Nuclear Engineering and Design 241 (2011) 4206–4222

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Uncertainty and sensitivity analysis of a LBLOCA in a PWR Nuclear Power Plant: Results of the Phase V of the BEMUSE programme

M. Perez[a], F. Reventos[a,*], L. Batet[a], A. Guba[b], I. Tóth[b], T. Mieusset[c], P. Bazin[c], A. de Crécy[c], S. Borisov[d], T. Skorek[e], H. Glaeser[e], J. Joucla[f], P. Probst[f], A. Ui[g], B.D. Chung[h], D.Y. Oh[i], R. Pernica[j], M. Kyncl[j], J. Macek[j], A. Manera[k], J. Freixa[k], A. Petruzzi[l], F. D'Auria[l], A. Del Nevo[l]

[a] *UPC, Technical University of Catalonia, Av. Diagonal, 647, Barcelona 08028, Spain*
[b] *AEKI, Hungary*
[c] *CEA, France*
[d] *EDO-GIDROPRESS, Russia*
[e] *GRS, Germany*
[f] *IRSN, France*
[g] *JNES, Japan*
[h] *KAERI, South Korea*
[i] *KINS, South Korea*
[j] *NRI, Czech Republic*
[k] *PSI, Switzerland*
[l] *UNIPI, Italy*

ARTICLE INFO

Article history:
Received 2 September 2010
Received in revised form 25 July 2011
Accepted 3 August 2011

ABSTRACT

This paper presents the results and the main lessons learnt from Phase V of BEMUSE, an international programme promoted by the Working Group on Accident Management and Analysis (GAMA) of OECD to address the issue of the capabilities of best-estimate computational tools and uncertainty analysis. The scope of Phase V is the uncertainty analysis of a Large Break Loss-Of-Coolant-Accident (LBLOCA) in a Pressurized Water Reactor. Fourteen participants from twelve organizations and ten countries participated in the Phase V of BEMUSE.

The paper starts with a general description of the BEMUSE programme including the objectives, structure, and the outline of the Phase V specification. Then it summarizes some general aspects on the uncertain model parameters and the results for the uncertainty analysis and for the sensitivity evaluation. To end with, general recommendations and conclusions are presented as practical guidance for uncertainty analysis performance.

1. Introduction

The use of best estimate codes in combination with evaluation of uncertainties, the so-called BEPU methodologies, is an accepted procedure by the regulatory authorities to carry out a deterministic safety analysis. Since the promulgation of the USNRC ECCS regulatory requirements in 1988, several BEPU approaches have been developed in this scope. Examples of activities promoted by the OECD/CSNI to assess such methodologies are the "Uncertainty Analysis Methods" workshop held in London (UK) 1994 (Wickett and Yadigaroglu, 1994), the "Best Estimate Methods in Thermal Hydraulic Safety Analysis" seminar held in Ankara (Turkey) 1998 (Aksan et al., 1998), and the "Uncertainty Methods Study" (UMS) study (Wickett et al., 1998). The UMS was the first international study on the uncertainty methodologies, a step by step comparison of the BEPU methods that was organized in response to the recommendations concluded in the UAM 1994 workshop.

Furthermore, the IAEA Safety Report series No.23 "Accident analysis for Nuclear Power Plants" (Allison, 2002), issued in 2002, recommends sensitivity and uncertainty analysis if best estimate codes are used in licensing analysis. A comprehensive overview about uncertainty methods can be found in the IAEA Safety Report Series No.52 "Best Estimate Safety Analysis for Nuclear Power Plants: Uncertainty Evaluation", issued in 2008 (IAEA, 2008).

The BEMUSE Programme has been promoted by the Working Group on Accident Management and Analysis (GAMA) of

* Corresponding author. Tel.: +34 934017143; fax: +34 934017149.
E-mail address: francesc.reventos@upc.edu (F. Reventos).

0029-5493/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.nucengdes.2011.08.019

Nomenclature

1D	1 dimensional
3D	3 dimensional
AEAT	AEA Technology plc
AEKI	Hungarian Academy of Sciences KFKI Atomic Energy Research Institute
BE	Best Estimate
BEMUSE	Best Estimate Methods – Uncertainty and Sensitivity Evaluation
BEPU	Best Estimate Plus Uncertainty
BL	Broken Loop
CCFL	Counter Current Flow Limitation
CEA	Comissariat à l'Energie Atomique
CFR	Code Federal Regulation
CHF	Critical Heat Flux
CIAU	Code with the capability of Internal Assessment of Uncertainty
CL	Cold Leg
CSAU	Code Scaling, Applicability and Uncertainty
CSNI	Committee on the Safety of Nuclear Installations
DWR	Downcomer
ECCS	Emergency Core Cooling System
EDO	Gidropress Experimental Design Office
ENUSA	Empresa Nacional del Uranio, SA
GAMA	Group on Accident Management and Analysis
GE	General Electric
GRS	Gesselschaft für Anlagen und Reaktorsicherheit mbH
HL	Hot Leg
HPIS	High Pressure Injection System
IAEA	International Atomic Energy Agency
ICAP	International Assessment and Applications Program
IL	Intact Loop
IPSN	Institut de Protection et de Sureté Nucleaire
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
ITF	Integral Test Facility
JNES	Japan Nuclear Energy Safety
KAERI	Korea Atomic Energy Research Institute
KINS	Korea Institute of Nuclear Safety
LBLOCA	Large Break Loss Of Coolant Accident
LOFT	Loss Of Fluid Test
LPIS	Low Pressure Injection System
LSTF	Large Scale Test Facility
LWR	Light Water Reactor
MPCT	Maximum Peak Cladding Temperature
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
NRI	Nuclear Research Institute Rez
OECD	Organisation for Economic Co-operation and Development
PCT	Peak Cladding Temperature
PDF	Probability Density Function
PIRT	Phenomena Identification and Ranking Table
PSI	Paul Scherrer Institute
PWR	Pressurized Water Reactor
RCS	Reactor Coolant System
ROSA-IV	Rig of Safety Assessment No.4 Programme
SBLOCA	Small Break Loss Of Coolant Accident
SET	Separate Effect Test
SOAR	State Of The Art Report
SPDF	Subjective Probability Density Function
TGTHSB	Task Group on Thermal Hydraulic System Behaviour
UH	Upper Head
UKAEA	United Kingdom Atomic Energy Authority
UMAE	Uncertainty Methods based on Accuracy Extrapolation
UMS	Uncertainty Methods Study
UNIPI	Università di Pisa
UPC	Universitat Politècnica de Catalunya
USNRC	United States Nuclear Regulatory Commission

OECD/NEA and endorsed by the Committee on the Safety of Nuclear Installations (CSNI). BEMUSE (Best Estimate Methods – Uncertainty and Sensitivity Evaluation) main objectives are:

- To evaluate the practicability, quality and reliability of Best Estimate methods including uncertainty evaluations in applications relevant to nuclear reactor safety.
- To develop a common understanding in this domain.
- To promote/facilitate the use of these methods by the regulatory bodies and the industry.

The application of these methods to a Large-Break Loss of Coolant Accident (LBLOCA) constitutes the main activity of the programme, organized into two main steps (six phases):

- Step 1: Best-estimate and uncertainty and sensitivity (BE + U + S) evaluations of the LOFT L2-5 test. It includes Phase I the description of the methods (Micaelli et al., 2005), Phase II the BE calculation of the test (Petruzzi et al., 2006) and Phase III the uncertainties and sensitivities analysis (de Crécy et al., 2007).
- Step 2: BE + U + S evaluations of a PWR Nuclear Power Plant. The aim of Phase V (Reventos, 2009) is the uncertainty analysis of a LB-LOCA based on a reference calculation performed in Phase IV (Reventos et al., 2008). For this particular and for the rest of the article it is understood that the reference case is a calculation using nominal best-estimate input values and default values for the computer code options and input data for models.

Finally Phase VI will summarize conclusions and recommendations of the whole exercise.

Background from previous phases has been used to produce final uncertainty results in Phase V.

The objectives of the activity are:

- To obtain uncertainty bands for the maximum cladding temperature (time trend), upper plenum pressure (time trend), maximum peak cladding temperature (scalar), 1st peak cladding temperature (scalar), 2nd peak cladding temperature (scalar), time of accumulator injection (scalar), time of complete core quenching (scalar).
- When using a probabilistic approach methodology: to evaluate the influence of the selected parameters on maximum cladding temperature (time trend) and upper plenum pressure (time trend).
- To compare procedures with experience gained in previous Phase III.

Fourteen groups from twelve organizations and ten countries have participated in BEMUSE Phase V (see Table 1). All participants have experience in the involved fields. Notable works of the organizations devoted either to comparative exercises, uncertainty evaluations or model verification are Glaeser et al. (1994), D'Auria (1998), Guba et al. (2003), de Crécy et al. (2008), Reventos et al. (2008), Song et al. (2010), Bukin et al. (2009) and Perez et al. (2010).