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Adaptation of the PIRT methodology to the Severe Accident domain

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Abstract

Severe Accidents (SAs) dominate the risk associated with the commercial production of nuclear energy. Despite the major achievements made in their understanding, upcoming new technologies such as Advanced Technology Fuels (ATFs) and Small Modular Reactors (SMRs), more stringent safety requirements, optimization of SA management, and other factors, point the need for an efficient use of research resources in the years to come. The SEAKNOT project (SEvere Accident research and KNOWledge management for LWRs), coordinated by CIEMAT, was born to address this need in all and every aspect. The present article describes how the PIRT (Phenomena Identification and Ranking Table) approach has been adapted to the entire SA domain to prioritize forthcoming research. A 13-step methodology aimed at source term (ST) release to the environment or its potential prevention/mitigation is outlined with particular emphasis on the challenges addressed while adapted. At the time this article is being written, the phenomena ranking process has already started.

KEY WORDS: SEVERE ACCIDENT, RESEARCH ROADMAP, PIRT.

1. INTRODUCTION

The concept of the PIRT dates back to the times when the USNRC developed the Code Scaling, Applicability and Uncertainty (CSAU) evaluation methodology to support the application of the BEPU (Best Estimate Plus Uncertainty) method in safety analyses of commercial Nuclear Power Plants (NPPs) [1]. Since then, there have been multiple applications with different purposes, particularly in the realm of Design Basis Accidents [2]. Nonetheless, the PIRT methodology has also been used in specific aspects of the SA domain [3] [4] [5]. The present report describes the adaptation done within the EU SEAKNOT project (<https://seaknot-project.eu/>) to apply the PIRT approach to the entire domain of SAs with the purpose to outline the research that needs to be done in the short- and mid-term, including new technologies like Water Cooled Small Modular Reactors (WC-SMRs) and ATFs [6]. After introducing the basic structure of a PIRT, the key aspects that required to be changed and the rationale underneath are here described.

2. PIRT FUNDAMENTALS

The PIRT, as considered in the present work, is a stepwise process consisting of 15 steps that were reviewed and sketched by [2], as shown in Fig. 1.

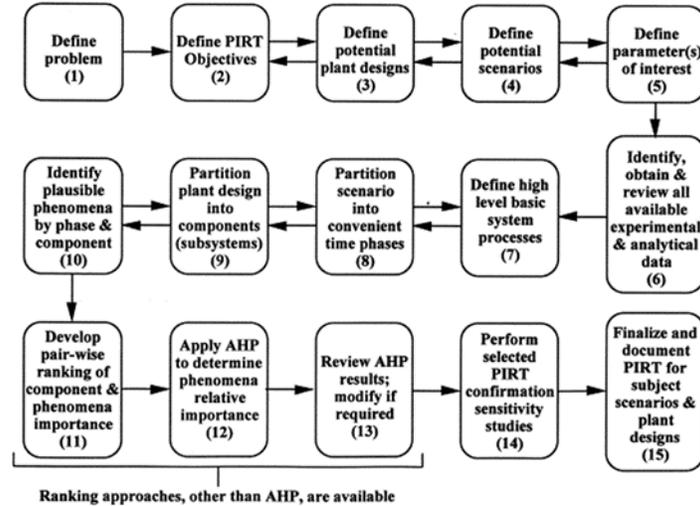


Figure 1. Schematics of the PIRT process [2]

Next a short description of each of them is given.

- **Problem definition.** The specific problem to be solved should be clearly stated. In such a statement, the resources available must be carefully considered, so that the minimum achievement with a high probability of effecting the resolution is identified.
- **Objectives.** The primary objective of a PIRT is to identify the relative importance of systems, components, processes and phenomena driving the plant response in the addressed scenario. As a secondary outcome, the PIRT provides insights into needs of new experimental data, and code developments/improvements and Uncertainty Quantification (UQ) to meet the primary goal.
- **Plant designs.** Plant design heavily influences the relative importance of processes and phenomena referred to above, starting from the possible scenarios to be focused on. Therefore, establishing the NPP types the PIRT has to be applied to is an essential step.
- **Potential scenarios.** As for plant design, the relative importance of processes and phenomena is strongly scenario-dependent, including the systems and sub-systems that might be active, some of which as a result of Accident Management (AM). Being the identification of potential scenarios strongly linked to plant design, it is straightforward that step 3 and step 4 highly interconnected.
- **Parameters of interest.** The evaluation criteria to assess the relative importance of processes and phenomena are based on specific variables selected. In the frame of DBAs, they are usually related to regulatory safety requirements, like the maximum cladding temperature or the produced hydrogen mass.
- **Experimental and analytical data.** Both experimental and analytical existing information should be identified and reviewed. This step sets demanding requirements on the team conducting the PIRT development: the collective expertise should extend over experimental programs of relevance,

models and code developments, and their application. Thus, the collective expertise should be broad and deep. In this step, sensitivity analyses proved to be helpful.

- **High level system processes.** Identification of high-level system processes might help focusing PIRT on essential processes and phenomena and assessing their relevance in different phases of the accident.
- **Scenario partition.** The relative importance of a single phenomenon might be time-dependent, and its assessment would require splitting the scenario in subsequent time phases.
- **Components and subsystems.** Subdividing the NPP into components and subsystems would allow differentiating local (component- or subsystem related) and cross-cutting processes and phenomena affecting several components and sub-systems.
- **Phenomena identification.** The major challenge of phenomena identification is to achieve completeness. Even if there is no “silver bullet” (quick solution to a difficult problem) how to do it, it heavily relies on the team expertise and open discussions to reach a plausible processes/phenomena list that is defensible. Phenomena ranking is not foreseen during this step.
- **Phenomena ranking.** Considered the core of the PIRT process, ranking consists in assessing the relative importance of the identified processes and phenomena with respect to the evaluation criteria selected as parameters of interest. Even though a proven decision-making tool is sometimes recommended, simpler ranking methods can be employed.
- **Sensitivity studies.** The PIRT development should be seen as an iterative process, and sensitivity analysis performed with validated numerical tools might be a powerful tool confirming the obtained ranking and/or providing results to support better balanced rankings to specific phenomena.
- **Documentation.** As the PIRT process should lead to a decision making affecting not just the time at which the PIRT development is carried out but, likely, future times at which the access to the full rationale behind the PIRT outcomes should be granted for its best understanding and proper use, a thorough documentation related to the process is of exceptional relevance. Namely, PIRT tables convey a good part of the information resulting from the exercise, but not all of it. Additional descriptions of plant, scenarios, phenomena and processes definitions, etc. should accompany the evaluations appearing in the tables

3. THE SEAKNOT ADAPTATION

As stated above, SEAKNOT is not the first initiative that brings the PIRT process into the SA domain. About twenty years ago, the EC EURSAFE concerted action (contract FIKS-CT2001-20147 of the Euratom Nuclear Safety Programme 1998–2002) conducted the first-of-a-kind PIRT on SAs with a full scope [7]. More than 1,000 phenomena were identified, and a few more than 100 were considered worth of investigation, being their safety significance substantial and the knowledge about them lacking. Later, some other PIRT exercises were carried out in the SA field, but with a limited scope.

Next the PIRT steps introduced above are addressed and their adaptation in SEAKNOT described.

- **Problem definition.** The specific problem to be addressed is the identification of the SA issues whose research would lead to a better characterization and, if possible, to a reduction of the related uncertainties, as well as to an efficiently enhanced preventive and mitigation of SA consequences.

The time window considered is 10 years after the SEAKNOT conclusion. The evolution expected in the technology of NPPs in that time range should be accounted for. This includes any innovation in reactors' design and fuels (like WC-SMRs and ATFs), as well as extension of the current technologies (i.e., high burnup fuels and plant-life extension).

- **Objectives.** The main objective of this PIRT is the determination and the effective mitigation of the ST, namely the radioactive release from an NPP. This places the focus of the study on two key elements of the ST: Fission Products (FPs) release and safety barriers (cladding; primary system; and containment) impairment. Mathematically, the approach is fully encapsulated in the ST integral:

$$J_i(t) = \int_0^{t_f} e(t) \cdot dt \cdot I \cdot F \cdot F_i \cdot \int_0^t s(t') \cdot dt' \cdot \exp \left[- \int_{t'}^t \varepsilon(t'') \cdot dt'' \right]$$

The first integral (dt) represents the containment leaking function; the second one (dt') describes how the "i" radionuclide is released from fuel; and the third one (dt'') estimates the probability of "i" to remain mobile (i.e., able to move or being carried easily) once it was released. The product I·F·F_i is the i-radionuclide inventory in fuel. In other words, the barriers performances are kept in the integrals: the first one for containment, the second one for cladding, and the third one embedding the containment and the primary system

- **Plant designs.** The scope of the PIRT, as for the nuclear technologies addressed, is decided on two major drivers: continuing the safe operation of the running NPPs (including life extension) and supporting the safe performance of new reactor technologies with potential to be licenced in Europe in the coming 10 years. On these grounds, the first driver points to PWR-Western type, VVERs, and BWRs, while the second one opens SEAKNOT to WC-SMRs (particularly to those explored as designs 1 and 2 in the EURATOM SASPAM-SA project, GA 101059853). Any of the above technologies will consider, as cross-cutting issues, the use of high burnup, high enrichments, and near-term ATFs to the extent feasible.
- **Potential scenarios.** There is no a uniquely established way to identify potential scenarios of interest. Given the difficulty of this task and the need to accommodate the effort to be made to the resources available within SEAKNOT, it was agreed to, first, identify a phenomenon, and then to prove its relevance in a risk-significant scenario.
- **Parameters of interest.** Given the objectives, the evaluation criteria will be based on the following variables describing the FP release to the environment: onset time; activity release rates; and composition. The target radionuclides will be those with a high impact on radiological consequences [8]; specifically: ¹³¹I; ¹³²I; ¹³⁷Cs; ¹⁰⁶Ru; ¹³²Te; ⁸⁸Kr; ¹³³Xe; ¹³⁵Xe. This short list might be extended or shortened, depending on whether enough technical support is brought up during the PIRT discussions to do it.
- **Experimental and analytical data.** The identification of relevant experimental and analytical data related to the entire domain of SAs is a need for a PIRT. Several measures have been taken in SEAKNOT to achieve the best conditions to reach that goal: the SA domain has been split in areas consistent with the PIRT objectives; each of the areas are coordinated by internationally recognized scientists, who play a visible role and have sound historical backgrounds in the SA research panorama; each evaluation area involves the participation of 6 to 8 partners with proven scientific

contributions in the field, and their collective expertise covers both experimental and analytical approaches.

- **High level features.** In the case of SAs, there are some processes, usually associated with the operation of safety systems brought in for managing the accident, which might drastically change the course of the event. They will be associated with accident locations (i.e., core, Reactor Pressure Vessel (RPV), Reactor Coolant System, containment, ...) and phases (in-vessel or ex-vessel), so this aspect should be taken into account together with the scenario phasing.
- **Scenario splitting.** The evaluation criteria adopted in the PIRT are ST dependent. Given the drastic difference expected in ST before and after the RPV failure, it would result natural in SEAKNOT to split the entire time domain into in-vessel and ex-vessel phases. During the in-vessel phase, FP-related and containment phenomena will be considered in-RPV. During the ex-vessel phase, all the phenomena related to the behaviour and interactions of molten and hot corium materials in the reactor pit, along with thermal-hydraulic phenomena ongoing in the containment and any related FP transport mechanisms will be dealt with.
- **Components and subsystems.** AM requires activating engineering safety features which will depend on plant type, scenarios and phases of accident. Among others, containment sprays, Passive Containment Cooling Systems (PCCS), suppression pools, fan coolers, Passive Autocatalytic Recombiners (PARs) and Filtered Containment Venting Systems (FCVS), can be mentioned. It is worth noting that these systems might entail phenomena that are component/sub-system specific or, otherwise, are sort of cross-cutting and appear with several systems performance, even if under different boundary conditions.

Needless to say, that steps 3.7 - 3.9 of the PIRT process should be reflected in the table template (see Table 1) used to first, list phenomena, and then, rank them. Table I shows how every aspect allocating each phenomenon (scenario phase and component/system related) are embedded in the template to be used for identification and ranking of phenomena (green background). The symbols legend appears at the foot of the table.

Table I. Fundamental PIRT template

Ref. Number	Phenomenon	Short Description	Comp/ Sub-system	Accident Phase	Knowledge		Safety Significance	Priority	Refs.
					Data	Model			
C-1	Homogeneous steam condensation	Phase change of steam in a gas atmosphere driven by a local oversaturation	N.A.	In-v	H	M	L	L	D [1], [2] M [3]
ST-1									D M

C-Containment; ST- Source Term; In-v – In-vessel; Ex-v – Ex-vessel; N.A. – Not Applicable

References

- [1]
- [2]
- [3]

- **Phenomena identification.** There are two key pillars when coming to phenomena identification: technical consensus on phenomenon to be listed (the “defensibility principle”), and fundamental

technical sources supporting it. The list completeness relies on the collective expertise of the individual teams set up in the different areas the SA domain is partitioned into, and also on avoiding any ranking consideration during the identification phase. The fundamental technical sources should start from the EURSAFE outcomes [7]. Then, some reference publications on priority updates published by SARNET [9] and NUGENIA/TA2 [10] [11] should be accounted for. To these global references, one should add recent State-Of-Art-Reports (SOARs), PIRTs and technical reports from SA-related projects concerning specific areas. With no intention to be comprehensive, there are a number of references that should not be missing though: [12], [13], [14], [15], [3], [16], [17], [18]. Individual project contributions, technical reports and workshops outcomes are also assets.

- Phenomena ranking.** Ranking consists in assessing the relative importance of processes and phenomena with respect to the evaluation criteria selected as parameters of interest. The research priority is being assessed based on existing knowledge and safety significance of each phenomenon; each of these concepts split in three levels (i.e., low, L; medium, M; high, H). Knowledge is weighed on data availability and representativeness, and modeling maturity; as in the case of priority, three levels are given to both data and models. Table II shows how knowledge and safety significance combine to define priority. It is high priority (H) whenever knowledge is poor (L) and safety significance is high. Low priority is attributed whenever safety significance is low and/or existing knowledge is high. The rest of cases (3) is given a medium ranking level but ordered by priority: the maximum (M1) given to high safety significance and the minimum (M3) to mid-impacting phenomena on which there is some knowledge.

Table II. PIRT ranking categories

		Safety Significance		
		Low	Medium	High
Knowledge	Low	L (Poor understanding; irrelevant)	M2 (Poor understanding; mild effect)	H (Poor understanding; impacting)
	Medium	L (Some understanding; irrelevant)	M3 (Some understanding; mild effect)	M1 (Some understanding; impacting)
	High	L (Sound understanding; irrelevant)	L (Sound understanding; mild effect)	L (Sound understanding; impacting)

- Sensitivity studies.** Along the PIRT creation, a number of phenomena might be considered in between medium or high priority issues, given the uncertainties associated with their evaluation. In such cases, analytical studies might be conducted to support the final option adopted in the PIRT process or conduction of “ad-hoc” tests. These calculation campaigns should be seen as a booster for mobility grants within SEAKNOT.
- Documentation.** The importance of documentation is not specific of the PIRT adaptation to SAs. The technical report that compiles the PIRT process should ensure the fulfilment of the three conditions associated to the ranking process. In short, technical arguments used to support each ranking should be clearly stated in enough detail as to allow a step-by-step follow-up, if needed. Special attention shall be provided on the documentation of the phenomena that will eventually be selected as those of highest priority.

The feedback from the End User Group (EUG) members concerning the documentation will be paid close attention to optimize a thorough understanding of every aspect related to the PIRT process, starting from the own methodology.

4. FINAL REMARKS

This paper walks through the adaptation process of the PIRT methodology to the full-scope SA realm. What described in the previous sections is the way to apply it based on the interpretation made of the main purpose of each of the steps in the original formulation of PIRT, which was developed in the DBA area. Even though the bases look sound and well established, it is likely that its practical use lead to variations that, without jeopardizing meeting the final objective, ease the PIRT building process as a whole.

Figure 4. shows an integral view of the full methodology. As may be noted, one of the “hidden” steps will be the merging of the rankings from individual SA areas. Currently, the intention is to do it based on three criteria:

- Source Term should be the guiding path (aligned with the PIRT objective). The bonds between source term issues highly ranked with phenomena responsible for and related to containment, in-vessel and ex-vessel domains will become essential to consistently merge the ranking.
- Containment and Source Term areas should split their ranking according to the SA phasing (i.e., in-vessel and ex-vessel), as there might be different phenomena or, even, the same phenomena under different prevailing conditions.

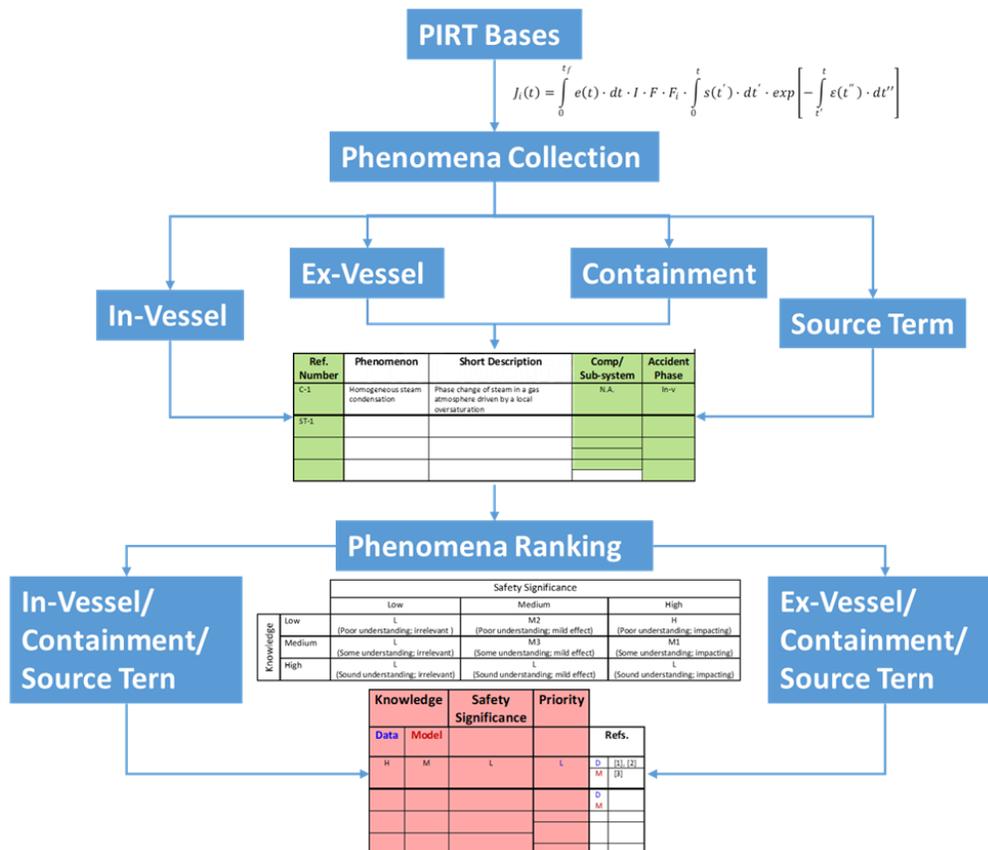


Figure 2. Flowchart of the SEAKNOT PIRT

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