Liquid Fuel Performance Characterization

Here's to You, Dr. Weinberg
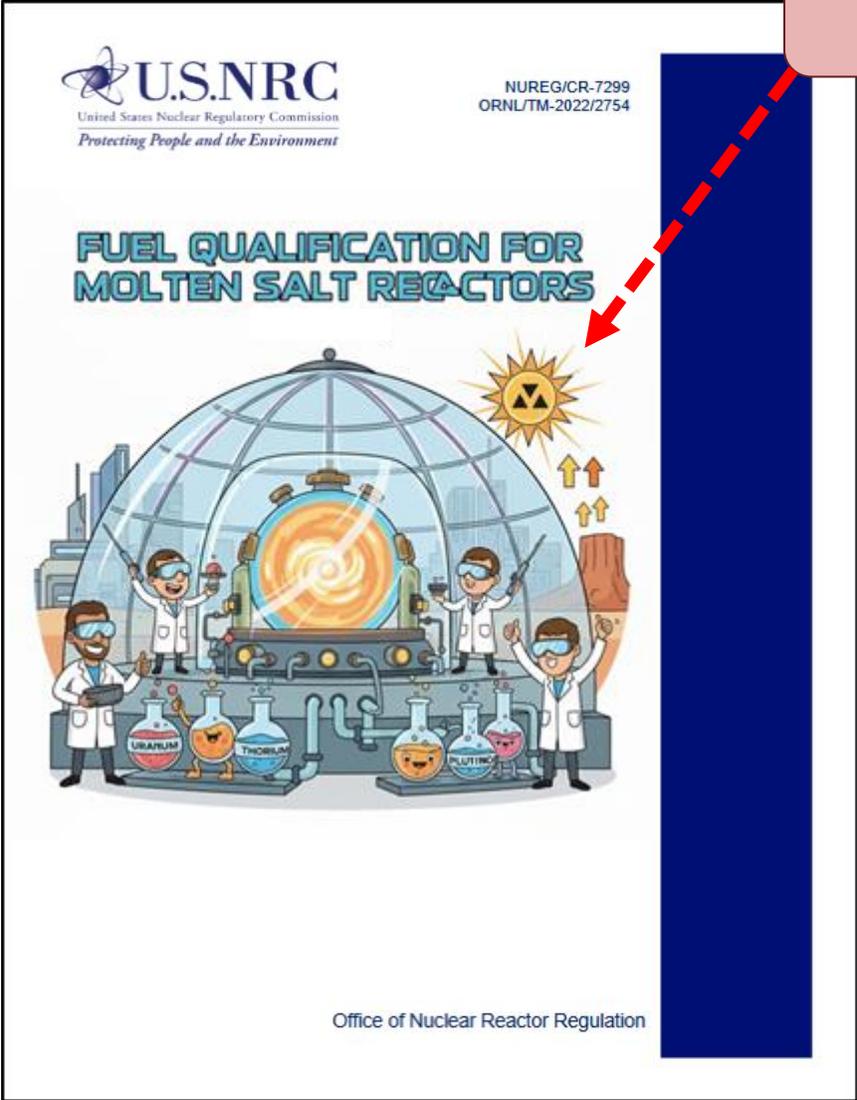
Dan Moneghan, PhD
Senior Technical Leader

30 January 2026
RP3C Community of Practice

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Historical Work
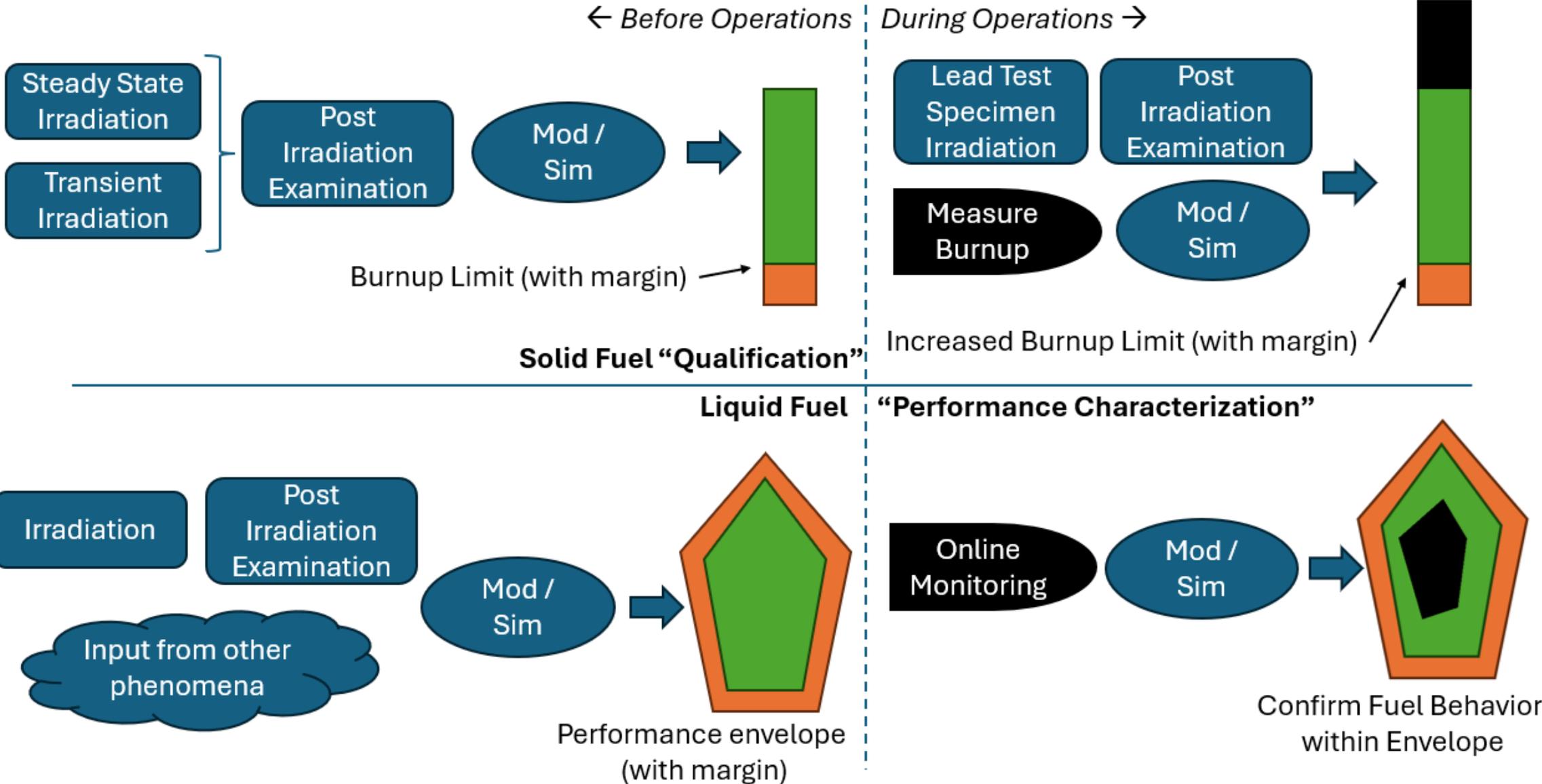*(circa 2022)*

Low-effort AI "art" added by me
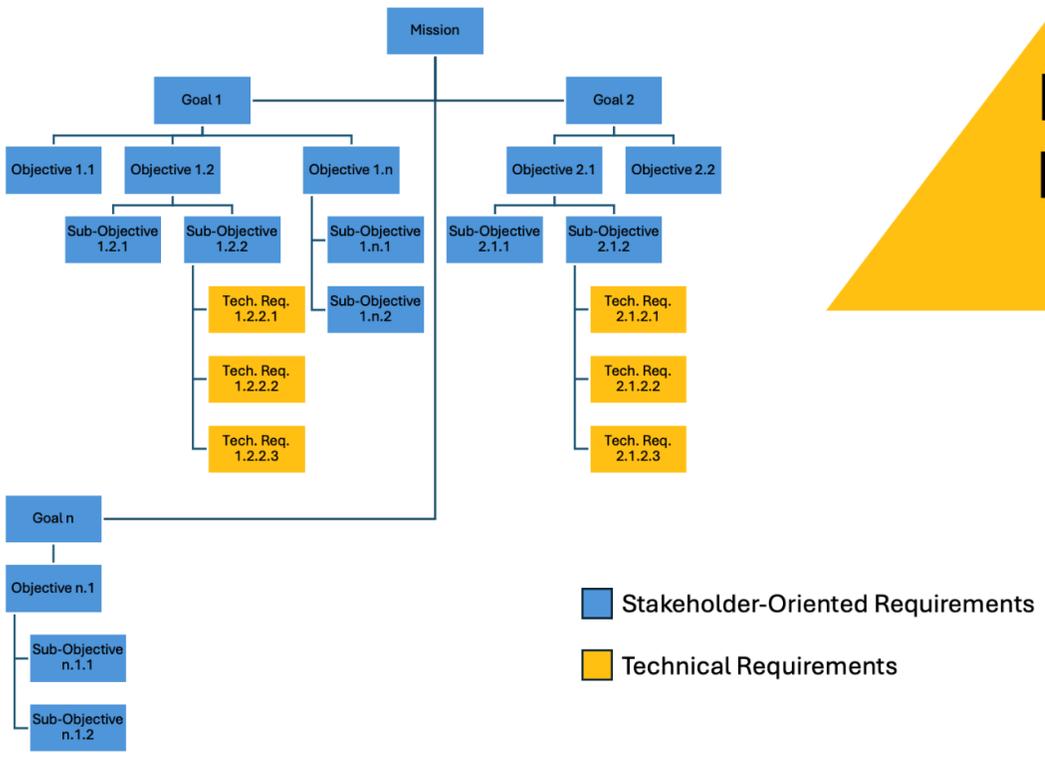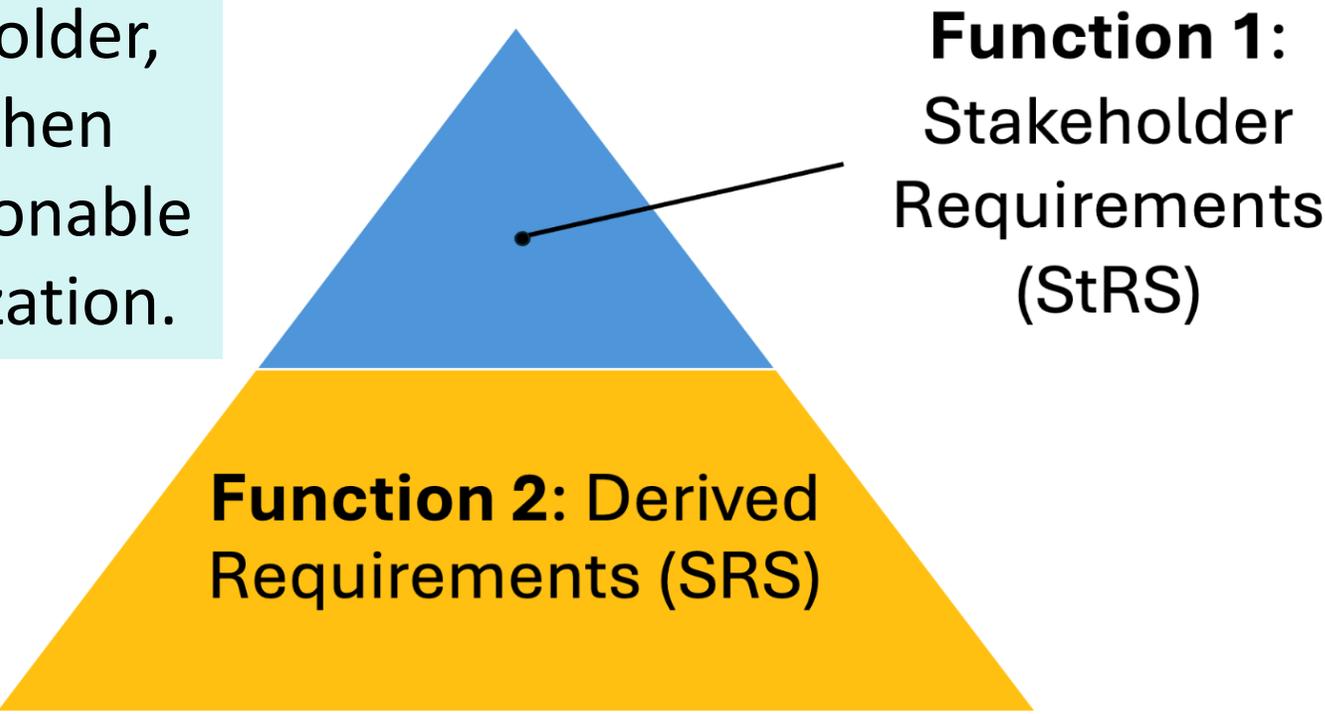
Acknowledgements
or, who did all the hard work

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- Kevin Kelly, Rodolfo Vaghetto – EPRI

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Qualification vs Characterization

← Before Operations | During Operations →

Steady State Irradiation, Transient Irradiation → Post Irradiation Examination → Mod / Sim → Burnup Limit (with margin)

Solid Fuel "Qualification"

Lead Test Specimen Irradiation, Post Irradiation Examination, Measure Burnup, Mod / Sim → Increased Burnup Limit (with margin)

Liquid Fuel "Performance Characterization"

Irradiation, Post Irradiation Examination, Input from other phenomena → Mod / Sim → Performance envelope (with margin)

Online Monitoring, Mod / Sim → Confirm Fuel Behavior within Envelope

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Identifying Requirements

Requirements come from a stakeholder, such as the regulator. These are then derived into more detailed and actionable requirements by the design organization.

Function 1: Stakeholder Requirements (StRS)

Function 2: Derived Requirements (SRS)

■ Stakeholder-Oriented Requirements

■ Technical Requirements

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Developing the Hierarchy Structure
Stakeholder Requirements

- ## Level 1: Regulator Mission Statement

| ASN 🇫🇷	ONR 🇬🇧	NRC 🇺🇸
▪ Ensure a high level of protection for workers, patients, the public and the environment…	▪ The public, workers and the environment shall be protected from the harmful effects of ionising radiation…	▪ Reasonable assurance of adequate protection of public health and safety

- ## Level 2: Fundamental Safety Functions

– Reactivity control – Containment of radioactive substances – Cooling of nuclear fuel	– Control of reactivity – Confinement of radioactive material – Removal of heat from the core	– Control reactivity – Limit release of radioactivity – Remove heat

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The System Being Evaluated

Primary Fuel Salt Flow Path ■

Line 100

Line 101

Line 102

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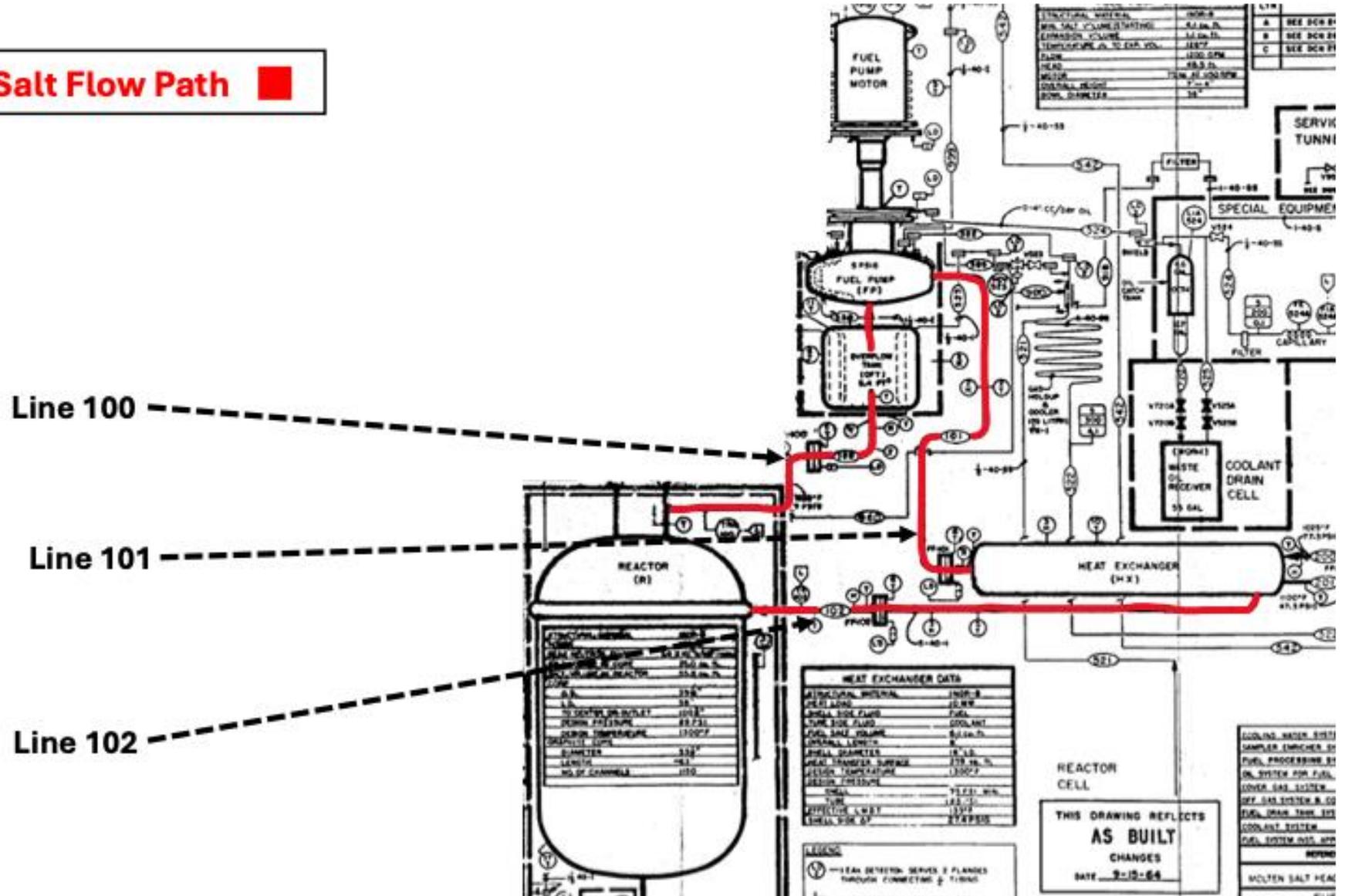
Developing the Hierarchy Structure
Derived Requirements

- **Level 3:** Identification of Interfacing Systems
  - *What systems are needed to support the fundamental safety function?*
  - *i.e. Heat removal is supported by fuel flowing through the reactor vessel*
- **Level 4:** Identification of Functional Requirement
  - *What must take place within the system to achieve the objective?*
  - *i.e. Reactor vessel interfaces must facilitate convective heat transfer*
- **Level 5:** Mechanistic Objectives
  - *What physics are at play in the system achieving the objective?*
  - *i.e. Convective heat transfer in the reactor vessel is partially determined by the flow regime, calculated using the Reynold's number*
- **Level 6:** Fuel Properties
  - *What properties of the fuel interact with the physics under consideration?*
 - *i.e. the Reynold's number is dependent on density and dynamic viscosity*

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Branch of the Hierarchy – Visualized
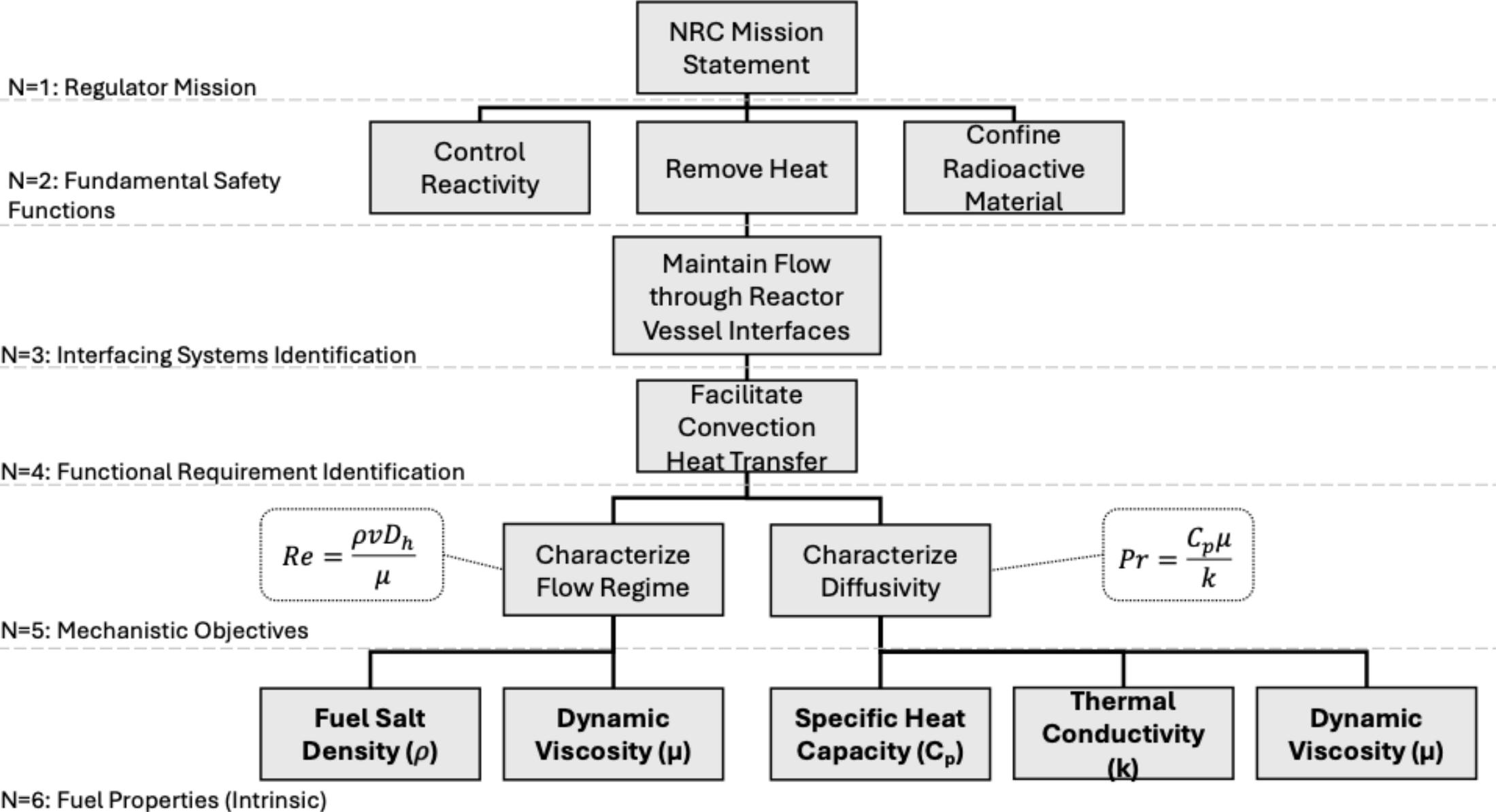
Objectives Hierarchy Branch for the MSRE

Regulator Mission Statement (N=1)	FSFs (N=2)	Interface Identification (N=3)	Functional Requirement Identification (N=4)	Mechanistic Objectives (N=5)	Fuel Properties (N=6)	Intrinsic or Extrinsic	Governing Equation
Provide Reasonable Assurance of Adequate Public Health and Safety	Remove Heat	Flow Through the Reactor Vessel and Internal Components	Enable Convection Heat Transfer in Fuel Inlet Piping Line 102	Facilitate Necessary Flow Regime Conditions in Fuel Inlet Piping Line 102	Fuel Salt Density	Intrinsic	$Re=(\rho v D)/\mu$
					Fuel Salt Dynamic Viscosity	Intrinsic	
					Fuel Chemical Composition	Extrinsic	-
				Facilitate Necessary Pressure Drop Conditions in Fuel Inlet Piping Line 102	Friction Factor	Extrinsic	$\Delta P=f\,(L/D)(\rho v^2)/2$
					Fuel Salt Density	Intrinsic	
					Fuel Chemical Composition	Extrinsic	-
				Facilitate Necessary Surface Conditions in Fuel Inlet Piping Line 102	Particulate Content	Extrinsic	-
					Redox Potential	Intrinsic	-
					Fuel Chemical Composition	Extrinsic	-
				Facilitate Necessary Diffusivity Conditions in Fuel Inlet Piping Line 102	Fuel Salt Specific Heat Capacity	Intrinsic	$Pr=(C_p\mu)/k$
					Fuel Salt Thermal Conductivity	Intrinsic	
					Fuel Salt Dynamic Viscosity	Intrinsic	
					Fuel Chemical Composition	Extrinsic	-

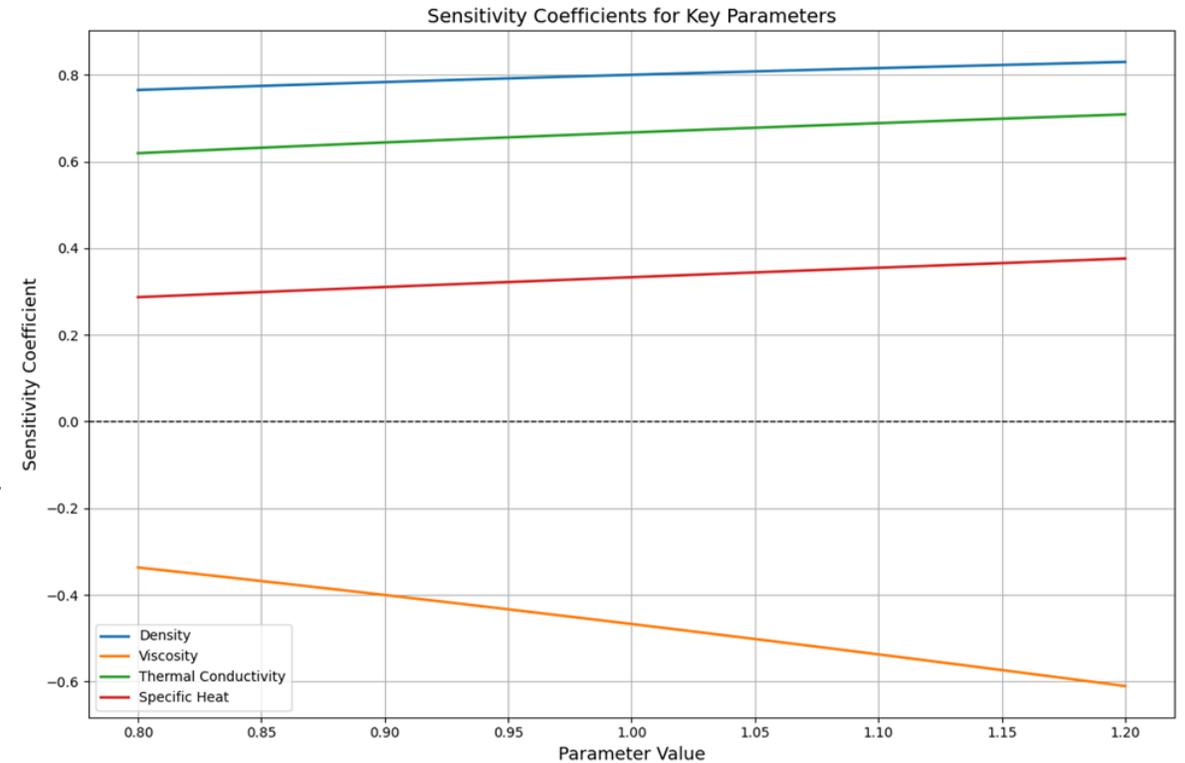Inlet Piping Line 102 is the pipe segment between the heat exchanger and the core

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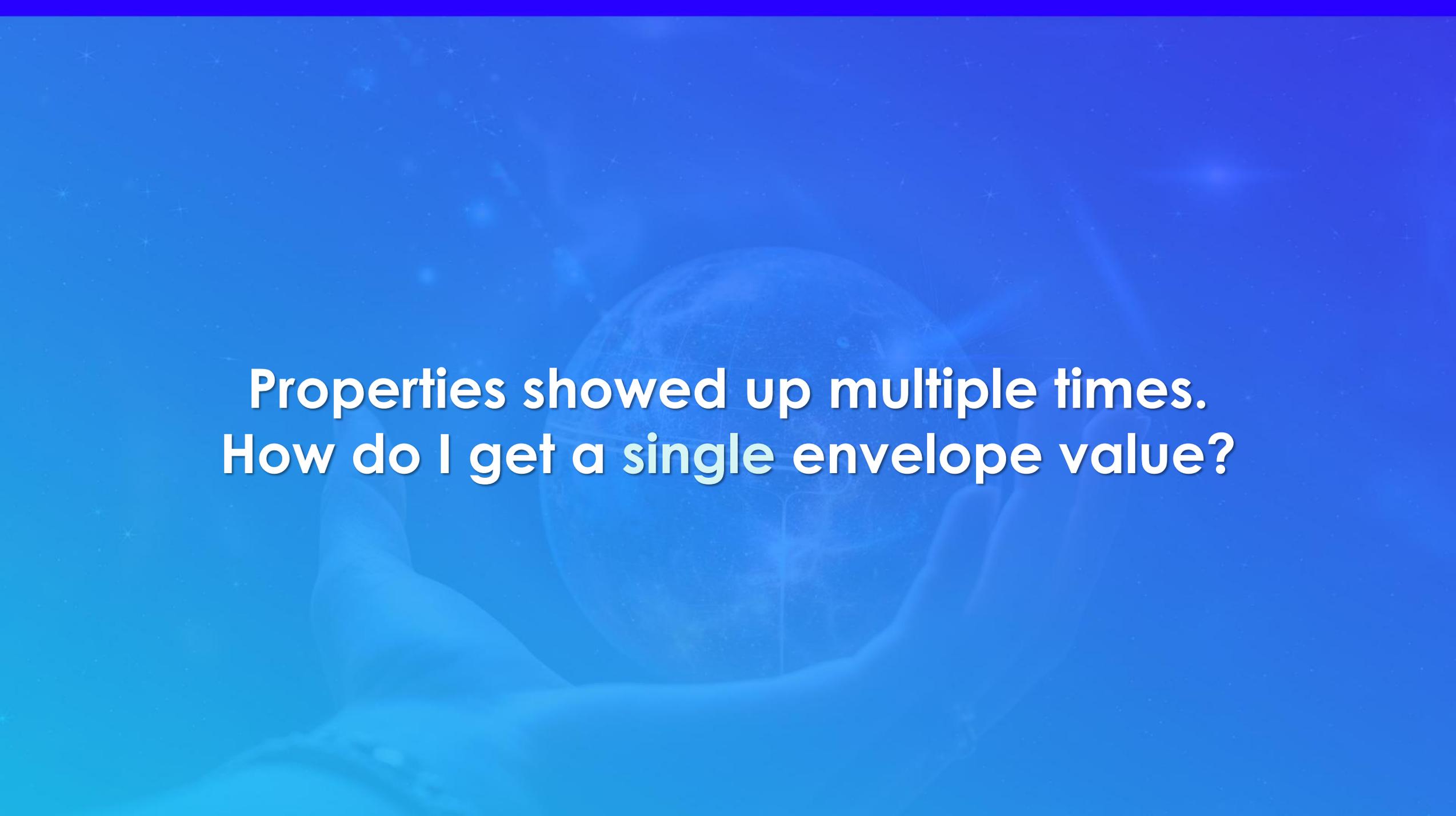
Properties showed up multiple times. How do I get a single envelope value?

Calculus*

$$S(f, u) = \frac{u}{f} \left(\frac{\partial f}{\partial u} \right)_u$$

"S, is conveniently defined as the dimensionless fractional variation of the observed system response, f(u), resulting from a given fractional variation of a selected input, u"
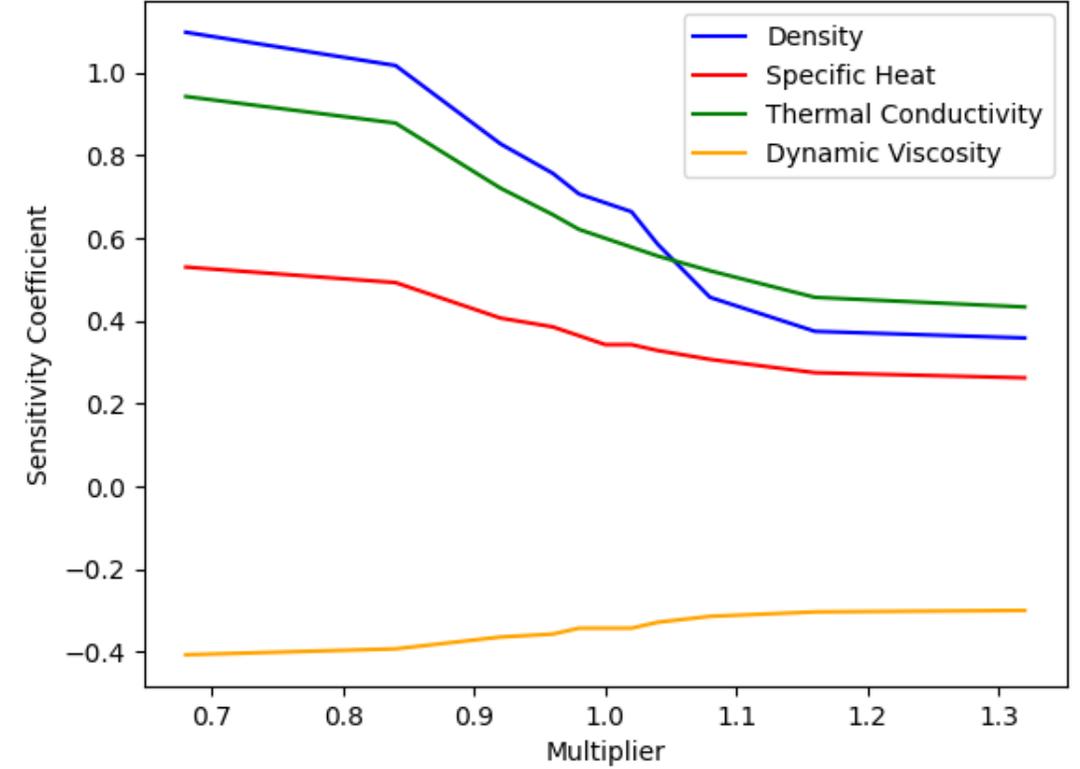

Sensitivity Coefficients for Key Parameters

- Density
- Viscosity
- Thermal Conductivity
- Specific Heat

*Hand calculation results in limited accuracy due to the tightly coupled multiphysics interactions not captured with analytical methods.

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Or GOTHIC
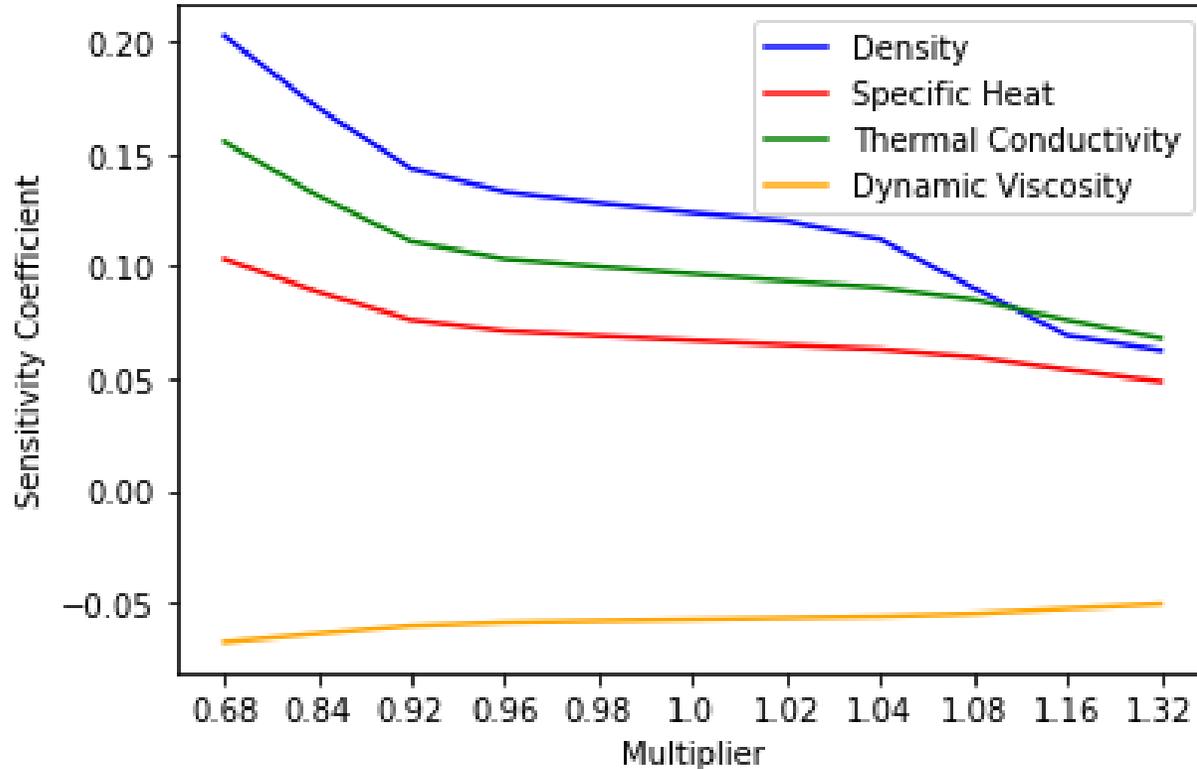
Evaluate each safety function's objectives against the properties that contribute to determine how values become bounding on different timescales. Build the envelope around your limiting combinations.

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Measurement Uncertainty

Ok… properties identified and bounded. Now what happens?

- Measure them precisely
- MSRE operated safely and successfully with modest uncertainties

  "For most cases, the uncertainty represents considerably more than either "goodness of fit" of an interpolation or internal consistency available from thermodynamics. Instead, the uncertainty may be considered as the largest probable combination of systematic and random errors associated with the value given for the property." (Cantor, 1968)
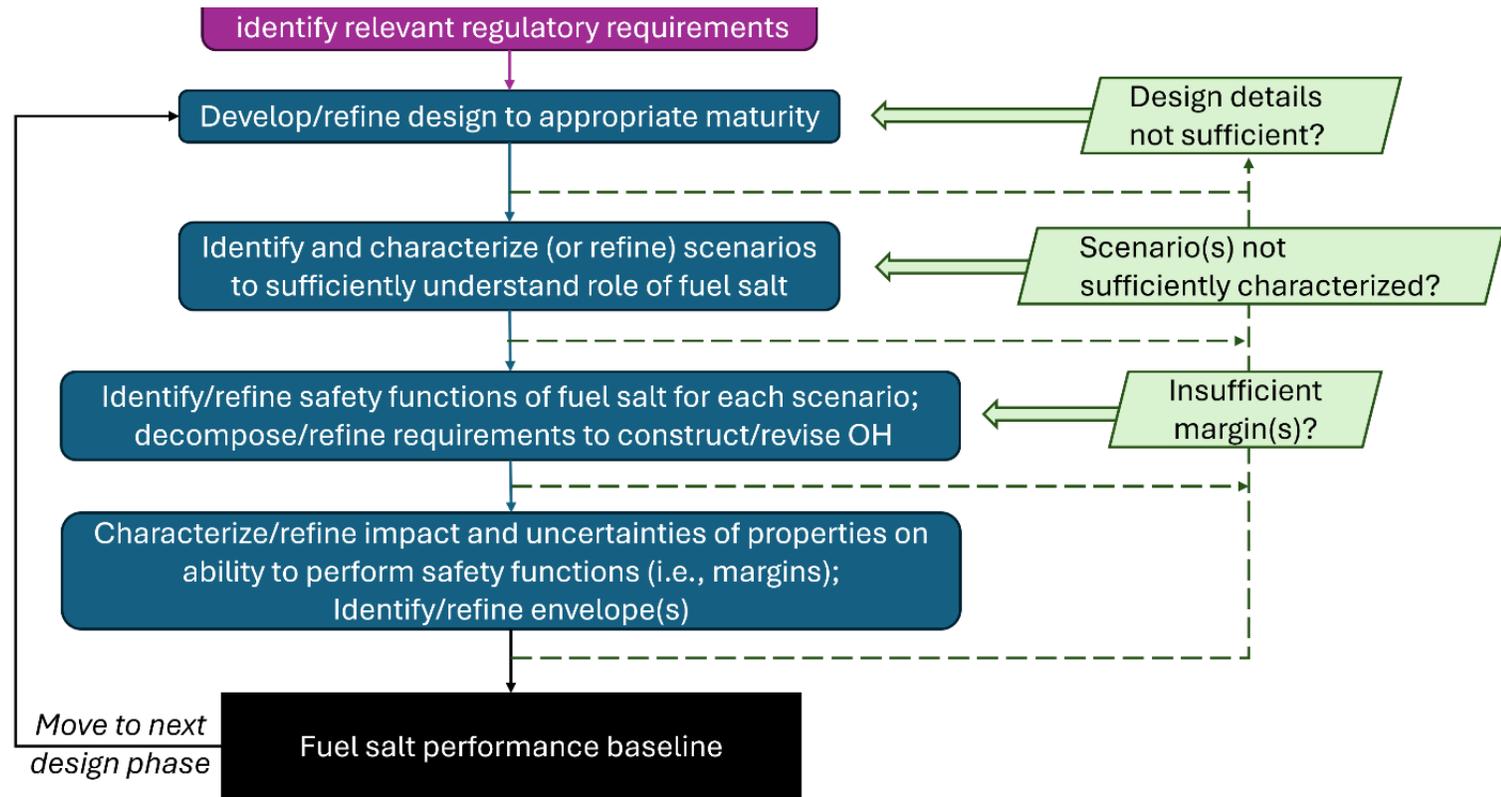
- Optimize your margins by valuing uncertainty reduction vs cost
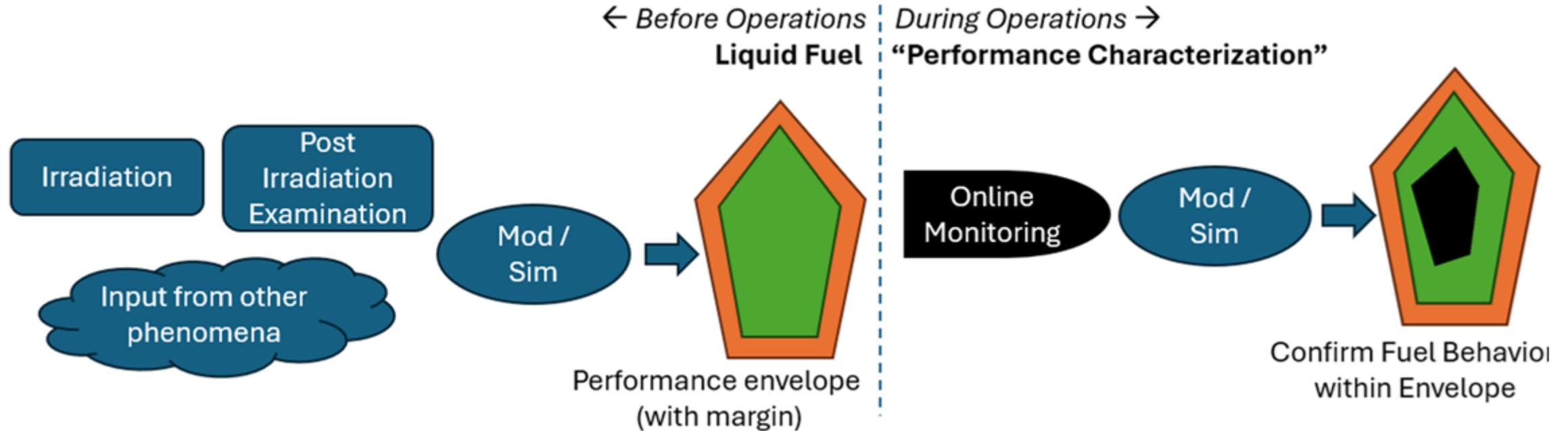
Table 9-3. Measured fuel properties from ORNL-TM-2316

Fuel Property	Sources of Data/Estimation Methods	Postulated Uncertainty
Viscosity	Estimated empirically from experimental data.	25%
Thermal Conductivity	Analytical expression	>25%
Electrical Conductivity	Estimated empirically from experimental data.	20%
Phase Transition Behavior	Estimated from phase equilibria studies.	Varied with fuel salt analyzed
Heat Capacity	Analytical expression	Liquid: 4% Solid: 10%
Heat of Fusion	Analytical expression	15%
Density	Analytical expression	3%
Expansivity	Analytical expression	25%
Compressibility	Analytical expression	Not provided
Vapor Pressure	Analytical expression	"A factor of fifty from 500-700 C"
Surface Tension	Analytical expression	10-30%

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Applying the Method

- Useful insights are not limited to the licensing phase of a project
- This method assists throughout design maturation
  - Replace Level 1 with any Mission Statement
  - Decompose into discrete enabling functions
  - Follow the process and develop the insights

identify relevant regulatory requirements

Develop/refine design to appropriate maturity ← Design details not sufficient?

Identify and characterize (or refine) scenarios to sufficiently understand role of fuel salt ← Scenario(s) not sufficiently characterized?

Identify/refine safety functions of fuel salt for each scenario; decompose/refine requirements to construct/revise OH ← Insufficient margin(s)?

Characterize/refine impact and uncertainties of properties on ability to perform safety functions (i.e., margins); Identify/refine envelope(s)

Move to next design phase

Fuel salt performance baseline

So… Is my fuel qualified for use?

- I don't know, we have to gain acceptance of the method first!
- Appropriate sensitivity studies and uncertainty measurement help define your margins
- If you operate within the bounding polyhedron governing your properties, your fuel is, at least, satisfying the safety functions

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