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D4.2 Target Accuracy Requirements for
the modelling of safety-related
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Executive Summary

This deliverable presents a preliminary framework for the definition of Target Accuracy Requirements (TARs) for modelling and simulation tools supporting the safety assessment of Molten Salt Reactors (MSRs), with particular attention to circulating-fuel concepts. Building on the Phenomena Identification and Ranking Table (PIRT) exercise performed in Task 4.1 of ENDURANCE, the work identifies safety-relevant phenomena, Figures of Merit (FoMs), and physical parameters for which predictive accuracy requirements should be established. Defining TARs for circulating-fuel MSRs presents specific challenges due to the strong coupling between neutron kinetics, fuel circulation, thermal hydraulics, heat transfer, and salt chemistry. These interactions introduce additional uncertainties and dynamic effects, while limited experimental evidence and operational experience constrain model validation. The proposed approach therefore addresses not only the accuracy of individual safety-related quantities but also the predictive capability, phenomenological completeness, and validation maturity of computational models.

The assessment combines the outcomes of the PIRT exercise, interactions with reactor designers and experts, and a review of the scientific and technical literature. Three main groups of safety-relevant phenomena are considered: (i) nuclear-driven phenomena and power excursions; (ii) heat removal, natural circulation, and thermal stratification; and (iii) operational support, reactor control, instrumentation, and observability. The analysis also identifies emerging modelling challenges, including circulation-dependent delayed-neutron kinetics, persistent power fluctuations, complex recirculation structures, thermal-hydraulic regime transitions, and coupled thermochemical phenomena. These observations require further investigation and validation. The main outcome is a preliminary set of qualitative and quantitative TARs covering reactor physics, critical loading conditions, delayed-neutron precursor transport, thermal-hydraulic behaviour, power excursions, decay heat removal, and operational control. Particular attention is given to the relationship between modelling accuracy and engineering decisions, including reactor controllability, equipment sizing, identification of circulation-regime transitions, and preservation of safety margins. Representative numerical targets include $\pm 7\text{--}10\%$ for critical loading conditions, $\pm 10\text{--}15\%$ for deposited energy during power excursions, $\pm 10\%$ for the heat-removal efficiency factor, and $\pm 5\text{--}7\%$ for total decay heat generation. The proposed requirements also address *defining parameters*, whose uncertainties influence the reliability of safety and control predictions. The numerical values should be regarded as preliminary engineering targets rather than regulatory acceptance criteria. Several recommendations are based on assessments of selected fast-spectrum, chloride-fuelled MSR configurations, and their applicability to other reactor concepts remains to be demonstrated. Further sensitivity analyses, uncertainty quantification, numerical assessments, and experimental validation will be required to consolidate and progressively refine the proposed requirements.

Keywords

Molten Salt Reactors (MSRs); Target Accuracy Requirements (TARs); Nuclear Safety Assessment; Multiphysics Modelling and Simulation; Uncertainty Quantification.



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1 Introduction

The objective of this deliverable is to establish a preliminary set of Target Accuracy Requirements (TARs) for the modelling and simulation of safety-relevant phenomena in molten salt reactors (MSRs), building upon and extending the outcomes of the Phenomena Identification and Ranking Table (PIRT) exercise performed in Task 4.1. The assessment also incorporates additional safety-relevant phenomena and modelling needs identified throughout the project.

The proposed TARs define the level of predictive accuracy required to support safety analyses, considering the relevant Figures of Merit (FoMs), associated acceptance criteria, and the corresponding uncertainties. Owing to the limited availability of representative experimental data and the varying maturity of MSR concepts, modelling approaches, and supporting databases, the requirements are formulated at different levels of confidence and technical detail.

These TARs are intended to provide an initial framework for sensitivity analyses, uncertainty quantification, and model assessment. They also serve as a basis for further refinement through the numerical evaluations presented in the appendix to this deliverable and through subsequent activities within WP4.



2 Context, Definitions and Structure of deliverable

Reminding that any nuclear reactor is fundamentally a thermal energy generation system [1] one could say that reactor core converts nuclear energy into heat, while the overall plant converts that heat into a useful energy product demanded by the end user, such as electricity, heat, hydrogen, or desalinated water. The reactor should therefore be viewed as part of an integrated energy-conversion chain rather than as an isolated source of power.

For molten-salt reactors, heat generation, heat transport, and fuel motion are intrinsically coupled. Unlike solid fuel reactors, the heat-generating medium itself circulates through the system, carrying fissile material, delayed-neutron precursors, thermal energy, and dissolved chemical species. Consequently, thermal power generation, thermal-hydraulic response, and reactor kinetics evolve simultaneously and cannot be treated independently.

In many proposed designs, the secondary salt circuit performs additional functions beyond heat transport. Owing to its thermal inertia and heat capacity, it may act as a thermal buffer between the fluctuating primary heat source and downstream energy-conversion systems. Such thermal buffering improves operational flexibility but also introduces additional safety and licensing questions associated with large thermal inventories, heat storage, fuel-salt leakage into secondary systems, and potential re-criticality scenarios [2].

The presence of circulating fuel introduces a more fundamental issue. In conventional reactors, reactor power, fission rate, neutron population, and reactivity are often assumed to be closely related. In circulating-fuel systems this relationship becomes less direct because fuel transport, delayed-neutron precursor motion, thermal-hydraulic delays, and spatial redistribution of fissile material introduce additional dynamic degrees of freedom. Reactor state is therefore influenced not only by local conditions but also by the history of fuel motion and heat transport throughout the entire system [3].

Consequently, several quantities routinely used for monitoring and control become reconstructed rather than directly measurable variables. Measurements of thermal power may depend on local flow conditions and thermal history. Similarly, inferred reactivity may no longer provide a unique description of the neutronic state because delayed-neutron transport, precursor trapping, circulation delays, and spatial power redistribution may all influence reactor behaviour. The system therefore exhibits memory effects and distributed feedback mechanisms that are largely absent from conventional solid fuel reactors [4].

These characteristics have important implications for modelling and simulation. The challenge is not limited to numerical solutions of the governing equations. It also concerns identification of the phenomena controlling reactor behaviour, formulation of appropriate Figures of Merit, assessment of observability and controllability, and establishment of validation strategies capable of demonstrating predictive capability under representative conditions. For many coupled phenomena, particularly those associated with power excursions, precursor transport, circulation instabilities, and control-system response, direct full-scale experimental demonstration may be impractical or impossible [5].

This creates a need for quantitative requirements on model performance. Such requirements may be expressed through Target Accuracy Requirements (TARs), which define the admissible uncertainty in model predictions consistent with preservation of engineering decisions, safety



conclusions, operational strategies, and licensing arguments. In practice, TARs establish a link between model uncertainty and safety-relevant Figures of Merit, thereby providing quantitative objectives for model development, verification, validation, and uncertainty evaluation.

The objective of the present work is not to develop a complete safety case for molten-salt reactors but to identify the principal phenomena, Figures of Merit, and governing model parameters that require dedicated accuracy targets. Attention is devoted to the interaction among reactor physics, thermal hydraulics, fuel transport, salt chemistry, controllability, and observability, since these interactions largely determine the predictive capability required from analysis tools intended for design, safety assessment, operational support, and future licensing activities.

The report is organized into four parts. The first reviews the concept of TARs and its relationship with the Best Estimate Plus Uncertainty (BEPU) methodology. The second summarizes key developments that emerged during the project and influenced the understanding of molten-salt-reactor behaviour, control, and safety assessment. The third identifies the principal classes of safety-relevant phenomena and proposes corresponding TARs for governing parameters and Figures of Merit. The fourth provides a synthesis of the main findings and outlines priorities for future research, validation programs, and development of technology.



3 Historical remarks on TARs and BEPU

Target Accuracy Requirements (TARs) can be considered from two complementary perspectives. On the one hand, TARs define the accuracy needed to support the design and deployment of nuclear technology. If the uncertainty associated with a relevant quantity exceeds the acceptable TAR, the corresponding design approach may not be sufficiently supported for deployment or licensing [6]. On the other hand, TARs can be formulated for individual models and computational tools. In many cases, however, the uncertainty associated with the model itself is already smaller than the uncertainty that is inevitably present in the physical input data and system parameters. This creates an important question of how the available accuracy should be distributed between input data, physical models, and the overall simulation chain.

The history of development of nuclear-data adjustment provides an important example of this problem. Work by Salvatores and collaborators demonstrated that integral reactor experiments could be used to adjust nuclear cross-section data to improve the consistency between calculations and measurements. The Superphénix start-up experiments provided an important example of this approach, where integral information was used to identify and reduce deficiencies in the nuclear-data set [6].

At the same time, comparisons of reactor parameters obtained with different generations of nuclear-data libraries have shown that replacing individual nuclear-data evaluations does not necessarily improve agreement with integral reactor measurements. This can result from compensation effects between different nuclear-data components. Such compensation does not need to be introduced explicitly during library preparation or few-group constant generation. It may arise naturally from the combined effect of several imperfect data components and the successive processing steps used to obtain the parameters applied in engineering reactor calculations. Energy condensation, self-shielding, homogenization, leakage and buckling treatments, and other approximations can therefore contribute to an overall compensation of individual discrepancies.

An older library may consequently provide better agreement with a particular reactor observable than a newer library, even when the newer library contains improvements in individual nuclear-data evaluations. The agreement obtained at the integral reactor level can therefore reflect compensation of errors accumulated across the modelling and data-processing chain rather than the accuracy of individual input data alone. This provides an early example of a more general problem in uncertainty quantification: improving the accuracy of individual model components does not necessarily improve the accuracy of the complete coupled calculation.

It should, however, be remembered that during the period when the adjustment of nuclear data and the development of computational tools were both costly and resource-intensive, the phenomenology of most reactor systems under consideration was already relatively well understood. Many of the governing physical mechanisms had been investigated through decades of experimental and theoretical research, while the remaining challenges were often sufficiently narrow to be addressed through targeted studies and expert judgment. As a result, the establishment of accuracy requirements was largely based on a mature understanding of the system's behaviour and on an extensive body of experimental evidence.

Today, the situation is fundamentally different. The nuclear engineering community increasingly faces reactor concepts whose phenomenology is considerably more complex and whose



governing processes involve tightly coupled multi-physics interactions. Equally important, the availability of dedicated experimental facilities, separate-effect tests, and large-scale integral experiments is often limited. Numerous studies and international discussions have highlighted this challenge, emphasizing the gap between the complexity of advanced reactor concepts and the amount of experimental information available for their validation [7].

Consequently, the approach adopted here for the establishment of Target Accuracy Requirements differs from that employed in previous generations of reactor studies. Owing to the limited phenomenological knowledge and the scarcity of validation evidence in some areas, the proposed framework incorporates not only fully quantified requirements but also semi-quantitative and qualitative requirements wherever a robust numerical specification cannot yet be justified.

In fact, the novelty of the present work lies not merely in the proposed values of TARs, but in the attempt to formulate TARs before a fully mature experimental and phenomenological basis exists. The challenge is therefore not only to determine how accurate a model should be, but also to identify which phenomena must be represented, which observables must be measured, and which evidence is required before meaningful accuracy requirements can be specified. From this perspective, TAR definition becomes inseparable from the broader problem of establishing predictive capability for advanced molten-salt reactor systems.

The application of Target Accuracy Requirements (TARs) in a regulatory framework is closely linked to the implementation of the Best Estimate Plus Uncertainty (BEPU) methodology. Although BEPU was originally developed for thermal-hydraulic licensing analyses of light-water reactors, it is increasingly regarded as a broader framework for risk-informed safety assessment of advanced nuclear systems [8], [9].

This evolution reflects a more general change in nuclear engineering. Modern reactor concepts are characterized by novel physical phenomena, limited operating experience, and reduced availability of representative experimental data. Under such conditions, safety cannot be demonstrated solely through conservative assumptions. Instead, it requires a scientifically defensible assessment of predictive capability, uncertainty, and safety margins.

Recent developments in the United States, including technology-inclusive and risk-informed licensing approaches, emphasize the identification of safety-significant functions, phenomena, and performance measures rather than reliance on technology-specific analytical procedures. In parallel, the European BEPU community increasingly views uncertainty analysis not as an isolated statistical exercise but as an integrated framework linking physical understanding, experimental evidence, model validation, and regulatory decision-making.

From this perspective, a model should not be regarded as suitable for safety assessment merely because uncertainty bands can be calculated. Rather, uncertainty quantification has value only when the underlying physical models demonstrate adequate predictive capability within their intended domain of application. Consequently, validation, applicability assessment, and representativeness of experimental evidence become prerequisites for meaningful uncertainty analysis and for the establishment of TARs.

For conventional reactors, TARs were generally formulated for quantities directly related to safety margins, such as peak fuel temperature, cladding temperature, pressure, or critical heat flux. Molten-salt systems, however, require a substantially broader perspective because the



reactor itself is a strongly coupled multi-physics system in which neutronics, fuel transport, thermal hydraulics, chemistry, and heat removal evolve simultaneously.

Therefore, TARs for molten-salt reactors should be established not only for traditional Figures of Merit but also for quantities governing the predictive capability of the underlying physical models. These include:

- neutron multiplication and reactivity coefficients;
- delayed-neutron precursor transport and inventory distributions;
- spatial and temporal power distributions;
- temperature and flow fields;
- heat-transfer coefficients and heat-removal rates;
- salt composition evolution and fuel inventory redistribution;
- characteristic time scales of thermal, hydraulic, and neutronic feedback;
- stability margins and observability-related parameters.

In this sense, the challenge extends beyond defining acceptable uncertainties for individual safety parameters. It requires the establishment of TARs for the physical processes themselves, ensuring that the coupled system dynamics are represented with sufficient accuracy to support reliable prediction, safety assessment, control-system design, and licensing decisions.

Indeed, for circulating-fuel molten-salt reactors, the principal question is not only *how accurately a given safety parameter must be predicted*, but also *which phenomena must be represented with sufficient fidelity for the prediction itself to be meaningful*. Consequently, TAR development becomes inseparable from the broader task of establishing predictive capability and validation strategies for advanced reactor technologies.

In other words, unlike traditional reactor applications, where TARs are primarily associated with safety-related output quantities, TARs for molten-salt reactors must also address the accuracy with which key coupled phenomena are represented. In this sense, TARs become not merely criteria for uncertainty acceptance but quantitative requirements on the predictive capability of the entire modelling and simulation framework.



4 Objectives and Baseline

As noted above, numerical modelling and simulation have become an inseparable component of virtually every advanced nuclear technology. Design development, design optimization, safety assessment, manufacturing support, commissioning, operation, maintenance, and lifetime management all rely, to varying degrees, on predictive computational tools and models.

This situation differs markedly from that of previous generations of nuclear technologies. Historically, many reactor concepts were developed based on extensive experimental programs, prototype testing, and engineering experience, while numerical simulations were often used as supporting tools rather than as central elements of the technological process. In contrast, the complexity of modern nuclear systems and the limited availability of large-scale experimental facilities make modelling and simulation an essential source of design knowledge rather than merely a means of interpreting experimental observations.

Today, it is difficult to regard technology as genuinely mature if its design, operation, and safety justification cannot be supported by an adequate modelling and simulation framework. In many cases, a technological concept effectively exists only to the extent that it can be represented, analysed, and ultimately controlled through predictive computational models.

Safety assessment is now inconceivable without the use of validated numerical tools capable of providing reliable predictions of reactor behaviour under both normal and off-normal conditions. Consequently, the question is no longer whether simulations should be used, but rather what level of predictive capability, validation, and uncertainty quantification is required for their results to be accepted with sufficient confidence [10].

Therefore, the objective is to create the necessary scientific and methodological basis for a comprehensive framework in which modelling and simulation are treated not merely as engineering support tools but as integral components of the technology itself. Within such a framework, Target Accuracy Requirements become quantitative measures of the predictive capability required for design, operation, control, safety assessment, and licensing of molten-salt reactor systems.

Since the discussion is concerned with the application of numerical tools within a risk-informed framework, the models and simulation tools involved must satisfy several fundamental requirements.

The first requirement is sufficient predictive capability maturity. The underlying physical models, numerical methods, and assumptions must be firmly grounded in physical reality and capable of reproducing the relevant phenomena with adequate accuracy. A simulation tool cannot support risk-informed decision-making unless its predictions can be demonstrated to be representative of the system under investigation.

The second requirement is the demonstrable superiority of advanced modeling over traditional conservative approaches. The adoption of a best-estimate methodology is justified only if it provides information that cannot be obtained through the systematic penalization of input data, models, or results. In practical terms, a best-estimate framework must be capable of reliably distinguishing among scenarios associated with different risk levels and safety margins.



These requirements may be regarded as a first category of high-level qualitative Target Accuracy Requirements (TARs). They form the upper tier of a hierarchical TAR structure, in which progressively more detailed and quantitative requirements are derived at subsequent levels.

Such considerations are particularly important for strongly coupled multi-physics systems such as molten-salt reactors. When one or more relevant physical processes are inadequately represented, the uncertainty associated with the neglected phenomena may become sufficiently large to dominate the overall assessment. Under such circumstances, the resulting uncertainty may be considered practically unbounded from a decision-making perspective.

Excessive uncertainty may also lead to a loss of discriminatory capability. Distinct initiating events, accident scenarios, or design vulnerabilities may become statistically indistinguishable within the prediction uncertainty. In this case, the risk assessment loses much of its practical value because it can no longer support prioritization among competing safety concerns. Consequently, excessive overestimation of uncertainty may be nearly as detrimental as underestimation, since both can impair rational decision-making.

Finally, methodologies, models, and computational tools should demonstrate credible proof of concept. Their applicability should be supported by systematic verification and validation activities or, at a minimum, by evidence demonstrating readiness for future validation programs. Given the current developmental stage of many molten-salt reactor concepts, such validation readiness should itself be considered a high-level TAR and a prerequisite for meaningful uncertainty quantification and risk-informed safety assessment.

For advanced molten-salt reactors, the ability to validate may be as important as the ability to predict. A model whose predictions cannot, in principle, be confronted with experimental evidence cannot constitute a reliable basis for risk-informed decision-making, regardless of its mathematical sophistication.

The baseline for achieving the present objective rests on three principal pillars: (i) the Phenomena Identification and Ranking Table (PIRT) process as a key element of the BEPU methodology; (ii) close interaction with reactor designers and concept developers to understand the rationale underlying ongoing design choices; and (iii) a comprehensive review of the literature on advanced reactor concepts, safety assessment methodologies, modelling and simulation, verification and validation, and uncertainty quantification.

The first pillar, the PIRT process, provides a structured framework for identifying safety-significant phenomena and the principal sources of uncertainty affecting model predictions. Within the present study, PIRT served as the primary mechanism for the identification and prioritization of uncertainty sources relevant to risk-informed analyses. Although the initial intention was to perform an exercise approaching a Quantitative PIRT (Q-PIRT), the available information ultimately supported a more traditional expert-driven process. Nevertheless, the exercise proved highly valuable, revealing significant differences in expert views regarding dominant physical mechanisms, feedback processes, and safety-significant interactions. As a result, PIRT contributed not only to the prioritization of phenomena but also to the identification of knowledge gaps and areas requiring further investigation.

The second pillar, continuous interaction with reactor designers and subject-matter experts, pursued two objectives. First, it provided insight into the scientific and engineering rationale behind the evolution of current reactor concepts. Second, it helped distinguish between design



features that are likely to evolve during subsequent development stages and those that are expected to remain largely invariant because of fundamental physical, technological, economic, or licensing constraints.

The third pillar, the literature review, provided a broader perspective on advanced reactor development, safety methodologies, model validation practices, and uncertainty quantification approaches. It enabled the identification of common methodological challenges, recurring best practices, and lessons learned from previous studies. In addition, the available literature offers valuable information regarding expected model accuracy, predictive capability, uncertainty treatment, and the level of evidence generally required to support risk-informed decision-making.

Taken together, these three pillars provide complementary sources of knowledge. The PIRT exercise identifies what is important, interactions with designers explain why it is important, and the literature review indicates how similar challenges have been addressed elsewhere. Their combination establishes a robust foundation for the development of Target Accuracy Requirements for advanced molten-salt reactor systems.

4.1 First pillar: PIRT and its main statements

The Phenomena Identification and Ranking Table (PIRT) process provided a structured basis for identifying the physical phenomena, mechanisms, and interactions most relevant to the safety and performance of molten-salt reactor systems. While conventional PIRT exercises are typically organized around accident sequences, the limited operational experience available for advanced molten-salt concepts suggests that a phenomenon-oriented approach is more appropriate than a scenario-oriented one. In other words, the primary objective is not merely to identify bounding transients but to determine which physical processes must be represented with sufficient fidelity to support credible safety assessments.

Viewed from this perspective, the identified phenomena naturally cluster into three interconnected families. The first comprises processes governed primarily by nuclear heat generation and reactivity effects, including power excursions and other reactivity-driven transients. The second encompasses processes controlled by the balance between heat generation and heat removal, where residual heat, fuel circulation, heat transfer, and thermal inertia determine system evolution. The third involves observability, controllability, instrumentation, and monitoring, recognizing that awareness of evolving system conditions is itself an essential component of safety provision.

This classification highlights two principal drivers governing reactor behaviour: nuclear power generation, including both controlled and uncontrolled reactivity changes, and residual-heat production following power reduction or shutdown. Against these drivers stand a limited number of mechanisms responsible for degradation of safety margins and barriers, notably excessive temperature, corrosion and erosion processes, redox-induced material degradation, and progressive loss of structural resistance.

Several representative transients repeatedly appeared throughout available PIRT studies. Reactivity-driven events such as unprotected transient overpower scenarios are governed predominantly by reactor-physics effects. Station-blackout conditions are largely controlled by residual heat and heat-removal capability. Loss-of-fuel or loss-of-coolant situations are strongly influenced by thermal-hydraulic behaviour and heat-transfer processes. Although different in



character, these transients are linked by a common set of underlying phenomena involving energy generation, energy accumulation, heat transport, and material response.

An important observation emerging from the PIRT review is that many safety-significant quantities cannot be evaluated solely through conservative assumptions without imposing excessive penalties on the design. Source-term evaluation, radionuclide transport, energy deposition, fuel enthalpy evolution, decay heat, and barrier degradation increasingly require mechanistic models capable of representing the underlying physics rather than purely conservative bounding approaches. Consequently, the role of modelling is not limited to reproducing reactor behaviour but extends to reducing epistemic uncertainty and supporting technically justified decisions.

The same conclusion applies to reactor operation and control. Stable flow regimes, reliable power determination, and effective control strategies depend on the ability to predict coupled neutronic and thermal-hydraulic behaviour. For circulating fuel systems, reactivity itself becomes a multi-physics quantity influenced simultaneously by fuel motion, temperature distributions, delayed-neutron transport, and inventory evolution. As a result, controllability becomes inseparable from predictive capability.

Several broader conclusions can be drawn from the PIRT exercises. First, realistic bed-type molten-salt reactors are likely to require dedicated shutdown and reactivity-control systems relying on absorber rods, drums, or equivalent control bodies. Consequently, even concepts often perceived as fundamentally different from conventional reactors remain subject to neutron-economy constraints and to the performance limitations imposed by control-system effectiveness. Second, many safety-relevant processes can be analysed using partially decoupled models or weakly coupled multi-physics approaches because one physical domain often dominates the overall response. Third, safety-related decision making requires models possessing sufficient predictive-capability maturity, meaning that uncertainties associated with individual models and coupling strategies must be consistently characterized and supported by validation evidence.

A more fundamental lesson concerns the relationship between safety assessment and available operating experience. In mature reactor technologies, the list of important phenomena is largely determined by accumulated operational knowledge and historical accident analyses. For advanced molten-salt reactors, such a knowledge base remains limited. Consequently, neither expert judgement nor predefined accident sequences alone can provide an entirely satisfactory basis for uncertainty assessment. The number of conceivable scenarios is effectively unlimited, while the available experience is insufficient to identify all potentially bounding cases with confidence.

For this reason, the present work adopts a phenomenon-oriented rather than a purely scenario-oriented perspective. The emphasis is placed on groups of physical processes whose uncertainties govern reactor behaviour across a wide range of operating conditions and transients. These groups include:

- energy deposition and potential mechanical-energy release during power excursions;
- residual and decay heat generation together with associated uncertainties;
- fuel-inventory evolution throughout reactor lifetime;



- fuel circulation, heat transfer, and heat-removal capability;
- reactivity feedback and delayed-neutron transport;
- degradation of structural barriers and material performance;
- observability, monitoring, and control effectiveness.

From the standpoint of Target Accuracy Requirements, the principal outcome of the PIRT process is therefore not the identification of specific accident scenarios but the identification of safety-significant phenomena requiring credible representation. Consequently, TARs should be formulated not only for traditional Figures of Merit but also for the physical processes responsible for their evolution. In this sense, PIRT provides the phenomenological basis for TAR development, while TARs themselves become quantitative expressions of the predictive capability expected from the modelling and simulation framework. The essential regulatory question is therefore not simply whether a model can perform a calculation, but whether it captures the dominant phenomena governing safety with sufficient credibility to support risk-informed decision making.

4.2 Second pillar: Design evolution, controllability and implications for TARs

Discussions with reactor designers and experts involved in concept development proved particularly valuable because they revealed that the problem extends beyond the selection of numerical methods or uncertainty quantification techniques [11]. Several fundamental assumptions concerning the operation, control, and safety assessment of molten-salt reactors evolved during the project, requiring a corresponding revision of both modelling priorities and Target Accuracy Requirements.

A central conclusion emerging from these discussions is that safety, controllability, and observability cannot be considered independently. The logical chain begins with abnormal system states and the consequences they may produce. Identification of abnormal states requires anomaly detection; anomaly detection relies on measurable observables; and meaningful observables can be defined only if the reactor is understood and represented as a controllable dynamical system.

Within this framework, reactivity control remains the primary mechanism for power control. In systems where heat generation and heat removal are inherently unsteady, the absence of direct reactivity control may result in uncontrolled power oscillations, degradation of heat-exchange performance, and progressive reduction of structural margins. Consequently, the capability to predict reactivity effects becomes one of the central requirements imposed on the modeling framework.

At the same time, the issue of reactor observability becomes considerably more complex than in conventional solid-fuel systems. Power can no longer be viewed as a directly measurable quantity. Instead, it must be inferred from indirect observables associated with neutron flux, fuel circulation, activation signatures, thermal-hydraulic conditions, or other measurable indicators. The reliability of such diagnostics therefore depends directly on the predictive capability of the models used to interpret measured signals.

Another important outcome of the design review concerns the role of control systems. The peculiarities of circulating fuel limit the effectiveness of control rods inserted directly into the core



cavity and favor the use of control bodies located in the reflector. However, the achievable control worth of reflector-based systems appears limited, making temperature control and density-related feedback an essential component of the overall control strategy. Consequently, accurate prediction of temperature-dependent reactivity effects becomes simultaneously a design requirement, a safety requirement, and a control-system requirement.

The discussions also revealed phenomena whose importance was not fully appreciated at the initial stage of the project. Among the most significant are fluctuating heat-generation regimes, non-stationary heat exchange, and the appearance of metastable hydrodynamic structures such as recirculation zones, large-scale vortices, and locally trapped fuel volumes. These structures may create regions with distinct delayed-neutron dynamics, effectively introducing multiple precursor drift time scales and transforming fuel circulation into an active component of reactor kinetics.

From a modelling perspective, this observation is particularly important. While conventional molten-salt-reactor analyses often assume a single characteristic precursor transport process, bed-type configurations may require the representation of several interacting precursor populations associated with different flow structures. As a result, the adequacy of point-kinetics and simplified transport assumptions becomes questionable, and considerably stronger requirements emerge regarding the accuracy of coupled neutronic-thermal-hydraulic calculations.

These developments have direct implications for Target Accuracy Requirements. The principal challenge is no longer limited to estimating uncertainties of calculated quantities. Rather, it becomes necessary to demonstrate that the dominant physical mechanisms governing safety, control, and observability are represented with sufficient fidelity. In this sense, TARs become indicators not only of numerical accuracy but also of phenomenological completeness and predictive capability maturity [10].

Double-bounded phenomena and accuracy requirements

Several safety-significant phenomena identified during the design review possess a particularly important characteristic: both overprediction and underprediction may lead to adverse consequences. Such situations naturally define the most demanding TARs.

Examples include:

- Gas-related reactivity excursions, where larger estimated reactivity insertions require stronger structural protection, while the resulting increase in structural dimensions may reduce reflector efficiency and control-system effectiveness.
- Fuel inventory evolution, where conservative assumptions regarding fuel loading may approach solubility limits, increase inventory uncertainty, and create conditions potentially favorable to criticality.
- Decay heat prediction, where overestimation may promote excessive cooling, salt freezing, or precipitation phenomena, while underestimation may lead to excessive temperatures and loss of thermal margins.
- Hydrodynamic heterogeneity and flow redistribution, where metastable vortex structures may generate persistent local overheating or overcooling despite limited influence on global reactivity.



- Heat-exchanger design, where increased structural robustness competes directly with heat-transfer performance, while increased secondary-salt inventory simultaneously improves thermal buffering and aggravates the consequences of potential leakage scenarios.

The common feature of these examples is that safety margins are bound from both sides. Consequently, acceptable prediction uncertainty is determined not only by regulatory acceptance limits but also by the need to distinguish physically meaningful operating states from undesirable ones. For such phenomena, TARs must be derived from the competing constraints governing the viability of the design itself.

Emerging TAR-relevant phenomena

Several additional phenomena identified during concept evolution appear particularly relevant for future TAR development:

- fuel inventory evolution and equilibrium salt composition;
- fuel precipitation and accumulation in low-velocity regions and piping junctions;
- interactions between fuel-solubility limits and criticality margins;
- leakage of fuel-bearing salt into secondary systems and associated criticality concerns;
- competition between thermal-energy buffering requirements and criticality-control requirements;
- time constants associated with heat generation and heat transfer;
- temperature-induced vessel deformation and associated reactivity effects;
- residual heat removal and its influence on fuel redistribution;
- delayed-neutron transport involving multiple characteristic circulation time scales;
- coupling between hydrodynamic structures and reactor kinetics.

Taken together, these observations suggest that future TARs for bed-type molten-salt reactors will have to be formulated not only for traditional safety parameters and Figures of Merit but also for quantities characterizing system controllability, observability, circulation-dependent kinetics, and the interaction between thermal-hydraulic and neutronic time scales. These features may ultimately become as important for licensing and safety demonstration as conventional temperature, power, or reactivity limits.

4.3 Third pillar: Bibliography overview

Several dozens of journal publications, conference papers, technical reports, and regulatory documents were reviewed, analysed, cross-compared, and synthesized to identify recurring methodological trends, unresolved challenges, and common expectations regarding predictive capability, uncertainty quantification, and model validation for advanced reactor systems. The resulting body of evidence was subsequently used as one of the principal inputs to the development of the Target Accuracy Requirements (TARs) discussed in the present work [12].

While the conclusions presented below are derived from this broader body of literature, it is particularly useful to refer to the OECD Nuclear Energy Agency report *Regulatory Perspectives on*



Analytical Codes and Methods for Advanced Reactors [10], because it provides a concise summary of regulatory expectations concerning the credibility of analytical methods and their suitability for safety-related applications. More importantly, the report demonstrates that the questions of predictive capability, validation, uncertainty treatment, and phenomenological completeness are not solely academic concerns but are increasingly recognized as central elements of advanced-reactor safety assessment.

The report consistently emphasizes that the suitability of a computational tool is determined not only by its ability to produce numerical results, but also by the adequacy of the underlying physical models, the quality of verification and validation activities, the treatment of uncertainties, and the ability to identify phenomena not sufficiently represented by the modelling framework. In this respect, regulatory expectations align closely with the general philosophy underlying Target Accuracy Requirements. Before quantitative accuracy targets can be assigned, confidence must exist that the essential safety-relevant phenomena are represented with an appropriate level of fidelity.

For molten-salt reactors, the report identifies several phenomena whose representation may be essential for defensible safety analyses. These include the thermophysical properties of molten salts at elevated temperatures, radiative heat transfer, salt chemistry evolution, tritium generation and transport, corrosion and deposition phenomena, salt-graphite interactions, delayed-neutron precursor transport, reactivity feedback mechanisms, compressibility effects associated with gas bubbles and fuel-salt compression, as well as thermal stratification, internal recirculation, and complex mixing processes within large fluid volumes. Several of these phenomena are either unique to liquid-fuel systems or acquire greater importance than in conventional solid-fuel reactor technologies.

The regulatory significance of these observations extends beyond the phenomena themselves. The report explicitly notes that simplified lumped-parameter approaches may not always be adequate when safety conclusions depend on complex flow structures, recirculation patterns, or spatially varying temperature distributions. At the same time, high-fidelity methods alone cannot be regarded as sufficient if their applicability remains insufficiently demonstrated. The required level of modelling sophistication must therefore be determined by the safety question being addressed and by the demonstrated predictive capability of the analytical methods employed.

In the context of Target Accuracy Requirements, this observation is particularly important. TARs should not be interpreted solely as numerical limits on acceptable prediction error. They also imply requirements concerning phenomenological coverage and model maturity. A highly accurate prediction of an incomplete physical model cannot provide a reliable basis for safety decisions. Conversely, the inclusion of all relevant phenomena without sufficient validation may lead to predictions whose uncertainties remain too large to support practical decision-making.

The report further highlights several areas where significant knowledge gaps remain for molten-salt technologies. Examples include uncertainties associated with thermal scattering data for molten salts, the impact of delayed-neutron drift on reactor kinetics, the coupling between pressure transients and reactivity through compressible gas phases, and the prediction of complex turbulent flow structures in heat-generating fluids. These topics are directly relevant to the establishment of TARs because they define areas where uncertainty may be dominated not by numerical precision but by limitations in phenomenological understanding and validation evidence.



This perspective naturally leads to a hierarchy of requirements. At the highest level, the analytical framework must demonstrate sufficient credibility to support safety conclusions. At an intermediate level, the framework must capture all phenomena capable of materially affecting safety margins, system controllability, or accident progression. Only after these conditions have been satisfied does it become meaningful to formulate quantitative accuracy targets for individual Figures of Merit, safety parameters, or model predictions.

Table 1 Safety-relevant phenomena highlighted in [10] and their implications for TARs development

Area	Safety-relevant aspects	Implications for TARs
Fuel salt and coolant	Thermophysical properties, radiative heat transfer, chemistry evolution, tritium behaviour	Accuracy requirements on material-property models and associated uncertainties
Structural materials	Corrosion, plate-out, fouling, salt-graphite interactions	TARs associated with lifetime predictions, thermal performance, and degradation mechanisms
Reactor kinetics	Delayed-neutron drift, reactivity coefficients, thermal scattering effects	TARs for neutronic models governing dynamic response and safety margins
Thermal hydraulics	Mixing, recirculation, stratification, heat transfer	TARs linked to model fidelity and representation of dominant flow phenomena
Multiphysics coupling	Temperature-reactivity feedback, fuel transport effects	TARs for coupled neutronic-thermal-hydraulic simulations
Accident scenarios	Gas compression effects, pressure-induced reactivity insertions, fuel-processing-system malfunctions	TARs for transient analysis and safety-related Figures of Merit
Validation basis	Availability and representativeness of experimental evidence	TARs on predictive capability maturity and validation coverage

The overall message emerging from the OECD/NEA review is therefore consistent with the broader methodology adopted in the present work. The key issue is not whether a model can calculate a transient, but whether the combination of models, data, validation evidence, and uncertainty assessment provides a sufficiently credible representation of reality for the intended safety application. From this standpoint, Target Accuracy Requirements become not merely measures of numerical performance, but indicators of the predictive capability maturity required to support risk-informed assessments of advanced molten-salt reactor systems.

**Table 2. Regulatory observations and consequences [10] for modelling requirements**

Regulatory observation	Consequence for modeling and simulation
Verification and validation are integral parts of the safety case	Predictive capability must be demonstrated, not assumed
Uncertainty must be explicitly addressed	TARs must include uncertainty-related criteria
Unknown or poorly represented phenomena require special consideration	Quantified uncertainty cannot compensate for missing physics
Model complexity should follow the safety question	Model fidelity must be justified rather than maximized
Code applicability must be demonstrated for intended use	Validation matrices and applicability assessments become part of TAR development
Safety conclusions depend on the credibility of analytical methods	TARs should characterize both accuracy and credibility



5 Target Accuracy Requirements: Scope, Classification and Discussion

The analysis of advanced molten-salt reactor concepts indicates that the principal drivers of potential hazardous releases can be reduced to a limited number of fundamental mechanisms. These include uncontrolled fission power generation, imbalance between heat production and heat removal, degradation or failure of residual heat removal systems, and, to a lesser extent, deficiencies in instrumentation, monitoring, and reactivity-control functions.

Within this context, an important distinction should be made between phenomena that can be represented by predictive models with an acceptable degree of confidence and those for which reliable prediction remains fundamentally limited. In many cases identified during the PIRT process and subsequent literature review, the objective of design development is not to mitigate the consequences of a specific event but rather to eliminate the corresponding conditions by design. For such phenomena, the principal role of modelling is to demonstrate that the undesirable state is either physically precluded or associated with a sufficiently low probability of occurrence.

Consequently, the role of modelling differs substantially among different classes of phenomena. Some areas largely rely on conventional predictive simulations and quantitative uncertainty analysis, whereas others are dominated by bounding arguments, design exclusion principles, and qualitative demonstrations of safety. This distinction is essential for the establishment of meaningful Target Accuracy Requirements (TARs).

5.1 Classification of Safety-Relevant Phenomena

From the standpoint of safety analysis and predictive capability assessment, three principal classes of phenomena can be distinguished.

5.1.1 Nuclear-Driven Phenomena and Power Excursions

The first category comprises nuclear-driven phenomena, particularly power excursions and inadvertent reactivity insertions. These processes are characterized by the direct conversion of nuclear energy into heat and mechanical energy and therefore belong to the class of potentially non-dissipative processes.

In severe cases, such phenomena may challenge the integrity of confinement barriers, shutdown systems, and defense-in-depth provisions. A fundamental difficulty arises from the fact that representative experimental validation is generally impossible. Validation would require experiments extending beyond the safety envelope of available facilities, which is neither technically feasible nor acceptable from a safety perspective.

Furthermore, molten-salt systems involve internally heated fluids whose heat generation depends nonlinearly on local temperature, composition, neutron flux, fuel circulation, and delayed-neutron transport. As a result, predictive capability is inherently constrained by the absence of representative experimental evidence.

From the TAR perspective, the objective is therefore not the highly accurate prediction of accident consequences but the demonstration that the corresponding conditions remain sufficiently remote from normal and anticipated operating regimes. TARs in this domain are



primarily associated with safety margins, exclusion of unacceptable states, and robustness of safety arguments.

5.1.2 Heat-Removal and Heat-Sink Driven Phenomena

The second category consists of phenomena associated with degradation of heat removal capability, including loss of cooling, insufficient residual heat removal, degradation of heat-transfer performance, and failures of heat-exchange systems.

Unlike power excursions, these phenomena are governed by dissipative processes and remain largely within the traditional domain of thermal-hydraulic analysis. The relevant physical mechanisms are generally well understood and can be investigated through experiments, separate-effects studies, integral tests, and validated numerical tools.

Because both heat sources and heat sinks remain physically bounded, these phenomena are amenable to conventional validation methodologies. Consequently, they provide the most natural domain for quantitatively formulated TARs.

In this category, TARs can be directly linked to temperatures, flow rates, heat-transfer coefficients, pressure losses, heat-removal rates, and margins to thermal limits.

5.1.3 Instrumentation, Control, and Reactivity Monitoring

The third category encompasses phenomena associated with reactor observability, instrumentation, monitoring, and control.

The primary challenge here is not necessarily the prediction of physical quantities themselves but the reconstruction of reactor state from incomplete and potentially ambiguous measurements. In circulating-fuel systems, power fluctuations, flow oscillations, delayed-neutron precursor transport, and thermal-hydraulic delays may produce signals that are difficult to interpret using conventional approaches [12].

Under such conditions, traditional inverse-kinetics techniques may no longer provide a unique estimate of reactor reactivity. Multiple physical mechanisms may produce similar measured responses, while identical integral measurements may correspond to substantially different spatial power distributions or thermal states.

Consequently, TARs for this class of phenomena should focus on observability, state reconstruction, robustness of feedback mechanisms, reliability of diagnostics, and acceptable uncertainties in reactivity and power estimation.

5.2 Modelling Objectives and TAR implications

The three categories differ fundamentally in terms of physical nature, validation potential, and intended use of modelling and simulation. Therefore, a single universal TAR framework is unlikely to be appropriate. Instead, TARs should reflect the role played by modelling within each class of phenomena.



Safety-relevant phenomena in molten-salt reactors may be grouped according to the primary objective of analysis: demonstration of safety, demonstration of heat-removal capability, and demonstration of controllability. Because these objectives differ fundamentally, the associated TARs cannot be established using a single universal criterion.

5.2.1 Nuclear-Driven Phenomena

This category includes power excursions, prompt reactivity insertions, re-criticality events, and other processes directly affecting reactor criticality.

- **Physical nature:** strongly coupled neutronic, thermal-hydraulic, and mechanical processes with pronounced nonlinear feedback.
- **Validation potential:** limited, since representative experiments are generally impractical or undesirable.
- **Modelling objective:** demonstrate exclusion or mitigation of unacceptable states and preservation of safety margins.
- **TAR implication:** emphasis should be placed on shutdown effectiveness, deposited energy, structural loading, and robustness of safety arguments rather than on detailed transient reconstruction.

The key question is: Can potentially hazardous states be reliably excluded or adequately mitigated by design?

5.2.2 Heat-Removal-Driven Phenomena

This group includes loss of cooling, heat-transfer degradation, circulation instabilities, thermal stratification, shutdown cooling, and residual heat removal.

- **Physical nature:** predominantly dissipative processes governed by conservation laws.
- **Validation potential:** generally high because representative experiments and thermal-hydraulic test facilities are feasible.
- **Modeling objective:** predict heat-removal capability, circulation regimes, and regime-transition boundaries.
- **TAR implication:** requirements can be formulated quantitatively in terms of temperatures, flow rates, heat-transfer coefficients, thermal margins, and circulation-stability indicators.

The key question is: Can generated and residual heat be removed under all relevant operating conditions?

5.2.3 Control, Monitoring, and State-Reconstruction Phenomena

This category includes power oscillations, precursor transport, reactivity-estimation errors, instrumentation limitations, and observability issues.

- **Physical nature:** coupled kinetics, thermal hydraulics, delayed feedback, transport processes, and stochastic fluctuations.



- **Validation potential:** intermediate, since relevant quantities are often indirect and the system behaviour is non-stationary.
- **Modelling objective:** demonstrate reliable observation, reconstruction, interpretation, and control of reactor state.
- **TAR implication:** emphasis should be placed on observability, measurement uncertainty, state-estimation accuracy, and control-system robustness.

The key question is: Can the reactor state be measured, reconstructed, and controlled with sufficient confidence?

5.2.4 Implications for the TAR Framework

These three categories correspond to three complementary TAR philosophies:

- **Nuclear-driven phenomena:** preservation of safety margins and exclusion of unacceptable states.
- **Heat-removal-driven phenomena:** quantitative prediction of thermal-hydraulic performance and heat-removal capability.
- **Control and monitoring phenomena:** reliability of observability, controllability, and operational decision-making.

This classification provides the methodological basis for the TAR matrix developed in the following sections and explains why different Figures of Merit require different acceptance criteria, validation approaches, and levels of predictive accuracy.

5.3 Summary of Target Quantities and Figures of Merit

Ultimately, TARs are established not for entire physics domains but for specific Figures of Merit (FoMs), parameters, observables, and decision-support variables. The preceding discussion suggests the grouping summarized below.

Table 3. Principal Figures of Merit Relevant to TAR Establishment [10]

Phenomena Group	Primary Figures of Merit
Nuclear-driven phenomena	Peak power, deposited energy, peak reactivity insertion, shutdown margin, maximum fuel temperature, criticality margins
Heat-removal driven phenomena	Fuel outlet temperature, peak salt temperature, vessel temperature, heat-removal rate, natural-circulation flow rate, heat-exchanger effectiveness



Control monitoring phenomena	and	Reactivity estimation error, oscillation amplitude, oscillation frequency, damping ratio, circulation-time estimation, detector response time, state-reconstruction uncertainty
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The groups of phenomena identified above provide the conceptual basis for the subsequent development of Target Accuracy Requirements. The following chapters discuss the associated physical mechanisms, modelling approaches, validation challenges, uncertainty sources, and proposed accuracy requirements in considerably greater detail.

Attention is devoted to the identification of measurable quantities, physically meaningful Figures of Merit, and defining parameters whose uncertainty propagates directly into safety, controllability, and observability assessments. Additional technical details, sensitivity studies, and supporting analyses are provided in the Annexes accompanying this report.

5.3.1 Nuclear-Driven Phenomena

Power excursions and re-criticality events are governed by a relatively limited set of physical parameters despite the complexity of the transient evolution. The purpose of TAR establishment is therefore not to reproduce all details of accident progression but to identify those parameters whose uncertainty directly affects the principal Figures of Merit, including deposited energy, peak temperatures, maximum pressure rise, and available shutdown margin.

Four groups of model parameters are of primary importance.

Reactivity-Insertion Parameters

This group characterizes the initiating conditions of the transient and includes:

- fuel inventory;
- fissile-material concentration;
- critical dimensions, critical mass, and critical aspect ratio;
- gas worth;
- control-device worth.

These parameters determine the available reactivity reserve and the magnitude of potential reactivity perturbations.

TAR objective: uncertainties shall remain sufficiently small to preserve conclusions regarding critical loading conditions, controllability, shutdown effectiveness, and re-criticality potential.

Kinetic Parameters

This group determines the intrinsic rate of transient development and includes:

- effective delayed-neutron fraction, β_{eff} ;

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- prompt-neutron generation time, Λ ;
- precursor residence-time distributions;
- precursor transport characteristics.

These parameters govern transient response, oscillatory behaviour, and the effectiveness of delayed-neutron stabilization mechanisms.

TAR objective: uncertainties shall not obscure the classification of transient severity, stability regime, or control-system effectiveness.

Feedback Parameters

This group governs self-stabilization mechanisms and includes:

- temperature-reactivity coefficients;
- density-reactivity coefficients;
- void and gas-reactivity coefficients;
- feedback-response characteristics.

These quantities determine both the sign and magnitude of the dominant feedback mechanisms.

TAR objective: uncertainties shall not lead to ambiguity in the prediction of dominant feedback mechanisms or available stabilization margins.

Thermal-Hydraulic Response Parameters

This group couples heat generation to structural loading and includes:

- circulation flow rate;
- heat-transfer coefficients;
- relaxation time constants;
- heat-removal capability;
- fuel-density evolution.

Although traditionally treated as thermal-hydraulic quantities, they directly affect deposited energy and transient severity.

TAR objective: uncertainties shall not alter conclusions regarding deposited energy, peak temperatures, or structural loading categories.

5.3.2 Heat Removal, Natural Circulation, and Thermal Stratification

For residual heat removal and normal heat transport, TARs should focus on parameters governing heat-removal capability, circulation stability, thermal stratification, and thermochemical behaviour rather than on local temperatures alone.



Circulation Parameters

These parameters determine transport of thermal energy from the core to the heat sink and include:

- circulation flow rate;
- circulation velocity;
- residence times;
- circulation relaxation times;
- stagnant-volume fraction.

TAR objective: uncertainties shall not alter the predicted circulation regime or heat-removal pathway.

Heat-Transfer Parameters

This group includes:

- effective heat-transfer coefficients;
- heat-exchanger effectiveness;
- heat-transfer resistances;
- heat-removal rates.

These quantities directly affect thermal margins and equipment sizing.

TAR objective: uncertainties shall not alter decisions related to heat-removal-system design, sizing, or operation.

Stratification and Saturation Parameters

This group characterizes circulation degradation and includes:

- internal Rayleigh number;
- saturation margin;
- thermocline location and thickness;
- thermal-stratification indices.

These parameters govern transitions between well-mixed, stratified, and partially isolated circulation regimes.

TAR objective: uncertainties shall not prevent identification of circulation-regime transitions or degradation of heat-removal effectiveness.



Thermochemical Parameters

This group includes:

- saturation margins;
- solubility limits;
- species redistribution rates;
- deposition and precipitation rates.

These quantities link thermal-hydraulic behaviour to long-term chemistry evolution.

TAR objective: uncertainties shall not obscure prediction of precipitation, deposition, or chemistry-related degradation mechanisms.

5.3.3 Operational Support, Control, and Instrumentation: Implications for TAR Definition

Operational support introduces a distinct class of TARs because reactor state is reconstructed from measurements and models rather than observed directly.

State-Characterization Parameters

This group includes:

- fuel inventory;
- precursor inventory;
- temperatures;
- pressures;
- flow distributions;
- material-condition indicators.

Together, these quantities define the position of the reactor within its multidimensional operating state space.

TAR objective: uncertainties shall not lead to misclassification of reactor operating state or safety condition.

Dynamic Parameters

This group characterizes transitions between states and includes:

- feedback coefficients;
- precursor transport parameters;
- circulation delays;
- thermal-memory effects;



- oscillation frequencies;
- damping characteristics.

TAR objective: uncertainties shall not alter conclusions regarding stability, controllability, or transient evolution.

Observability Parameters

This group includes:

- state-reconstruction error;
- reactivity-reconstruction uncertainty;
- instability-detection time;
- sensor-coverage indicators;
- forecast uncertainty.

These quantities determine whether control actions can be based on reliable information.

TAR objective: uncertainties shall not compromise detection of unsafe conditions or timely initiation of corrective actions.

5.3.4 General Interpretation of TARs

For all three categories, TARs should be understood as requirements on those model parameters whose uncertainty can influence:

- safety conclusions;
- engineering decisions;
- equipment specification;
- operating limits;
- control strategies;
- validation and experimental programs.

Accordingly, the TAR hierarchy follows the logical chain **Safety-Relevant Phenomenon** → **Figure of Merit** → **Governing Parameter** → **Target Accuracy Requirement** and not vice versa. The purpose of TAR establishment is therefore to ensure that uncertainty in governing parameters remains sufficiently small to preserve the engineering and safety conclusions derived from the analyses.



6 High-Level Target Accuracy Requirements for Multi-Loop MSRs

For conventional reactor technologies, Target Accuracy Requirements (TARs) are normally derived from extensive operational and experimental experience. For advanced circulating-fuel molten-salt reactors, particularly fast-spectrum chloride concepts, such a knowledge base is incomplete. Consequently, TARs cannot be established solely from historical benchmarks or from scenario-based safety analyses. Instead, TARs should be formulated from three complementary perspectives:

1. Safety functionals, determining margins to unacceptable conditions;
2. Control functionals, determining the ability to maintain and restore desired operating states;
3. Defining functionals, determining the physical characteristics that govern reactor behavior and establishing the validity of safety and control assessments.

This distinction is essential because some quantities, such as the effective delayed neutron fraction, precursor residence times, circulation delays, or flow-distribution characteristics, are not safety metrics themselves. However, they determine the validity of all subsequent safety and controllability predictions.

The resulting hierarchy may therefore be represented schematically as $TAR_{defining} \Rightarrow TAR_{control} \Rightarrow TAR_{safety}$, where the uncertainty of defining parameters propagates into control-system performance and subsequently into safety margins.

6.1 Qualitative TARs

At the highest level, modelling and simulation shall demonstrate the capability to:

Safety

- predict margins to criticality and prompt criticality;
- predict deposited energy during power excursions;
- predict residual heat removal capability;
- identify conditions leading to thermal stratification, precipitation, or heat-transfer degradation;
- demonstrate the effectiveness of shutdown systems.

Control

- reconstruct reactor states with sufficient non-ambiguity;
- distinguish physically different causes of identical measured responses;
- identify oscillatory regimes before safety limits are approached;
- quantify stability margins under realistic operating conditions;
- support diagnosis and recovery following abnormal events.



Defining Characteristics

- predict delayed-neutron behaviour in circulating fuel;
- characterize circulation delays and residence-time distributions;
- predict flow redistribution among loops;
- quantify feedback mechanisms and relaxation times;
- predict inventory evolution and chemistry-related effects.

Recommended Model Hierarchy

The TAR framework should not rely on a single universal model. A hierarchical structure is preferable.

Table 4. Model Hierarchy [7]

Level	Purpose
Level 1	Multi-loop circulation and transport model
Level 2	Spatial thermal-hydraulic model
Level 3	Coupled neutronics and precursor-transport model
Level 4	Instrumentation, state-estimation and digital-twin model

The hierarchy allows efficient exploration of large parameter spaces while maintaining traceability to high-fidelity analyses.

6.2 Control-Related Accuracy Requirements for Critical Loading Parameters

In contrast to conventional solid-fuel reactors, the controllability of a fast-spectrum molten-salt reactor may be inherently constrained by several design-specific features. First, the achievable worth of mechanical control devices is limited by geometric and technological constraints. The reactor vessel contains a heat-generating fluid in a nearly closed primary circuit, leaving only limited capability for accommodating pressure- and volume-driven salt redistribution. Furthermore, the available locations for reactivity control devices are restricted. The upper part of the system is typically occupied by gas treatment and off-gas management systems, whereas the lower regions are dedicated to drainage and passive decay-heat-removal functions. Consequently, insertion of control rods from conventional axial directions is often impractical, and side-entry solutions may experience substantial thermo-mechanical loading. The resulting guide structures may require significant wall thickness, thereby reduce neutron economy and ultimately decrease control-rod worth.



Consequently, reactor control may rely on a combination of reflector control drums, gas injection systems, and maintenance of elevated salt temperature during subcritical or shutdown conditions. Under such circumstances, the available reactivity compensation capacity becomes comparable to the uncertainties associated with the prediction of the reactor critical state itself. Therefore, the efficiency of the control system becomes directly dependent on the accuracy with which the critical loading condition is predicted.

A particularly important feature of circulating fuel systems is that heavy-metal inventory determines not only the multiplication state of the reactor but also several feedback mechanisms simultaneously. Variations in fissile inventory produce nearly proportional variations in excess reactivity, modify temperature and density feedback coefficients, alter reflector and moderator effectiveness, affect control drum worth, and change the gas concentration required to maintain a given shutdown or operating state. Consequently, uncertainties associated with critical loading propagate through multiple feedback pathways and directly influence overall controllability.

From a safety perspective, this issue becomes especially important in scenarios involving gas-bubble transport and collapse. Local collapse of gas voids may rapidly remove negative reactivity associated with gas holdup and potentially generate prompt positive reactivity insertions. Since the available control authority is limited, excessive uncertainty in the prediction of the critical loading condition may significantly reduce the available margin against prompt-critical excursions.

For this reason, the traditional requirement on eigenvalue prediction accuracy is reformulated here as a requirement on the prediction of critical loading parameters, including critical heavy-metal inventory, critical concentration, critical dimensions, and critical core aspect ratio. Analysis of representative fast-spectrum molten-salt reactor configurations indicates that the overall uncertainty associated with the prediction of the critical loading state should not exceed approximately $7\div 10\%$. This range corresponds to the historically accepted eigenvalue uncertainty of roughly $300\div 500$ pcm and represents the maximum uncertainty compatible with maintaining adequate control-system effectiveness throughout the expected operational envelope.

The proposed Target Accuracy Requirement is therefore formulated as follows: the predicted critical loading condition, expressed in terms of critical mass, critical concentration, critical dimensions, or critical aspect ratio, should be determined with an uncertainty not exceeds approximately 7% for high-confidence design assessments and 10% for preliminary engineering evaluations. Larger uncertainties would lead to significant degradation of predicted control-device worth, gas-control effectiveness, and shutdown capability, thereby compromising the robustness of reactor control and safety demonstration. Of course, the quantities are relevant to only some recently published conceptual schemes.

Delayed-Neutron Fraction as a Dynamic Figure of Merit

One of the most visible and frequently discussed phenomena in molten-salt reactors with circulating fuel is the reduction of the effective delayed-neutron fraction, β_{eff} , caused by precursor transport outside the active core region. Nevertheless, the practical safety significance of this effect should not be overestimated. Unlike conventional solid-fuel reactors, the relationship between reactivity, neutron population, and reactor control is fundamentally altered by fuel circulation, spatially distributed precursor transport, and intrinsic power fluctuations.



Therefore, traditional interpretations of reactivity measurements and conventional control concepts become only partially applicable.

The underlying physics is reminiscent of phenomena observed in pulse reactors and periodically forced multiplying systems, where delayed feedback may under certain conditions appear with an effective phase shift. When characteristic precursor transport times become comparable to characteristic oscillation periods, circulation-induced feedback may interact with power fluctuations in a resonant or near-resonant manner. In such situations, a feedback mechanism that is nominally negative may locally manifest itself as an apparent positive contribution to neutron kinetics because of temporal phase lag between precursor production and delayed-neutron emission.

Additional complexity may arise from metastable hydrodynamic structures within the core cavity. Vortex-dominated flow regions, recirculation zones, and other long-lived hydrodynamic traps may introduce a second characteristic precursor transport timescale. In addition to the conventional circulation-induced precursor drift, delayed-neutron precursors may experience temporary retention within such structures before being released back into the primary flow. Consequently, precursor transport may be characterized by two effective velocities: the bulk circulation velocity and a reduced effective velocity accounting for retention within metastable hydrodynamic structures. This mechanism may further modify the dynamic value of β_{eff} and enhance the uncertainty associated with its prediction.

From the standpoint of safety and controllability, the accuracy requirements associated with β_{eff} are inherently asymmetric. Overestimation of the dynamic (circulation-dependent) delayed-neutron fraction may lead to a non-conservative assessment of reactor controllability, transient response, and available operational margins. In contrast, underestimation generally results in conservative predictions of reactor behavior. Therefore, the allowable uncertainty should not be symmetric with respect to the nominal value.

For the class of systems considered in the present study, overestimation of the dynamic value of β_{eff} should preferably not exceed approximately 5% of the predicted value, whereas underestimation may be tolerated up to approximately 10–12%. For the stationary or time-averaged delayed-neutron fraction, where circulation-induced fluctuations are averaged out, a less restrictive target appears adequate, and the uncertainty should not exceed approximately 20% of the corresponding relative value.

It should be emphasized that these estimates are not intended as universally applicable Target Accuracy Requirements. They are derived from analyses of a limited set of fast-spectrum molten-salt reactors employing chloride-based fuel salts, primarily within the small-to-medium power range (up to approximately 200–300 MW thermal). Consequently, the proposed values should be regarded as preliminary engineering estimates reflecting current understanding of this reactor class. Their applicability to larger systems, breeder configurations, thermal-spectrum molten-salt reactors, or reactors employing fluoride-based fuel salts remains to be demonstrated through dedicated analysis, validation experiments, and future prototype operation.

High-Level Quantitative TARs

The values below should be regarded as engineering targets intended for concept assessment and multi-physics validation. They should not be interpreted as regulatory limits.

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**Table 5. TARs for stand-alone Reactor Physics modeling**

Quantity	Recommended TAR
Critical loading state (critical mass, critical concentration, critical dimension or critical aspect ratio)	$\pm 7\%$ (design studies), $\pm 10\%$ (licensing support)
Differential reactivity effects	$\pm 100 \div 150$ pcm
Density reactivity coefficients	$\pm 10\%$
Power reactivity coefficients	$\pm 5\%$ (to ensure compliance with mechanical energy deposition limits)
Dynamic effective delayed-neutron fraction, β_{eff}	$+5\%$ / $-10 \div 12\%$ (overestimation / underestimation)
Stationary effective delayed-neutron fraction, β_{eff}	$\pm 20\%$ of relative value
Neutron generation time	$\pm 10\%$

For fast chloride-fuelled molten-salt reactors, analysis indicates that the limiting consequences of power excursions are primarily governed by thermal and mechanical loading rather than by phase-transition phenomena. The temperature margins to salt boiling, significant vapor generation, or other large-scale phase changes remain substantially larger than the corresponding margins to structural overheating. As a result, the principal Figures of Merit for transient safety assessment are peak temperatures of fuel, vessel, and internal structures, deposited energy, and the maximum adiabatic overpressure developed within the primary circuit. This observation directly affects the establishment of TARs, since predictive capability should preferentially target quantities controlling thermal and mechanical integrity rather than phase-transition thresholds that are unlikely to be approached under credible transient conditions.

6.3 Thermal-Hydraulic Saturation and Internal Rayleigh Criterion

One of the principal thermal-hydraulic phenomena requiring dedicated investigation is the establishment and long-term stability of forced and natural circulation regimes. In molten-salt reactors, the coolant is simultaneously a viscous heat-generating fluid circulating within a closed primary circuit. Consequently, the mechanisms governing circulation establishment differ from those traditionally encountered in water-cooled reactors.

Attention should be devoted to the possibility of circulation saturation. In compact reactor cavities, increasing volumetric heat generation does not necessarily result in a proportional increase of global heat transport toward external heat exchangers. Beyond a certain threshold, the flow may reorganize into localized recirculation structures, thermal stratification layers, vortex-dominated regions, or hydraulic "short-circuit" pathways. Under such conditions, fluid



motion remains present within the system, yet a substantial fraction of the generated thermal energy becomes trapped within local circulation cells rather than being transported to the heat-removal system.

A convenient criterion for characterizing the onset of such behaviour may be formulated through an internal Rayleigh number $Ra_i = \frac{g \beta_T \dot{q}''' L^5}{\nu \alpha k}$, where g is gravitational acceleration, β_T is the thermal expansion coefficient, $\dot{q}'''$ is the volumetric heat-generation rate, L is a characteristic dimension of the core cavity, ν is the kinematic viscosity, α is the thermal diffusivity, and k is the thermal conductivity.

The parameter Ra_i may be interpreted as a measure of the competition between buoyancy production driven by internal heat generation and dissipative mechanisms associated with momentum and thermal diffusion. At relatively low values of Ra_i , the system tends to establish a stable global circulation pattern linking the core cavity and the heat exchanger. As Ra_i increases, flow instabilities, thermal stratification, and multi-cell recirculation structures gradually emerge. Beyond a critical range, $Ra_i > Ra_{sat}$, the system may enter a thermal-hydraulic saturation regime in which additional heat generation produces only marginal enhancement of global heat removal capability.

A dimensionless saturation factor may therefore be introduced: $\Psi = \frac{Q_{HX}}{Q_{gen}}$, where Q_{HX} is the heat transferred to the heat exchanger and Q_{gen} is the total heat generated within the core region.

For efficient global circulation, $\Psi \approx 1$, whereas the development of internal recirculation structures and circulation short-circuiting leads to $\Psi < 1$.

The onset of saturation may be formally associated with $\frac{\partial \Psi}{\partial Ra_i} < 0$, indicating that increasing buoyancy forcing no longer improves, and may even degrade, the effectiveness of heat transport to the heat-removal system.

From the standpoint of Target Accuracy Requirements, prediction of the transition region around Ra_{sat} is more important than prediction of average temperatures alone. Therefore, simulation tools should be capable of predicting:

- onset of thermal-hydraulic saturation (Ra_{sat});
- transition from global circulation to multi-cell recirculation;
- thermal stratification intensity;
- circulation short-circuiting;
- degradation of heat-removal efficiency (Ψ);
- resulting peak fuel-salt and structural temperatures.

For molten-salt reactors this formulation is preferable because it explicitly accounts for internal heat generation, which is the actual driving mechanism for buoyancy.

Implications for TAR Definition and Engineering Decision-Making

The practical value of thermal-hydraulic modelling is determined not by its ability to reproduce flow fields alone, but by its capability to support engineering and operational decisions associated

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with circulation management and heat-removal control. Consequently, TARs should be formulated not only for traditional quantities such as temperature, pressure, or flow rate, but also for quantities defining regime transitions and controllability of heat transfer.

Table 6. Example TARs for Thermal-Hydraulic Regime Management [10]

Quantity	Proposed TAR	Engineering Purpose
Internal Rayleigh number, Ra_i	$\pm 20\%$	Identification of approach to saturation region
Saturation Rayleigh number, Ra_{sat}	$\pm 15\text{--}20\%$	Prediction of onset of circulation degradation
Heat-removal efficiency factor, $\Psi = Q_{HX}/Q_{gen}$	$\pm 10\%$	Determination of available heat-exchange surface
Transition boundary between global circulation and localized recirculation	$\pm 15\%$	Definition of operating envelope
Circulation flow redistribution	$\pm 10\%$	Management of local overheating risks
Thermal stratification index	$\pm 10\%$	Early detection of stagnant zones
Characteristic transition time between regimes	$\pm 20\%$	Determination of operator response time
Peak local salt temperature during transition	$\pm 15\text{ K}$	Protection against salt overheating
Peak structural temperature during transition	$\pm 20\text{ K}$	Structural integrity assessment

For example, if simulations are intended to support the operation of a gas-regulated heat exchanger, the uncertainty associated with prediction of the circulation-regime transition boundary should be sufficiently small to allow timely adjustment of the available heat-exchange surface. The same requirement applies to the prediction of thermal-hydraulic saturation and circulation short-circuiting, where engineering decisions may depend on only a narrow interval of operating conditions.

One more time, the rationale behind these values is straightforward. If the uncertainty in predicting the transition from global circulation to thermal-hydraulic saturation is comparable to or larger than the operational margin available to the designer, simulation results no longer provide meaningful support for sizing heat exchangers, defining operating limits, or selecting



control strategies. In contrast, uncertainties of approximately 10-20% allow reliable identification of transition regions and provide sufficient confidence to implement preventive actions before significant degradation of heat-removal capability occurs. Particularly important is the prediction of the saturation threshold Ra_{sat} .

An uncertainty exceeding approximately 20% in the prediction of this threshold may lead to significant uncertainty in the determination of permissible power density, required heat-exchanger capacity, and allowable flow-distribution patterns. Therefore, the recommended TAR of ± 15 -20% is derived primarily from its influence on engineering decisions rather than from numerical considerations alone.

More generally, the objective of thermal-hydraulic modelling should be to answer three practical questions:

1. At which operating conditions does a transition between circulation regimes become possible?
2. Which measurable indicators provide sufficiently early warning of the approaching transition?
3. Which operational parameters (power, inventory, pressure losses, heat-exchanger capacity, gas content, etc.) can be adjusted to prevent or suppress the transition?

The corresponding TARs should therefore be interpreted as requirements on the capability of the modelling tools to support these engineering decisions, rather than merely requirements on the accuracy of calculated temperatures or flow velocities. This philosophy is consistent with the general principle adopted throughout the present work: a TAR should be linked to its impact on safety demonstration, design optimization, controllability, and operational management.

The TARs presented above address regime prediction and circulation stability. However, additional requirements are needed when simulation results are used for equipment sizing, hydraulic tuning, and specification of engineering solutions. In such cases, the required accuracy should be sufficient to ensure that model uncertainty does not alter decisions related to component sizing, operating limits, control strategies, or heat-removal capability. Accordingly, TARs should be linked not only to physical quantities but also to the intended engineering use of predictions.

Table 7. Equipment-Oriented TARs

Equipment Function /	Quantity	Recommended TAR	Acceptance Criterion
Gas-regulated heat exchanger	Effective heat-transfer area, A_{HX}	$\pm 10\%$	Predicted control action (increase/decrease of active area)
Gas-regulated heat exchanger	Heat-removal capacity, Q_{HX}	$\pm 10\%$	Error does not affect sizing or operating strategy



Heat exchanger	Pressure drop	$\pm 10\%$	Hydraulic regime correctly predicted
Heat exchanger	Overall heat-transfer coefficient, U	$\pm 10\%$	Required heat-transfer surface maintained within design margin
Core cavity	Heat-removal efficiency factor, Ψ	$\pm 10\%$	Correct classification of circulation regime
Primary circuit	Circulation flow rate	$\pm 5\%$	Pumping or natural-circulation requirements
Flow-distribution devices	Local flow split	$\pm 10\%$	Hot-spot location and severity correctly identified
Hydraulic restrictions / orifices	Pressure-loss coefficient	$\pm 10\%$	Flow-balancing strategy
Drain and shutdown systems	Salt transfer rate	$\pm 10\%$	Required draining time correctly predicted
Gas injection system	Gas worth / void fraction	$\pm 10\%$	Required shutdown and control capability preserved
Off-gas system	Gas residence time	$\pm 15\%$	Noble-gas inventory classification
Monitoring and control system	Regime-transition time	$\pm 20\%$	Available operator response time not overestimated

In addition, it seems reasonable to specify the following TARs for Control-Oriented Modelling (see Table 8)

Importance should be assigned to predictions supporting active management of circulation and heat removal. The objective of the simulations is not merely to determine temperatures and flow rates, but to identify the conditions under which circulation degradation may occur, the observable indicators preceding such transitions, and the corrective actions required to maintain stable operation. For systems employing gas-regulated heat exchangers, the models should provide quantitative guidance regarding when the available heat-transfer surface should be modified, which indicators signal the onset of instability, and whether specific combinations of power level, inventory, hydraulic resistance, and heat-removal capacity can prevent the



occurrence of undesirable circulation regimes altogether. Consequently, the acceptance criterion for most equipment-oriented TARs is preservation of engineering decision rather than preservation of a numerical value alone.

Table 8. Additional TARs for Control-Oriented Modelling

Quantity	Recommended TAR	Engineering Purpose
Saturation margin M_{sat}	$\pm 10\%$	Maintain operation away from circulation degradation
Transition boundary Ra_{sat}	$\pm 15\text{-}20\%$	Define safe operating envelope
Thermal stratification index	$\pm 10\%$	Detection of local overheating conditions
Residence-time distribution variance	$\pm 15\%$	Identification of recirculation zones and vortex trapping
Dominant oscillation frequency	$\pm 5\%$	Detection of circulation instabilities
Transition time between regimes	$\pm 20\%$	Specification of control-system response requirements

This criterion is particularly attractive for the TAR framework because it links thermal-hydraulic modelling accuracy directly to the physically meaningful question: whether the generated heat is effectively transported from the core cavity to the heat exchanger or becomes trapped in internal recirculation structures.

6.4 Nuclear-driven power excursions

Power excursions in bed-type molten-salt reactors may be initiated by either inadvertent or intentional reactivity insertion. Moreover, because of the intrinsically fluctuating nature of power generation in circulating-fuel systems, transient departures from the nominal state should not be viewed as exceptional events but as a natural feature of reactor operation. The objective of the safety analysis is therefore not to demonstrate the impossibility of such events, but to demonstrate adequate understanding, prediction, and management of their consequences.

Several mechanisms may contribute to positive reactivity insertion. These include gas redistribution and gas-bubble collapse, uncertainties associated with gas-based control systems, local changes in fissile-material concentration, fuel-salt inventory redistribution, and deposition of heavy metals or lanthanides on structural surfaces. Consequently, complete exclusion of



reactivity insertion events cannot be regarded as a realistic design objective. Instead, the design should tolerate credible excursions while maintaining the integrity of safety-significant structures.

Numerous analytical and experimental studies have demonstrated that molten-salt reactors possess substantial inherent resistance to severe power-excursion consequences. Strong temperature feedback, thermal inertia of the salt inventory, and relatively slow system response tend to limit transient progression. For the reactor class considered here, the feasibility of maintaining structural integrity during representative reactivity transients has been demonstrated, provided that adequate mechanical margins are incorporated into the design.

However, these margins are not obtained without penalty. Mitigation of transient overpressure and thermal loading generally requires increased vessel and piping wall thickness. In compact fast-spectrum systems, thicker structures reduce neutron economy and decrease reflector effectiveness. Since reflector efficiency directly affects the worth of reflector control drums and other external control devices, the resulting design trade-off becomes one of the double-bounded constraints governing reactor development. Increasing mechanical protection may reduce controllability, while increasing controllability may reduce available structural margins [13].

This observation has an important consequence for TAR development. Contrary to the intuitive perception of a "salt explosion", analysis indicates that credible power excursions do not lead to rapid explosive energy release. The dominant loading mechanisms arise from relatively slow thermal energy deposition and subsequent pressure development within a confined heat-generating fluid. Therefore, the principal safety-relevant quantities are not the instantaneous power peak itself but rather the total deposited energy, the duration of the power excursion, the resulting adiabatic overpressure, and the associated structural temperature rise [14].

From an engineering perspective, deposited energy becomes the primary Figure of Merit. Changes in predicted deposited energy directly affect vessel thickness, mechanical design margins, allowable power density, heat-removal requirements, and ultimately the effectiveness of neutron reflectors and control systems. Accordingly, TARs should first constrain uncertainty in deposited-energy predictions.

Based on current engineering assessments for compact fast-spectrum chloride-fuelled molten-salt reactors, an uncertainty of approximately 10-15% appears acceptable for deposited energy. The precise value depends on reactor power, fuel inventory, isotopic composition of heavy metals, and lanthanide accumulation. Similar considerations apply to peak power itself. Although peak power is not the dominant loading parameter, it influences local fuel heating, feedback activation rates, and transient pressure development. Consequently, a comparable TAR range is recommended.

The requirement on power-reactivity feedback coefficients should remain more restrictive. As discussed previously, uncertainties in these coefficients affect both accident-transient predictions and the amplitude and frequency of spatially distributed power fluctuations occurring during normal operation. For this reason, a TAR of approximately $\pm 5\%$ remains justified [15].

The recommended TARs are derived not from the requirement to reproduce the exact shape of a transient, but from the requirement to preserve engineering decisions related to structural design, reactor controllability, pressure protection, reflector configuration, and decay-heat-removal capability. Consequently, the acceptance criterion for power-excursion modelling is the



preservation of safety-relevant design conclusions rather than agreement with individual transient characteristics alone.

Table 9. TARs for Power Excursions

Quantity	Recommended TAR	Acceptance Criterion	Engineering Significance
Deposited energy	$\pm 10\text{-}15\%$	Structural loading category	Vessel thickness, pressure margins, reflector efficiency
Peak power	$\pm 10\text{-}15\%$	Transient classification	Local heating and feedback activation
Peak structural temperature	$\pm 20\text{ K}$	Structural acceptance decision	Mechanical integrity
Maximum adiabatic overpressure	$\pm 10\%$	Pressure-protection strategy	Vessel and piping design
Transient reactivity response	$\pm 100\text{ pcm}$	Control-system response	Controllability assessment
Power-reactivity feedback coefficient	$\pm 5\%$	Stability classification	Fluctuation and transient prediction
Characteristic power-peak duration	$\pm 10\%$	Deposited-energy category	Structural loading evaluation
Time to peak conditions	$\pm 10\%$	Operator and control-system response	Operational management

6.5 Decay heat removal systems and processes

Specific attention should be devoted to reactor shutdown and subsequent heat removal. The importance of this issue has been clearly demonstrated by lessons learned from severe accident analyses and operational experience accumulated throughout the nuclear industry. For molten-salt reactors, shutdown cooling should be considered a principal design function rather than an auxiliary operating mode [16].



The PIRT activities performed within the present work indicate that the dominant phenomenon governing shutdown safety is the establishment and maintenance of stable convective heat removal. Depending on reactor configuration and operating conditions, heat removal may rely on natural circulation, forced circulation, or a combination of both. The principal challenge is not merely providing sufficient cooling but maintaining appropriate thermal conditions throughout the primary system.

Both insufficient cooling and excessive cooling may become undesirable. Excessive cooling may promote precipitation and plate-out of heavy metals or lanthanides, potentially affecting future criticality conditions, chemistry control, and restart capability. Insufficient cooling may result in excessive temperatures, accelerated corrosion, degradation of structural materials, and undesirable salt chemistry evolution. Consequently, cooling regimes must be selected and managed within an appropriate operating window.

Table 10. Decay Heat Removal and Shutdown Cooling

Quantity	Recommended TAR	Acceptance Criterion	Engineering Significance
Total decay heat power	$\pm 5\text{--}7\%$	Cooling-system sizing	Shutdown-cooling design
Decay heat source distribution	$\pm 10\%$	Hot-spot classification	Local cooling requirements
Heavy-metal inventory	$\pm 3\%$	Decay-heat category	Source-term prediction
Fission-product inventory	$\pm 5\%$	Cooling strategy	Residual-power prediction
Actinide inventory	$\pm 5\%$	Long-term cooling requirements	Extended shutdown analysis
Passive heat-removal capacity	$\pm 5\%$	Passive safety classification	Safety-system qualification
Heat-removal efficiency	$\pm 5\%$	Cooling selection mode	Natural-circulation management
Peak salt temperature during cooldown	$\pm 15\text{ K}$	Salt chemistry limits preserved	Plate-out prevention
Minimum salt temperature during cooldown	$\pm 10\text{ K}$	Precipitation limits preserved	Restart capability



Thermal stratification during cooldown	$\pm 10\%$	Cooling regime classification	Local overheating or overcooling
Cooldown time to safe-storage conditions	$\pm 10\%$	Operational procedure	Shutdown management
Natural-circulation flow rate	$\pm 10\%$	Cooling performance	Passive heat removal
Heat-exchanger performance during shutdown	$\pm 5\%$	Required heat-transfer area	Equipment specification

In contrast to nuclear-driven power excursions, shutdown cooling is dominated by dissipative processes. Following reactor shutdown, no significant mechanisms exist for self-amplifying power growth. Heat generation is governed primarily by radioactive decay of fission products, actinides, activation products, and accumulated transuranic isotopes. Therefore, the principal challenge is not control of reactivity but prediction of the heat source term and the resulting heat-removal requirements [16].

Accurate prediction of decay heat becomes particularly important for fast-spectrum molten-salt reactors employing chloride fuels and significant transuranic inventories. Long-lived actinides, alpha-decay chains, and spontaneous-fission contributors may represent a significant fraction of residual power. As a result, uncertainties associated with isotopic composition, burnup history, heavy-metal inventory, and fission-product concentrations directly propagate into uncertainty of decay-heat predictions.

For engineering purposes, the total uncertainty associated with prediction of the heat source term should preferably remain within approximately 5-7%. Although such a target may appear demanding, it directly affects the sizing of shutdown cooling systems, specification of passive heat-removal capabilities, determination of cooling schedules, and assessment of acceptable temperature evolution during long-term cooling.

6.6 Consolidated TAR matrix and final observations

As discussed throughout the present work, reactor design cannot be reduced to the specification of geometry, material properties, or nominal operating conditions. Design also includes the definition of operating strategies, monitoring approaches, diagnostic capabilities, controllability concepts, and management of anticipated instabilities. Recent studies have highlighted the importance of flow-induced fluctuations, circulation-dependent kinetics, spatially distributed effects, and other coupled multi-physics phenomena that are often difficult, expensive, or even impossible to investigate experimentally under representative reactor conditions. Consequently, a substantial fraction of the knowledge required for technology development can only be obtained through predictive modelling and simulation [17].

An equally important aspect is that modelling supports not only reactor design itself but also the design of experiments. Demonstration of feasibility, controllability, operational flexibility, and



safety requires dedicated experimental programs whose configuration, instrumentation, operating conditions, and success criteria must be defined before the experiments are performed. Therefore, modelling constitutes an integral component of technology development, validation planning, and experimental design. Although this topic was intentionally considered outside the scope of the present study, it should be recognized that it introduces additional classes of TARs that are not explicitly represented herein.

For this reason, the proposed list of TARs should not be regarded as exhaustive. Additional requirements will inevitably emerge as dedicated experimental facilities are developed, validation databases expand, and specific engineering solutions progress toward deployment. Nevertheless, the framework developed in the present work provides a practical basis for prioritization of research activities, planning of validation campaigns, specification of experimental needs, and establishment of problem-oriented fundamental research programs aimed at reducing the most safety-significant uncertainties.

In this context, Table 11 should be interpreted not merely as a collection of recommended numerical accuracy targets but as a consolidated traceability matrix linking physical phenomena, Figures of Merit, engineering decisions, operational objectives, validation needs, and corresponding modelling requirements. Each TAR included in the table reflects a quantity whose uncertainty may influence design choices, safety conclusions, equipment specification, operational procedures, or experimental planning. Consequently, the matrix may also serve as a roadmap for future research and technology maturation by identifying those areas where improvements in predictive capability are expected to provide the greatest benefit for reactor development.

Table 11. Consolidated TARs Matrix

Domain	Primary FoM	TAR
Reactor physics	Critical loading state	$\pm 7\text{-}10\%$
Reactor physics	Dynamic β_{eff}	$+5\% / -10\text{-}12\%$
Reactor physics	Feedback reactivity coefficients	$\pm 5\text{-}10\%$
Power excursions	Deposited energy	$\pm 10\text{-}15\%$
Power excursions	Peak structural temperature	$\pm 20\text{ K}$
Power excursions	Adiabatic overpressure	$\pm 10\%$
Thermal hydraulics	Heat-removal efficiency factor ψ	$\pm 10\%$
Thermal hydraulics	Saturation margin	$\pm 10\%$
Thermal hydraulics	Internal Rayleigh number	$\pm 20\%$



Thermal hydraulics	Transition boundary Ra_{sat}	$\pm 15\text{-}20\%$
Shutdown cooling	Total decay heat	$\pm 5\text{-}7\%$
Shutdown cooling	Passive heat-removal capability	$\pm 5\%$
Shutdown cooling	Cooldown peak temperature	$\pm 15\text{ K}$
System integration	Fuel inventory	$\pm 2\text{-}3\%$
System integration	Heavy-metal inventory	$\pm 5\%$
System integration	Lanthanide inventory	$\pm 10\%$

It is therefore important to recognize that Target Accuracy Requirements are not static quantities. They evolve together with the technology itself, becoming progressively more refined as knowledge, experimental evidence, and operational experience accumulate. The consolidated matrix presented in Table 11 summarizes the currently proposed TARs while simultaneously identifying the principal areas where further analytical, experimental, and methodological development remains necessary.

The most important conclusion is that TARs for molten-salt reactors should not be established exclusively for traditional safety figures of merit. A significant fraction of the uncertainty budget must be allocated to defining parameters such as β_{eff} , circulation-time distributions, loop-to-loop flow asymmetries, precursor transport, and feedback time constants, because these quantities determine the validity of both safety analyses and control-system assessments. Consequently, TAR establishment becomes an exercise in preserving predictability, controllability, and observability simultaneously, rather than merely reproducing individual output parameters.



7 Conclusion

The present work represents an initial attempt to establish a structured framework for Target Accuracy Requirements (TARs) applicable to advanced circulating-fuel molten-salt reactors. Unlike conventional reactor systems, where TARs can be derived largely from accumulated operational feedback, extensive experimentation, and mature modelling practices, molten-salt reactors introduce a fundamentally different challenge. The reactor core itself becomes a continuously evolving multi-physics system in which neutronics, fuel transport, thermal hydraulics, chemistry, heat transfer, and control are tightly coupled. These interactions modify not only reactor behaviour but also the very interpretation of traditional concepts such as power, reactivity, controllability, and safety margins.

Three major classes of phenomena were identified as particularly relevant to the establishment of TARs:

- **Nuclear-driven phenomena**, dominated by reactivity excursions, deposited energy, delayed-neutron transport, and redistribution of fissile material. For these phenomena, the key issue is not solely the prediction of consequences but also the demonstration that unacceptable states remain sufficiently remote or physically excluded by design.
- **Heat-removal and residual-heat phenomena**, governed by thermal-hydraulic processes, natural circulation, stratification, heat-transfer degradation, precipitation, and coupled thermochemical effects. These processes remain comparatively accessible to traditional validation approaches and therefore represent the domain where quantitative TARs can be most rigorously formulated.
- **Control, instrumentation, and observability phenomena**, involving reactivity reconstruction, power measurement, delayed-neutron transport, state estimation, oscillatory behaviour, and dynamic stability. In these areas, the challenge is often not the lack of numerical accuracy but the ambiguity of the underlying observations themselves.

A central conclusion emerging from the study is that TARs for molten-salt reactors cannot be limited to conventional Figures of Merit such as peak temperature, pressure, or power. Equally important are the so-called defining parameters and processes, including effective delayed-neutron fraction, circulation-time distributions, inventory evolution, precursor transport, feedback time constants, stratification characteristics, and observability indicators. Uncertainty in these quantities directly propagates into both safety and controllability assessments.

The proposed TAR framework therefore combines:

- quantitative TARs, where sufficient physical understanding and validation evidence exist;
- semi-quantitative TARs, where sensitivity and dominant phenomena can be identified but numerical justification remains incomplete;
- qualitative TARs, addressing predictive capability maturity, validation readiness, phenomenological completeness, and model applicability.

An equally important observation concerns uncertainty itself. For advanced molten-salt systems, uncertainty is not limited to aleatory and epistemic sources. A significant fraction arises from



ontological uncertainty associated with incomplete phenomenological understanding, evolving design concepts, and the absence of representative experimental evidence. Consequently, some TARs cannot yet be expressed solely through numerical limits because the corresponding physical mechanisms remain insufficiently characterized.

Recommendation for Future Work

A significant fraction of the phenomena identified during this study should be regarded as provisionally characterized rather than fully understood. This is true as well for:

- long-term fuel-inventory evolution;
- circulation-dependent delayed-neutron kinetics (double velocity);
- metastable hydrodynamic structures;
- coupled thermal-hydraulic and neutronic instabilities;
- nonlinear oscillatory regimes and bifurcation behaviour;
- precipitation and deposit formation under non-equilibrium conditions;
- observability and identifiability limits in circulating fuel systems;
- interactions among reactor control, fuel circulation, and heat exchange processes.

For many of these phenomena, currently available evidence is insufficient to support fully quantified TARs. Additional analytical studies, dedicated experiments, separate-effects facilities, and integrated prototype-scale investigations will be required before robust predictive capability can be demonstrated. In several cases, meaningful resolution of the underlying uncertainty may not be achievable until the commissioning and operation of the first prototype or demonstration reactors.

Such a situation should not be viewed as a weakness of methodology but rather as an inherent characteristic of knowledge-intensive innovative technologies. Historically, major technological advances have often preceded the availability of complete phenomenological understanding. As a result, the development of predictive capability, validation evidence, and Target Accuracy Requirements must progress iteratively alongside the maturation of the technology itself.

Consequently, the TAR values proposed in the present report should be interpreted as a structured starting point for future development rather than as final acceptance criteria. Their primary purpose is to identify the phenomena, variables, and uncertainties that will ultimately determine the feasibility, controllability, observability, and safety demonstration of advanced molten-salt reactor systems. As experimental evidence accumulates and reactor concepts mature, these TARs should be continuously refined, expanded, and, where necessary, reformulated to reflect the evolving understanding of the underlying physics.

In this sense, the principal result of the present work is not a definitive set of numerical accuracy limits, but the establishment of a coherent methodology for connecting safety, controllability, observability, validation, predictive capability, and uncertainty quantification within a unified framework for advanced molten-salt reactor development.



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