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Adoption of the Phenomena Identification and Ranking Table (PIRT) Methodology for Safety Assessment of a 1 GWe Stellarator Fusion Power Plant

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The safety assessment of fusion power plants has historically relied on methodologies originally developed for fission reactors, with adaptations to address fusion-specific phenomena. However, a systematic and traceable methodology to identify and prioritize physical processes influencing plant safety has not yet been established in the fusion domain. In this work, we present the first application and formal adoption of the Phenomena Identification and Ranking Table (PIRT) methodology to the safety assessment of a 1 GWe stellarator fusion power plant (Chartreuse-P reactor). Building on the fission safety experience summarized by IAEA-FIP/P3-20 and OECD/NEA's best-estimate and uncertainty frameworks, our study develops a fusion-adapted PIRT framework that integrates with model-based systems engineering (MBSE) and digital safety environments. The methodology enables structured expert elicitation, scenario-driven ranking of thermal-hydraulic, magnetohydrodynamic, tritium transport, and structural integrity phenomena, and their mapping to system functions and safety criteria. The resulting Fusion PIRT matrix serves as a foundation for experimental planning, model validation, and code development—bridging safety demonstration requirements with digital verification workflows. Its implementation within the Chartreuse-P safety program supports the French regulatory process, including the Dossier d'Options de Sûreté (DOS) and proposes a case study for future regulatory licensing of stellarator facilities under ASNR guidance. This paper therefore establishes PIRT as a cornerstone methodology for fusion reliability and risk assessment, promoting traceability, transparency, and prioritization of safety-critical research activities within next-generation fusion power plant programs.

Keywords: — PIRT, Fusion Safety, Stellarator, Safety Assessment, Phenomena Ranking, Reliability.

1. Introduction

Fusion power plant safety is entering a critical transition as the field moves from experimental facilities toward industrial prototypes and first-of-a-kind reactors. To date, fusion safety analyses have largely relied on tools and methodologies inherited from fission reactor safety, adapting fission accident analysis techniques to fusion-specific phenomena. While this approach has provided valuable insights, it has lacked a dedicated and systematic framework specific to fusion to identify, structure, and prioritize the physical phenomena that drive fusion plant safety. In fission reactor safety, this role is fulfilled by the Phenomena Identification and Ranking Table (PIRT) methodology, which provides a structured, expert-driven process to rank phenomena according to their safety importance and state of knowledge. Despite its widespread use in fission, no formal PIRT has yet been completed for a fusion power plant, leaving a gap in the traceability and completeness of fusion safety assessments.

PIRT was developed in the late 1980s and formalized in the 1990s as part of the best-estimate safety analysis paradigm (Wilson and Boyack, 1998). It relies on expert elicitation to identify phenomena relevant to define safety figures of merit and to rank them according to importance and knowledge level. The resulting prioritization highlights phenomena that are both safety-significant and poorly understood, thereby guiding experimental programs, model development, and code validation. Over the past decades, PIRT has become a standard tool in fission reactor safety, applied across thermal-hydraulics, severe accidents, fuel behavior, and materials degradation to support risk-informed decision-making (NRC, 2012; OECD NEA, 2017). Notable applications include OECD/NEA PIRTs following the Fukushima accident to prioritize spent fuel pool research (OECD NEA, 2017), NRC studies on high-burnup fuel fragmentation and dispersal (NRC, 2024), and industry-led PIRT exercises supporting dry storage modelling (EPRI, 2018).

Extending the PIRT methodology to a fusion energy system as a first of kind systems with its own fusion specific challenges to safety is therefore a natural and necessary step. Fusion facilities are expected to meet regulatory expectations as illustrated by ITER's licensing framework, including defense-in-depth and robust safety demonstrations. PIRT provides a systematic means to identify and prioritize fusion-specific challenges to safety functions, such as magnet quench behavior, tritium confinement, plasma transients, and coolant or vacuum system failures. Previous studies have highlighted the relevance of such an approach: Panayotov (2018) noted the absence of formal PIRTs in fusion safety studies and emphasized their potential value for structuring safety assessments and research priorities. More broadly, the application of PIRT in fusion offers a defensible framework for identifying critical knowledge gaps, guiding experimental and modelling efforts, and supporting safety margin evaluation and regulatory review.

In this context, the present work introduces the first formal application of the PIRT methodology to a fusion power plant, focusing on the Chartreuse-P 1 GWe stellarator concept. Building established fission PIRT practice and guidance from the IAEA and OECD/NEA (IAEA, 2022; OECD NEA, 2017), a fusion-specific PIRT framework is developed and implemented. At the time of this study, Chartreuse-P was in an early design safety-definition phase, and the PIRT objective was to identify safety-significant phenomena, major knowledge gaps, and priorities for analysis, testing, and model development rather than to qualify a final design.

The following sections describe the adapted methodology, including the definition of systems and scenarios, expert elicitation and ranking of phenomena, and a complementary quantitative scoring approach. The resulting PIRT provides a structured basis for prioritizing safety-relevant research and supports the development of a credible safety case for next-generation fusion power plants (Figure 1).

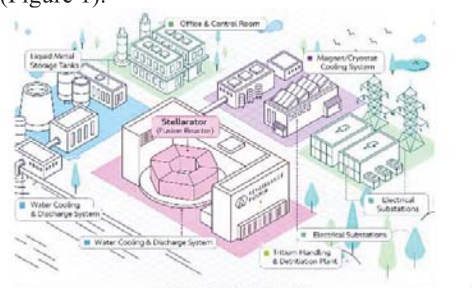

Figure 1 General layout of the Chartreuse P Fusion Power Plant

2. PIRT Framework And Adaptation To Fusion Systems

The Chartreuse-P 1 GWe stellarator project, currently in an early design and safety-definition phase at Renaissance Fusion, adopts a PIRT methodology aligned with established nuclear safety frameworks. Building on fission reactor applications, the approach follows guidance from the U.S. NRC and Pacific Northwest National Laboratory (e.g. NUREG/CR-7307 (NRC, 2024); PNNL-28437 (Geelhood and Luscher, 2019)), lessons from prior PIRT exercises (OECD NEA, 2017), and fusion-specific safety insights (Panayotov, 2018). Formal PIRT applications in fusion remain scarce; consequently, Chartreuse-P represents one of the first comprehensive PIRT implementations for a fusion power plant.

The standard PIRT process was adapted to account for fusion-specific features, including a plasma-facing liquid metal (Li–Pb) blanket, advanced plasma-facing components, and superconducting magnet and cryogenic systems. In addition to traditional confinement and structural criteria, fusion-specific safety functions were defined, such as plasma stability, tritium confinement, and magnet cryogenic integrity. Novel fusion-relevant scenarios, including lithium evaporation events and magnet quenches, were explicitly introduced. The resulting framework applies PIRT consistently across all Chartreuse-P subsystems that may influence plant safety, performance, or reliability, ensuring systematic treatment of multi-physics interactions inherent to stellarator designs.

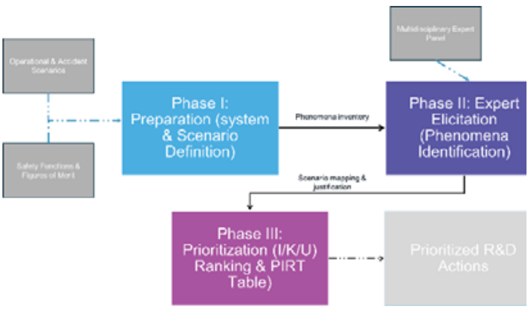

Figure 2 PIRT workflow developed in this study

Figure 2 summarizes the fusion-adapted PIRT workflow implemented for the Chartreuse-P fusion power plant. The methodology is structured into three main phases. Phase I (Preparation) defines the system scope, safety functions (figures-of-merit), and a representative set of normal and off-normal scenarios. Phase II (Expert Elicitation) involves a multidisciplinary expert panel to identify and characterize safety-relevant phenomena for each subsystem and scenario. Phase III (Prioritization and Ranking) evaluates each phenomenon according to its Importance, Knowledge, and Uncertainty (I/K/U), yielding a ranked PIRT matrix that supports design decisions and R&D prioritization. Key inputs and outputs of the process are indicated by dashed connections.

2.1. *Phase I: Preparation (System Definition & Scenario Development)*

In Phase I, the System Under Evaluation (SUE) was defined to include all major systems and subsystems of the Chartreuse-P fusion power plant that could affect safety, performance, or uncertainty. These include plasma confinement and heating systems, plasma-facing liquid metal breeder loops, the vacuum vessel and shielding, superconducting magnets and cryostat, cooling and power conversion systems, tritium fuel cycle and detritiation systems, and supporting balance-of-plant and safety systems. This comprehensive scope ensures that cross-system interactions, such as plasma transients affecting vacuum systems or magnet faults impacting blanket behavior, are explicitly captured.

Subsystems were assigned to dedicated technical working groups (plasma physics; MHD and thermal-hydraulics; materials and tritium; magnet and cryogenics; safety and licensing), consistent with NRC system-level PIRT guidance. Each group defined system functions, boundaries, assumptions, and interfaces relevant to safety evaluation.

Safety Functions (Figures of Merit): were established to guide subsequent PIRT scoring. These included maintaining vacuum vessel integrity, ensuring plasma confinement and stability, controlling tritium inventory, preventing energetic or chemical reactions (e.g. lithium fires or hydrogen release), containing activation products such as dust and aerosols, and preserving magnet and cryogenic system safety. Defining these figures-of-merit upfront ensured that all subsequent evaluations remained explicitly safety-focused. Quantitative operating bounds (e.g. temperature and pressure ranges, 10.2 T magnetic field, neutron flux levels, allowable impurity concentrations) were also collected to anchor scenario definitions.

A structured set of representative operational, transient, and accident scenarios was then developed based on design and safety documentation. These included normal operation and startup/shutdown, off-normal events such as partial loss of liquid-metal flow or vacuum degradation, and bounding accident conditions including plasma–liquid metal interface excursions, magnet quenches, cryogenic failures, vacuum vessel breaches, and lithium or hydrogen release events. Each scenario was classified by initiating mechanism, operational phase, characteristic timescale, and confinement state. This structured scenario framework ensures explicit linkage between identified phenomena and credible initiating events, forming the basis for systematic PIRT evaluation.

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2.2. *Phase II: Expert Elicitation and Phenomena Identification*

Phase II employed a structured expert-elicitation process consistent with NRC and PNNL guidance to identify safety-relevant phenomena for each system and scenario. A multidisciplinary panel of approximately fifteen experts was convened, covering plasma physics, MHD and thermal-hydraulics, materials and chemistry, neutronics, structural mechanics, safety analysis, operations, and instrumentation and control.

The panel reviewed available empirical data from fusion experiments (e.g. ITER, W7-X), fission analogues, and separate-effects tests, including liquid-metal MHD loops, lithium handling experiments, plasma–material interaction studies, and historical incident data. In parallel, state-of-the-art modelling and simulation results were examined, including MHD and CFD analyses of liquid-metal flows, plasma edge transport modelling, structural finite-element analyses, and tritium transport calculations. Particular attention was given to fusion-specific cross-cutting phenomena involving coupled physics, such as plasma–liquid metal interactions, transient high-power plasma events, dust and condensate lifecycles in vacuum systems, and tritium or coolant leak propagation paths. Instrumentation and control-related phenomena affecting detectability and control effectiveness were also explicitly considered.

Using guided brainstorming informed by the Phase I scenario set, each working group produced structured phenomenon statements describing physical mechanisms and potential safety consequences. These were subsequently reviewed and consolidated by the full panel to remove redundancies and ensure consistent terminology. The outcome of Phase II was a comprehensive inventory of approximately one hundred phenomena spanning all major systems, providing the technical basis for prioritization.

Table 1 two sample phenomena from the Chartreuse-P PIRT inventory

	Lithium evaporation & condensation in vacuum spaces	**Magnet quench dynamic loads**
System / Location	Plasma-facing liquid metal (LM) surface; vacuum vessel; vacuum pumping system	Superconducting magnets; cryostat; magnet support structures
Description	Evaporation of Li/LiH from the liquid metal surface during transient plasma–LM interaction, followed by transport and condensation in colder vacuum regions and pumping ducts, leading to pressure excursions and contamination	Sudden loss of superconductivity resulting in rapid coolant boil-off, pressure transients, and mechanical loads on magnet supports and surrounding structures
Representative Scenario(s)	Plasma–LM interface excursion; vacuum pump trip / degraded pumping leading to LM vapour pressure build-up	Magnet quench during operation (superconducting magnet accident scenario)
Operational Phase	Plasma operation; transient; upset conditions	Plasma operation; accident
Confinement State Affected	Primary confinement (vacuum vessel); dynamic confinement via vacuum system	Secondary confinement (cryostat); structural integrity of safety-related supports

Table 1 illustrates two representative phenomena from the Chartreuse-P PIRT inventory, showing how each phenomenon is mapped to specific systems, scenarios, operational phases, and confinement states. This explicit scenario mapping is a key innovation of the fusion PIRT approach and ensures full traceability between identified phenomena and credible initiating events within an MBSE framework.

2.3. *Phase III: Prioritization, Ranking and PIRT Table Development*

In Phase III, each identified phenomenon was evaluated using the standard PIRT axes of Importance (I), Knowledge (K), and Uncertainty (U), following NRC and OECD/NEA guidance with minor adaptations for fusion terminology. Importance reflects the potential impact on defined safety functions, independent of likelihood. Knowledge captures the maturity of understanding and predictive capability under reactor-relevant conditions, while Uncertainty represents the degree to which outcomes remain poorly bounded or subject to expert disagreement.

Initial I/K/U scores were proposed by subsystem teams based on evidence from Phase II and were subsequently reviewed by the full expert panel to ensure consistency across domains. Common criteria were agreed for high-impact safety challenges, such as loss of tritium confinement or magnet integrity. Knowledge and uncertainty rankings explicitly considered limitations in experimental validation and modelling maturity, particularly for fusion-specific phenomena extending beyond existing databases. Where expert disagreement persisted, conservative uncertainty rankings were adopted.

Based on the resulting I/K/U evaluations, phenomena were grouped into three priority classes: P1 (high importance and low knowledge), P2 (intermediate cases), and P3 (lower consequence or well-understood phenomena). Uncertainty rankings were used to highlight urgency within each priority class. The resulting PIRT matrix provides a ranked and traceable representation of safety-relevant phenomena for Chartreuse-P and forms a living reference to be updated as design maturity and knowledge evolve

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3. Results and Discussions

3.1. *Overview of PIRT Outcomes*

Application of the adapted PIRT methodology to the Chartreuse-P stellarator fusion power plant produced a comprehensive, system-wide inventory of safety-relevant physical phenomena spanning plasma physics, liquid-metal thermo-hydraulics, magnet and cryogenic systems, materials and chemistry, neutronics, tritium management, and confinement and exhaust systems. To date, more than one hundred distinct phenomena have been identified and mapped to representative operational, off-normal, and accident scenarios, following established NRC and OECD/NEA PIRT practices.

For each phenomenon–scenario pair, the PIRT matrix provides an explicit ranking of Importance (I), Knowledge (K), and Uncertainty (U) with respect to clearly defined safety functions. This structure ensures traceability between physical phenomena, the safety functions they challenge, and the resulting safety or licensing concerns, consistent with best-estimate plus uncertainty (BEPU) principles (NRC, 2012). A key outcome is the clear stratification of phenomena into priority classes P1, P2, and P3, enabling focused identification of dominant safety drivers and critical knowledge gaps relevant to the Chartreuse-P safety case.

In addition to the qualitative I/K/U ranking, a quantitative PIRT-based scoring framework was applied to further prioritize the phenomena. Each phenomenon was rated on a discrete 1–5 scale for four knowledge-related attributes—(a) level of physical understanding, (b) maturity of engineering-level models, (c) maturity and validation status of high-fidelity numerical simulations, and (d) availability of experimental data under relevant or representative conditions—as well as for a criticality attribute reflecting the potential of the phenomenon to challenge primary safety functions. A Knowledge Score ($KS = a \cdot b \cdot c \cdot d$) and a Global Score ($GS = KS/CS$) were then computed to support relative prioritization he Criticality Score (CS) is assigned directly from the criticality rating. Low GS values identify phenomena that combine high safety significance with limited knowledge or validation. All P1 phenomena exhibit among the lowest Knowledge Scores and Global Scores, reflecting their combination of high importance and limited understanding. Representative examples of high-, medium-, and low-priority phenomena are shown in Table 2, while the resulting GS ranking is illustrated in Figure 3.

Table 2 Example PIRT scoring for selected phenomena (high-, medium-, and low-priority), a: Understanding, b: Model Maturity, c: CFD/MHD Maturity, d: Data Availability. KS: Knowledge Score CS: Criticality Score GS: Global Score .

Phenomenon	a	b	c	d	KS	CS	GS	Priority
Plasma–LM interface excursion (Li evaporation & aerosol)	2	2	1	1	4	5	0.8	P1
MHD flow redistribution in blanket channels	4	3	3	3	108	3	36	P2
Thermal expansion of piping (within design limits)	5	5	5	5	625	1	625	P3

As shown in Table 2, a P1 phenomenon such as a plasma–liquid metal interface excursion combines very low knowledge with the highest criticality, yielding a very low GS. In contrast, better-understood or lower-impact phenomena produce higher GS values. This quantitative ranking is fully consistent with the qualitative PIRT priority tiers and allows additional discrimination within a given priority class.

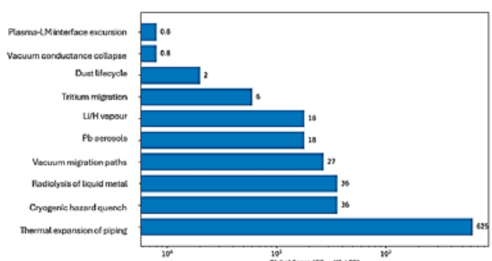

Figure 3 Global score (GS = KS/CS) used for final prioritization

3.2. *Dominant Safety-Relevant Phenomena*

3.2.1. *High-Priority (P1) Phenomena*

P1 phenomena are predominantly associated with fusion-specific interfaces and strongly coupled multi-physics processes rather than isolated component failures. This is consistent with earlier fusion safety studies highlighting the central role of plasma-facing, liquid-metal, vacuum, and magnet systems.

Table 3 presents representative P1 phenomena identified for Chartreuse-P. These phenomena are characterized by high safety consequences, limited experimental validation under fusion-relevant conditions, and significant uncertainty. Many involve direct challenges to fundamental safety functions such as confinement integrity, tritium inventory control, plasma stability, and magnet structural or cryogenic safety. Their identification as P1 outcomes aligns with prioritization logic applied in fission PIRT studies (NRC, 2024; OECD NEA, 2017).

Table 3 examples of P1 phenomena identified in the Chartreuse-P PIRT

Phenomenon	Primary Safety Functions Challenged	I	K	U
Plasma–liquid metal interface excursion (Li/LiH evaporation, Pb aerosolization)	Plasma stability; tritium confinement; source-term control	H	L	H
Vacuum system conductance collapse due to condensation and dust loading	Confinement integrity; mobilizable source-term control	H	L	H
Dust and aerosol lifecycle (generation → transport → re-entrainment)	Activation product containment; worker dose	H	L	H
Magnet quench–induced thermo-mechanical transients	Structural integrity; cryogenic safety	H	M	M

Phenomenon	Primary Safety Functions Challenged	I	K	U
Tritium transport outside breeder loop (vacuum, deposits, joints)	Tritium inventory control	H	L	M

3.2.2.*Medium-Priority (P2) Phenomena*

P2 phenomena generally correspond to processes that are either well understood in other nuclear or industrial contexts but applied here in novel configurations, or that indirectly challenge safety functions by eroding operational margins. Examples include MHD-driven flow redistribution in complex blanket channels, long-term material corrosion and erosion in liquid-metal environments, degradation of diagnostics and instrumentation, and thermal stratification during partial loss-of-flow events.

Although individually less critical than P1 phenomena, P2 phenomena may escalate when combined, reinforcing the importance of system-level and scenario-based analysis. As such, many P2 items warrant continued monitoring and targeted study.

3.2.3.*Lower-Priority (P3) Phenomena*

P3 phenomena are typically bounded by existing design provisions, associated with mature technologies, or analogous to well-characterized fission or industrial processes. These phenomena are documented to ensure completeness but do not currently drive safety-critical R&D or design decisions, consistent with graded PIRT application principles. They are periodically reviewed to confirm their continued low priority as the design evolves.

The overall distribution of phenomena in the Importance–Knowledge space is shown in Figure 5, which illustrates the clustering of P1 phenomena in the high-importance, low-knowledge region.

Figure 3 importance-knowledge matrix for identified PIRT phenomena

3.3.*Cross-System and Coupled Effects*

A central outcome of the Chartreuse-P PIRT is the dominance of cross-system phenomena arising at interfaces between plasma physics, liquid-metal behavior, vacuum systems, and materials chemistry. Examples include plasma radiative instabilities triggered by transient metal vapour influx, vacuum degradation due to condensation and dust deposition, and magnet quench events inducing liquid-metal drainage and structural loading. These results reinforce the conclusion that interface phenomena, rather than isolated component failures, represent the primary licensing challenge for fusion power plants.

3.4.*Knowledge Gaps and Uncertainty Drivers*

The Knowledge and Uncertainty rankings highlight systematic gaps, including the lack of integrated experiments combining plasma exposure, strong magnetic fields, liquid metals, and high temperatures; scaling uncertainties from laboratory tests to full-scale stellarator geometry; sparse data on dust lifecycle behaviour; and incomplete tritium accounting outside breeder loops. These gaps correspond to phenomena with Low Knowledge and/or High Uncertainty and indicate areas where model validation and experimental programs are most urgently needed. Until such gaps are closed, conservative design margins and uncertainty treatment remain essential.

3.5. *E. Implications for Design, R&D, and Licensing*

The Chartreuse-P PIRT results directly inform (i) prioritization of R&D programs targeting high-priority knowledge gaps, (ii) safety-driven design refinements in areas such as vacuum pumping, liquid-metal handling, and magnet protection, (iii)

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instrumentation and monitoring enhancements to improve early detection and mitigation, and (iv) licensing strategy. By providing traceable linkage from phenomena to scenarios, safety functions, and mitigation measures, the PIRT strengthens the credibility and transparency of the safety case. Consistency between expert-based and quantitative rankings further enhances confidence in the prioritization.

3.6. *Lessons Learned on Applying PIRT to Fusion*

This first application also provided methodological lessons. For a first-of-a-kind fusion system, PIRT is most valuable not as a definitive ranking tool, but as a traceable framework for making assumptions, interfaces, and knowledge gaps explicit. Compared with fission, the fusion PIRT was more strongly driven by cross-system phenomena, requiring clearer scenario definition and closer integration of multiple expert domains. The Importance/Knowledge/Uncertainty logic remained applicable, but knowledge scoring had to reflect limited reactor-relevant data and greater reliance on expert judgement. Overall, for fusion, PIRT is best used as an iterative tool for design guidance and R&D prioritization.

4. *Conclusion*

This work establishes the Phenomena Identification and Ranking Table (PIRT) methodology as a useful framework for fusion power plant safety assessment. We presented the first comprehensive fusion PIRT, applied to the Chartreuse-P 1 GWe stellarator, and showed how the method can be adapted to fusion's multi-physics challenges. The framework combines expert elicitation, quantitative scoring of knowledge and importance, and deterministic validation, and shows that in a first-of-a-kind system PIRT is especially valuable as a traceable, iterative process for structuring expert judgement and prioritizing work under high epistemic uncertainty. Key findings from the Chartreuse-P PIRT include the importance of interface phenomena, such as plasma–liquid metal interactions and vacuum–materials effects, and the identification of major knowledge gaps, including dust behavior and tritium migration outside the fuel cycle. The results directly informed design refinements and helped prioritize experiments and modelling needs. More generally, the exercise showed that fusion PIRTs require stronger scenario definition and interface management than typical fission applications. PIRT therefore provides a transparent basis for safety-case development and risk-informed decision-making as fusion systems progress toward commercial deployment.

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