BEPU and Safety Margins in Nuclear Reactor Safety

F. D'Auria[1], H. Glaeser[2], N. Debrecin[3]

[1] University of Pisa (DESTEC/GRNSPG), Pisa, Italy

[2] Consultant, Eching, Germany

[3] University of Zagreb (FEEC), Zagreb, Croatia

E-mail contact of main author: f.dauria@ing.unipi.it

Abstract. Approaches like Best Estimate Plus Uncertainty (BEPU) and concepts like Safety Margins (SM) are well established in Nuclear Reactor Safety (NRS). However continuous improvements in analytical techniques and in the sophistication of hardware products do not necessarily correspond to new industrial applications within Nuclear Power Plants (NPP) technology. The declining condition for nuclear technology also contributes to the lag between developments and applications definitely causing NPP safety at a level below the achievable level. The possibility to extend BEPU to all areas of the Final Safety Analysis Report (FSAR), so-called BEPU-FSAR is outlined in the paper. This should be combined with the Extension of the SM concept (E-SM). BEPU-FSAR techniques may be at the origin of E-SM which also will need specific monitoring hardware. All of this may open new horizons for NRS and for acceptance of NPP by the public and the decisions makers. The paper describes recent accomplishments in the areas of BEPU and E-SM.

Key Words: Licensing, Best Estimate Plus Uncertainty, Safety Margins.

1. Introduction

Nuclear Reactor Safety involving fission and water cooled or moderated reactor constitutes the general framework for the paper. NRS is an established technology since several decades, starting from the discovery of nuclear fission. On the one hand well known accidents have challenged the sustainability of nuclear technology and undermined the trust of the public. On the other hand, innovative ideas and proposals are possibly needed to restore the confidence and to escape the irreversible loss of competence primarily in those Countries where the technology was developed and exploited for several decades since its discovery.

The last statement shall be seen as the triggering point for the present paper which is based upon activities discussed in refs. [1] to [5].

Licensing is the legal part of NRS. Country specific laws must be pursued within the licensing process, e.g. the Code of Federal Regulation in the United States. The Final Safety Analysis Report which is related to individual NPP units is the end results of the licensing process and brings to the permission of operation of the unit. The documentation of Accident Analysis (AA) is the key part of the FSAR. Noticeably, procedures to perform safety assessment and thresholds of acceptability fixed by Regulatory Bodies are part of the licensing and of AA.

Acceptance criteria are the common words used for the 'thresholds of acceptability'. Safety Margins (SM) may be considered as a consequential concept derived from acceptance criteria, see e.g., ref. [6]. According to ref. [7], "*The safety margin is the distance between an acceptance criterion and a safety limit. If an acceptance criterion is met, the available safety* *margin is preserved*". An extension of the SM concept is discussed in ref. [4]: let's call this extension E-SM.

Best Estimate Plus Uncertainty is an approach which is consistent with the capabilities of system thermal-hydraulic codes and their application to the AA, [8]. BEPU has been widely applied to the analysis of Large Break Loss of Coolant Accidents (LBLOCA), [9], and more recently to the overall set of accidents part of the Chapter 15 of the FSAR, [10], see also [1] and [2]. BEPU can be extended to all the analytical parts of the safety analysis report as discussed in ref. [11]: the extended application is called BEPU-FSAR.

The purpose of the present paper is to connect BEPU-FSAR and the E-SM which can be derived from the application of numerical codes or procedures. Snapshot information necessarily incomplete and not systematic about BEPU and E-SM is provided first.

2. The Extended Safety Margin Concept

The concept of 'Safety Margins' is well established within the NRS and in related AA. The SM value can be defined as the difference or the ratio in physical units between the limiting value of an assigned parameter (typically, the threshold value for the connected acceptance criterion) the surpassing of which leads to the failure of a system or component, and the actual value of that parameter during the life of the plant.

The existence of suitable margins ensures that Nuclear Power Plants operate safely in all modes of operation during their life. Sample SM relate to physical barriers designed to protect against the release of radioactive material, such as fuel matrix and fuel cladding (limiting values are associated with departure from nucleate boiling ratio, fuel temperature, fuel enthalpy, clad temperature, clad strain, clad oxidation), reactor coolant system boundary (pressure, stress, material condition) and containment (pressure, temperature); other SM are connected with dose to the public being close or far from the NPP.

The accident phenomenology and the related timing are estimated as complete as necessary within the Deterministic Safety Assessment (DSA) framework. In turn, the Probabilistic Safety Assessment (PSA) approach allows demonstration of the completeness of the set of different scenarios and best estimate methods. The approaches have been developed rather independently from each other. This poses the problem of consistent integration. Hence, a generalization of the concept of safety margin may be beneficial. In addition, the concepts of safety margins and of quantifying changes in safety margins are key components of the discussions for modifications in plant design parameters and operational conditions. This includes, for example, power up-rates, life extensions, use of mixed oxide fuels, different cladding materials, design and operation of passive systems and changes to technical specifications. Those modifications impact safety margins in deterministic analyses, while others impact the reliability of systems and components, and yet others impact safety margins and reliability simultaneously.

Looking at the evolution of occurred accidents in complex systems, an extended definition of SM appears worthwhile. For instance, this may include the consideration of pilot mental status history and of conditions for locking the cabin door in case of aircraft as well as the surveillance of the construction site for a NPP. A multidimensional space for SM in NRS has been envisaged, [4]. This shall have multi-face and multi-field attributes because of the several design-safety-licensing aspects and involved technological fields.

The multidimensional space can be defined for SM noting that risk space shall be taken as synonymous of safety space. The dimensions for the space embracing the definition of SM can be defined as, [4]:

A) The key elements characterizing NRS.
B) The technological sectors or the key scientific disciplines of NRS and NPP design and operation.
C) The Systems, the Sub-systems and the Components (SSC) constituting the NPP.
D) The time spans which form the life of the NPP.

Human factors shall be considered as part of any of the ‘dimensions’ above. Furthermore, the definitions of elements, sectors, SSC and time spans with a consequent sub-categorization process allow arriving at a few ten thousands detectable SM quantities, thus constituting the E-SM ensemble. Monitoring the combination of possibly un-influent E-SM values contributes to the additional safety barrier against the release of fission products. For instance, the combination of a certain number of signals (e.g. in the case of TMI-2 leaking pressurizer valve combined with the presence of a manual valve in the auxiliary feed-water line having the possibility to remain close, etc.) shall prevent the operation of reactor unit well before conditions are created for the occurrence of a safety relevant event.

Pairs of quantities are needed to form an E-SM: on the one hand there is the monitored or the calculated value; on the other hand there is the threshold or the acceptable value. It is intended that monitored values come from specific hardware and calculated values from BEPU-FSAR as mentioned in next section; and threshold value needs an endorsement by regulators.

3. The Best Estimate Plus Uncertainty Approach

A textbook is needed for a comprehensive description of BEPU: on one side, it is straightforward to discuss the outcomes of a BEPU calculation; on the other side it is difficult to explain shortly what BEPU is. An attempt is made hereafter to give an idea of BEPU.

The complexity of nuclear thermal-hydraulics and the impossibility to obtain analytical solutions from equations derived from fundamental principles of physics is at the origin of BEPU. The following limitations can be mentioned in this connection:

- Turbulence is a property of moving fluids. Turbulence is barely known for single phase flows; moreover two- or more-phases flows of technological interest are inherently turbulent. Equations to calculate turbulence in transient situations either do not exist or are not qualified.
- No model exists to calculate the motion of a set of bubbles in a boiling-condensing system involving formation, growth, coalescence and collapse processes (partly connected with the turbulence statement above).
- Convection heat transfer and pressure drops, i.e. the fundamental mechanisms involved with two phase flow mixture evolutions, are calculated based on empirical formulations which are based upon a variety of drawbacks.
- Complex processes or mechanisms relevant in NRS like reflood, radiation heat transfer, countercurrent flows and those characterizing component (e.g. fuel rods, pumps, valves, separators) performances also need specific empirical/imperfect formulations: in most cases those formulations cannot be proved at the scale of the NPP target of the calculations.

- The averaging in time and space, noticeably at the levels of flow cross section area and of volume occupied by fluid, is unavoidable: the size of the integration domain is typically larger than the scale of involved phenomena.

Therefore, approximations are at the basis of any numerical approach to simulate a system of interest. Thus, the objective of a model is to calculate the reality in the best possible way consistently with current knowledge, hence the words Best Estimate (BE). The application of those BE models to experimental situations shows unavoidable (known) errors sometimes referred as accuracy of a calculation. Then errors are expected in the prediction of NPP system performances: those (unknown) errors constitute the uncertainty of a calculation, [12], hence the words Plus Uncertainty and the final acronym BEPU. In principle the uncertainty of a calculation must consider all the approximations introduced in modeling of reality.

Verification and Validation (V & V), scaling, procedures for uncertainty quantification, for the consistent application of computational tools to AA and for coupling of numerical codes constitute the pillars of current BEPU. The intimate connection between PSA and DSA is also part of BEPU.

4. BEPU-FSAR and the connection with E-SM

BEPU, as it is now, constitutes a recognized resource for the application of nuclear thermal-hydraulics system codes and the AA, [2]. The established BEPU methods and procedures can be extended to any part of the FSAR where an analytical derivation is needed. This ensures a homogeneous consideration of requirements in the different sectors of FSAR: for instance, the probability and the consequence of external hazards shall be modeled and evaluated by techniques having same rigor and similar consideration of errors as the techniques utilized for internal accident analysis. Furthermore, the systematic identification of boundaries in chains of adjacent technological areas constitutes a valuable consequence of the extension. One example is geology, soil properties, soil-structure interaction, civil structure resistance and mechanical structures resistance: combined BE calculations shall be performed where stresses in primary system piping following an earthquake are a function of local soil amplification or damping of waves originated at the epicenter. The bases for the extension of BEPU techniques to cover all areas of NRS have been put, [11], and called BEPU-FSAR.

BEPU-FSAR constitutes the logical framework for the systematic identification and characterization of E-SM quantities and for computing the actual margins in case of accident or during the lifetime of the concerned NPP. An overly simplified example dealing with clad ballooning during LBLOCA is outlined hereafter:

- Ballooning occurrence is unavoidable and calculated at least in selected fuel assemblies. This causes crack openings and release of fission gases.
- Fuel fragmentation causes at least two main problems: a) accumulation of fragmented UO_2 debris in the bottom part of the ballooned region with possible difficulty in cooling; b) exit of solid fission products from the crack.
- Parameters can be defined and calculated to give rise to a few E-SM based on: 1) tolerable burn-up combined with linear heat generation rate; 2) emergency system design conditions to cope with the ballooned region; 3) tracking of solid fission products possibly demonstrating their confinement into the containment.

5. Conclusions

BEPU-FSAR and E-SM constitute the two-tier integrated proposal for improving NRS technology. Introducing related findings in NPP design has the potential:

A) to create an additional safety barrier to the release of fission products;
B) to prevent severe accident occurred so far.

Innovation in NRS seems essential to restore the confidence towards nuclear technology. Cost of the (proposed) innovation shall be below 1% the cost of one individual NPP.

References

[1] D'AURIA, F., MAZZANTINI, O., "The Best-Estimate Plus Uncertainty (BEPU) Challenge in the Licensing of Current Generation of Reactors", IAEA Int. Conf. on Opportunities and Challenges for Water Cooled Reactors in the 21st Century, Vienna (A), Oct. 27-30, 2009.

[2] D'AURIA, F., CAMARGO, C., MAZZANTINI, O., "The Best Estimate Plus Uncertainty (BEPU) approach in licensing of current nuclear reactors", J. Nuclear Engineering and Design, Vol. 248, 2012, pp 317-328.

[3] D'AURIA, F., DEBRECIN, N., "Perspectives in licensing and nuclear reactor safety technology", Invited at Conf. Innovative Designs and Technologies of Nuclear Power, ISTC NIKIET, Moscow, (Ru), Oct. 7- 10, 2014.

[4] D'AURIA, F., GLAESER, H., KIM, M-W., "A Vision for Nuclear Reactor Safety", Key-Speaker at 46th Jahrestagung Kerntechnik Annual Meet., Berlin (G), May 5-7, 2015

[5] D'AURIA, F., GLAESER, H., DEBRECIN, N., "Independent Assessment for new Reactor Safety", ENS TopSafe Conf., Vienna (A), Feb. 9-12, 2016.

[6] IAEA, "Accident Analysis for Nuclear Power Plants", Safety Report Series, SRS-23, Vienna (A), Nov. 2002.

[7] IAEA, "Implications of power up-rates on safety margins of nuclear power plants", TECDOC 1418, Vienna (A), Sept. 2004.

[8] IAEA, "Deterministic Safety Analysis for Nuclear Power Plants", Specific Safety Guide, SSG-2, Vienna (A), Dec. 2009.

[9] GALETTI, M. R., D'AURIA F., "Questions arising from the application of Best-Estimate Methods to the Angra-2 NPP Licensing Process in Brazil", Int. Meet. on Best-Estimate Methods in Nuclear Installation Safety Analysis (BE-2000) IX, Washington D.C. (US), Nov. 10-13, 2000.

[10] PETRUZZI, A. et al., "The BEPU Evaluation Model with RELAP5-3D for the Licensing of the Atucha-II NPP", J. Nuclear Technology, Vol 193, pages 113-160, Jan. 2016.

[11] MENZEL, F., et al., "Using of BEPU methodology in a Final Safety Analysis Report", International Nuclear Atlantic Conference – INAC 2015, Sao Paulo (Brazil), Oct. 4-9, 2015.

[12] IAEA, "Best Estimate Safety Analysis for Nuclear Power Plants: Uncertainty Evaluation", Safety Report Series, SRS-52, Vienna (A), 2008.