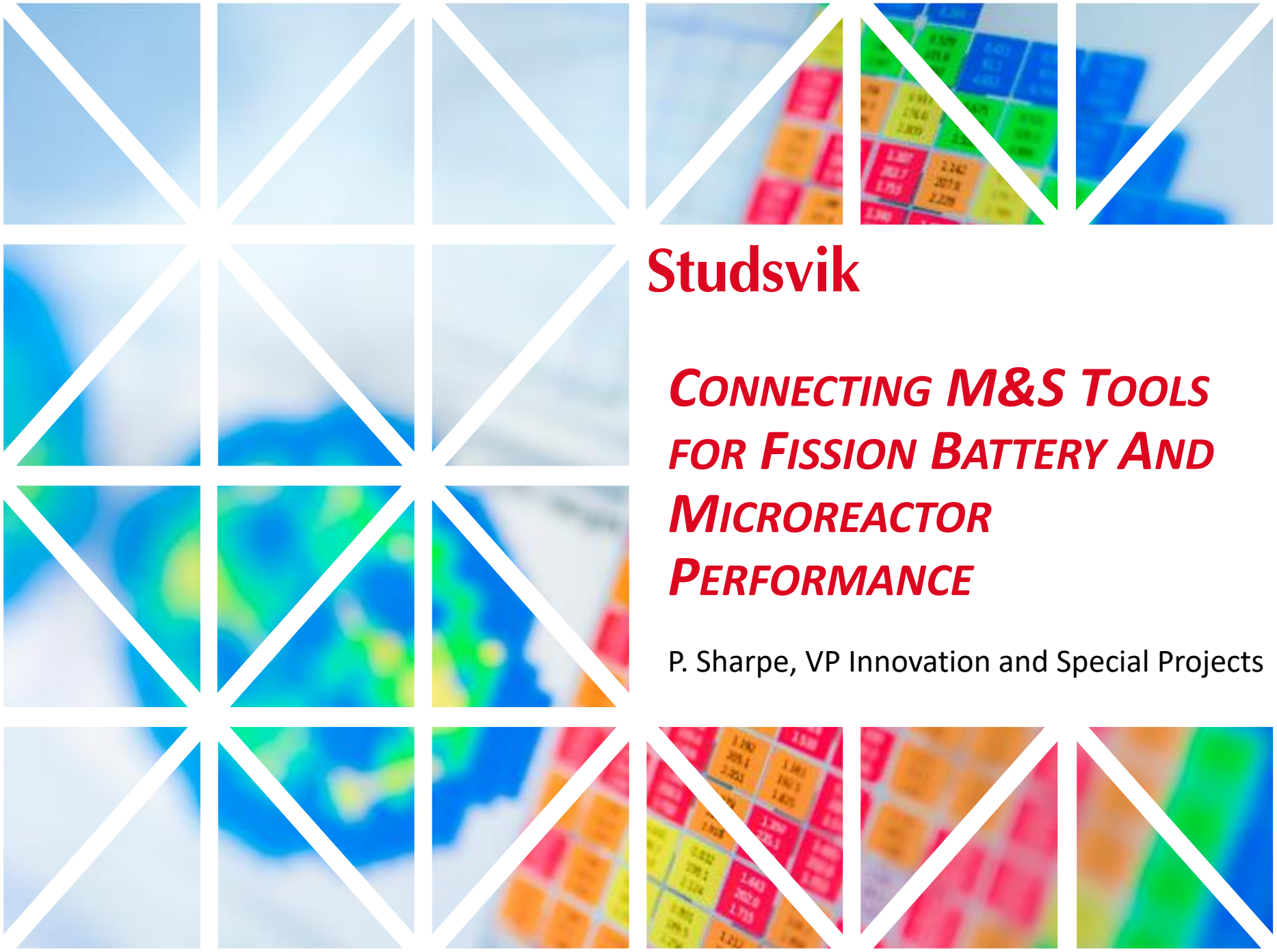

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# Connecting M&S Tools for Fission Battery And Microreactor Performance

P. Sharpe, VP Innovation and Special Projects

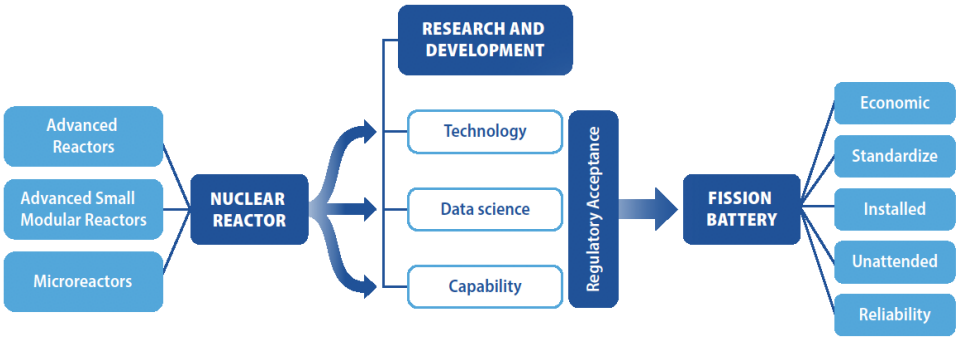
# Small Nuclear Power Systems May Be Inevitable

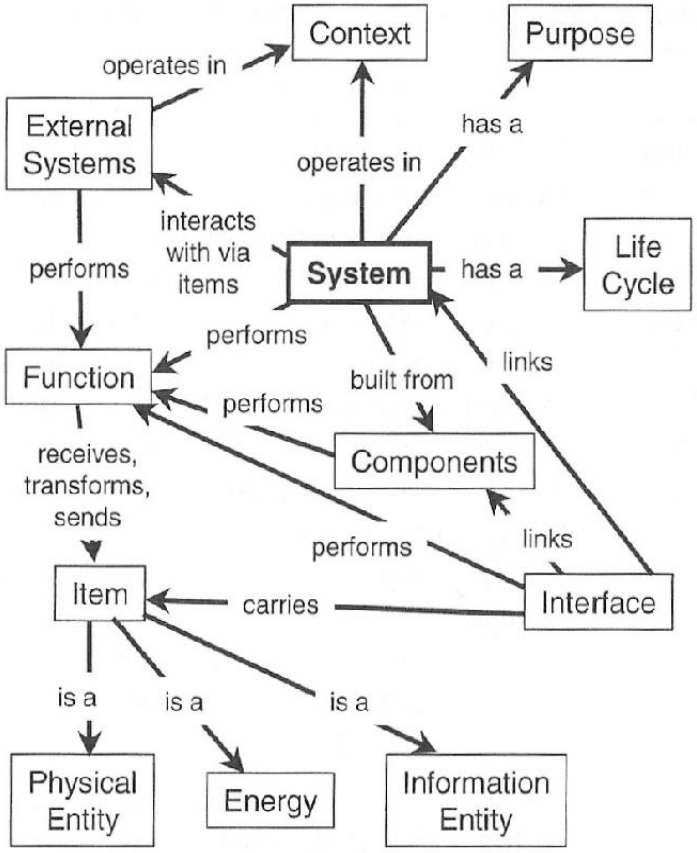
- Trends toward distributed generation (DG) driven in part by support and deployment of low energy density renewables
- Energy generation and distribution market structures are evolving to accommodate DG, both in developed and developing economies
- Reinforced by de-centralization of other mature industries (communications, computing, retail, etc.) and the infrastructure to support (e.g. just-in-time supply chain)
- The continually growing urgency around the human condition, environmental damage, climate change, and …

*Natural extension for nuclear power technology into smaller scalable DG packages – towards the microreactor and nuclear battery.*

# Defining the Design – A Prerequisite for Any Microreactor or Fission Battery Concept

- What SHOULD the system be able to do? What CAN the system do in actuality?
- The *Fission Battery Initiative* outlines targeted ***Attributes*** for transformation into ***Design Requirements***

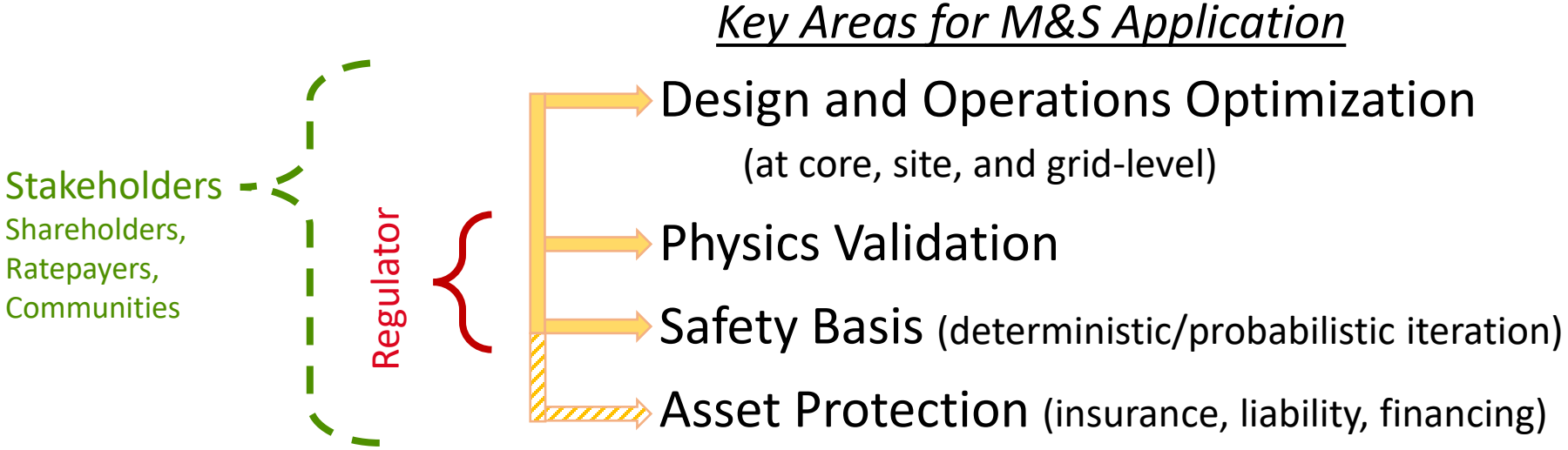



[Buede and Miller, *The Engineering Design of Systems*, 2016.]

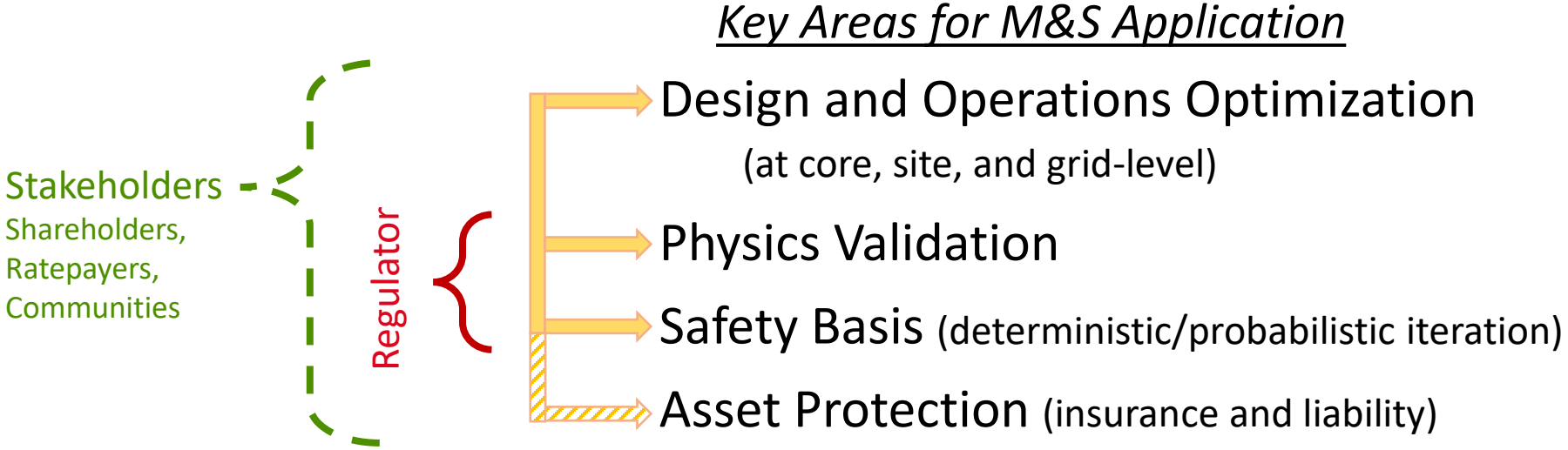
- Modeling and Simulation (M&S) Tools are developed and/or adapted to inform and define specifications

# How Could M&S Tools Fit Into the Picture?



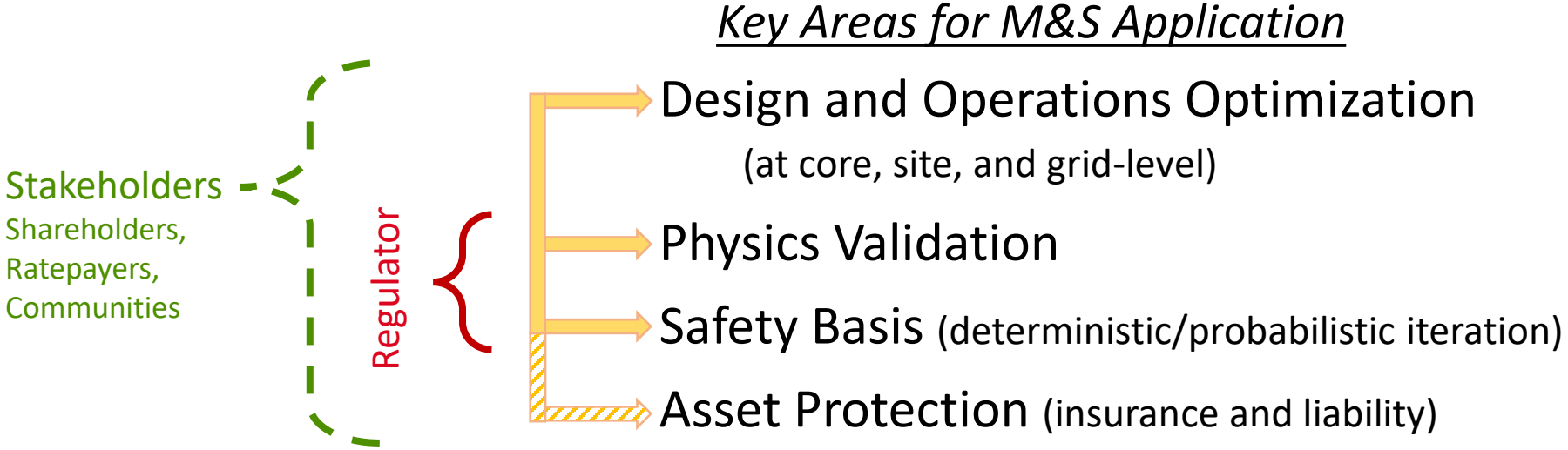

- ***Engineering-scale M&S Tools*** suitable for *Design and Operations Optimization* as well as *Asset Protection*
  - Real-time or better -> fast running, accurate calcs to explore large design space
  - Suitable basis for PIRT's and focus of refined modeling
  - Guidance for design of experiments
  - Derivative use of Reduced Order Models, and adaptive to Dynamic PRA
  - Applies outcome of machine learning/AI and basis of autonomous control systems
  - Owner/Operator usage – market policy changes, IRP's, scalable applications…

# How Could M&S Tools Fit Into the Picture? (cont.)




- ***High-fidelity M&S Tools*** needed for *Physics Validation* and *Safety Basis*, where precision in quantity and sequence are paramount
  - Large and complex models typically with slower runtimes and/or high-performance computing needs (supercomputer cluster)
  - Explore unexamined multi-physics- ”complex interactions of competing phenomena”
  - Detailed examination with Separate Effects and Integrated Effects testing
  - Higher Regulator scrutiny
  - Basis for ROM’s, mineable results for machine learning, inform dynamic PRA,…

# How Could M&S Tools Fit Into the Picture? (cont.)

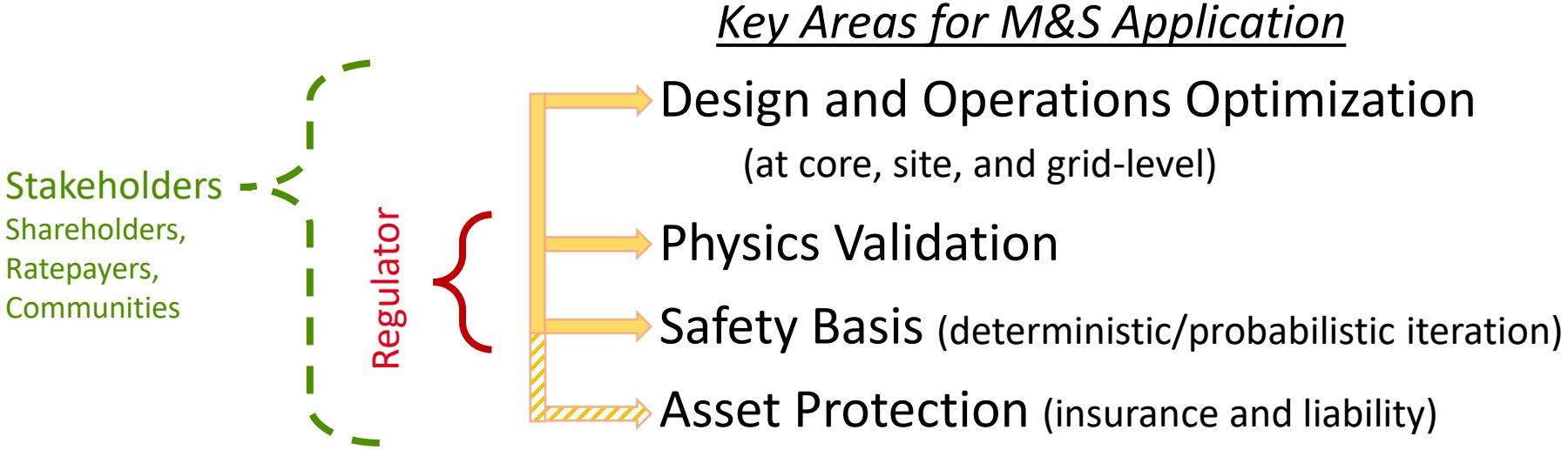



Where lies the transition from ***High Fidelity*** to ***Engineering Scale*** M&S?

**Wherever the needs dictate!**

*Often return to the design requirements…*

# How Could M&S Tools Fit Into the Picture? (cont.)




*Regardless of M&S scale, I&C requirements highly influence how the models are effectively used.*

Instrumentation design and tolerance specifications establish the ***interface*** between M&S and the real machine:

- Adaptive control logic
- AI/machine learning for a digital twin
- Semi to full autonomy
- Designed-in reliability

# Examples of Commercial M&S Tools Used in Practice

- Studsvik Scandpower (SSP) develops and maintains a set of reactor core analysis tools for commercial nuclear power plants


- Engineering-scale tools with some advanced (computational) features tuned for LWR's (no other real market at present...)
- Applications built around these tools are used in plant operations and core optimization


- General development directed by use in established reactors; however newer concepts also use these tools (water-based SMR's)

# Leverage Experiences to Align M&S Tool Development for Fission Batteries Initiative

How to connect M&S tools for use in compact fission systems?

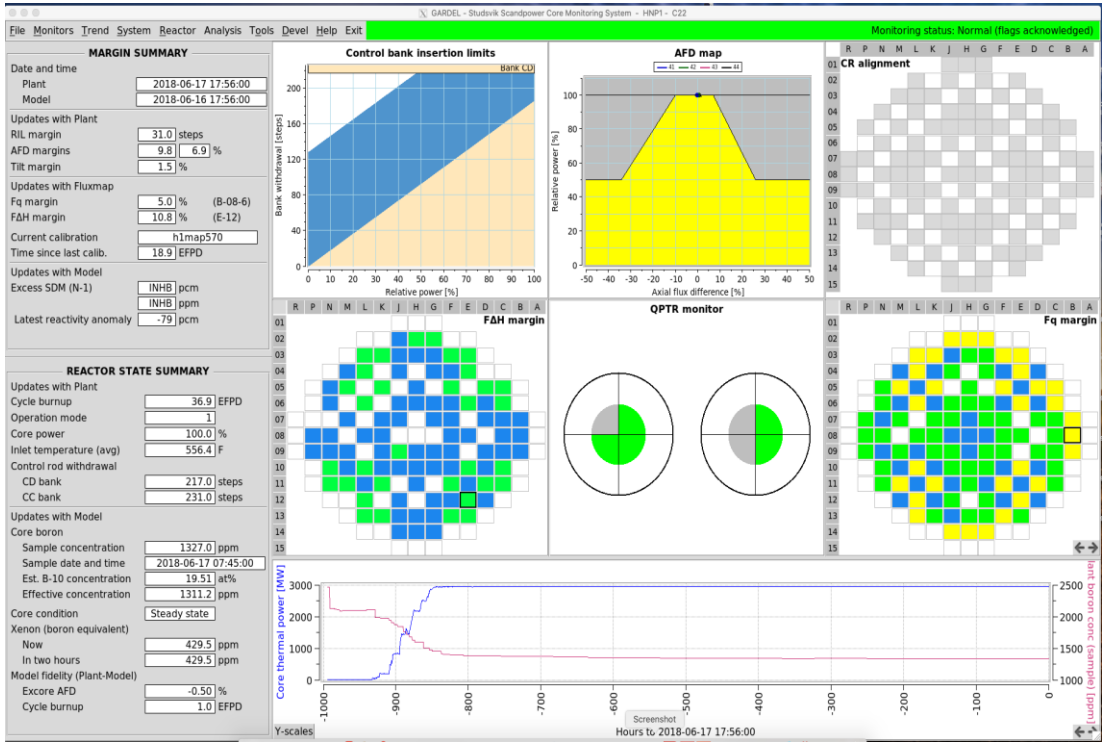
An example – *Core Monitoring*

- One key facet includes models connected through continual sensing and assessing reactor condition (e.g. core health monitor)
  - Inventory of large analysis basis from high-fidelity M&S establishing ROM's for real-world application
  - Models to track derived parameters unable or impractical to measure
  - Short and long term trending to anticipate degradation before failure (enabled by digital twining)
- Requires suitable sensor suite over entire mission life
  - SPND's, temperature, pressure, strain -> evolutionary not exotic…

# SSP Lessons from Core Monitoring Applications

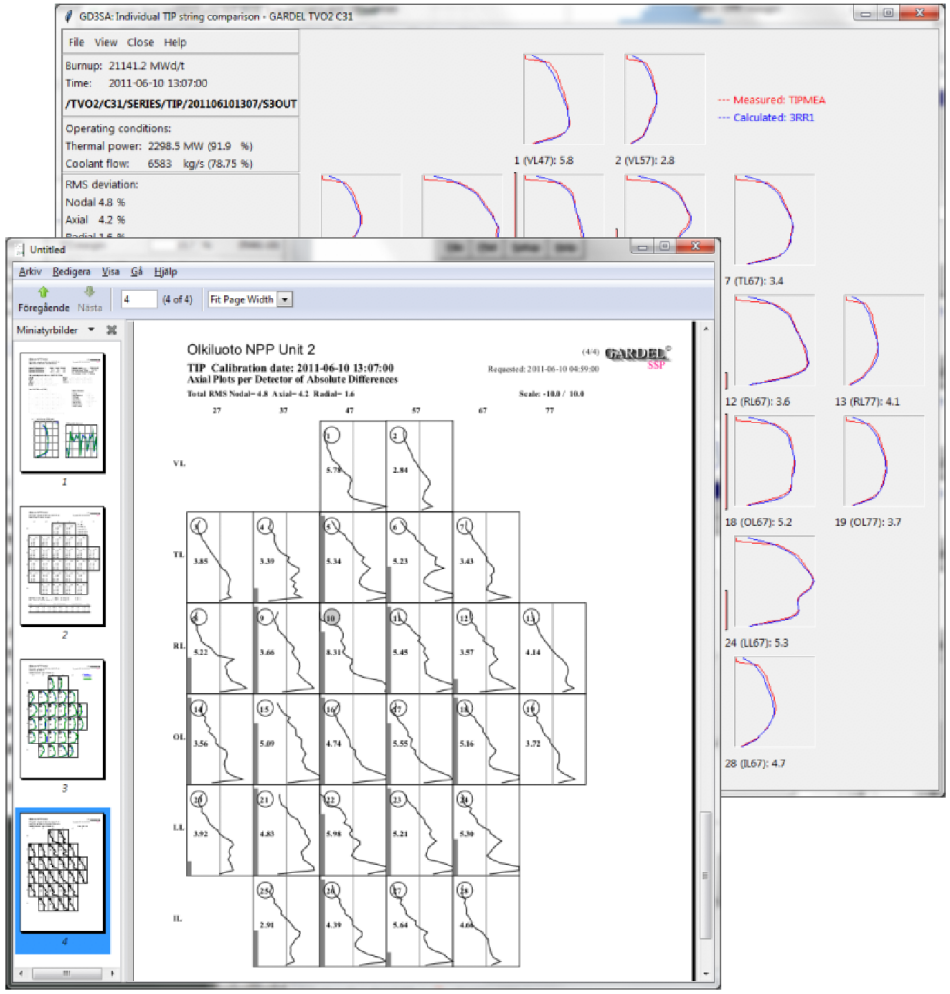
- GARDEL Core Monitoring Software is an Engineering-scale M&S tool scalable from large to small reactors
  (not yet tested on microreactors, but planning underway…)

— CASMO/SIMULATE methods underly GARDEL functionality in PWR, BWR, VVER configurations
— Cycle follow calculations, highly accurate fuel depletion and reactivity calculations -> key performance in trip recovery (most AOO's)
— Automated use for Tech Spec Surveillances, reactivity maneuvers (temperature program, boron letdown, etc.) load following, operator calculation aides…



# SSP Lessons from Core Monitoring Applications (cont.)

- Meaningful results are only as good as the most recent flux map!




- Limited by performance characteristics of the nuclear instrumentation system – both in-core and ex-core
- Detector degradation can be tracked from core follow calcs, leveraging ML for trends
- A few US plants are facing systematic instrumentation replacement (SLR…)
- Some robustness seen in SPND's…

# SSP Lessons from Core Monitoring Applications (cont.)

*A few thoughts related to Fission Battery M&S Tools and Instruments*

- In-core flux detectors are important for smaller reactor systems, at least for prototypes/demonstrations (establish data pedigree for M&S)
- Neutron leakage and detection by ex-cores remains suitable for power limits (AO/AFD/QPTR), but inadequate for depletion and eventual core disposition (core lifetime design requirement ~ 5 yrs)
- Compact core means even more compact detectors, possibly with larger uncertainty and localized flux distribution effects
- High fidelity modeling of core and detector region could be highly useful for refining instrument design specs and response functions
- Lifetime component with no moving parts (e.g. depletion limits for SPND's)

# Aim for Effective Balance of High-fidelity and Engineering-scale M&S Tools

- Keep in mind the end user, since can be quite different for deployment of Fission Batteries in numbers sufficient for society impact and economy of scale
- With much reduced source term, perhaps a different level of regulatory scrutiny… Any want to take that bet???
- Test, test, test, and test. M&S can't do it alone. The legacy of nuclear power is incomparable (no WASH-740 or WASH-1400 analog in the aviation or pharmaceutical industries).
- *Many other aspects for consideration in this and other workshops as the Fission Battery Initiative drives to success!*

***Thanks for hearing our views!***

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