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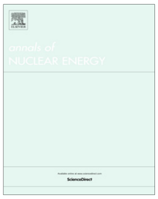

Feasibility study for detection of reactor state changes during severe accidents via external gamma radiation measurements

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ABSTRACT

The gamma radiation field outside of a nuclear reactor carries information about the coolant inventory and the nuclear fuel distribution inside the reactor pressure vessel. Hence, it may serve as an indicator for changes in the reactor internal structures, e.g. in the course of a severe accident. To study the feasibility of using external gamma radiation measurements for the detection of reactor state changes, three-dimensional Monte-Carlo simulations were performed to evaluate the vertical gamma flux distribution outside of a generic pressurized water reactor pressure vessel. The gamma flux was calculated for a reactor with different decreased coolant levels and different core melt states. The results indicate that the gamma flux is very sensitive to the reactor states. The shape and magnitude of the gamma flux distribution are unequivocally subject to the coolant levels and to the relocation of corium into the reactor lower head. Therefore, the results strongly suggest that a measurement of the external gamma radiation distribution, especially if coupled with sophisticated algorithms for state detection, should be sufficient to infer the state of the reactor during a severe accident. A simple state detection algorithm was tested to infer predefined reactor states. The results of the test showed that upon the measured gamma flux distribution the reactor state can be inferred with an approximate accuracy of 0.983.

1. Introduction

In 1979, reactor 2 of the Three Mile Island (TMI) nuclear power plant experienced a severe accident with a partial core meltdown. One of the factors that contributed to the severity of the scenario was the misinformation about the water level inside the reactor pressure vessel (RPV) due to faulty and non-redundant instrumentation (Walker, 2004). During the accident at the Fukushima Daiichi power plant in 2011, the reactors 1–3 presumably experienced a core meltdown and a possible RPV failure with subsequent relocation of corium into the containment (Tanabe, 2012; Hoshi et al., 2013). Due to the lack of appropriate instrumentation, the full extent of the meltdown is unknown up to date, which slows down the organization of future clean-up operations. In both of these accidents, information about the state of the RPV inventory, i.e. the coolant level and the extent of a possible core meltdown, would have been highly advantageous.

The experience at the TMI and Fukushima Daiichi clearly demonstrated the need for reliable instrumentation systems, which are able to provide direct and unambiguous information on the reactor core state in both normal and severe accident conditions. One possible system that can meet these requirements is based on the measurements of high-energy (several MeV) gamma radiations outside of the RPV via an axial array of gamma detectors located in or near the biological shield. The gamma emitted from the fission products and the gamma radiation produced by the neutron capture in the hydrogen and structural materials (mainly in the RPV wall) are very sensitive to the coolant inventory and the nuclear fuel distribution inside the RPV. Therefore, the shape and magnitude of the measured gamma radiation distribution outside of the RPV can be used to infer the reactor core state. In a case of a severe accident, such a system could deliver valuable information for mitigative measures.

The subject of using gamma radiation measurements for coolant level monitoring was previously studied by (De Volpi, 1984; Markoff et al., 1986; Markoff, 1987). Markoff and DeVolpi developed a simple one-dimensional transport analysis model for the Loss-of-Fluid Test (LOFT) research reactor and for the mock pressurized water reactor (mock-PWR) geometry. They evaluated the gamma detector response to the coolant voiding in the core, and validated the results by a comparison with the LOFT experimental data. The results showed that an ex-core gamma measurements system is able to respond to changes in the coolant

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inventory within the RPV. Later study by (Kodeli and Bignan, 1997) confirmed this conclusion using two-dimensional diffusion-based transport calculations. The aforementioned studies provide the incentive to better assess the feasibility of using an ex-core gamma measurements system to detect changes in coolant level as well as the relocation of corium into the lower head by using a more realistic three-dimensional geometry model. Therefore, in the present study, several three-dimensional Monte-Carlo simulations were performed to estimate the gamma flux distribution outside the RPV of a generic German PWR. The main objective of this work is to investigate whether the intensities and the shape of the gamma fluxes outside of the RPV are sufficient and suitable enough to provide meaningful information on the RPV inventory.

2. Description of the geometry and reactor state models

To assess the feasibility of using external gamma radiation measurements for the detection of reactor state changes during severe accidents, nine simplified reactor states were defined and evaluated. The reactor states were defined to represent a decreasing coolant level and a meltdown with relocation of corium into the lower head. The reactor states were modeled using the MCNP6 code (Goorley et al., 2012), and the gamma radiation flux outside of the RPV was calculated. The models were based on a generic "Vor-Konvoi"-type German PWR with 193 fuel assemblies. The reactor core has an active height of 390 cm and an average diameter of about 360 cm. The total power of the reactor is about 3900 MWt. It should be noted that sub-critical state was assumed for all the calculations. Fig. 1 shows cut-through views of the reactor model, that is, a vertical view from the reactor sump to about 1 m above the upper core edge, and a horizontal view from the fueled core to the biological shield. Additionally, the simulated potential location of the gamma ray detectors is indicted, which is between the reactor pressure vessel and the biological shield.

For the Monte-Carlo calculations, the fuel regions of the fuel elements were modeled as homogeneous cells. The fuel compositions were extracted from a generic calculation of an equilibrium core with a typical low-leakage loading. It included fuel assemblies from virtually fresh to a burnup of 60 GWd/T of UO_2. Unlike the fuel region, the foot and head regions of the fuel elements were modeled to a scale of about 1 cm to avoid simulation inaccuracies in these rather inhomogeneous regions. The same applies to the components between the core and the biological shield.

As mentioned above, nine different core states were modeled and evaluated. The first state (state I) represents a completely intact reactor after scram (completely flooded core), while the eight remained states represents a reactor with an accident scenario. Fig. 2 illustrates the accident scenario states: four states mimicking a decreasing coolant level and anther four states mimicking material relocation from the core into the lower plenum. For the coolant level decrease models, the water above a certain height level is removed. The water level is at the top of the active core for the first coolant level decrease model (C_{top}), at half height of the core for the second one (C_{mid}), and at the bottom of the active zone for the third one (C_{bot}). In the fourth coolant level decrease model (C_{dry}), the water is completely removed from the reactor pressure vessel. For the core melt models, the material was virtually removed from the center of the core so that a cylindrical cavity emerged in its center at the top. The removed material was then adequately inserted as corium into the lower head. The volume of the corium layer was adjusted using a typical mixture density of $\rho = 8.0\ g/cm^3$ (Heuss, 2006; Tusheva et al., 2015). The four states M_2, M_5, M_{10} and M_{20} have an amount of material relocated corresponding to 2%, 5%, 10% and 20% of the total core inventory, respectively.

3. Computational tools and analysis methodology

Monte-Carlo simulations were carried out to evaluate the gamma radiation flux outside of the RPV for each of the above mention core state models using the MCNP6 code. All the core state models were based on one standard model of the intact reactor state. The accident state models were created by the removal and addition of the respective material volumes from the intact reactor state model. In that way, errors due to accidentally different geometries were avoided. The reactor model takes advantage of symmetry by representing a quarter of the reactor in the radial direction. As mentioned above, the model contains all relevant components in the vicinity of the core and extends to the outside of the biological shield.

To estimate the gamma radiation source distribution to be used for the Monte-Carlo calculations, relevant fuel compositions have been determined via a generic equilibrium core calculation with a common low-leakage loading pattern. The accident scenarios were conservatively postulated to occur at the beginning of the cycle with fresh fuel, when the gamma radiation field is still weak and thus less favorable for a detection system. The corresponding data was provided by E.ON Kernkraft GmbH. Based on these material compositions, the source term (gamma radiation spectra as well as absolute intensities) was calculated for each fuel assembly after one hour of decay using the FISPACT inventory code, which is part of the European Activation System EASY (Forrest et al., 2005; Forrest, 2007a, b). The time of one hour was chosen because this is roughly the time in many accident scenarios with emergency core cooling failure where the water level drops below the upper core edge (Heuss, 2006). Preliminary calculations indicated that gamma radiation from activated construction materials does not have to be considered because of the small values (<10% of total radiation at the detectors). Therefore, the activation of the components was calculated after 34 years of operation. For the core meltdown states, the activation of the components was calculated assuming that the corium inside the lower plenum is a homogeneous material mixture of the material missing from the core with homogeneous emission characteristics. Here, neither an additional decay time nor additional gamma radiation sources, such as the radiation emitted by activated reactor components, were taken into account.

The gamma radiation fluence strongly decreases along the transport to the detectors. Therefore, the use of variance reducing techniques is beneficial. Geometry splitting/Russian roulette by using of cell weights is one of the oldest, most widely used and effective techniques in Monte Carlo simulations. The cell weights were determined during preliminary calculations and were used practically for all calculations. Thus, it was possible to obtain good statistical values at reasonable calculation times.

The gamma radiation flux was tallied at the inner surface of the biological shield, and averaged over the whole of the model in the azimuthal direction, with a vertical resolution of 30 cm and a spectral resolution with 12 energy bins between 0.05 and 4.0 MeV, yielding twenty estimated axial detector values per simulation. It should be noted that in this stage the background radiation emitted by the activated RPV and other reactor components was taken into account. All the estimated gamma radiation fluxes were converged with statistical uncertainties below 5%. The calculations were performed on a Linux cluster within a computing time of about six hours and with 10^9 source particles.

4. Results and discussion

As mentioned above, the gamma radiation flux was calculated at the inner surface of the reactor biological shield. For an easier visual demonstration of the feasibility of using external gamma