Abstract

Fusion tokamak reactors might become a valuable source of energy for the future if experiments prove that commercial operation is possible under profitable conditions. Safety considerations would also play an important role in future decisions regarding fusion power. Abnormal events can lead to radioactive releases to the environment, and those have to be addressed by designing a confinement strategy. To ensure a defense-in-depth approach, several confinement barriers surrounding the process systems are to be employed.

The objective of the present research project is to develop a methodology using probabilistic risk assessment techniques for evaluating the performance of the design of the radiological confinement barriers of tokamak fusion reactors within the context of a limited allowable risk. Thus, accident sequence models are developed for each of the confinement barriers whose performance should be evaluated. The undesired consequences at each step are radioactive releases from the corresponding confinement barrier.

The first step is to describe the conceivable accident sequences that might lead to failure of the first confinement barrier through various failure modes. Each accident sequence is characterized by a pair of parameters consisting of an annual frequency and a radioactive release. The second step is to continue the branches where the first confinement barrier has failed with accident sequences for the second confinement barrier. These latter accident sequences will end with events expressed in terms of the second confinement barrier failure modes.

A new approach is used in this work for the development of the accident sequences. Combined influence diagram/event tree models are developed instead of the reliance on event trees alone, which is the traditional probabilistic risk assessment tool. This way conditional events and probabilities can be explicitly defined in the influence diagram, which also contains all the frequency, probability and consequence data, while the time sequence is represented in the event tree. Thus, more compact system models are obtained, rather than the usual very large event trees.

A challenge was to find an appropriate form to express the results of the accident sequences analysis for each barrier in a meaningful way that allows comparison of the results to a design requirement for limiting the releases. A complementary cumulative frequency of radioactive releases is proposed, because it takes into considerations important criteria such as: the overall plant risk, the rate at which accident frequency decreases with increasing accident consequences (risk aversion attitude), and the impact of high frequency-low consequence accidents from a public policy stand point.

The International Thermonuclear Experimental Reactor (ITER) was used as a reference design. The Design Description Documents as published in June 1995 contain the confinement strategy analyzed in this project. The current ITER design requirements set radioactive release and dose limits for individual event sequences grouped in categories by frequency. We argue that this form presents drawbacks such as not considering a limit on the plant overall risk, and the difficulty of accounting for event uncertainties in both frequency and consequence. Thus, an analytical form for a limit line is derived having the form of a complementary cumulative frequency of radioactive releases to the environment satisfying the three criteria mentioned above.

After building and analyzing the models for the first and second confinement barriers of ITER, we concluded that a third confinement barrier may be required in order to comply with restrictive design limits on radioactive releases, particularly for events with large uncertainties. However, confidence in this result needs to be gained by improving the failure probability data. A database containing the failure probabilities (conditional or independent) corresponding to various systems failure modes was developed based on the available references, but a comprehensive fault tree analysis was not performed as part of this work.

Finally, a decision model using multi-attribute utility function theory was constructed to help with choosing the type of the ITER tokamak building (the third barrier). Besides safety of the design, other attributes such as construction cost, project completion time, public attitude and technical feasibility were considered. The decision model allows for performing sensitivity analysis on relevant parameters, and for design features of new options for the ITER tokamak building.