EPRI Body of Knowledge for Application of Fusion Relevant Safety Analysis Based on Established Industry Practice

Fusion Energy Strategic Program

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IAEA Consultancy Meeting on the Development of a Fusion Safety Standard Roadmap
March 30 - April 2, 2026

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Commercial fusion will be embedded in an industrial facility

(presenting both radiological and non-radiological hazards)

Power Conversion

Engineering, Construction, and Project Management

Mission, Products, Markets, Economics, and Integration

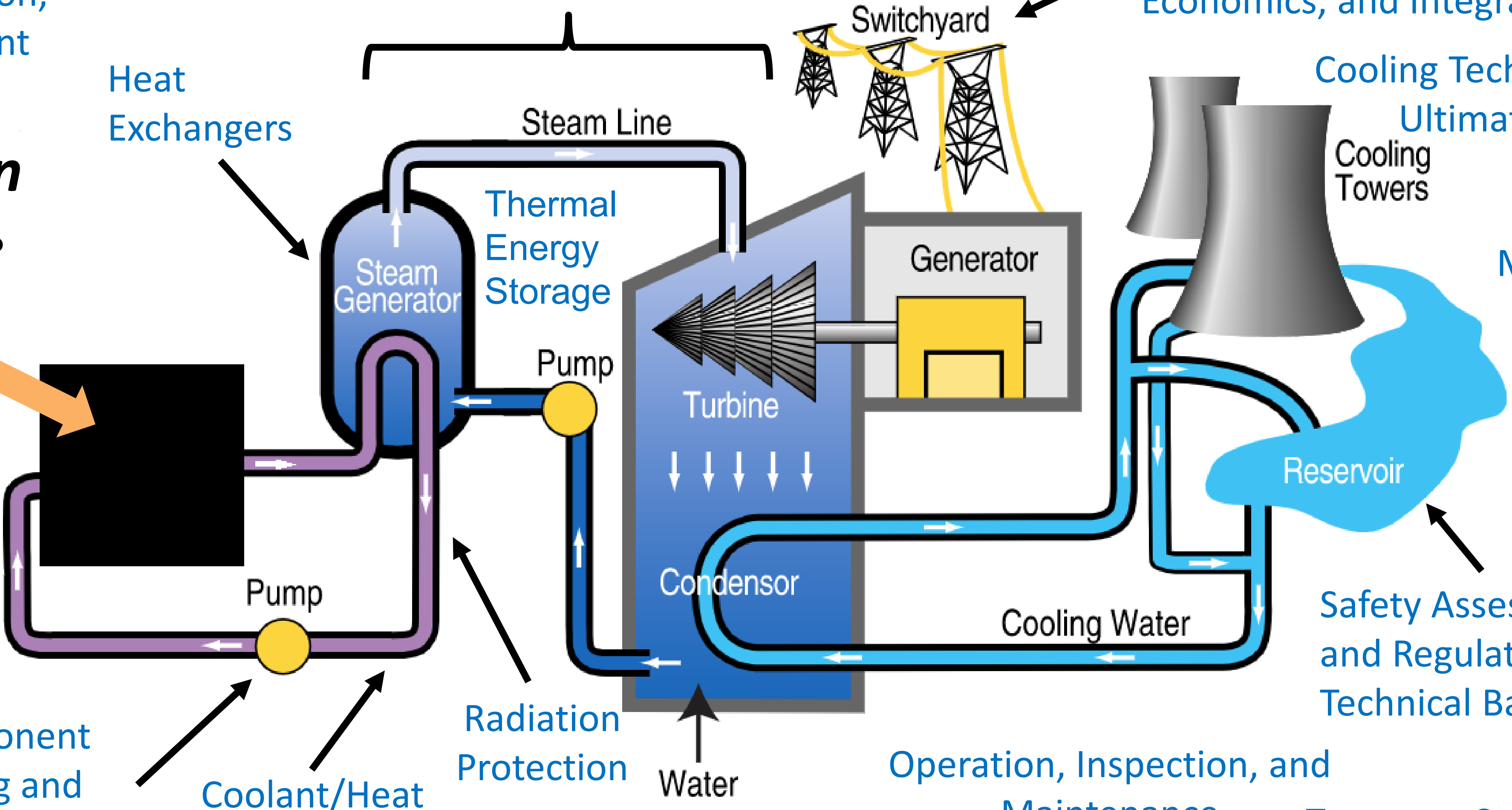
Heat Exchangers

Cooling Technology and Ultimate Heat Sink

Insert Fusion Heat Source Here

Thermal Energy Storage

Waste Management



Materials, Manufacturing, and Code Qualification

Safety Assessment and Regulatory Technical Basis

Component Testing and Qualification

Coolant/Heat Transfer Chemistry

Radiation Protection

Operation, Inspection, and Maintenance

Turnover, Commissioning and Initial Operations

Balance-of-Plant (BOP)

Adapted from image courtesy of TVA; Wikimedia Commons

IAEA Consultancy Meeting Terms of Reference

"…fusion facilities give rise to radiation risks and fall under the IAEA Fundamental Safety Principles and General Safety Requirements.

No fusion-specific requirements or guidance currently exist, representing a gap as fusion technologies are expected to advance in the coming decades toward demonstration and commercial deployment."

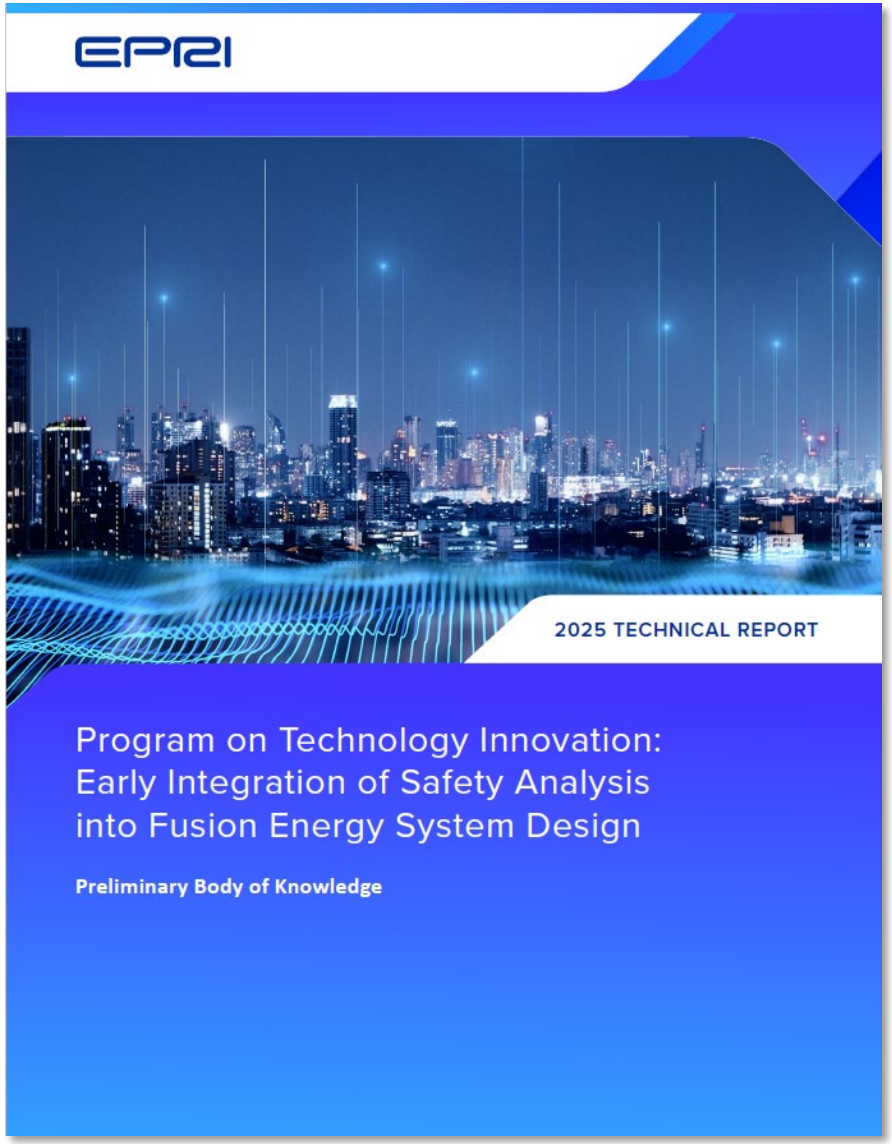
- ***However, there are existing methods and approaches for safety analysis that are standardized, technology-inclusive, and fit-for-purpose.***

EPRI Safety-in-Design (SiD) Methodology Exists

- Presentations at recent IAEA fusion TMs:
  - *Building a Body of Knowledge to Inform a Technology Inclusive, Iterative Safety Assessment Methodology for Fusion Facilities*. IAEA Technical Meeting on Fusion Design Safety & Regulation, Vienna, Austria. 23 October 2023.
  - *Starting with a Clean Slate: Integrating Technology-Neutral Safety Assessment Tools and Methods into Fusion Plant Design. IAEA TM on Design Safety, Safety Assessment and Regulatory Activities to Facilitate Further Development and Future Deployment of Fusion Facilities.* Grenada, Spain. June 3, 2025.
- Presentations & Conference Papers at TOFE 2024 and SOFE 2025
- TOFE 2024: Krahn, S., et al. (2025) "Building a Body of Knowledge to Inform a Technology-Agnostic Iterative Safety Assessment Methodology for Fusion Facilities". Fusion Science and Technology, available online.
- SOFE 2025: Ferrington, B., et al. "Developing a Safety-in-Design Methodology for a Fusion Safety and Reliability Case." Presented at SOFE 2025; IEEE Transactions on Plasma Science, in press.
- ISFNT 2025: Ferrington, B., et al. (2025) "Integration of Safety into the Design of Fusion Power Plants" Presented at ISFNT 2025.

- **Publication of EPRI SiD Body-of-Knowledge: *Early Integration of Safety Analysis into Fusion Energy System Design: Preliminary Body of Knowledge*. EPRI, Palo Alto, CA. December 2025. 3002031117.**

EPRI SiD Body-of-Knowledge (BoK)



- Curated summary of relevant work and experience to date published in 2025
  - Provides an accessible compilation of technical information for early safety and design efforts and stakeholder engagement
  - **Provides a fusion-specific starting point for applying SiD to fusion plants and facilities**
- BoKs are a common approach for documenting the state-of-the-art in a technical field; particularly useful for addressing:
  - Novel and diverse designs
  - New (different) safety concerns and magnitudes
  - New systems/components and reliability concerns
  - Lack of operating experience of key systems and components in an integrated plant

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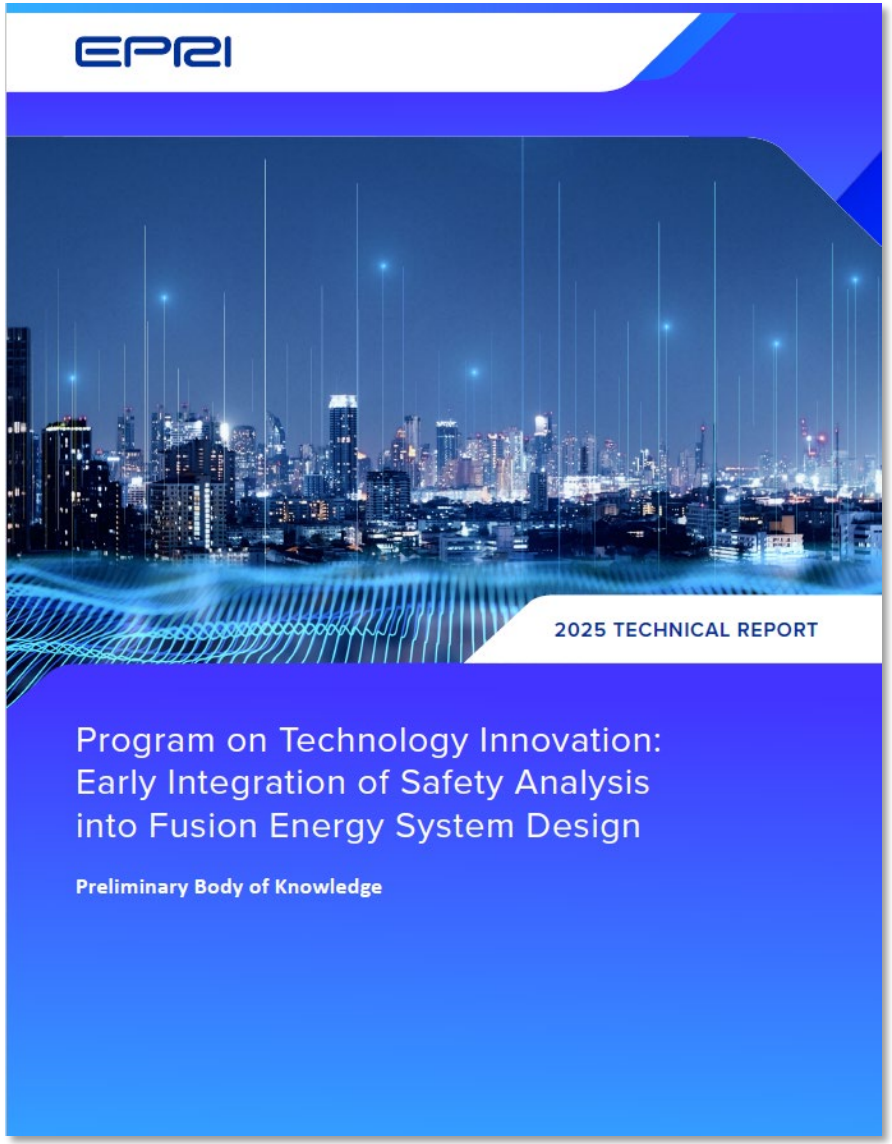
EPRI SiD Body-of-Knowledge (BoK)



- > 100 articles screened, reviewed
- **Takeaways**
  - **Public vs. private:** Current experience is largely derived from and focused towards large, government funded projects—NIF, JET, ITER, DEMO—though broader risk & reliability considerations are similar
  - **Regulator interactions:** Diverse handling of fusion per country—US (10 CFR 30), UK (EA & HSE vs. ONR), and France (ASN & hold points); SiD can help facilitate public-private collaboration, preparation of relevant safety analyses, and regulator interaction
  - **Inspiration from fission experience:** The best-studied safety concerns are fission-adjacent—LOCA, radiation safety—while fusion-specific concerns—tritium handling, PFCs, heat management, etc.—have been more difficult to study without adequate operations experience
  - **Inspiration from other non-fusion experience:** Fuel cycle and accelerator experience fits well as a basis for further risk and reliability case development
  - **Taking advantage of limited prior experience:** JET, Wendelstein 7-X, Princeton TFTR, ITER all provide valuable experience from different pieces of the design-license-build-operate-decommission process

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EPRI Fusion BoK Topic Areas

- **Fusion Technology** provides a brief introduction to the current state of fusion designs, providing an overview and discussion of various systems, with emphasis on those systems shared between design concepts, and their associated hazards.
- **Safety Analysis of Fusion Systems** discusses the methods and results of previous safety analyses that have been conducted for fusion systems.
- **Reliability** introduces the role of the collection and potential use of reliability data in a safety case, and availability evaluations, for fusion power.
- **Non-Fusion Risk Analysis** compiles key safety assessment experience from other facilities—advanced reactors, accelerators, fission fuel cycle facilities, etc.—and discusses their potential applicability to fusion power.
- **Fusion Regulations & Standards** summarizes the status of international fusion regulation, discussing the various approaches that governments are taking to their interactions with their respective domestic fusion industries.
- **Safety, Environment, Fuel Cycle, & Decommissioning** outlines the safety-significant systems within a theoretical fusion plant, with a focus on radiological hazards throughout the plant's entire lifecycle—through decommissioning.
- **Industrial Hazards** discusses the hazards posed by systems and materials in a fusion plant (e.g., magnets, electrical energy, hazardous chemicals) where the extensive experience in other industries may be helpful.
- **Commissioning & Operations** compiles references associated with the available experience commissioning and operating fusion machines in practice.
- **Expert Judgement** introduces the use of expert elicitation in safety assessments, for peer review and informing analysis, on topics with little prior experience.

Fusion Technology

- While the SiD methodology is technology-inclusive, EPRI deliberately chose to limit scope to magnetic fusion confinement technologies for this first version for pragmatic reasons
- **BoK is intended to be a living document to revised and expanded with time**
- Key fusion technology aspects and functions described in BoK:
  - Fuel Handling
  - Fusion Plasma Control and Startup
  - Blanket Systems
  - Confinement of Radioactivity
  - Radiation Shielding
  - Gas Handling
  - Byproduct Materials and Waste Management
  - Cooling Systems
  - Power Conversion and Production
  - Instrumentation and Controls (I&C) and Control Room

Example Excerpt from EPRI Fusion BoK

Section 5. NON-FUSION RISK ANALYSIS

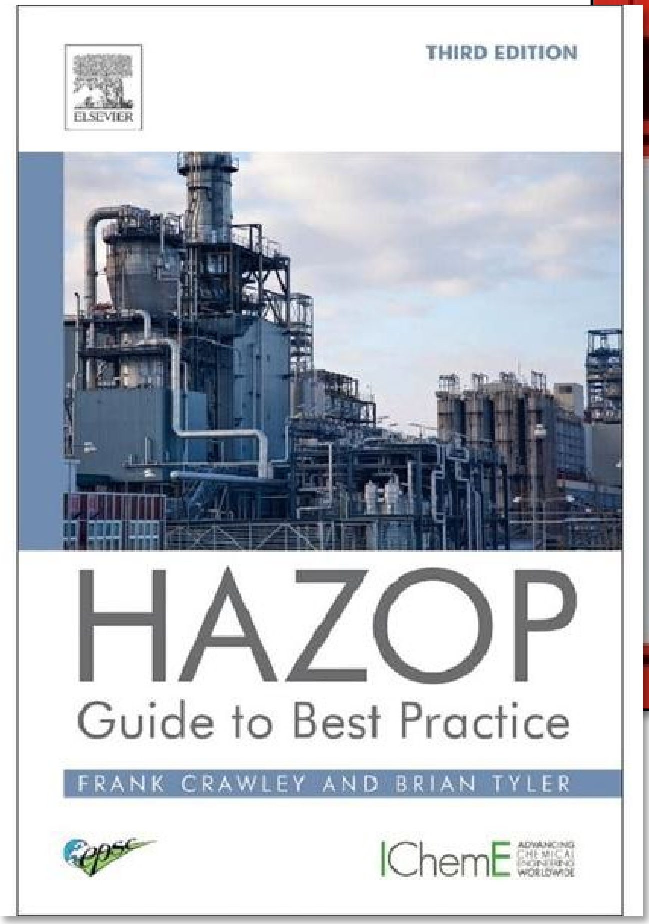
Selected References

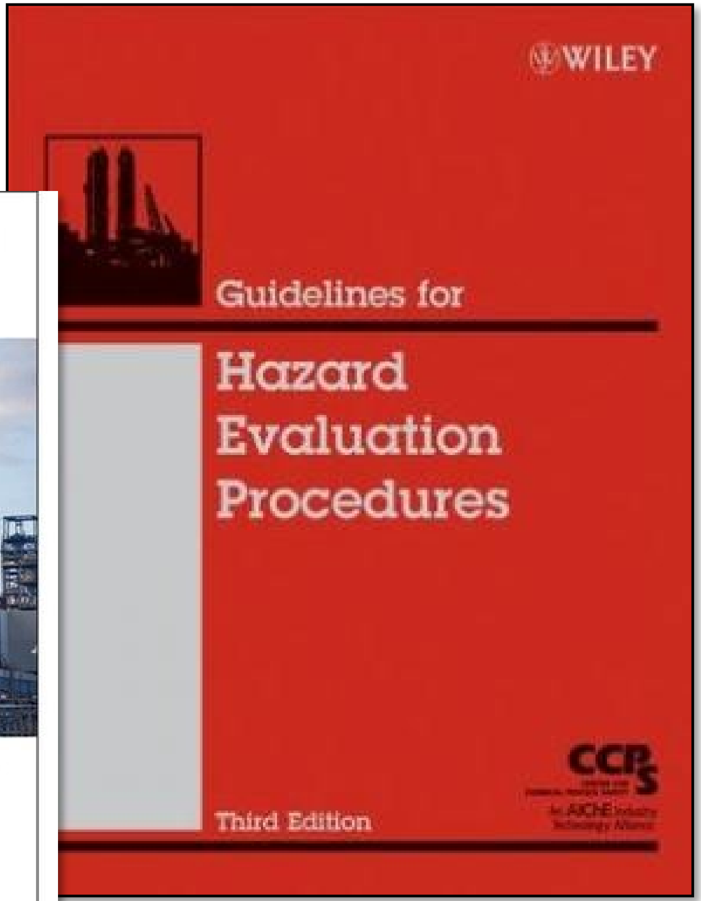
EPRI. (2019). Early Integration of Safety Assessment into Advanced Reactor Design: Project Capstone Report. Report No. 3002015752; Program on Technology Innovation.

This report provides a detailed discussion of the SiD methodology: its development, definition, demonstration, application to real-world designs, and potential steps for further enhancement. SiD was developed with an eye towards advanced fission concepts with little operations experience that incorporate novel design features or source terms—providing a method to allow developers of such designs to incrementally develop a defensible safety case. This risk-informed, technology neutral methodology is based on industry-standard PHA methods, which consist of qualitative and semi-quantitative analyses, including HAZOP, ETA and FTA—many of which are codified in international standards[94]. Case studies were conducted on the Molten Salt Reactor Experiment and a Kairos Power fluids test loop; in-process feedback on the SiD methodology was provided by the NRC, Southern Company, UCLA's Garrick Institute for Risk Sciences, Kairos Power, the NRC, and several Industry Forums.

Safety-in-Design for Fusion

- Technology inclusive, industry-standard process hazard analysis (PHA) and associated methods exist and:
  - were established for the systematic identification and characterization of hazards associated with complex industrial processes and facilities
  - **are well-suited for application to fusion energy plants and facilities**

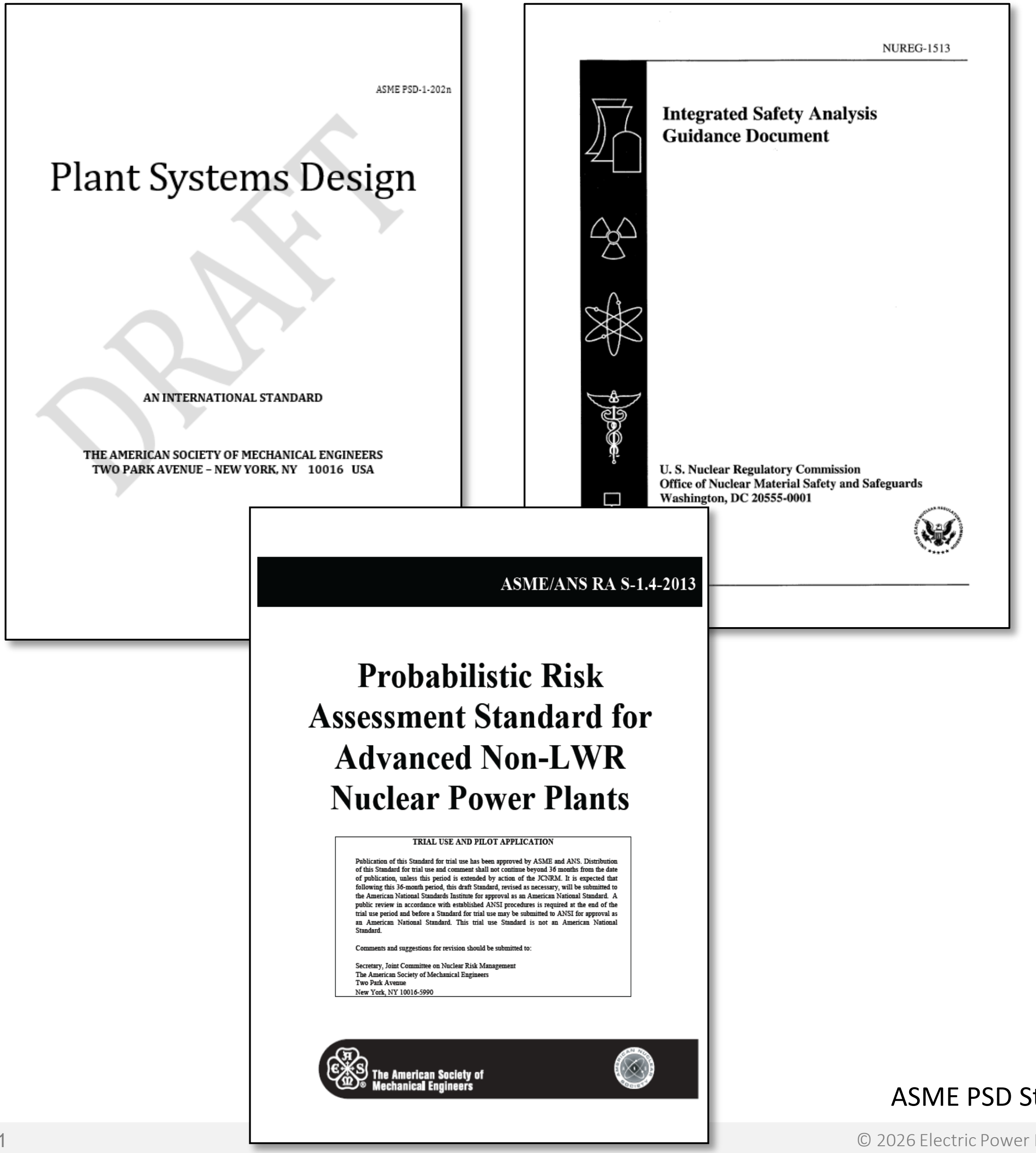




PHA is the application of one or more analytical methods to identify and evaluate process hazards for the purpose of determining the adequacy of or need for control measures.*

*DOE Handbook: Chemical Process Hazards Analysis. August 2004. DOE-HDBK-1100-2004.

PHA Provides the Basis for SiD Methodology



- PHA provides structured, systematic methods and tools backed by industry standard to identify potential hazards and operability problems
- Identifies potential **causes** and potential **consequences** of upsets and accidents, i.e.:
  - What can go wrong?
  - What are the consequences?
- Typically, qualitative evaluations of process upsets and how event sequences promulgate
- Can be used as the starting point for quantitative risk assessment (*if needed or desired*)
- Adaptable, amenable to iteration with increasing detail – fit for purpose

- **ASME Plant System Design Standard (PSD-1) has been approved for publication** as a technology neutral standard for design of any commercial plant or facility featuring hazards.

ASME PSD Standard Committee: https://cstools.asme.org/csconnect/CommitteePages.cfm?Committee=102652169

Global Adoption and Application of PHA Across Industries

- OSHA 29 CFR Part 1910.119: Process Safety Management of Highly Hazardous Chemicals, Explosives, and Blasting Agents (PSM Rule)
- ISO 31000 Risk Management Series (and associated standards)
- DOE-HDBK-1100-2004: Chemical Process Hazards Analysis. August 2004.
- DOE-STD-1628-2013: Development of Probabilistic Risk Assessments for Nuclear Safety Applications
- DOE-STD-1189-2016: Integration of Safety into the Design Process
- ANSI/ASME/ANS RA-S-1.4-2021: Probabilistic Risk Assessment Standard for Advanced Non-Light Water Reactor Nuclear Power Plants
- NUREG-1513: Integrated Safety Analysis Guidance Document
- NUREG-1520: Standard Review Plan for the Review of a License Application for a Fuel Cycle Facility

Many PHA Methods Available for Fit-for-Purpose SiD Application

From AIChE CCPS Guidelines:

- Preliminary Hazard Analysis
- Safety Review
- Relative Ranking
- Checklist Analysis
- What-If Analysis
- Chemical Interaction Matrix
- What-If/Checklist Analysis
- Hazard and Operability (HAZOP) Study
- Failure Modes and Effects Analysis (FMEA)
- Fault Tree Analysis (FTA)
- Event Tree Analysis (ETA)
- Cause-Consequence Analysis

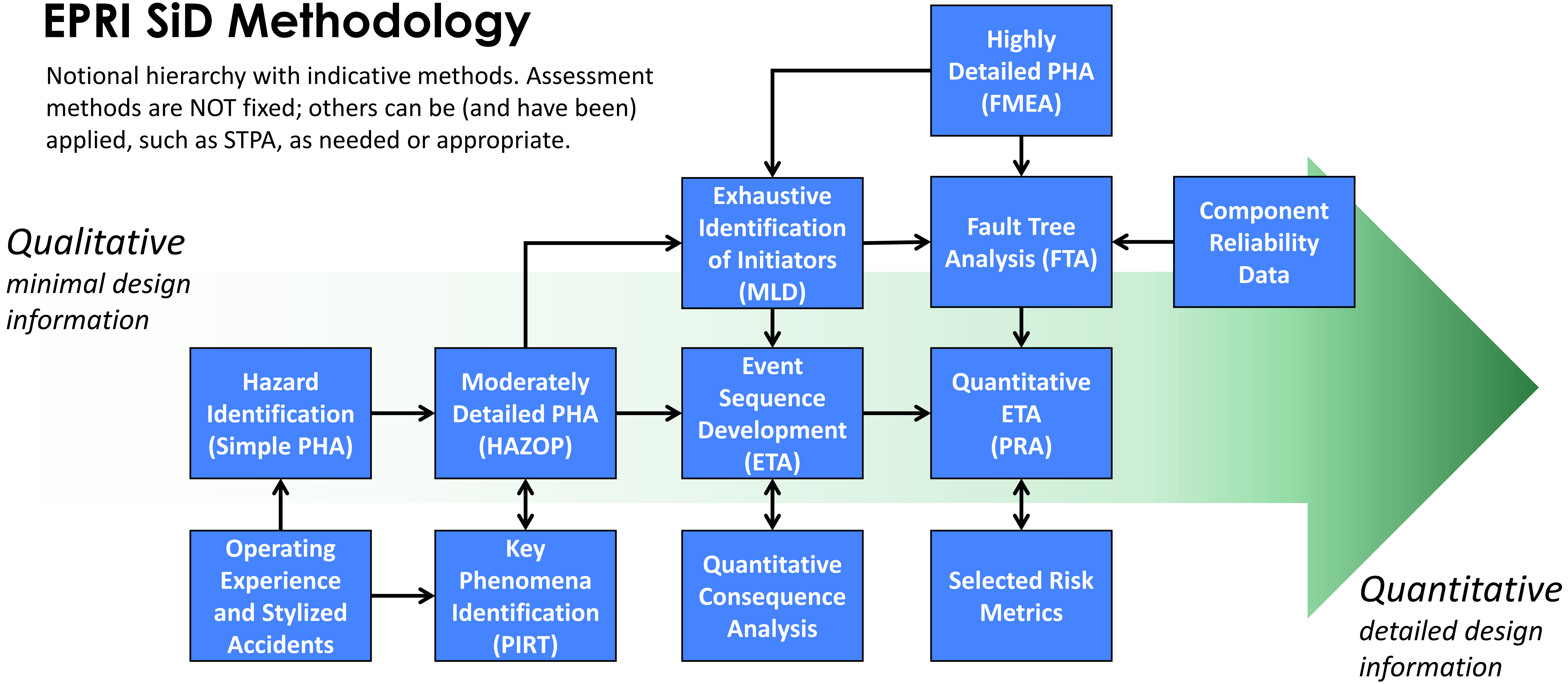
Others:

- Functional Failure Modes and Effects Analysis (FFMEA)
- Systems Theoretic Process Analysis (STPA)
- Master Logic Diagram (MLD)
- Initiating Event Literature Survey

NOTE: PHA methods in blue have been applied in prior evaluations by EPRI and/or Vanderbilt University research teams.

EPRI SiD Methodology

Notional hierarchy with indicative methods. Assessment methods are NOT fixed; others can be (and have been) applied, such as STPA, as needed or appropriate.



PHA – Process Hazards Analysis	FTA – Fault Tree Analysis	PRA – Probabilistic Risk Assessment
FMEA – Failure Modes and Effects Analysis	HAZOP- Hazards and Operability [study]	PIRT – Phenomenon Identification and Ranking Table
MLD – Master Logic Diagram	ETA – Event Tree Analysis	

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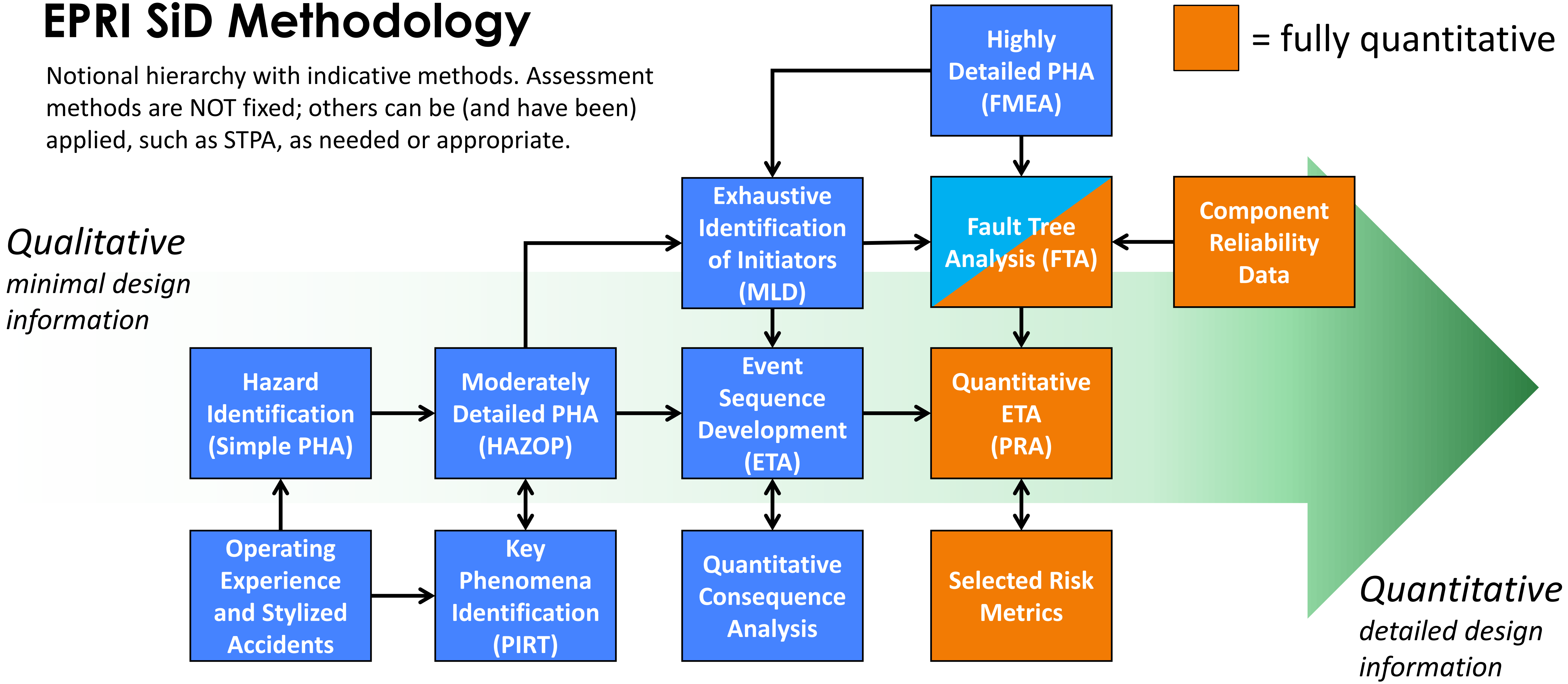

PHA – Process Hazards Analysis
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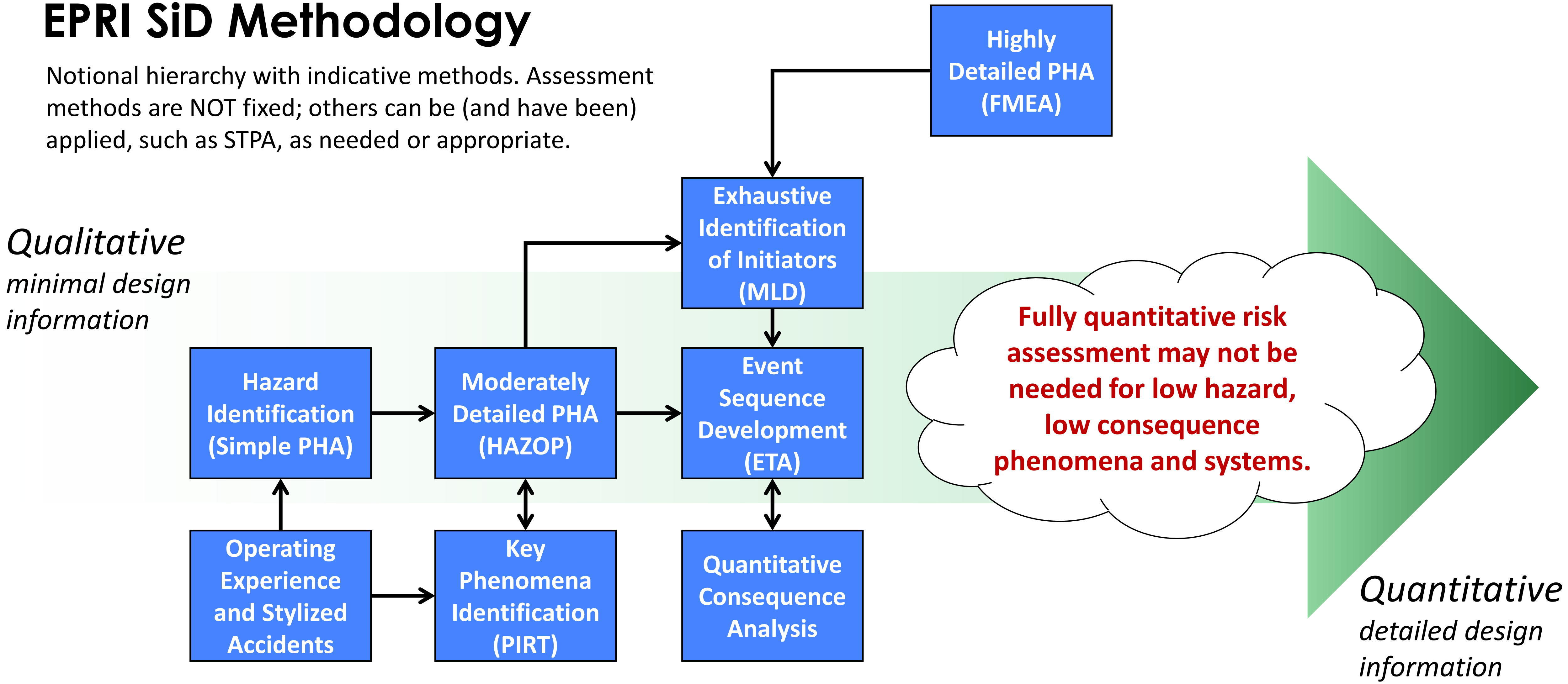

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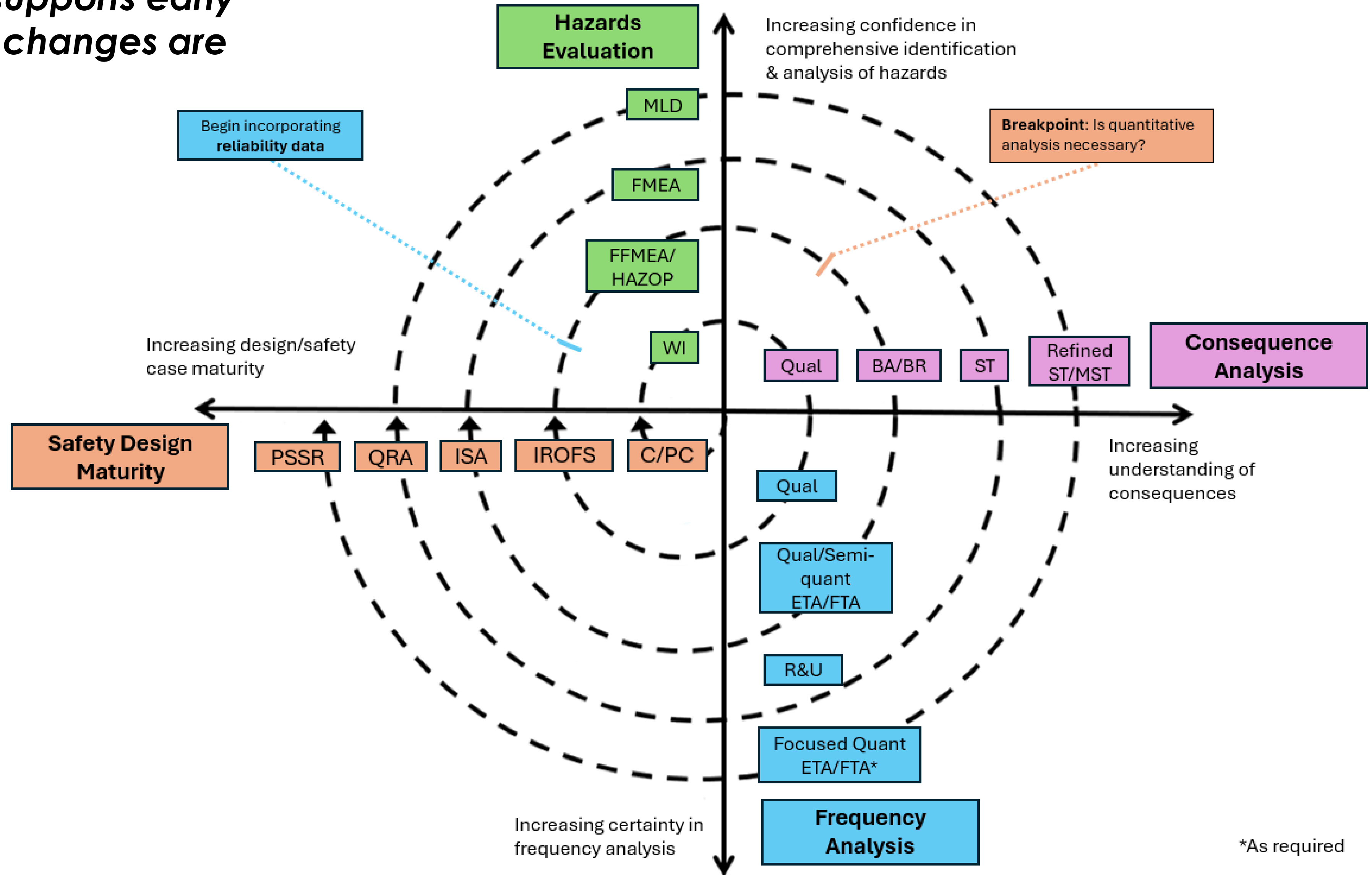
Fusion SiD Design Spiral

Iteration as design matures supports early identification of issues when changes are least costly and impactful.

Key
C/PC: Conceptual/Pre-Conceptual design
IROFS: Items Relied On For Safety
ISA: Integrated Safety Analysis
QRA: Quantitative Risk Assessment
PSSR: Pre-Startup Safety Review
WI: What-If? Analysis
FFMEA: Functional Failure Modes & Effects Analysis
HAZOP: Hazards and Operability Analysis
FMEA: Failure Modes and Effects Analysis
MLD: Master Logic Diagram
FTA: Fault Tree Analysis
Qual/Quant: Quantitative/Qualitative analysis
BA/BR: Bounding Accident/Bounding Release
ST: Source Term Estimate
MST: Mechanistic Source Term
ETA: Event Tree Analysis
R&U: Reliability & Uncertainty



*As required

EPRI Development of SiD Guidance for Fusion Application

- **Body of Knowledge** published in December 2025 as a publicly available EPRI technical report
- **MBSE** integration with SiD methodology is being demonstrated
- **Case studies** to apply and revise SiD methodology for fusion include:
  - **Kyoto Fusioneering** collaboration on safety case development with SiD and incorporation of MBSE
  - **TVA & Southern Company** support for application of SiD to fusion design review
  - **Internal JET AGHS** HAZID analysis with interactions matrix as preliminary application
  - **Continued exploration** of collaborative opportunities with fusion community
- **Presentations & Conference Papers** at TOFE 2024, SOFE 2025, ISFNT 2025
- **Briefings** to IAEA 2023 and 2025 TMs on Fusion Safety
- **Industry workshop in October 2025** to elicit fusion developer feedback on SiD

Key Takeaways

- Existing international, standardized, technology-inclusive PHA (and supporting) tools and methods offer a structured, fit-for-purpose way to implement a fit-for-purpose approach for fusion safety analysis

- EPRI’s curation of PHA and supporting methods into SiD methodology for safety analysis of new generation technologies (advanced fission and fusion) spans 10 years of documentation, peer-review, regulatory review, and pilot demonstrations

- Publication of EPRI’s body of knowledge SiD for fusion applications offers a tangible starting point for application and maturation of methodology for international community

Acknowledgements

VANDERBILT School *of* Engineering

- The Safety-in-Design methodology was initially developed and applied for advanced fission applications through EPRI sponsored research and collaboration with Professor Steve Krahn and his research team at Vanderbilt University.

- This work was also made possible in part by support from and collaborations with many organizations, including:
  - Southern Company
  - Kairos Power
  - General Atomics
  - FLiBe Energy
  - Oak Ridge National Laboratory
  - B. John Garrick Institute for the Risk Sciences at UCLA

- Demonstrations of SiD were supported in part by funding from the US DOE Office of Nuclear Energy and ARPA-E

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References and Additional Context

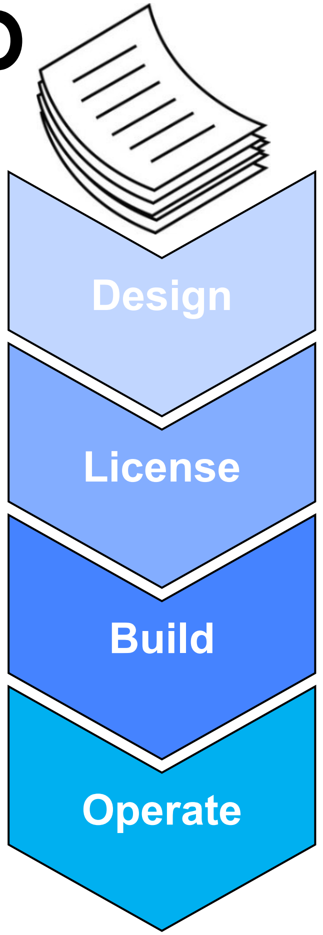
Origin of Process Hazard Analysis (PHA)[1,2]

- December 3, 1984, Bhopal, India: Early morning gaseous release of methyl isocyanide resulted in >3,000 deaths and >100,000 injuries (exact figures are not known).
  - Worst process chemical accident on record.
  - Exposed lack of a formalized process safety mindset, assessment methods and tools, and resources.

- In response, the American Institute of Chemical Engineering (AIChE) established Center for Chemical Process Safety (CCPS) in 1985 to promote process safety and prevent future catastrophic incidents.
  - AIChE published first process safety guideline book, Guidelines for Hazard Evaluation Procedures, in 1987.

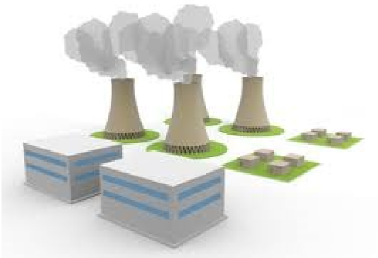
[1]AIChE Center for Chemical Process Safety (CCPS). History. https://www.aiche.org/ccps/history
[2]UK Health & Safety Executive. Union Carbide India Ltd, Bhopal, India. 3rd December 1984. https://www.hse.gov.uk/comah/sragtech/caseuncarbide84.htm

A Decade of EPRI Development & Application of SiD



- Motivated by the challenges faced by advanced fission developers in creating a safety case for technologies that may have limited to no commercial operating experience; incorporate novel structures, systems, and components (SSCs); and present unique source terms
- Assembled a methodology to facilitate early integration of safety assessment the design of advanced (fission) reactors
- Produced a body of knowledge (BoK) on application of relevant process hazard analysis (PHA) methods for advanced reactor designs
- Illustrated application of approach with historical and unique Molten Salt Reactor Experiment (MSRE) case studies
  - supported Licensing Modernization Project via MSR “table-top” exercise
  - briefed to USNRC staff and Advisory Committee on Reactor Safeguards (ACRS)
- Demonstrated utility via pilot applications with advanced reactor developers

Kairos Power | Southern Company | TerraPower | moltex clean energy | Oak Ridge National Laboratory



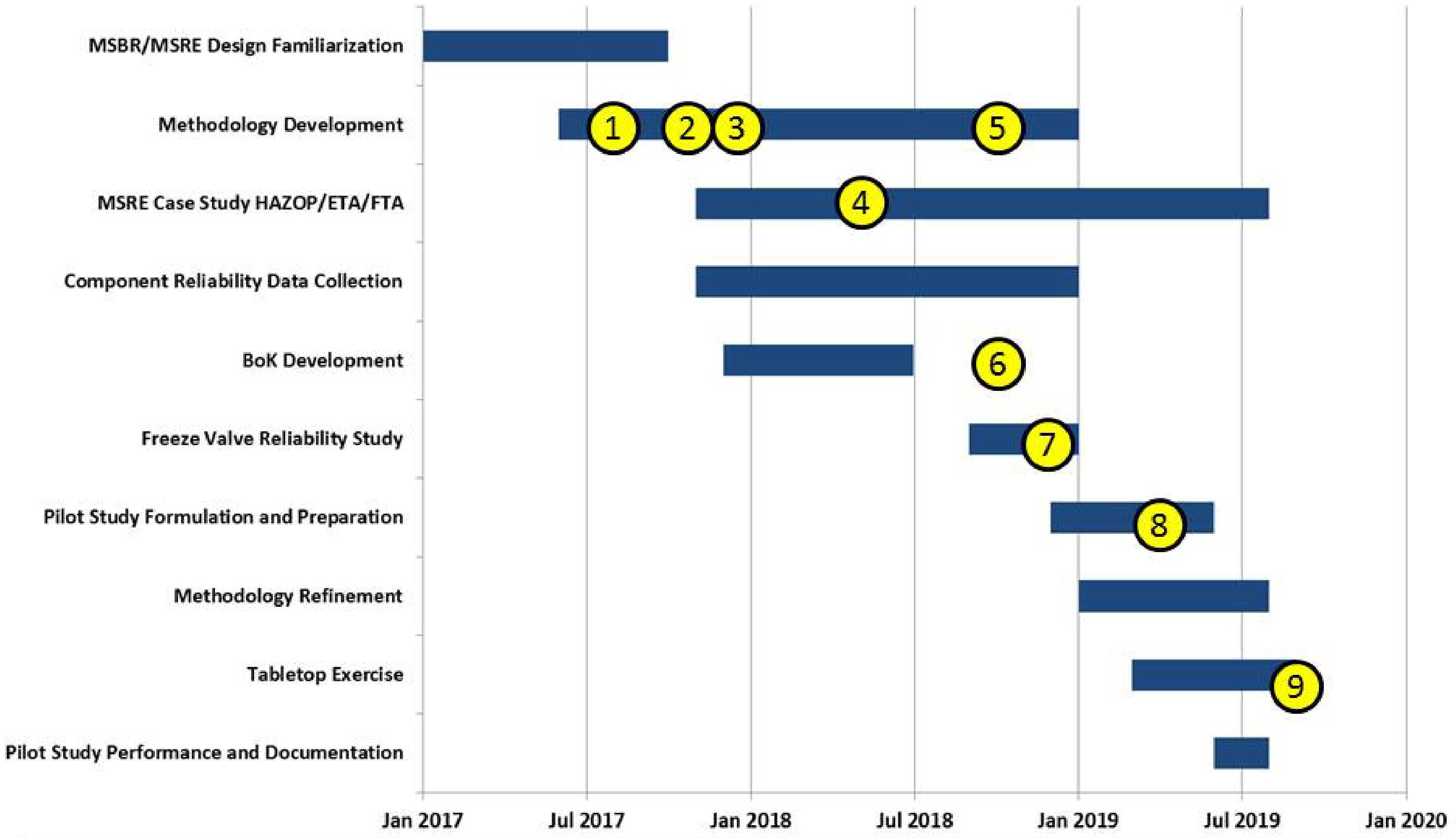
Documentation of development and application for ARs is publicly available.

Full Retrospective Application of EPRI SiD Methodology to the Historical Molten Salt Reactor Experiment (MSRE) Design

	Operating Experience and Stylized Accidents	Hazard ID	Key Phenomena Identification	HAZOP Study	Event Sequence Development	Quantitative Consequence Analysis	FMEA	FTA	Component Reliability Data	Quant. ETA	Risk Metric Selection
Off-Gas System and Component Cooling System	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
Fuel Salt Loop	✓	✓	✓	✓	✓						✓
Freeze Valve	✓						✓	✓	✓		
Fuel Processing System	✓	✓	✓	✓	✓						✓

Details for this matrix can be found in Table 1-1, “Roadmap to technical work for MSRE Case Study (EPRI Report 3002018340)

SiD Methodology Development — Peer Review and Input



1 - P2P Workshop	4 - ICAPP 2018 Presentation	7 - 2018 Winter ANS Presentation
2 - 2017 MSR Workshop Presentation	5 - PSAM14 Presentations	8 - PSA 2019 Presentation
3- 2017 Winter ANS Presentation	6 - Preliminary Body of Knowledge and Methodology Report	9 - MSRE OGS Tabletop Report

Note: See Table 1 for list of abbreviations used in this figure

Acronyms

ANS – American Nuclear Society

ETA – Event Tree Analysis

FTA – Fault Tree Analysis

HAZOP – Hazards and Operability [study]

ICAPP – International Congress on Advances in Nuclear Power Plants [conference]

MSRE – Molten Salt Reactor Experiment

OGS – Off Gas System

PHA – Process Hazards Analysis

PSA – International Topical Meeting on Probabilistic Safety Assessment [conference]

PSAM – Probabilistic Safety Assessment and Management [conference]

SiD References (1 of 3)

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- Submittals to Regulator for Review (USNRC)
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Argument for MBSE Application for Fusion

- Several applications have already been documented to a degree in the literature.
  - UKAEA (STEP)
  - ITER
  - Wendelstein 7-X
- Fusion systems are logical candidates for integrated safety analysis leveraging MBSE due to:
  - Novel designs with limited operational experience
  - Potentially new hazards that have not been previously identified or analyzed
  - Inherent complexity associated with ‘systems-of-systems’ (i.e., fusion systems)

Potential MBSE Application Areas to Support Fusion SiD

- Development of tailored system models that serve as “single sources of truth” for system designs.
- Elicitation of hazard and/or risk profiles appropriate for fusion systems.
  - Recent example with advanced fission: passive decay heat removal system case study.
- Capturing and tracing system requirements to system elements that satisfy them.
- Facilitating stakeholder engagement by capturing the design in an integrated system model.

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