Open Architecture for Nuclear Cost Reduction

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The Challenge

- All SMRs rely on standardized repeat build to get the economics to work
- Dozens of SMRs – unmitigated this could lead to lots of FOAKs being built and inhibit standardization
- Aside from ‘learning rates’, the one-off design and licensing cost can be ~$1Bn

SMR Vendors

ARC NUCLEAR CANADA, INC.

Candu — An SNC-Lavalin Technology

GE HITACHI

HOLTEC INTERNATIONAL

moltex clean energy

NUSCALE — Power for all humankind

TERRESTRIAL ENERGY

U BATTERY — Local Modular Energy

USNC — ULTRA SAFE NUCLEAR

Westinghouse

X energy

Dual Fluid

https://smractionplan.ca/
https://www.energy.gov/ne/articles/infographic-advanced-reactor-development

Objectives

(1) To develop a method for open architecture-enabled standardized design of modules and interfaces across the wide **variety of ARs of different temperatures, sizes, pressures and producing different energy products** and evaluate the extent to which this is possible – **UW-Madison**

(2) To develop a method for open architecture-enabled standardized design of modules and interfaces across the wide **variety of possible AR plant sites** and evaluate the extent to which this is possible – **UC Berkeley**

(3) To identify how open architecture would facilitate **AR licensing and regulation**, and how to overcome the **commercial and legal challenges** to collaboration and info sharing among companies – **U. Wyoming**

(4) To identify and evaluate through quantitative modelling how open architecture can simplify construction, shorten schedules and therefore **reduce costs** – **Idaho National Laboratory**

… supported by stakeholder interaction (**TerraPraxis**)

International collaborator (**University of Cambridge**)

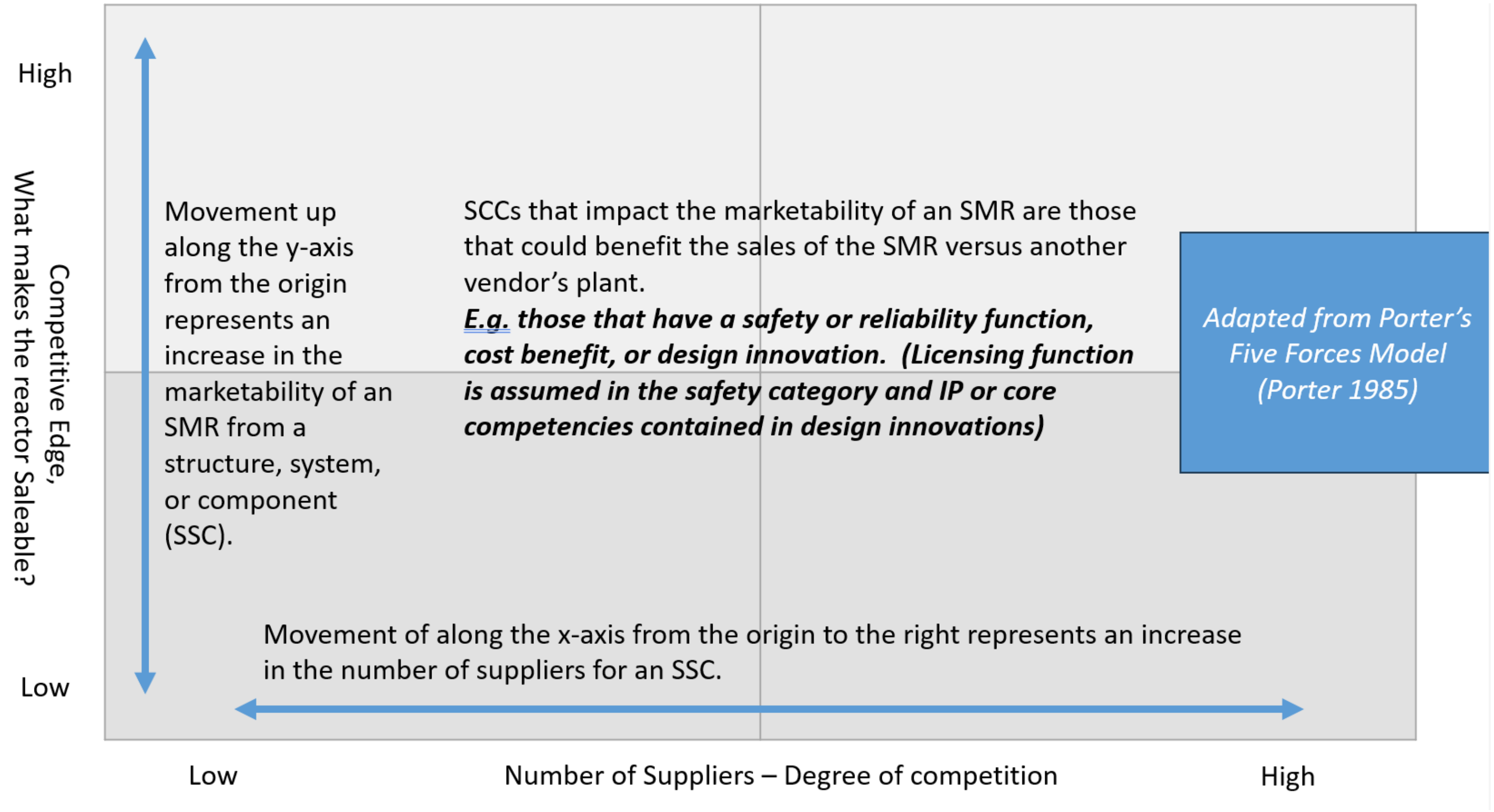
Open Architecture

- **WHAT:** defining and publishing requirements of SSCs in functional and/or interface terms, utilizing technical standards in widespread use.
- **WHY:**
  - Widen supply chain for nuclear plant SSCs through facilitating traditionally non-nuclear suppliers to participate in the design and supply chain, thus exploiting optimization and learning in these suppliers (one-to-many)
  - Harmonize functional and interface requirements for some SSCs so they can be reused in multiple reactor designs. This increases the construction frequency of that system, and reduces the (enormous) cost of designing a new reactor (many-to-one)
- **WHERE:**
  - Identify and prioritize areas
  - Not a set menu, a la carte

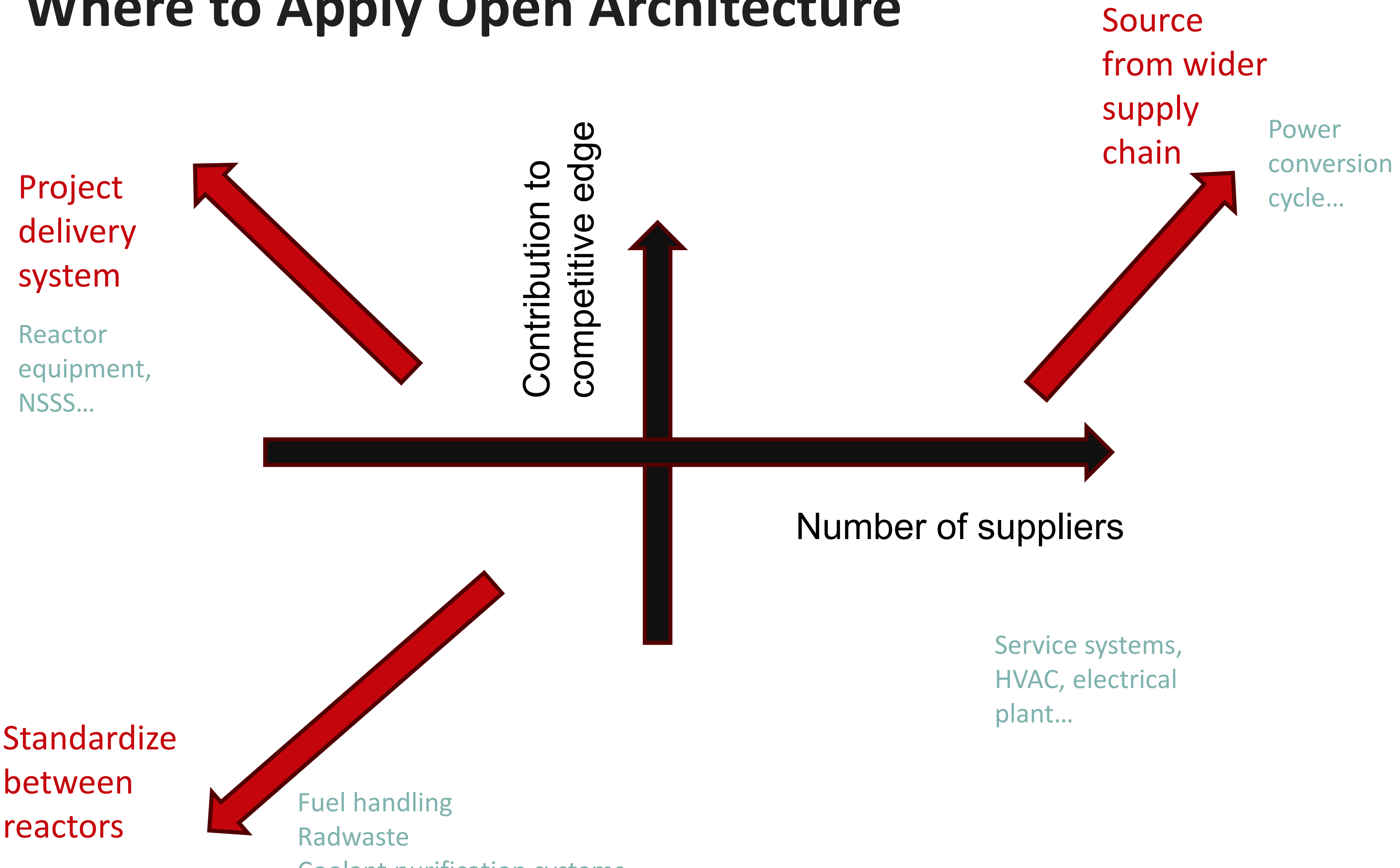
Core Competencies & Unique Selling Points

- To date, we surveyed 13 SMR/AR vendors spanning wide range of sizes and types
- Most (nearly all) vendors see the core & primary system as their **point of differentiation** and **core competence**
- Substantial **opportunity** to apply Open Architecture elsewhere in the reactor
- Challenges include **protection of IP** – for most (but not all) vendors this is less of a concern away from the primary system.

System Classification

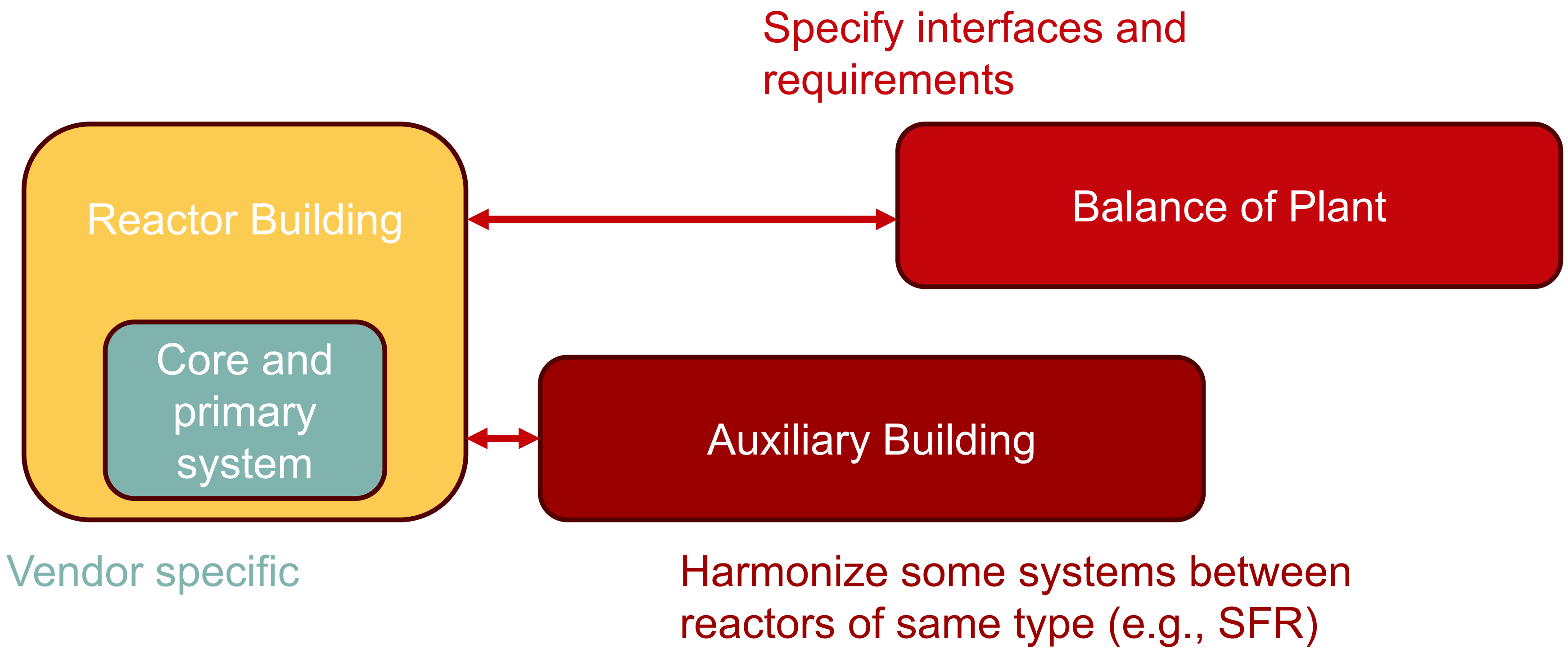


System Classification:
Where to Apply Open Architecture



Work performed by Mphil Student Dan Lamb at U.Cambridge, UK

Open Architecture Opportunities (A La Carte)

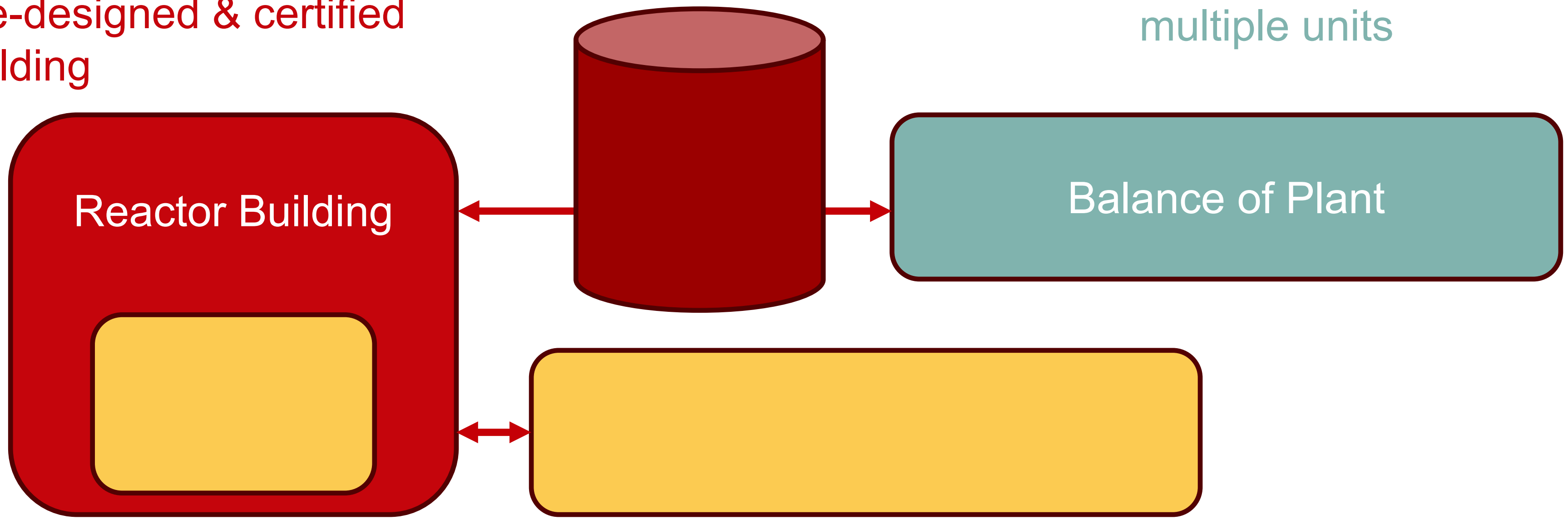


One Step Further

Thermal energy storage(TES) decouples reactor power from BOP power

Define one TES/BOP envelope that can cover multiple ARs/ multiple units

Pre-designed & certified building



Cost Modeling Methodology

- Start from reference cost account breakdown for LWR, SFR, HTR and MSR
  - Some differences, e.g. SFR appears to have more expensive coolant purification and waste treatment systems; HTR has more expensive civil structures.
- Adjust for plant size, modularization and standardization using previously developed cost models – account for size of program and number built per year.
  - Site learning ~2%
  - Production learning rate $\propto \ln(\text{production rate})$
  - $Cost \propto (1 - \text{production learning rate})^{b}$ where $b = \frac{\ln(\text{Number produced})}{\ln(2)}$
- Postulate cost model for Open Architecture input and investigate sensitivity of whole plant cost to cost reductions in SSCs utilizing OA:
  - **One to many:** increase to production learning rate and increase to b investigated
  - **Many to one:** to be performed, but experience from semiconductor industry suggests shared industry learning is 1/3 as effective as individual firm learning”. This could lead to adjusting production learning rate and number produced to include contributions from other vendors
- Hence identify areas where OA can have largest impact (one-to-many and many-to-one)
- **Then** investigate technical feasibility of each approach

Standardized design across different advanced reactor plant sites

Roadmap:

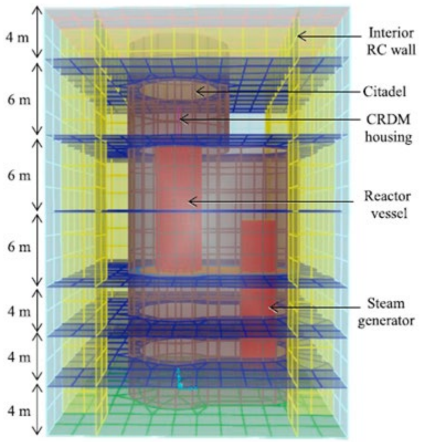
1. Generalized method for treating dynamic interactions (done)
   - Investigated the influence of excluding equipment on structural responses

2. Standardized mitigation method for site-specific seismic hazards (in progress)
   - Define site-specific seismic hazards
   - Define range of allowable peak floor acceleration, limits on peak isolator displacements
   - Define baseline structure + different isolation systems

Progress

1. Discussion with vendor about general sizes and needs of reactor buildings
   - Gather dimensions and weights of reactor buildings, information on attachment methods for major equipment, and information on utilities in/out
   - Have discussed with one vendor, working on NDAs with 2 others

2. Determining if major equipment needs to be considered in dynamic analyses for design of structure
   - Each vendor has own reactor core technology that is generally confidential. Thus, want a design that does not require that information for analysis

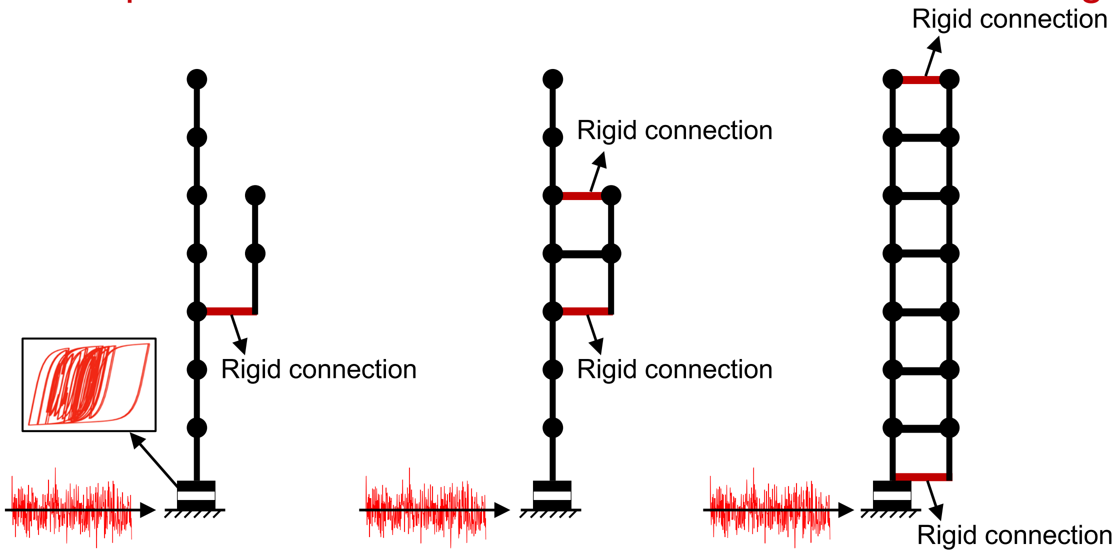


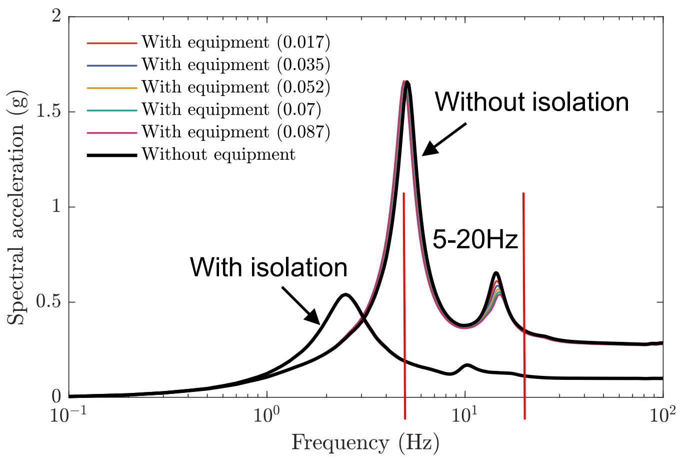
From Parsi et al. 2022

3. How to define seismic hazards across the US?
   - Cannot describe seismicity as a single value as the characteristics of the hazard vary greatly across locations with different tectonic regions and local soil types
   - Need to be able to design a finite number of solutions to make standardized design useful and cost efficient

Influence of excluding equipment (reactor vessel) in dynamic analysis

Simplified structural models for different reactor buildings



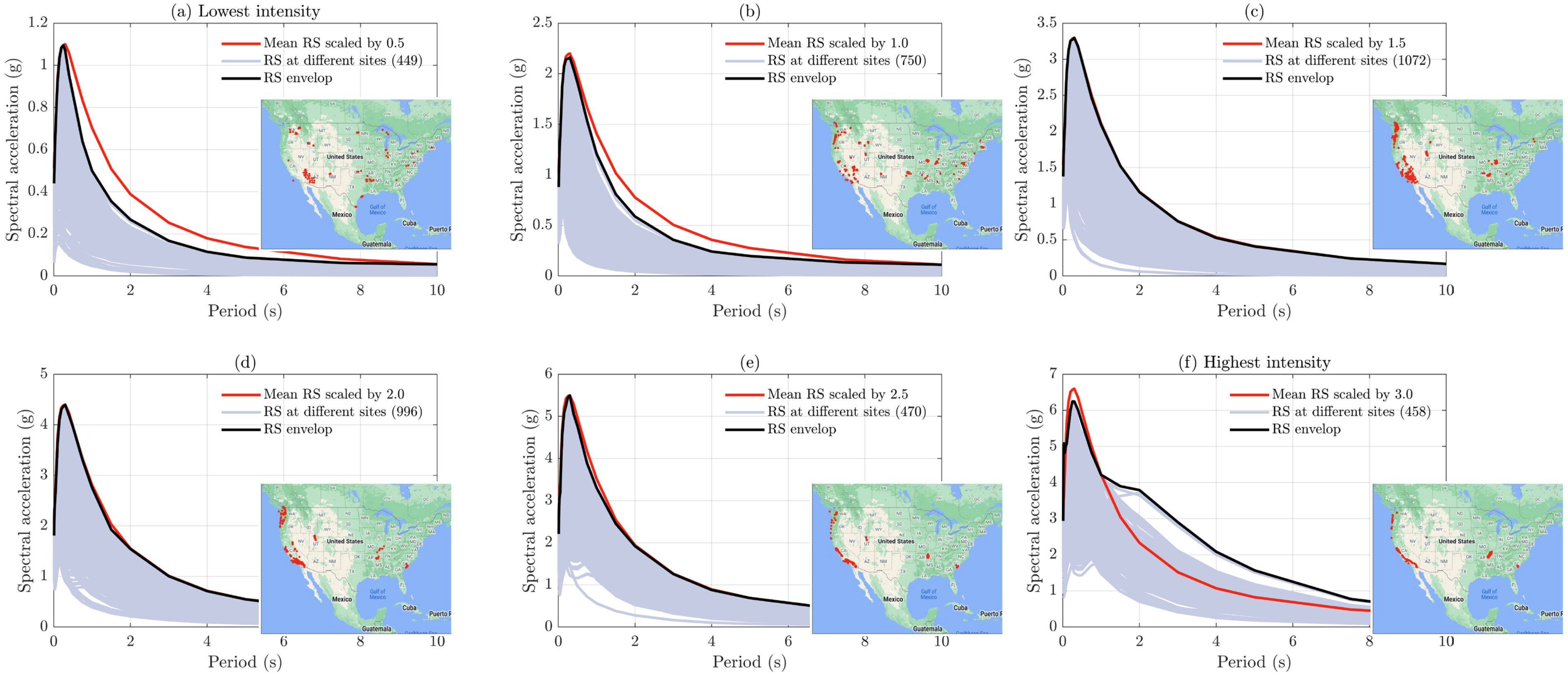


- For isolation types that are mass dependent (**rubber**), excluding the equipment
  - increases the peak floor acceleration (good)
  - increases Sa in (5-20 Hz <- typ. equipment frequency range) range (good)
  - decreases the isolation displacement (bad)
- For isolation types that are mass independent (**friction**), excluding the equipment
  - has minimal effect on the peak floor acceleration (<1%)
  - has minimal effect on Sa in (5-20 Hz) range
  - has minimal effect on the isolation displacement (<2%)

So, initial design of the building and isolation system can be done without knowing the exact design of reactor vessel, etc.

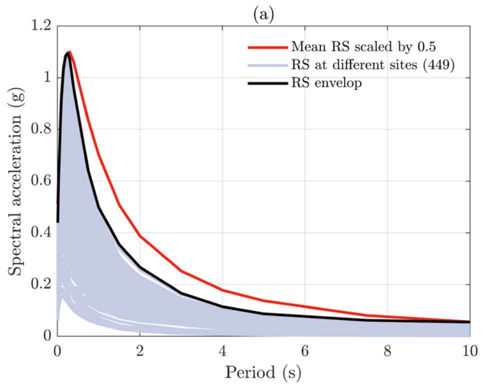
Classification of site-specific response spectra

- Recurrence period: 10000 years (Seismic Design Category 3 per ASCE 43-19)
- From USGS, get vs30 (soil type) and associated response spectra for 4195 sites
- Divide into **6 groups** based on scaled mean response spectra
- Design will be based on enveloped response spectra (black lines)
    - Use same design for all locations with spectrum below envelope curve



Next up: Standardization designs of reactor buildings

- Seismic inputs (one design for each envelope curve)
- Select a suite of ground motions to represent the seismic hazard
- Performance goals: satisfy requirements of peak floor acceleration (PFA) and peak isolator displacement (PID)
- Design isolation systems (start with friction pendulum?) assuming rigid superstructure
- Design superstructure (building)
- Validate whole system performance with range of equipment and attachments etc



Standardization design table (a)

Seismic input (a)	PID1	PID2	…
PFA1	$T_{b1}/T_{b2}/T_{b3}$	$T_{b1}/T_{b2}/T_{b3}$	…
PFA2	$T_{b1}/T_{b2}/T_{b3}$	$T_{b1}/T_{b2}/T_{b3}$	…
…	…	…	…

Standardization design table (b)

Seismic input (b)	PID1	PID2	…
PFA1	$T_{b1}/T_{b2}/T_{b3}$	$T_{b1}/T_{b2}/T_{b3}$	…
PFA2	$T_{b1}/T_{b2}/T_{b3}$	$T_{b1}/T_{b2}/T_{b3}$	…
…	…	…	…

Licensing and Commercial Implications

- Completed analysis of licensing and regulatory frameworks and potential compatibility with open architecture and standardization
- Currently developing interview questions for stakeholder group to assess concerns about intellectual property in an open architecture model

Modularity in NEPA and Safety Analyses

- Both EIS and safety analyses have become more modular through successive rulemaking efforts – reducing redundancies within and between projects.
    - GEIS use for relicensing, now being developed for advanced reactors
        - Reduces redundant consideration of impacts that are common to all projects
        - Allows project developers to incorporate parts of GEIS – taking a modular approach

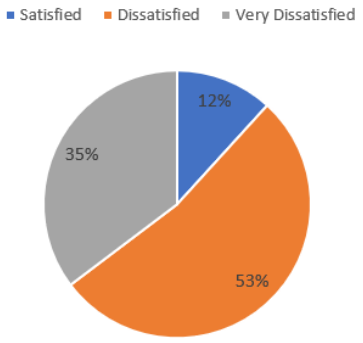
Treating Regulation as a Design Problem

- Standardization across designs would increase extent to which impacts are common, potentially allowing a more expansive GEIS
  - High level of adoption would likely be necessary to justify the additional expense of expanding GEIS scope.
- Decoupling and similar strategies clearly segment facilities along regulatory boundaries with the nuclear island subject to NRC jurisdiction and the energy island regulated according to state law
  - Parts of the NPP outside NRC jurisdiction may not require NEPA environmental analysis (though connected actions doctrine could still require consideration of impacts of full plant), construction could begin earlier, and more commercial parts could be used.
  - Vendors would not need to have the same qualifications, potentially widening supply chain and service providers
- Modular designs could allow innovation in some modules without requiring entirely new safety review if margins and interfaces stayed constant. i.e. A site that has an early site permit would not require a new review if the plant design changed, as long as the revised design still fit within the suitability parameters within which the site was analyzed.

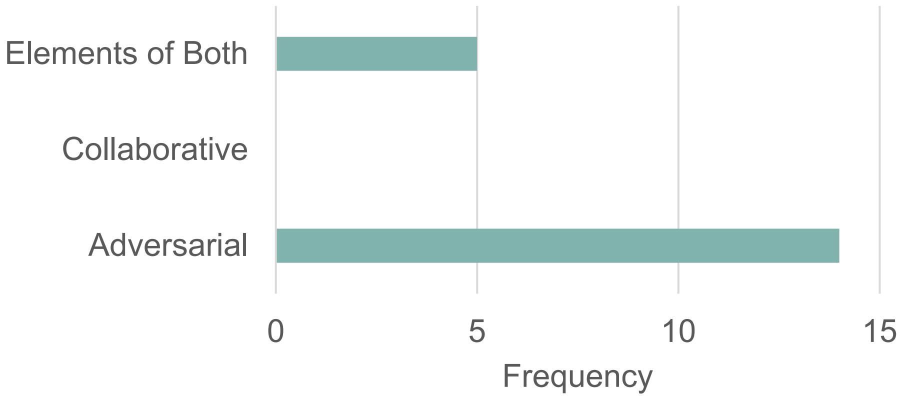
Open Architecture and Licensing

- OA is consistent with NRC regulations. Nothing prohibits it.
- OA would be expected to result in some efficiencies from replication. Under current regulations, new configurations would still require separate design certification, but use of familiar systems may streamline safety analysis.
- Existing regulatory tools (code cases, guidance, standards) may be powerful mechanisms to implement OA
- In other contexts, such as defense contracting, Congress has required OA or had a preference projects that use OA when selecting vendors. Similar opportunities exist:
  - Preference for vendors using OA in federal procurement programs
  - Preference for reactor developers using OA when selecting projects that receive public funding from ARDP or similar programs.
- OA may require policy support for implementation since greatest benefits would be to new market entrants.

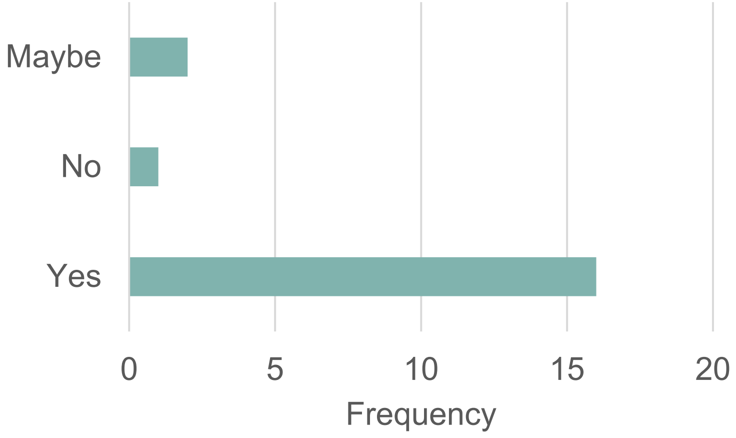
Project Delivery System – Potential Role for Integrated Project Delivery



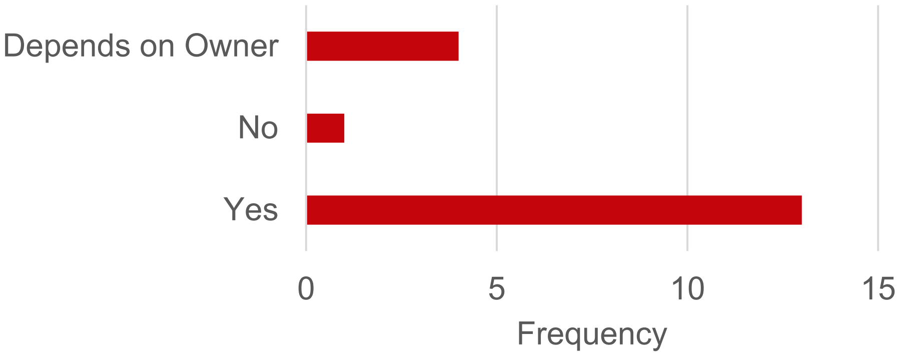
High level of dissatisfaction with nuclear construction project delivery



Current construction process is viewed as adversarial



Majority believe a collaborative approach will be accepted.



Owners generally willing to take a more active role in project

Conclusion

- Most vendors' core competence is the reactor, not the whole power plant
- Most (not all) vendors we surveyed are open to standardization away from systems within their core competence/ IP space
- Building design (for a geographic region of U.S.) can be specified without knowing exact specifications of reactor vessel etc.
- Open architecture can in principle reduce design costs, streamline analyses and accelerate learning rates
- From regulatory perspective, open architecture could be facilitated through use of existing mechanisms such as code cases, standards and guidance
- Initial cost modelling indicates that benefits are highest when size of build program is small – this is the reality we may find ourselves in as multiple SMR types are deployed
- Industry is open to collaborative approach to project delivery (IPD)

Acknowledgements

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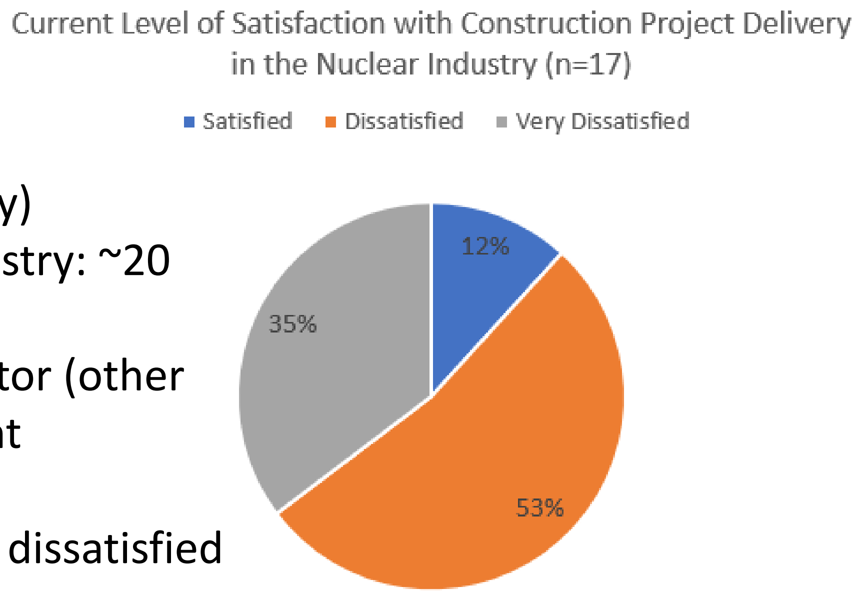
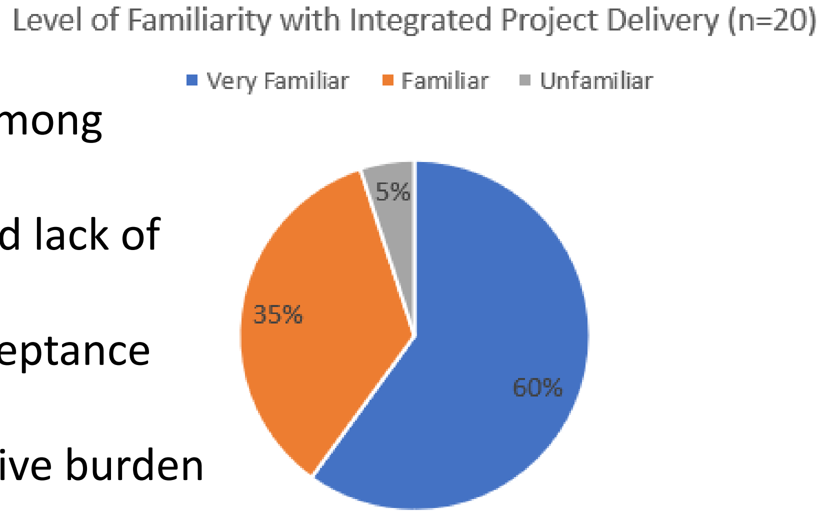
Analysis of risks and challenges with integrated project delivery (IPD) in nuclear through industry interviews

- Interviewed 20 individuals (17 in nuclear industry)
  - Average years of experience in nuclear industry: ~20 years
  - 40% of interviewees are in public utility sector (other industries include owner's rep, management consultant, constructor)
  - 88% of interviewees are dissatisfied or very dissatisfied with current project delivery
- Common IPD challenges (from interviews)
  - Learning to trust when current relationship among stakeholders is adversarial
  - Limits to liability due to lack of experience and lack of trust
  - Developing performance metrics and risk acceptance for shared risk/reward pool
  - Resources for front end planning/administrative burden on owners

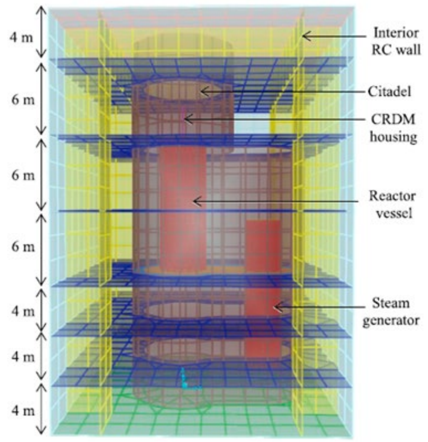




Discussion with vendor about general sizes and needs of reactor buildings

- Information from Parsi et al. 2022
  - ➢ Information on reactor building
    - Physical dimensions: 20m(width)x24m(length)x34m(height)
    - Weight: 11500T
    - Frequency (first): 5~6Hz
  - ➢ Information on reactor vessel (major equipment)
    - Weight: 250T
    - Frequency (first): 8Hz

- Information from vendor
  - ➢ Information on reactor building
    - Physical dimensions: From 14mx80mx10.5m to 24mx110mx15m
    - Weight: From 12000T to 35000T
  - ➢ Information on reactor vessel (major equipment)
    - Weight: ~800T
  - ➢ Attachment methods
    - Roller/sliding supports; anchored at base and top



From Parsi et al. 2022

Initial Results – One-to-many for light water SMRs

- Cost reductions in this model from OA are in green
- Depending on reactor size and build program, cost savings of order 3-8% with this model
- Savings are higher when build program is smaller – because less chance to achieve conventional learning effects
- Combining with many-to-one OA elsewhere may improve cost savings
- Impact of standardizing TES with ARs also to be investigated
- Impact of reducing design costs (e.g. on home office services) also to be investigated