# IMAGING THE CORE OF FUKUSHIMA REACTOR WITH MUONS

The 9.0-magnitude earthquake, followed by the vast tsunami on March 11, 2011, caused a nuclear crisis at the Fukushima Daiichi reactors. Damage of the reactor cores attracted worldwide attention to the issue of the fundamental safety of nuclear energy. The Japanese government announced a cold shutdown in December 2011, and began a new phase of cleanup and decommissioning.

However, it is difficult to plan the dismantling of the reactors without a realistic estimate of the extent of the damage to the cores and knowledge of the location of the melted fuel. Access to the reactor buildings is very limited due to high radiation fields. Los Alamos researchers have used experiments and modeling to show how muon imaging with detectors external to the reactors can enable damage assessment inside Fukushima. *Physical Review Letters*, *AIP Advances*, and the *Journal of Applied Physics* have published different aspects of this work.

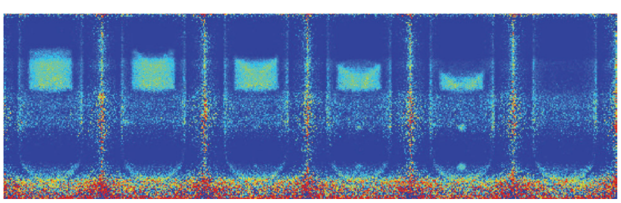
*Image from "Los Alamos, Toshiba probing Fukushima with cosmic rays," Los Alamos National Laboratory YouTube video.*

Muon imaging offers the potential to image the nuclear reactor cores without access to the cores. The method utilizes naturally occurring cosmic-ray muons to image dense objects. There are two types of muon imaging: transmission and scattering. In practical applications, muon transmission imaging often suffers from poor position resolution due to the continuous scattering along the muon path, and from poor signal-to-noise ratio due to the small detection area (typically on the order of 2 $m^2$). In addition, calculating transmission requires precise knowledge the incident muon flux that can be difficult to estimate.

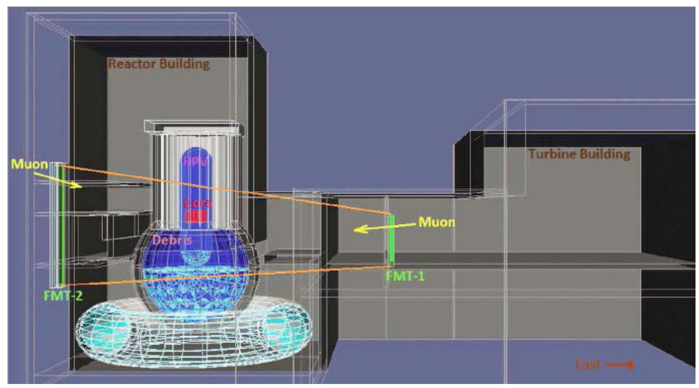
Los Alamos researchers developed a more sensitive technique, called muon scattering radiography. The scattering method uses two muon trackers to measure incoming and outgoing tracks of individual muons, where the region of interest is contained within the acceptance of the tracker pair. Combining the incoming and outgoing tracks provides better spatial resolution when compared with the transmission method where only the information from the outgoing muons, which are lower in energy and scatter more than the incident muons, is available.

The scattering method has high sensitivity to high-Z materials such as the uranium in nuclear fuel, making it useful for detecting uranium in a background of low-Z material. Laboratory scientists have applied this method to scan trailers and shipping containers for special nuclear material. Los Alamos National Laboratory in collaboration with Decision Sciences International Corporation received an R&D 100 Award for the cargo scanning application. It is also a promising technique for the International Atomic Energy Agency's nuclear safeguards and nonproliferation work.

To image Fukushima Daiichi reactors the scientists developed a new analysis, called the displacement method. For the image reconstruction, the Los Alamos method measures muon trajectories both before and after the object, giving a clearer image.



**Results of the GEANT4 simulations for Unit 2. (From left to right): The simulations were run with intact core (left), 10%-, 30%-, 50%-, 70%-melted core and no core (right). Two spherical debris of 10-cm (under 10%-melted core), 20-cm, 30-cm and 40-cm (under 70%-melted core) radii were placed in the lower region of the reactor pressure vessel.**




**Muon imaging setup for Fukushima Daiichi Unit 2. FMT-2 is installed inside a concrete radiation shield in front of the reactor building. Typical muon scattering angles are a few degrees.**

The researchers examined the feasibility of imaging the Fukushima Daiichi reactors with cosmic-ray muons to assess the damage to the reactors. Muon scattering imaging has high sensitivity for detecting uranium fuel and debris even through thick concrete walls and a reactor pressure vessel. The team made technical demonstrations using a reactor mock-up, detector radiation tests at Fukushima Daiichi, simulation studies using the CERN code GEANT, and demonstration experiments on reactors at the University of New Mexico, and are currently imaging the Toshiba Nuclear Critical Assembly reactor at Yokohama, Japan in collaboration with TEPCO (Tokyo Electric Power Company) and Toshiba.

References: "Cosmic Ray Radiography of the Damaged Cores of the Fukushima Reactors," *Physical Review Letters* **109**, 152501 (2012); "Imaging Fukushima Daiichi Reactors with Muons," *AIP Advances* **3**, 052133 (2013); "Imaging a Nuclear Reactor Using Cosmic Ray Muons," *Journal of Applied Physics* **113**, 184909 (2013).

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# LOS ALAMOS IMAGING SYSTEM GOING LIVE AT FUKUSHIMA DAIICHI

***First step toward dismantling reactors is identifying nuclear fuel's location***

By the end of 2015, a muon imaging system pioneered at Los Alamos National Laboratory will be deployed at Japan's Fukushima Daiichi power plant. The goal is to reveal the amount, condition, and location of highly radioactive nuclear fuel remaining inside the reactors, without exposing workers to the high radiation fields inside the reactor facilities.

*Courtesy of Mark Saltus, DSIC*

**The detector, mounted in horizontal mode, at the Toshiba facility in Yokohama where the detectors were assembled.**

The Los Alamos Threat Reduction team in Subatomic Physics (P-25), together with Toshiba Corporation and Decision Sciences International Corporation (DSIC), will image reactor unit No. 2 using cosmic muons.

The Los Alamos technique will provide Tokyo Electric Power Company with a "map" so it can safely remove nuclear fuel from the plant, which was severely damaged in a 2011 tsunami and earthquake, leading to concerns that molten nuclear fuel spread from the reactor core to the pressure and containment vessels.

The imaging system is being assembled at a Toshiba facility in Japan, and consists of two ~ 7m x 7m tracking detectors made of gas-filled drift tubes provided by DSIC, which are read out by Toshiba electronics. One detector will be deployed in front of the reactor building, the other on the second floor of the turbine building on the opposite side of the reactor unit. The Los Alamos team developed tracking software and recently tested it on data taken with a smaller prototype.

Muon radiography uses secondary particles called muons, generated when cosmic rays collide with upper regions of Earth's atmosphere, to create images of the objects that the particles penetrate. Los Alamos researchers, in particular, exploit muons' multiple scattering in the object of interest to obtain three-dimensional images. This imaging technique was first pioneered by Christopher Morris (P-25) more than 10 years ago.

This technology is currently deployed in locations around the world to help detect smuggled nuclear materials. The Los Alamos team is also exploring applications in nuclear safeguards, where muon tomography can be used to detect the diversion of spent fuel from dry storage casks. In addition, muon tomography is being developed for potential use in international treaty verification.

Muon tomography and development of its application at Fukushima were made possible in part through Los Alamos's Laboratory-Directed Research and Development program, which uses a small percentage of the Laboratory's overall budget to invest in new or cutting-edge research.

**Los Alamos National Laboratory Muon Radiography team members stand in front of the damaged Fukushima Daiichi reactor complex during a visit to evaluate whether Los Alamos's scattering method for cosmic-ray radiography could be used to image the location of nuclear materials within the reactor buildings.**

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