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Original Article

Development of an Accident Sequence Precursor Methodology and its Application to Significant Accident Precursors

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ABSTRACT

The systematic management of plant risk is crucial for enhancing the safety of nuclear power plants and for designing new nuclear power plants. Accident sequence precursor (ASP) analysis may be able to provide risk significance of operational experience by using probabilistic risk assessment to evaluate an operational event quantitatively in terms of its impact on core damage. In this study, an ASP methodology for two operation mode, full power and low power/shutdown operation, has been developed and applied to significant accident precursors that may occur during the operation of nuclear power plants. Two operational events, loss of feedwater and steam generator tube rupture, are identified as ASPs. Therefore, the ASP methodology developed in this study may contribute to identifying plant risk significance as well as to enhancing the safety of nuclear power plants by applying this methodology systematically.

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1. Introduction

Operational events occurring at nuclear power plants provide information on the safety and reliability of these plants. Through risk assessment for operational events of a nuclear power plant, vulnerabilities can be identified and the safety of plants can be improved. Systematic management of the results of risk assessments for operational events is essential for improving the safety of plant operation and the design of new models of nuclear power plants.

Accident sequence precursor (ASP) analysis, one of methodologies of quantitative risk assessment for operational events occurring in nuclear power plants, uses probabilistic risk assessment (PRA) to systematically evaluate the risk significance of operational events and to select precursors by applying quantitative criteria. Precursors are the operational events that can cause inadequate core cooling or core damage. Systematic management of the selected precursors plays an important role in improving the safety of nuclear power plants [1].

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In this study, recent analyses regarding ASP were surveyed to develop a methodology to reflect the current state of the art; furthermore, the developed analysis methodology was applied to operational events occurring during full power operation as well as low power/shutdown operation.

2. Literature review

Since the establishment of the United States Nuclear Regulatory Commission (U.S. NRC) in 1979, ASP analyses have been performed, with results intended to be utilized for 35 years. Because of the great deal of analysis experience and technical development that has been accumulated, ASP analyses by the U.S. NRC have become a basis for the development of ASP analysis methodologies in other countries.

After the issuance of the WASH-1400 (Reactor Safety Study) [2], the first PRA report, the U.S. NRC formed the Risk Assessment Review Group (Lewis Committee) to provide an independent review of this report. In 1978, the Lewis Committee recommended an assessment of the risks of operational events actually occurring in nuclear power plants using the PRA methodology and, immediately after the occurrence of the TMI-2 accident in 1979, the Division of Risk Analysis of the U.S. NRC established the ASP program. Currently, the ASP program is operated by the Nuclear Operations Analysis Center of Oak Ridge National Laboratory, Oak Ridge, TS, USA; the results of the selection of precursors are documented and posted on the NRC website.

The ASP analysis status reports have been annually documented and open to the public. The first analysis report is "NUREG/CR-2497, Precursors to Potential Severe Core Damage Accidents: 1969–1979" published in 1982 [3]. For this report, Licensee Event Reports on 19,400 operational events at nuclear power plants in the U.S. between 1969 and 1979 were reviewed; 169 events that could cause core damage and severe accidents were selected and ASP analysis for these events was performed. Among the selected events, 52 events turned out to be precursors [3]. In 1984, "NUREG/CR-3591, Precursors to Potential Severe Core Damage Accidents: 1980–1981" was published and 58 precursors were selected [4]. These reports were published every year as a series of "NUREG/CR-4674, Precursors to Potential Severe Core Damage Accidents" from 1986; 17 reports were published until 2001 [5]. After the occurrence of the 9/11 attacks in 2001, the U.S. NRC has been annually posting ASP analysis results as commission papers (SECY), removing from the results information that might be sensitive with regard to U.S. security.

In addition, after the introduction of the Risk-informed, Performance-based Regulation by the U.S. NRC, the Reactor Oversight Process has been implemented since 2000 and, as part of the Reactor Oversight Process, the ASP program, the Significance Determine Process, and the MD 8.3 program have been used to assess nuclear power plant operational performance.

In the USA, 63,005 operational events were reported and evaluated from 1969 to 2005. Among them, 262 (0.42%) events were identified with conditional core damage probability (CCDP) values of 1.0×10^{-6} or more; 237 events were identified with CCDP values of 1.0×10^{-5} or more; 166 events were identified with CCDP values of 1.0×10^{-4} or more, 26 events were identified with CCDP values of 1.0×10^{-3} or more, five events were identified with CCDP values of 1.0×10^{-2} or more, and three events, including the fire at the Brown's Ferry nuclear power plant, were identified with CCDP values of 1.0×10^{-1} or more [6].

According to the report on the ASP analyses of operational events occurring over 10 years since 2005, the number of component failure-related precursors that occurred was 104, which was larger than the number of initiating event-related precursors, which was 54 [7]. Representatively, the number of operational events occurring in 2013 that were analyzed was 458 in total. Among these, a total of 17 precursors had a CCDP value greater than 1.0×10^{-6}, consisting of six initiating event-related precursors and 11 system or component failure-related precursors [6].

The AVN, the Belgium regulatory authority, introduced the PSA-based Event Analysis (PSAEA) methodology to analyze power plant operational events. The AVN has performed PSAEA for Belgian nuclear power plants since 1997 and, from its analysis, 13 operational events were selected consisting of eight component failure-related events. Among these eight component failure-related events, five events were assessed to have a CCDP value greater than 1.0×10^{-6} and these were selected as precursors. Similar to the ASP methodology, PSAEA analyzes operational events using the PRA technique. It is mainly used in European countries, including Belgium, Finland, and Switzerland. As with ASP, it selects operational events with CCDP values greater than 1.0×10^{-6} as precursors and those with CCDP values greater than 1.0×10^{-4} as important precursors [8].

In Japan, ASP analyses have been performed since 1994 at the Institute of Nuclear Safety and Nuclear Power Engineering Corporation (INS/NUPEC) with the support of the Ministry of Economy, Trade and Industry. To develop quantification models for the ASP analysis, the INS/NUPEC classified the total of 51 nuclear power plants (BWR: 28, PWR: 23) located in Japan into six types of plant and developed full power and low power/shutdown operation-related quantification models. In addition, through a review of the impact of accidents, such as cases in which the redundancy of the safety system was lost and important single failure events from the viewpoint of severe accidents, the INS/NUPEC selected 12 events from the operational events that had occurred over the past 20 years. When the selected events were analyzed, the CCDP of power operated relief valve (PORV) failure events during the steam generator tube rupture (SGTR) accidents was assessed to have the highest value (7.5×10^{-4}). The CCDP of very small loss of coolant accident (LOCA) (VS-LOCA) accidents was evaluated to have a value of 1.0×10^{-4} and failure of normal bus switching after a manual reactor outage was assessed to have a CCDP value of 1.3×10^{-6} [9].

Therefore, not only the initiating event-related risk significance, but also the component failure-related risk significance have been recognized to be important and, when the ASP methodology was developed, component failure related contents were mainly checked.

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