities of the items in the waste container but also the atomic number (Z-number) and absolute densities of the contents of the waste container. Using this information enables the differentiation of organic and inorganic materials, a capability that greatly facilitates the inspection process. This material property information will be used to identify with a high-degree of confidence the specific materials in the waste matrix.

The development program will use dual-energy systems that will generate two temporally interlaced x-ray beams, one at ~5MeV and the other at ~9MeV. The interlaced beams peak at different energies and thus produce two independent x-ray images. Heavy elements in the inspected target are more effective at absorbing high energy x-rays while light elements are more effective at scattering low energy x-rays. While areas of heavy elements are dark in both views, areas of light elements are darker in the lower energy view. The interaction of x-rays with materials varies with the energy of the beam. Algorithms have already been developed that will compare the absorption of x-rays at two energies to obtain information on the effective atomic number, a unique physical property, and mass of the target material. Lighter organic materials are differentiated from heavier inorganic materials and are assigned colors according to the contents of an inspected target.

As the energies of the impinging x-rays increases, the type of interaction changes, and directly impacts the algorithms used to calculate the effective atomic number. At low energies, the absorption of x-rays varies roughly as the fifth power of the atomic number, making dual energy x-rays very effective in determining the composition of a wide range of items. At higher energies x-ray absorption is non-linear with atomic number, which makes calculation of atomic number more challenging. This will be the subject of a further development program.

CONCLUSION

The anticipated successful development of high energy x-ray inspection and characterization techniques in this High Energy facility will provide the ability to characterize RH waste, and other nuclear waste in storage configurations that are unable to be characterized by current low energy non-destructive examination techniques.

Characterization of RH waste in drums or other containers by non-destructive examination will reduce the need to open the containment and to visually examine the waste. The immediate benefits are a reduction in risk of operator dose uptake, a reduction in the generation of additional waste, and the saving of time and cost within the process.