Annals of Nuclear Energy 98 (2016) 90–111

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Verification of SAMGs in SBO sequences with Seal LOCA. Multiple damage domains

C. Queral [a,*], L. Mena-Rosell [a], G. Jimenez [a], M. Sanchez-Perea [b], J. Gomez-Magan [c], J. Hortal [b]

[a] *Universidad Politécnica de Madrid, Spain*
[b] *Consejo de Seguridad Nuclear, Justo Dorado 11, Spain*
[c] *NFQ Solutions, Claudio Coello 78, Madrid, Spain*

A R T I C L E I N F O

Article history:
Received 21 October 2014
Received in revised form 12 July 2016
Accepted 13 July 2016
Available online 4 August 2016

Keywords:
Integrated Safety Assessment (ISA)
Damage Domain
Station Blackout (SBO)
Seal Loss of Coolant Accident (SLOCA)

A B S T R A C T

The Integrated Safety Assessment (ISA) methodology, developed by the Spanish Nuclear Safety Council, has been applied to PWR Station Blackout (SBO) sequences in the context of the IDPSA (Integrated Deterministic-Probabilistic Safety Assessment) network. The ISA methodology allows obtaining the Damage Domain (DD), the region of the uncertain parameters space where the damage limit is exceeded, for each sequence of interest as a function of the operator actuation times. Several damage limits have been taken into account within this analysis: cladding embrittlement criteria (Peak cladding temperature >1477 K); Inadequate core cooling conditions (Core Exit Thermocouples temperature >922 K); local fuel melting (fuel temperature >2499 K); fuel relocation in lower plenum and vessel failure. Other continuous damages, such as percentage of relocated fuel are also studied. Every one of these damage variables provides a specific DD. The application to the severe accident management (SAM) actions shows the capability of a methodology such as ISA in order to analyze the impact of different SAM strategies and to obtain the available times for different operator actions.

1. Introduction

Over the past few years, increasing trends towards Risk-Informed Regulation as well as certain concerns about the limitations of standard Probabilistic Safety Analysis (PSA) have led to increase the attention on some proposals that include dynamic aspects in PSA beyond those already considered in the determination of success criteria. Dynamic methodologies for PSA use a time-dependent phenomenological model of system evolution along with its stochastic behavior to account for possible dynamically induced dependencies between failure events, (Aldemir, 2013).

ISA methodology, developed by the Modeling and Simulation Branch of the Spanish Nuclear Safety Council (CSN), lies within those dynamic methodologies, see Ibañez et al. (2016), Aldemir (2013) and Izquierdo et al. (2016) for more details. It has been proved as an adequate method to perform an analysis of the impact of uncertainties in nuclear safety analysis, especially suited for those sequences where some events occur at uncertain times.

One of the main results of ISA methodology is the identification of the Damage Domain (DD) of the sequence, which is defined as the region of the space of uncertain elements (times or parameters) of interest where a plant transient would result in the exceedance of some limit, and constitutes a useful tool for the verification of nuclear safety analyses. Similar concepts can be found in other methodologies (Ibañez et al., 2016; Adolfsson et al., 2012; Kan et al., 2013; Di Maio et al., 2014; Rabiti et al., 2015; Rychkov et al., 2013; Zio et al., 2010). In this work, an analysis of Station Blackout (SBO) sequences with Seal LOCA (SLOCA) in the Reactor Coolant Pumps (RCPs) has been performed by means of the ISA methodology with its computerized platform SCAIS (Simulation Code System for ISA) coupled to MAAP thermal-hydraulic code, and using the model of a commercial 3-Loop PWR Westinghouse design.

The main goals of this work are the following:

a) To verify the adequacy of Emergency Operating Procedures (EOPs) and Severe Accident Management Guidelines (SAMGs) related to this scenario (SBO with SLOCA) by means of ISA methodology.
b) To assess the impact of SLOCA in SBO sequences and appraise the time evolution of the different damages that come up during the sequence.

This article is divided into the following sections: Section 2 provides a brief overview of ISA methodology and some details

* Corresponding author.
E-mail address: cesar.queral@upm.es (C. Queral).

http://dx.doi.org/10.1016/j.anucene.2016.07.021

Nomenclature

AC	Alternating Current
ACC	Accumulator
AFW	Auxiliary Feedwater
BL	Broken loop
BWR	Boiling Water Reactor
CCW	Component Cooling Water
CET	Core Exit Thermocouple
CSN	Spanish Nuclear Safety Council
CVCS	Chemical & Volume Control System
DC	Direct Current
DD	Damage Domain
DDI	Discrete Damage Indicator
DET	Dynamic Event Tree
DFC	Diagnostic Flow Chart
ECCS	Emergency Core Cooling System
EDMG	Extended Damage Mitigation Guidelines
EOP	Emergency Operative Procedure
FP	Fission Product
FW	Feedwater
HPSI	High Pressure Safety Injection
ICC	Inadequate core cooling
IDPSA	Integrated Deterministic-Probabilistic Safety Assessment
ISA	Integrated Safety Assessment
LOCA	Loss of Coolant Accident
LPSI	Low Pressure Safety Injection
LWR	Light Water Reactor
MAAP	Modular Accident Analysis Program
MDD	Multiple Damage Domain
MDP	Motor-Driven Pump
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PCT	Peak Cladding Temperature
PD	Previous Damage
PORV	Power Operated Relief Valve
PSA	Probabilistic Safety Analysis
PWR	Pressurized Water Reactor
PZR	Pressurizer
RCP	Reactor Coolant Pump
SA	Severe Accident
SAG	Severe Accident Guideline
SAM	Severe Accident Management
SAMG	Severe Accident Management Guideline
SBO	Station Blackout
SCAIS	Simulation Code System for ISA
SCST	Severe Challenge Status Tree
SG	Steam Generator
SLOCA	Seal Loss of Coolant Accident
SV	Safety Valve
TDP	Turbine-Driven Pump
TH	Thermal-hydraulic
TSC	Technical Support Center
TSD	Theory of Stimulated Dynamics
UL	Unbroken Loop

of the MAAP4 plant model; Section 3 analyzes SBO sequences and characterizes a base case; in Section 4, ISA methodology is applied to sequences with Discrete Damage Indicators (DDI; those damage indicators with Boolean logical values, such as core uncovery, Peak Cladding Temperature -PCT- limit, Inadequate Core Cooling Condition -ICC-, fuel relocation in lower plenum and vessel failure), in order to obtain DDs as a function of the uncertain times of AC power recovery and DC power failure; Section 5 is devoted to quantify Continuous Damage Indicators (CDI) like percentage of relocated fuel or hydrogen generation; Section 6 describes another ISA application to SBO sequences without AC recovery. Finally, Section 7 summarizes the main conclusions of the study.

2. Materials and methods

This section presents a brief overview of the ISA methodology (Section 2.1) as well as the PWR-3 Loop model for MAAP Code (Section 2.2).

2.1. Integrated Safety Assessment (ISA) method and tools

In the framework of dynamic PSA methodologies, the literature reports on a variety of methods apart from ISA, e.g. ADS-IDAC, MCDET, ADAPT, GA-IDPSA, see references (Aldemir, 2013; Zio, 2014; Nuclear Energy Agency, 2011a,b; Chang and Mosleh, 2007; Kloos et al., 2008; Kloos and Pesche, 2006; Hakobyan et al., 2008; Catalyurek et al., 2010; Rychkov et al., 2013) for more details. The different groups which currently work in the field have joined in an international network called IDPSA, see references (Di Maio et al., 2015; Aldemir, 2013; Izquierdo et al., 2016; Zimmerman, 2013; Adolfsson et al., 2012, 2011) for more details. These methods of probabilistic dynamics enable the analyst to fully account for the interaction between dynamic and stochastic aspects of the plant evolution which result in mutual dependencies between the evaluation of accident consequences and the probabilities of events occurring during an accident sequence. In particular, this kind of methodologies can be applied, among other applications, to EOPs and SAMGs verification.

The ISA methodology aims at providing with an adequate method to perform a general uncertainty analysis, with emphasis in those sequences where some events occur at uncertain times as in the case of sequences containing operator actions. This methodology allows among other results, obtaining the DD for each sequence of interest as a function of the values that uncertain elements (occurrence times or parameters) can take. Of particular interest are damage domains resulting from uncertain crew actuation times. DDs are then regions of the uncertainty space with as many dimensions as the number of uncertain elements involved in the analysis of the sequence. In the present case (SBO with SLOCA), only two uncertain times (DC power failure and AC/DC power recovery) have been considered, and then DD are up to two-dimensional.

The ISA methodology introduces some differences with respect to classical PSA. The most important of these differences which apply to this analysis are listed here:

- **Damage Condition**: In PSA Level 1 the damage condition is the transition to severe accident, which in practice is equivalent to the LOCA acceptance criterion, Max PCT > 2200 F (1477.15 K). In ISA methodology several damage criteria can be handled within the same analysis.
  For instance, in a previous ISA application to Steam Generator Tube Rupture sequences dose limits were considered for concurrent iodine spike and pre-accident iodine spike in addition to PCT, see Rebollo et al. (2016) for more details.
  In this application to **SBO sequences**, two kinds of damage indicators are taken into account: discrete damage indicators (DDI, e.g. core uncovery, PCT limit, beginning of fuel relocation, vessel failure…) and continuous damage indicators (CDI, e.g. percentage of relocated fuel, hydrogen generation).