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SHORT COMMUNICATION

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An old issue and a new challenge for nuclear reactor safety

Abstract Nuclear reactor safety (NRS) and the branch accident analysis (AA) constitute proven technologies: these are based on, among the other things, long lasting research and operational experience in the area of water cooled nuclear reactors (WCNR). Large break loss of coolant accident (LBLOCA) has been, so far, the orienting scenario within AA and a basis for the design of reactors. An incomplete vision for those technologies during the last few years is as follows: Progress in fundamentals was stagnant, namely in those countries where the WCNR were designed. Weaknesses became evident, noticeably in relation to nuclear fuel under high burn-up. Best estimate plus uncertainty (BEPU) techniques were perfected and available for application. Electronic and informatics systems were in extensive use and their impact in case of accident becomes more and more un-checked (however, quite irrelevant in case of LBLOCA). The time delay between technological discoveries and applications was becoming longer. The present paper deals with the LBLOCA that is inserted into the above context. Key conclusion is that regulations need suitable modification, rather than lowering the importance and the role of LBLOCA. Moreover, strengths of emergency core cooling system (ECCS) and containment need a tight link.

Keywords large break loss of coolant accident (LBLOCA), nuclear reactor safety (NRS), licensing perspectives, basis for design of water cooled nuclear reactors (WCNR)

1 Introduction

After E. Fermi demonstration of sustainability of fission reaction chain (1942) and Adm. Rickover decision to design and construct the prototype pressurized water cooled reactor (PWR), the concern for break in one pipeline in those reactors was raised [1]. In different terms, the large break loss of the coolant (LBLOCA) issue entered the nuclear technology. Needless to add, the use of water as a coolant-moderator imposed high pressure and the presence of a reactor pressure vessel (RPV) embedding the radioactive material in the core. This affected the layout and the size of components for those reactors: the core had to remain intact following the full rupture, or double ended size, or guillotine break, or 2 × 100% pipeline area, of the largest pipe connected with the RPV.

Later on, in 1971, when the design of commercial reactors was available and several dozen nuclear power plants (NPP) were in operation, the US regulators issued the interim acceptance criteria (IAC) for the design of emergency core cooling system (ECCS). These ended up into 10 CFR 50.46 [2]. (The maximum allowed clad surface temperature is 1477 K. The maximum allowed clad thickness reacted is 17%. The maximum H_2 production allowed is 1%. It needed ensuring long-term cooling, e.g., considering debris in containment sump. Coolable geometry is kept: e.g., changes in core geometry is such that the core remains amenable to cooling, and mechanical loads following break opening are considered). Huge projects from industry and institutions followed to demonstrate compliance of reactor design with requirements: the era of large experiments supported by more and more powerful computer and applicable numerical models started.

Up to 1979, because of the Three Mile Island Unit 2 (TMI-2) event, notwithstanding the Rasmussen report [3], the attention of the scientific community was focused on LBLOCA as the key accident scenario to demonstrate the safety of water cooled nuclear reactors (WCNR). Thereafter, a number of different scenarios were considered as a lesson learned from TMI-2, moving the frontier of analyses from LBLOCA to small break LOCA, to accident management situations (around the 90s) and, following the recently introduced terminology, to design extension conditions (DEC-A and DEC-B) in addition to design basis conditions (DBC) [4].

Until 2020, sophisticate computational tools and

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procedures have been developed and successfully applied for safety evaluations and licensing in relation to LBLOCA: the best estimate plus uncertainty (BEPU) approach was proposed [5], although outside the scope for discussion here.

Fuel weaknesses and connected clad failure mechanisms always posed challenge to the acceptability thresholds for LBLOCA: ballooning and consequential creep type of clad rupture have been the topic of investigation for decades. Besides, the technological compromise of only fission gases leaving the core has been conveyed into the safety analysis field. Even before the present century, evidence from nuclear fuel material technology brought to a mismatch between ECCS acceptance criteria and LBLOCA radiological impact resulting from safety analyses. The definition of 'mismatch', according to the information in Refs. [6–8] is as follows: high burn-up fuel following LBLOCA may not fulfill the ECCS requirement dealing with maximum clad thickness reacted when the allowed limit passes from 17% (past and current) to 2%–6% (envisaged future).

Two main ways have been pursued by industry and regulators: reducing the focus toward LBLOCA by considering probability of the event supported by construction and maintenance quality, and developing the accident tolerant fuel (ATF). Lower attention apparently goes by the scientific community toward drastic changes in regulations and even less to re-discussing the pillar for those regulations.

A multi-faceted and controversial issue is thus occurring: this deals with nuclear fuel weakness, LBLOCA scenario, role of containment, and ECCS licensing rule. Then, the purpose for the present paper is to focus upon an established topic in technology, i.e., the LBLOCA, connecting this with recently detected nuclear fuel weaknesses and the licensing rule. This constitutes a challenge for the coming future and a test case for NRS: the control, or better the streamline, of public acceptance for nuclear technology may be affected by directions proposed by decision makers [1]. Historical cornerstones in the NRS technology and significant design features of PWR are relevant and recalled in Sections 3 and 4.

2 The LBLOCA issue

The main motivation for the present paper is the detected inconsistency (the mismatch defined above), between ECCS design requirements [2], and expected results of analyses: in other terms, nuclear industry may not fulfil licensing thresholds; this is specifically true for high burn-up fuel (i.e., average burn-up greater than 45 GWd/tU).

References [9–11] discuss the USNRC documents [6–8], which provide details to characterize the nuclear fuel weakness resulting from experimental testing and investigations during the last two decades. Namely, embrittlement mechanisms associated with interacting chemical and physical processes which occur during the long-term permanence of fuel in reactor cores (four years or more) in combination with (typically high) burn-up, make the clad vulnerable following LBLOCA within the envelope of design basis conditions (DBC). Therefore, the fulfillment of ECCS design criteria is affected.

The fuel failure mechanisms identified as ballooning, already known to nuclear industry since 1970s, despite the aggravating load caused by fuel relocation in the bottom part of the balloon [12], may cause radioactivity releases still compatible (at least under certain hypotheses) with ECCS design criteria [2]. This may not be the case when nuclear fuel weaknesses characterized during the last two decades are considered. Selected possibilities to deal with LBLOCA are:

(1) To perform safety analyses (e.g., BEPU) and to underline overpassing of ECCS thresholds of acceptability, claiming that regulators may accept the results and allow the operation of the concerned reactors. No regulator may guarantee this solution.

(2) To delete the LBLOCA from the list of transients within the DBC: risk-informed and/or risk-supported analyses together with quality in construction, operation and maintenance, e.g., including the established leak before break (LBB) approach may justify this possibility. Drawbacks are fixing the 'reasonable' break size for the acceptable LOCA (what size and why?) and demonstrating the fuel integrity with that size in addition to introducing an inconsistency related to what has been done till now.

(3) To adapt the licensing rules with detected fuel weaknesses. This may create third parties and public concern: i.e., rules are adapted to reactor design deficiencies.

(4) To design nuclear fuel that withstands the LBLOCA loads, or ATF. This is a logic long-term solution: acceptability will require in-core demonstrations; furthermore, the use of ATF for the entire reactors fleet in the world may need more than a couple of decades.

3 A historical outline

Any description of the history of nuclear technology embedded into the XX century is well beyond the target for the paper as well as any new interpretation of facts; rather, a few details are (in a chronological order):

(1) 1942: the fission chain can be controlled to produce power.

(2) 1943–1950 (around): water was selected as coolant – therefore high pressure, then (need of) RPV, then (consideration of) LOCA.

(3) 1954: first nuclear reactor (submarine) in operation.

(4) 1950 (around)–1960 (around): PWR design finalized including containment and ECCS.

(5) 1970/1971: ECCS design criteria established, so

called Interim Acceptance Criteria (IAC).

(6) 1970–2020: safety of water cooled nuclear reactors (WCNR) demonstrated according to IAC.

(7) 2000 (around)–2020 (around): nuclear fuel weaknesses prevent fulfilling IAC in some LBLOCA conditions.

Remarks from historical outline are: the LBLOCA issue entered the reactor design and NRS technology before IAC were established; LBLOCA affected the design of the WCNR cooling loop; and the containment became part of WCNR design before the IAC, although this received limited consideration by those IAC.

Containment constituted since the beginning of the nuclear era the ultimate physical barrier (i.e., accounting for possible lack of knowledge) against the release of fission products to environment and LBLOCA, primarily, determined its design features.

4 The LBLOCA cross-link with current technology

The LBLOCA appears as an emblem of controversy interior to technology of high-pressure water-cooled nuclear reactors and therefore of the exploitation of fission power for electricity production. A complementary (related to what given above) interpretation of the controversy is that, on the one hand the LBLOCA scenario is embedded into the design and the construction of WCNR: 'Interim acceptance Criteria' for the design of ECCS issued in 1971 basically targeted LBLOCA; up to the occurrence of TMI-2 in 1979, the LBLOCA was the main focus for the analyses by technological community. On the other hand, modeling weaknesses continuously challenged deterministic safety demonstration for LBLOCA: among the other things, regulators introduced the threshold of 95% acceptability, too. Moreover, once the industry and the research community established suitable predictive capabilities for LBLOCA, i.e., at the end of the last century, the interest toward nuclear technology sharply decreased in selected countries. Suitable predictive capabilities include phenomena modeling and procedures like verification and validation, scaling, uncertainty and code coupling (i.e., within the BEPU approach). Selected countries are those countries that primarily contributed to the development of the technology. All of this left room to lack of directions for progress in the area and lack of common understanding within the technological community. Furthermore, nuclear fuel failure mechanisms characterized more recently and related modeling [13,14], confirm inadequacy of connection between LBLOCA scenario and licensing-design requirements.

LBLOCA affects a myriad of issues of WCNR design, construction, operation and maintenance; the entire spectrum of nuclear reactor safety is concerned, e.g., involving the levels of defense-in-depth (DiD) and the outcomes of risk informed analyses.

Still part of an oversimplified picture, Sections 4.1 to 4.4 deal with double ended guillotine break (DEGB) LBLOCA in cold leg of PWR, except for Section 4.4 which deals with boiling water reactor (BWR) containment, too.

4.1 Regulatory trend

Mandatory fulfillment of regulations may depend on country specific strategies and agreements between licensee and licensor.

A recent (2019) IAEA statement, SSG-2 rev1 [4], gives "*3.20. Certain limiting faults (e.g., large break loss of coolant accidents, main steam or feed-water pipe breaks, and control rod ejection in pressurized water reactors or rod drop in boiling water reactors) have traditionally been considered in deterministic safety analysis as design basis accidents. These accidents should be considered because they are representative of a type of accident against which the reactor has to be protected. They should not be excluded from the category of design basis accidents unless careful analysis and quantitative assessment of their potential contribution to the overall risk, including conditions arising that could lead to an early radioactive release or a large radioactive release, indicate that they can be excluded.*" In Annex II of the same report, a frequency which is greater than 10^{-6} event per reactor-year is representative for DBC.

4.2 LOCA and reactor primary system design

In addition to the need to transfer fission power to steam generators (SG), natural circulation and LOCA are at the basis of the thermal-hydraulic design of WCNR including PWR. Primary coolant system layout and reactor pressure vessel (RPV) configuration are distinguished and LOCA design is considered.

The layout of coolant system, primarily mutual position of RPV and SG, aims at making possible removal of decay power by natural circulation with main coolant pumps at rest. However, in case of LOCA, having recognized that cold leg is the most dangerous location for a break, attention is paid to minimizing the impact of stagnation point upon core cooling and to facilitating reflood.

Figure 1 is a simplified sketch of RPV in which red dotted lines 'D', 'E', and 'F' plus bottom of active fuel (BAF) and top of active fuel (TAF) are geometric parameters directly related to LOCA. Namely, the capability for the system to withstand the DEGB LOCA brings to the diameter of the cold leg 'D'.

Quantification of mutual relationships between LBLOCA and reactor design parameters is highly reactor dependent. Some information is directly discussed or referenced in Ref. [5].

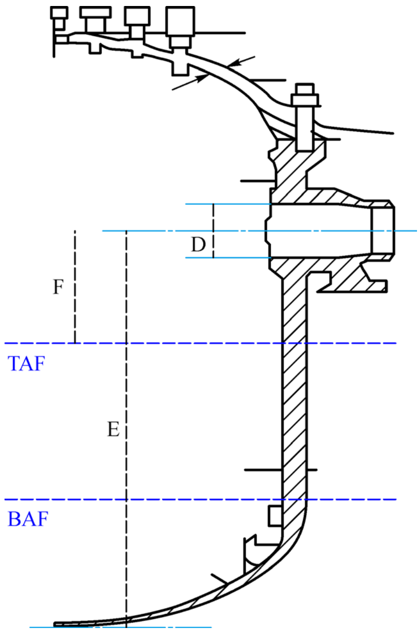

Fig. 1 LOCA related parameters in RPV design.

4.3 ECCS

A variety of ECCS design parameters connect with LOCA and DEGB-LBLOCA conditions. Among the others, accumulator design (i.e., number of accumulator tanks, volume, pressure, liquid mass, and size of discharge line) shall satisfy the needs coming from the analysis of LBLOCA. The 'somewhat historical' thermal-hydraulics phenomena like ECCS bypass, early core rewet, downcomer penetration, counter current flow limitation at core upper plate and steam binding, other than reflood and quench front progression, associate ECCS actuation and LBLOCA.

The size design of hot and cold leg and direct vessel injection ECCS pipelines, or interfaces between ECCS and primary coolant system depend upon LBLOCA.

4.4 Containment

LBLOCA analyses determine containment design parameters, namely maximum pressure and temperature and sump configuration (needed in order to get a suitable level during long-term cooling, i.e., preventing residual heat removal pump cavitation).

The list of keywords representative of phenomena for the interconnection between containment and LBLOCA includes pipe whip, jet impingement and jet thrust, pressurization (of containment), missiles, and appearance of debris in containment sump for long-term cooling.

In the case of BWR, the fluid-dynamic interactions between wet-well and dry-well constitutes an additional LBLOCA challenge.

5 Streamlining the 'rule change'

None of the possible way-outs to the LBLOCA issue, discussed in Section 2, is without key drawbacks. The proposal here aims at proposing minimum-reasonable changes to the current ECCS rule to take into account the (now evident) nuclear fuel weaknesses. Figure 2, adapted from a similar diagram in Ref. [10], deals with selected logical aspects:

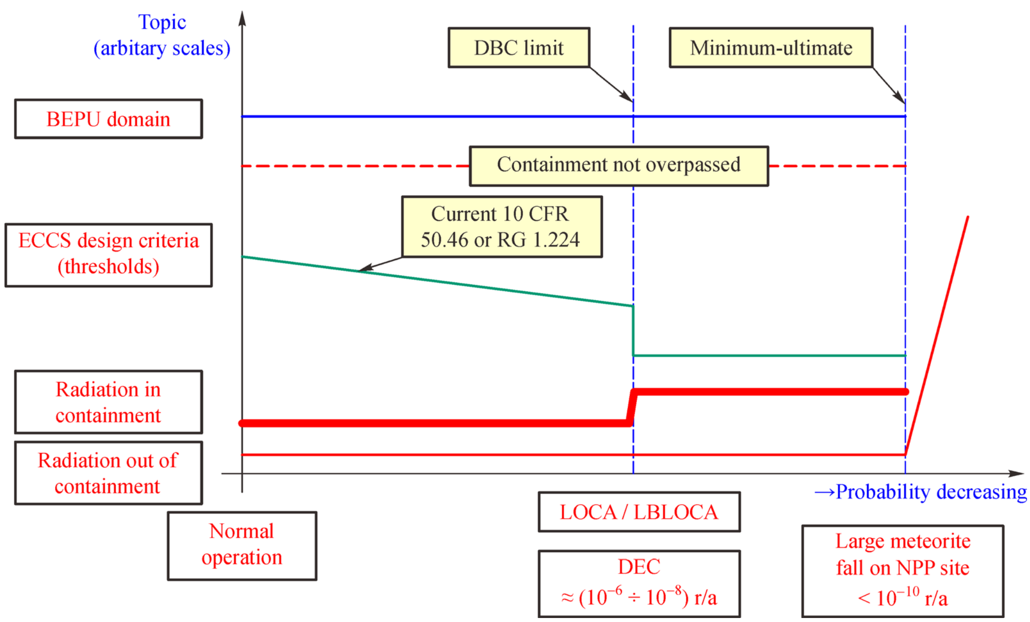

Fig. 2 A view for LOCA and possible (proposed) regulatory framework.

(1) The hierarchic mutual importance between LBLOCA and IAC (from a historical review, Section 3) is relevant: LBLOCA constitutes a precursor for IAC.

(2) The LBLOCA plays a key role in reactor design-to-safety (Section 4): that role shall remain in the future.

(3) Containment shall play a (deeper) role in establishing NRS requirements with main connection with IAC for ECCS (Section 4).

Further details from Fig. 2 are:

(4) High and low probability boundary values for DEC need to be established: DEC-A high probability value could be consistent with LBLOCA probability of occurrence; on the other boundary, the minimum-ultimate probability is introduced (discussion below).

(5) ECCS rule should follow the current graded method (i.e., more restrictive thresholds when event probability is high-left part of diagram – and steeply relaxed thresholds at DEC probability value).

(6) Containment should protect the environment consistently with current law (thus ensuring continuity with current regulation): radiation allowed inside containment is higher at probability of an event lower than DEC probability.

An 'extremely' low probability value for any event and the BEPU approach in safety analysis are part of the picture (e.g., item (4) above). The minimum-ultimate probability value should get a physical meaning. This can be (the probability of) the catastrophic fall of a powerful meteorite upon the reactor site. There is no means to protect the reactor surroundings in this extreme situation. At the same time, there is no reason within the current technology to justify significant radiation releases to environment for any event having a higher probability. Furthermore, the application range for BEPU includes the identified probability domain (blue line in Fig. 2); current BEPU features, procedures, and capabilities [15] appear suitable for dealing with both the old and the new (expected) ECCS-containment rule.

The envisaged ECCS rule, i.e., item (5) above, should combine current 10 CFR 50.46 and RG 1.224, namely in relation to the allowed oxidization limit for clad thickness reacted during the event [2,8]. When entering DEC-A from the high probability region in Fig. 2, the following can be considered, e.g., rule relaxation at a low probability. ① ECCS design cannot cope with recently identified fuel weaknesses. ② Containment strength could be combined with ECCS to minimize the impact on the environment of fuel damage: role of containment should be consistent with specific licensing requirements (not mentioned here). ③ Radiation exiting the core should be evaluated according to new criteria (e.g., Ref. [8]), as well as radiation transport into containment and toward the environment. ④ Current acceptability limits for radiation releases to the environment should be kept (radiation control means may need to be introduced in containment).

6 Conclusions

The LBLOCA role in safety analysis, the ECCS design criteria, and the containment constitute heterogeneous polar-concepts in nuclear reactor technology: related interconnections are re-discussed in order to orient safety and design of existing and future WCNRs. The probability values identified as < DBC limit > and < minimum-ultimate > may prove to be helpful to decision makers in this connection. The key conclusions are:

(1) DEGB-LBLOCA probability needs additional characterization at the < DBC limit > .

(2) Containment resistance should be ensured until the < Minimum-ultimate > probability value.

(3) Tight link between containment design and ECCS rule constitutes a challenge for future regulation.

(4) Thresholds of ECCS acceptance criteria may have a discontinuity at < DBC limit > : namely, threshold values should be relaxed and the control of acceptable safety margins should move up to the allowed radiation impact (item 5 below).

(5) The threshold for radiation impact to environment should ensure continuity with the current regulation.

Therefore, the LBLOCA shall remain at the center of the attention for safety evaluations and licensing of WCNRs.

The development of accident tolerant fuel (ATF) constitutes an important roadmap in nuclear technology that is independent of any outcome of the present paper.

Other LOCA scenarios (i.e., in addition to DEGB-LBLOCA) need proper investigations within the present area according to their relevance within a risk informed framework.

Rule change, and/or setting the limits of acceptability constitutes (and must be) an entitlement for regulators. Nevertheless, regulators may consider the information coming from any source: this drove the issue of the present paper.

Finally, and not discussed in the present paper, the LBLOCA phenomena need attention in future thermal-hydraulics research: this is particularly the case of reflood. However, break opening time, depressurization wave propagation inducing voids and mechanical loads are other example of the LBLOCA phenomena that need future investigation.

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