INL/CON-24-77499-Revision-0

Design Basis Model for Hosting Small Modular Reactors

September 2024

Ronald David Claghorn

Changing the World's Energy Future

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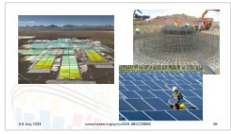
Introduction

Rising Demand for Electrical Power

Major Sources of Growth

- Electric vehicles
- Manufacturing of renewable energy components

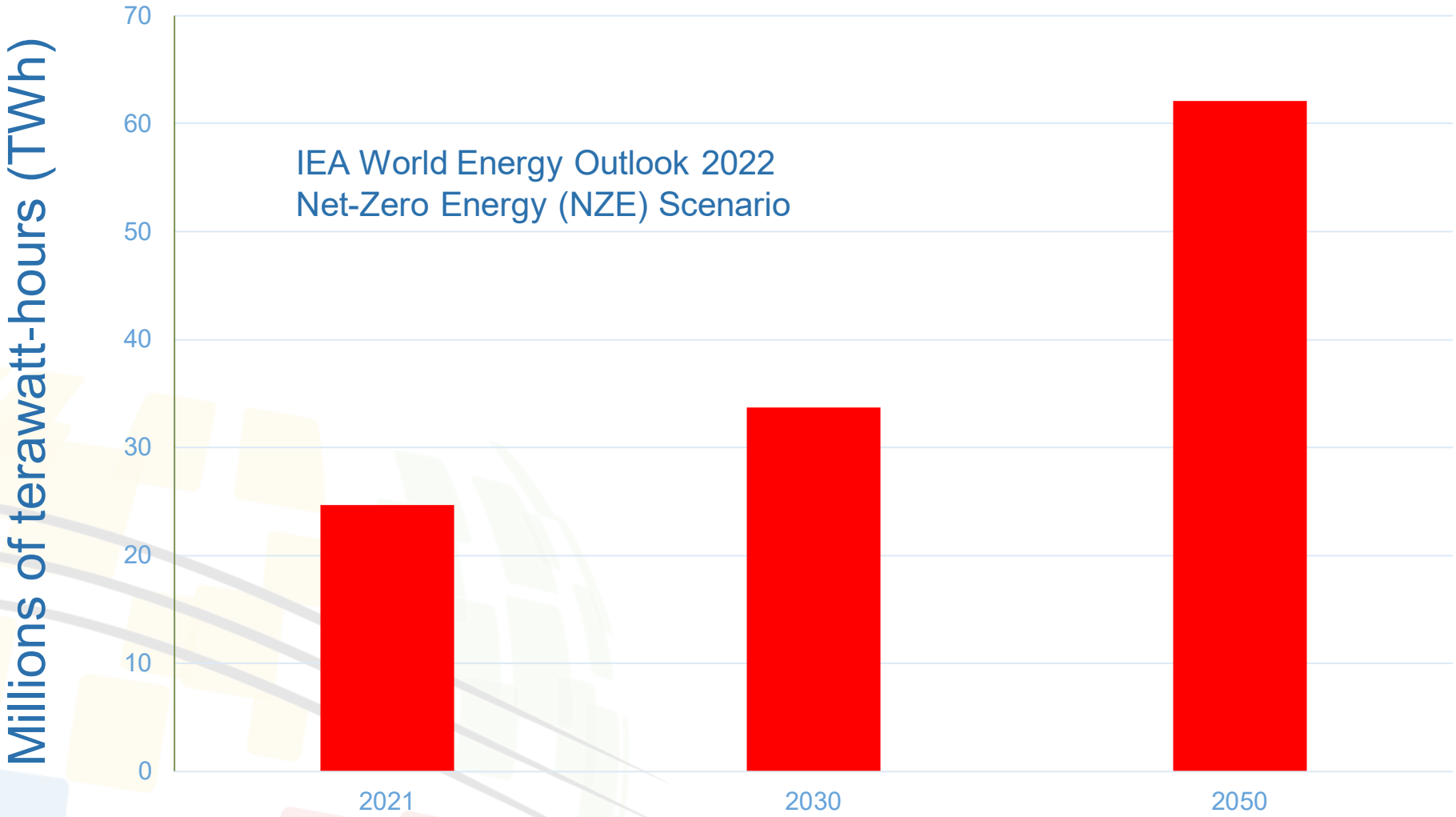


- Switch from gas to electrical appliances

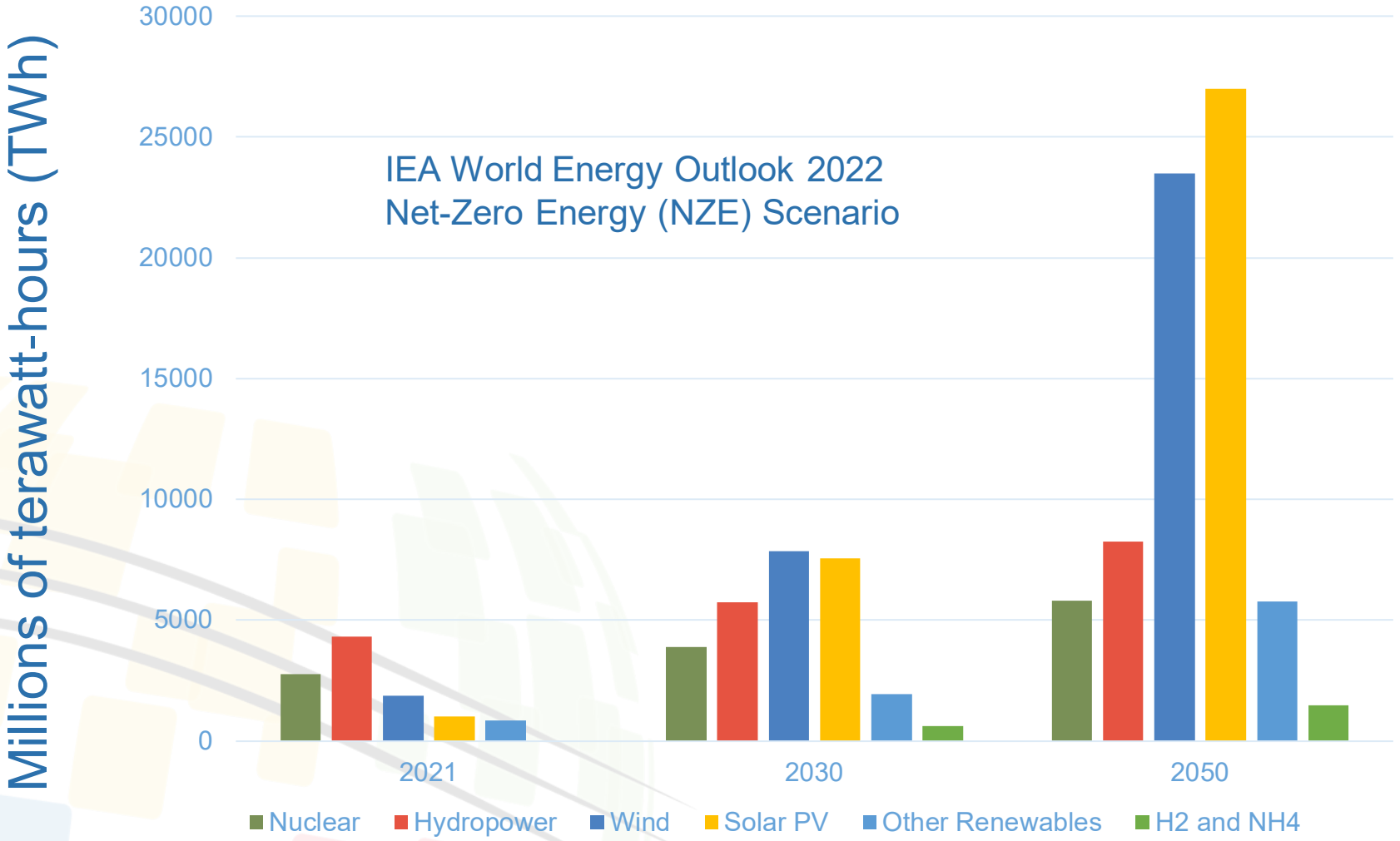
- Data centers and AI

- Video streaming, online shopping, and gaming

Global Demand for Electrical Power



Future Energy Supply



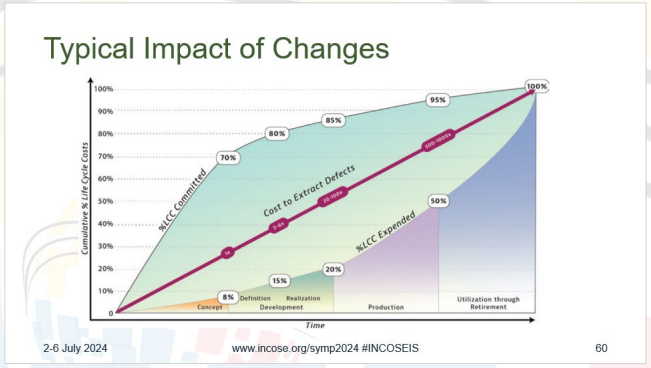
Conclusions from the IEA Net-Zero Energy Scenario

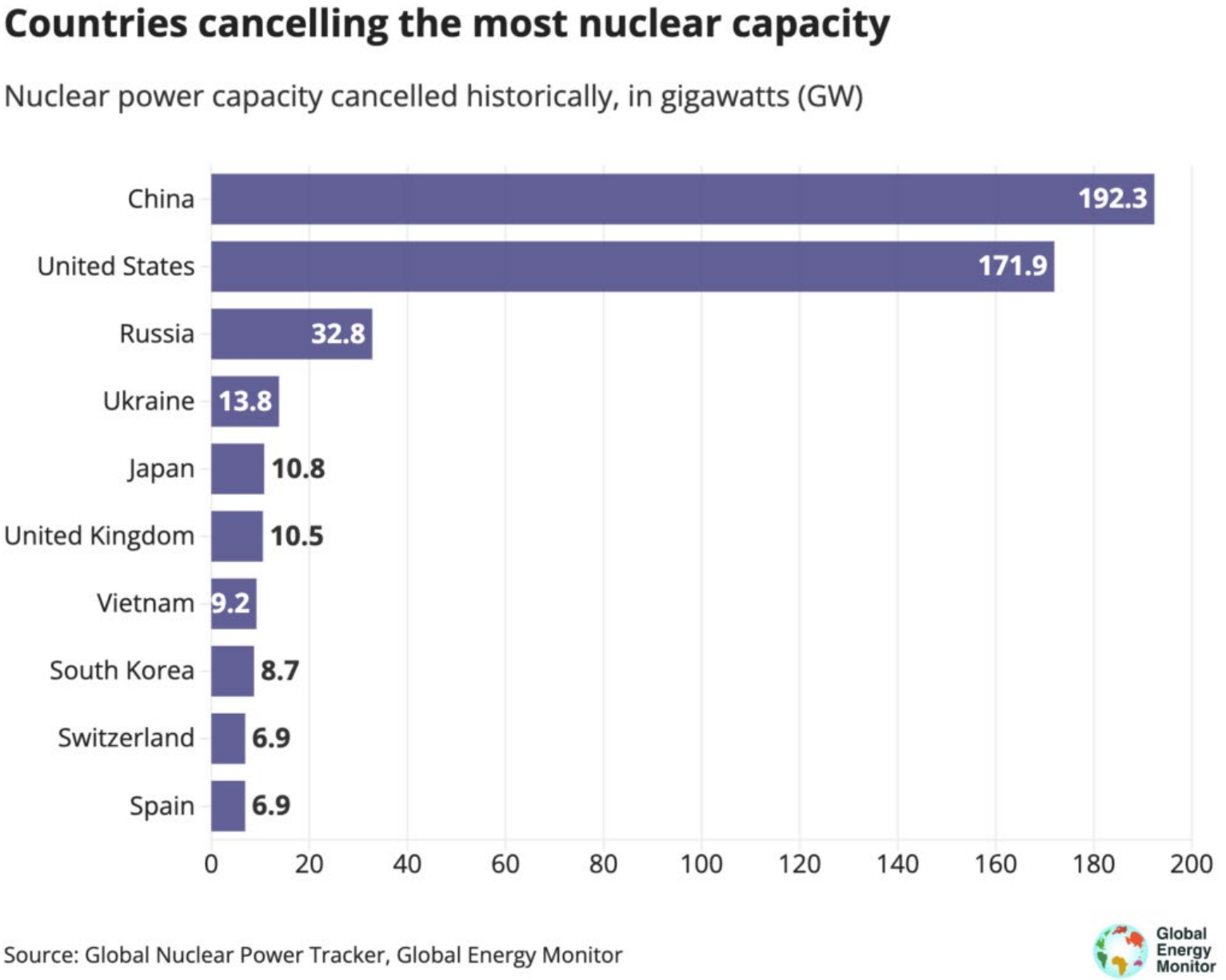
- Very ambitious with many uncertainties.
- Pathway to net zero emissions by 2050 is very narrow.
- Heavy reliance on hydropower, wind, and solar.
- Everyone needs to give up gas cars and gas-powered utilities.

Why the small role for nuclear power?

Risks to:

- Public safety: Need safer reactors.
- Investors: Need reliable estimates of cost and schedule.





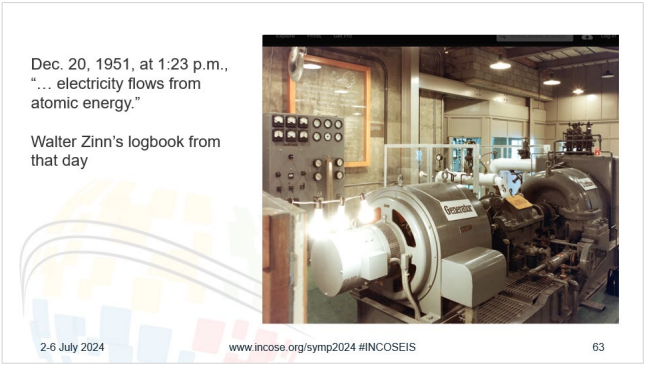
Research, testing, and development activities

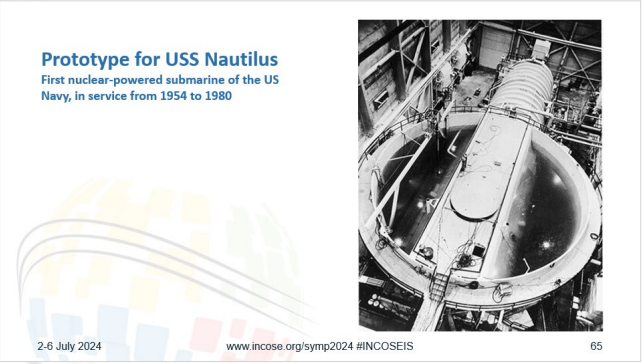
Reducing Risk to Public Safety

70 Years at the Idaho National Laboratory (INL)

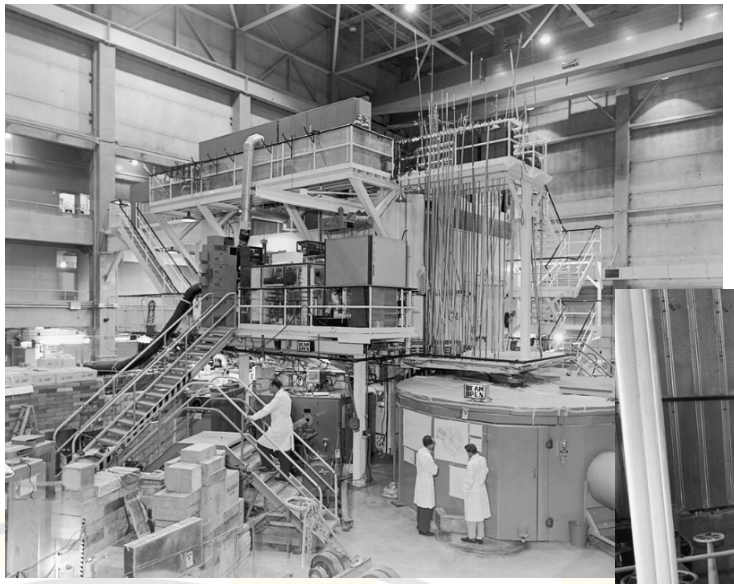
1st

- Nuclear power plant
- U.S. city to be powered by nuclear energy
- Test of a submarine reactor

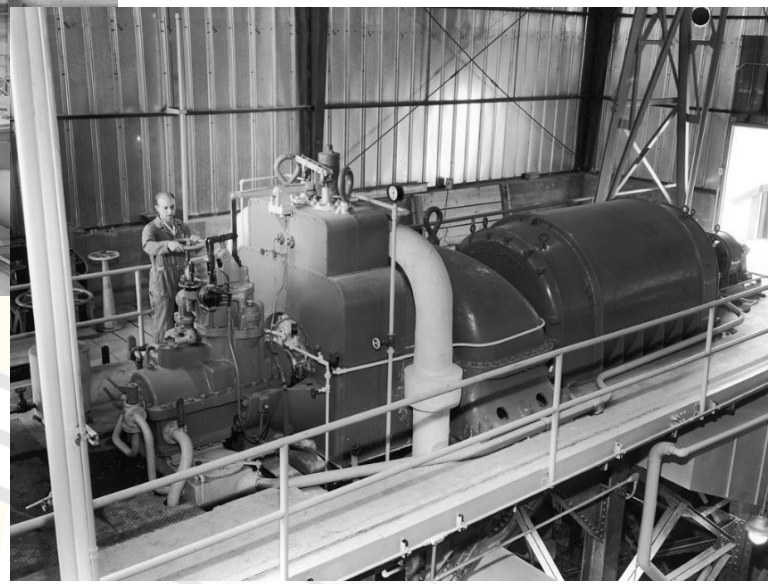


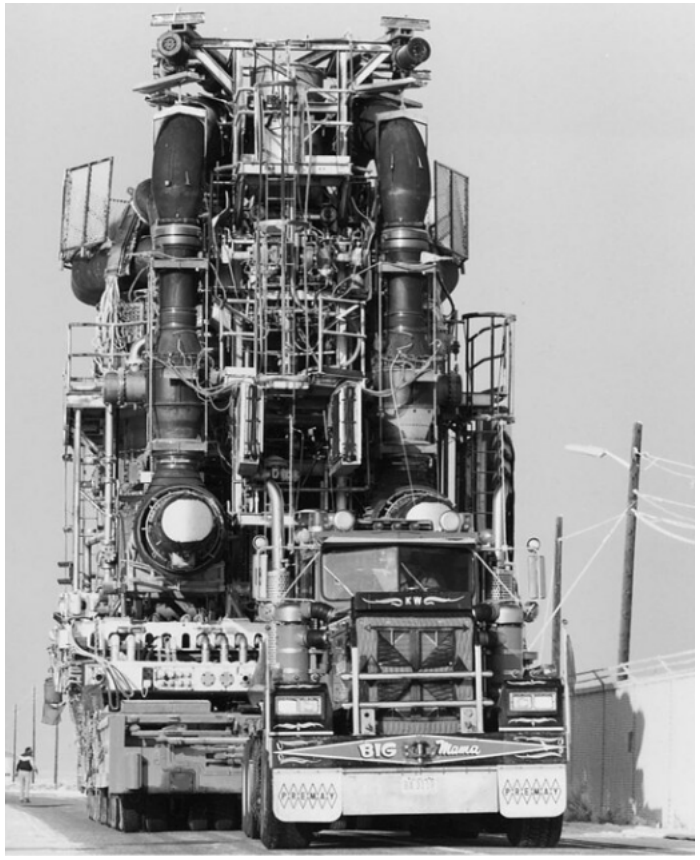


Since 1951 INL has operated 50+ reactors



A large body of nuclear experience





INL research, testing, and development capabilities

Hot Fuel Examination

Irradiated Materials Characterization

NRIC-DOME Test Bed

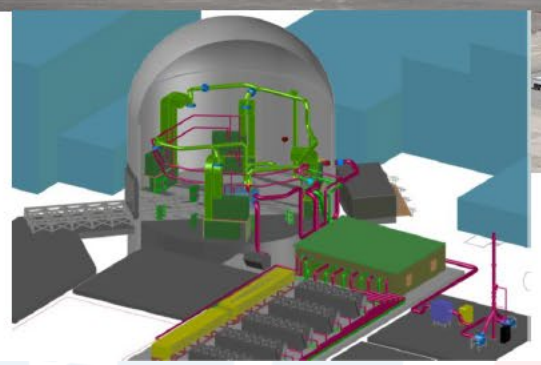
(Demonstration of Operational Microreactor Experiments)

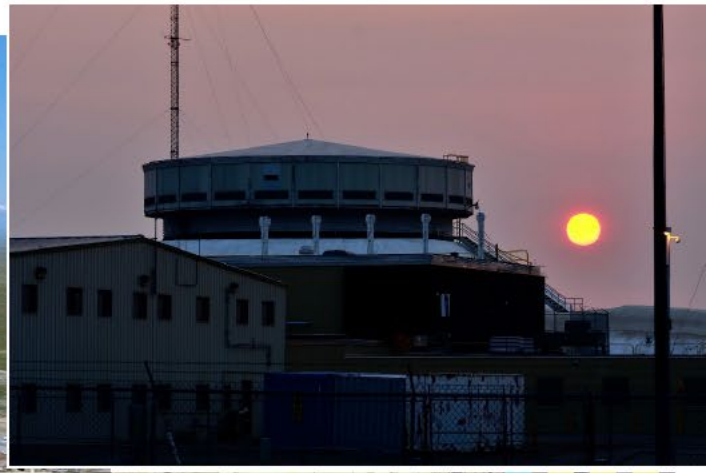
- Test bed for microreactors less than 20 MWt
- Reestablish capabilities of existing infrastructure

NRIC-LOTUS Test Bed

(Laboratory for Operations and Testing in the United States)

- Experimental test bed with 500kW heat rejection system



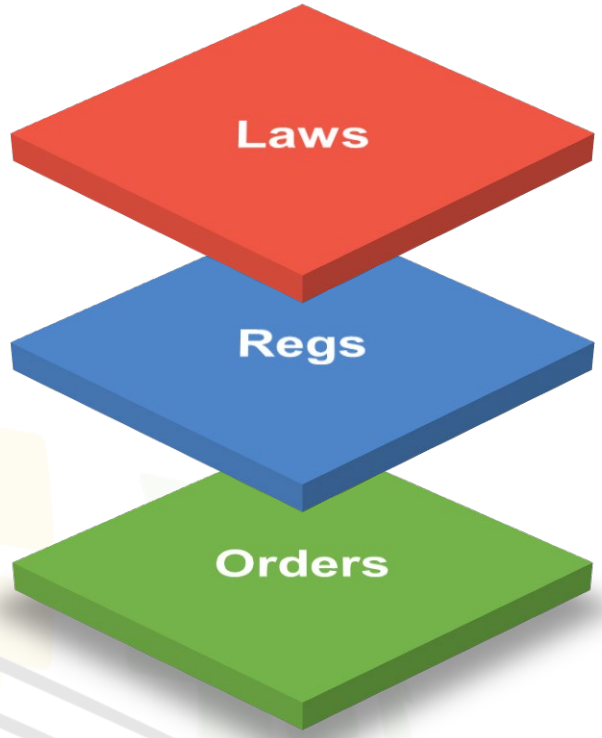


Navigating and Interpreting Regulatory Issues

Laws

Regulations

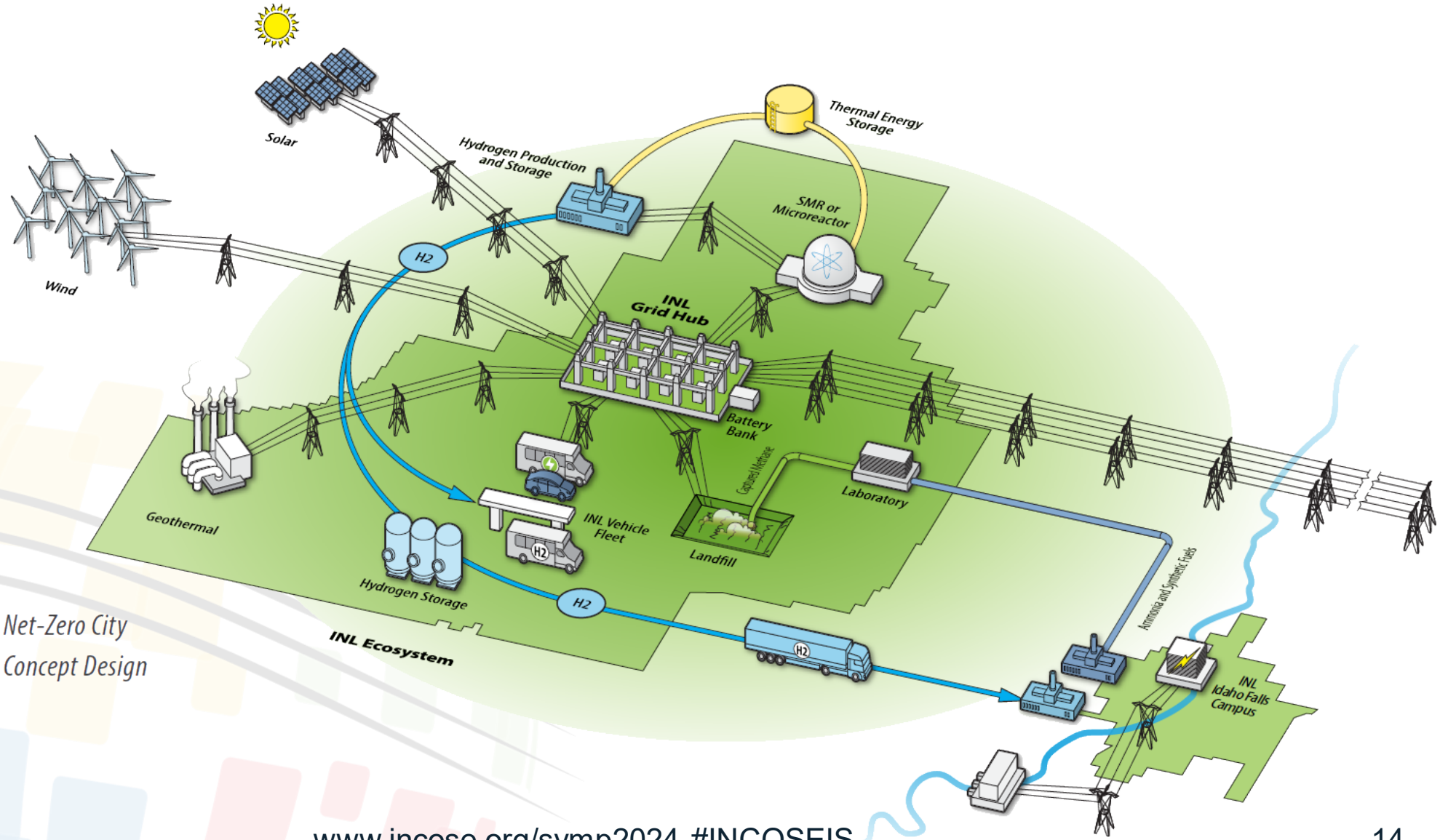
Government Orders



10,000 References to Codes and Standards:

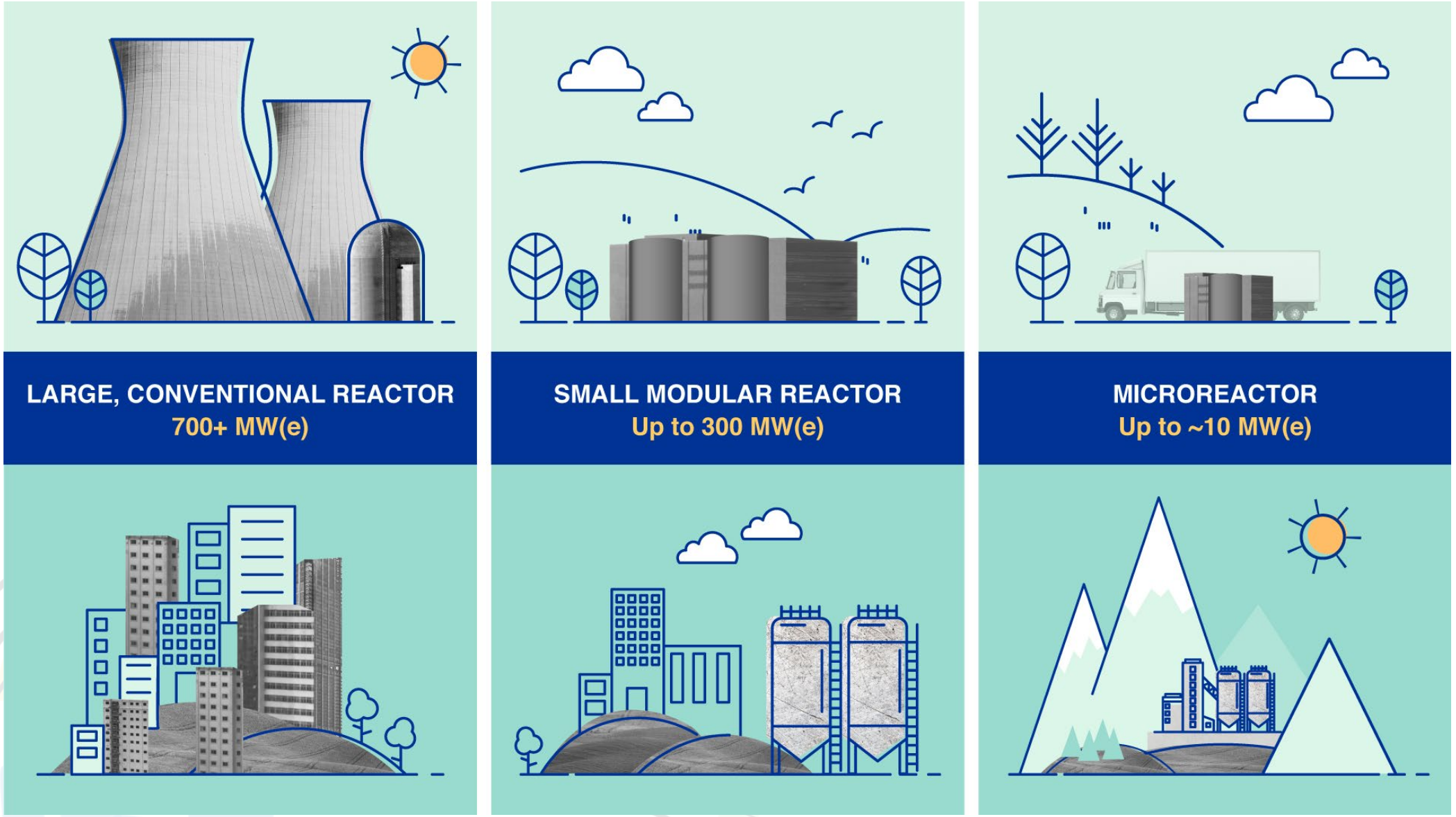
- Which ones are requirements?
- INL procedures and standards have interpreted these references.

NZE Research at the Idaho National Laboratory



Design Basis Model for Hosting Small Modular Reactors

Small Modular Reactors

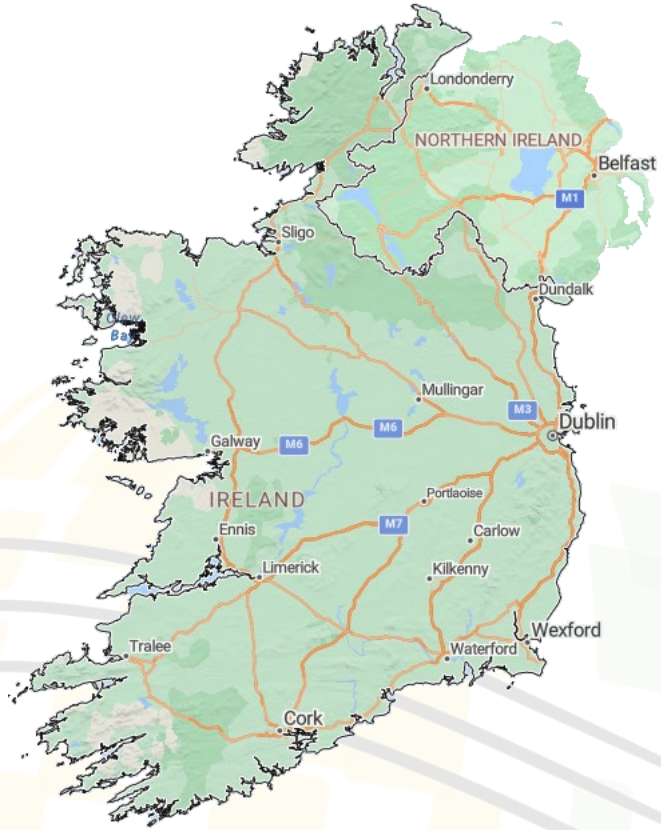


A. Vargas/IAEA 2024

Advantages of a Microreactor

- Much smaller and simpler than traditional nuclear power reactors.
  - Minimum site preparation
  - Standard, commercial components
  - Flexible operation
  - Enhanced safety
  - Refueling (every 2-10 years)
  - Operational lifetime: 5 –20 years.

What can you do with a 10 MWe microreactor?



The average Irish household uses 3.594 MWh per year of electricity (www.cso.ie 2024)

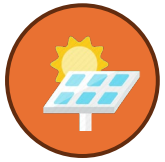
A 10 MWe microreactor produces 10 MW * 24 hours/day * 365.25 days/year =
87,660 MWh/year

Therefore, one 10 MWe microreactor would support 87,600 / 3.594 = 24,391 households

Footprint of Energy Sources

Stevens, L. (2017)

Electricity Source	Acres (km^2) for 10 MW
Hydro[1]	3152.2 (12.8)
Wind[2]	706.4 (2.86)
Solar[3]	435.0 (1.76)
Nuclear[4]	127.1 (0.514)

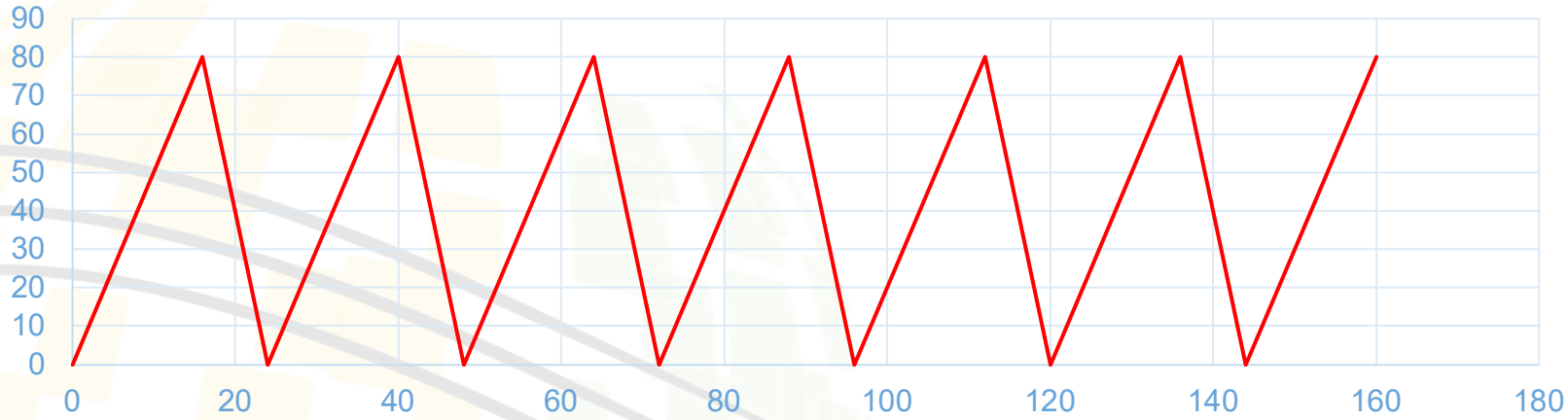


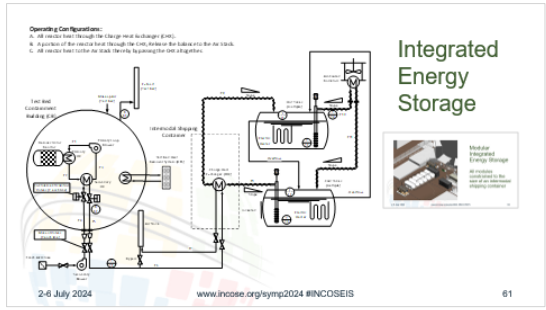
Does not include batteries for intermittent power production. Does include:

1. Concrete production, reservoir, and electricity transmission.
2. Concurrent land use (farming) and recycling of components (no waste)
3. Material production, manufacturing, no waste, small rooftop panels
4. Plant, fuel production, transmission, and waste storage.

Make the reactor even smaller by integrating Thermal Energy Storage (TES) for intermittent users such as district heating

For example: Charge at 5 MW/hr for 16 hrs; supply 10 MW/hr for 8 hrs





Reducing Risk to Investors

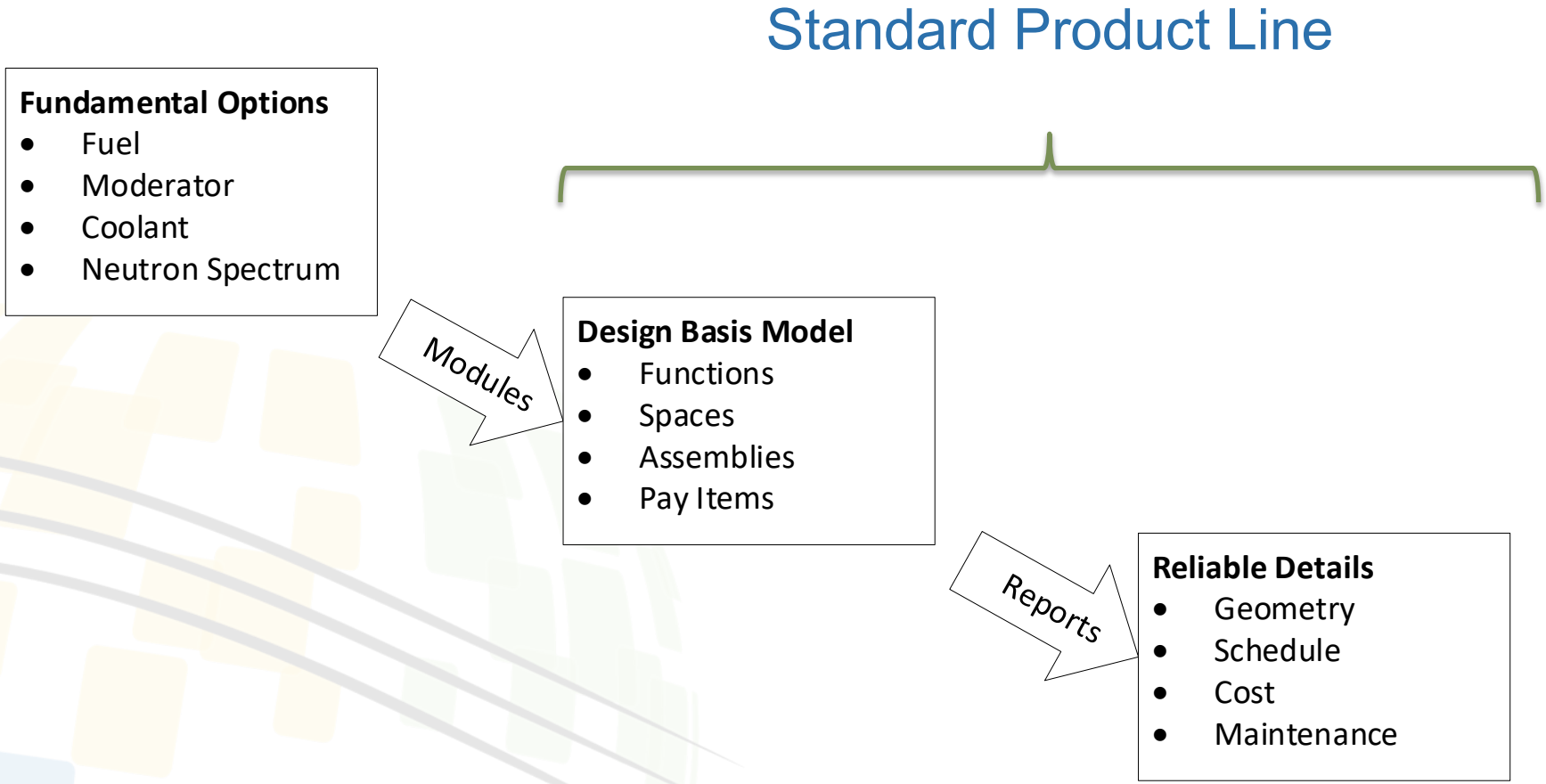
Standardize to the Extent Practical

- **Product Line Engineering** (INCOSE Primer): A single production system rather than a multitude of first of a kind (FOAK) products.
- **Use Proven Patterns** (INCOSE Handbook): Shift away from creating unique models to using proven patterns to rapidly configure and apply a model.

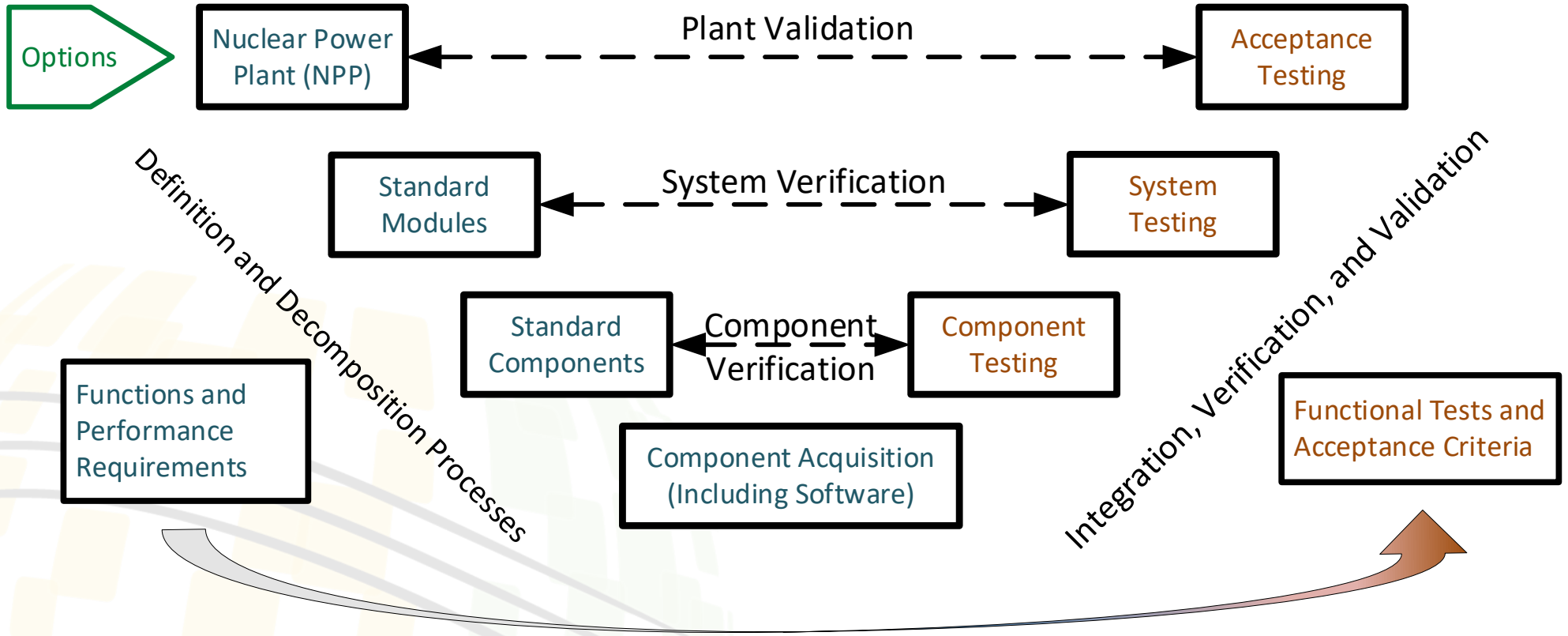
Economic Models for Nuclear Power Plant

- Traditionally, economic models for Nuclear Power Plants (NPPs) focused on data obtained from large, legacy NPPs.
- Newer models attempt to extend those older models for application to microreactors.
- However, INL's latest test beds offer an opportunity to identify a product line and use existing patterns for modeling NPP economics.

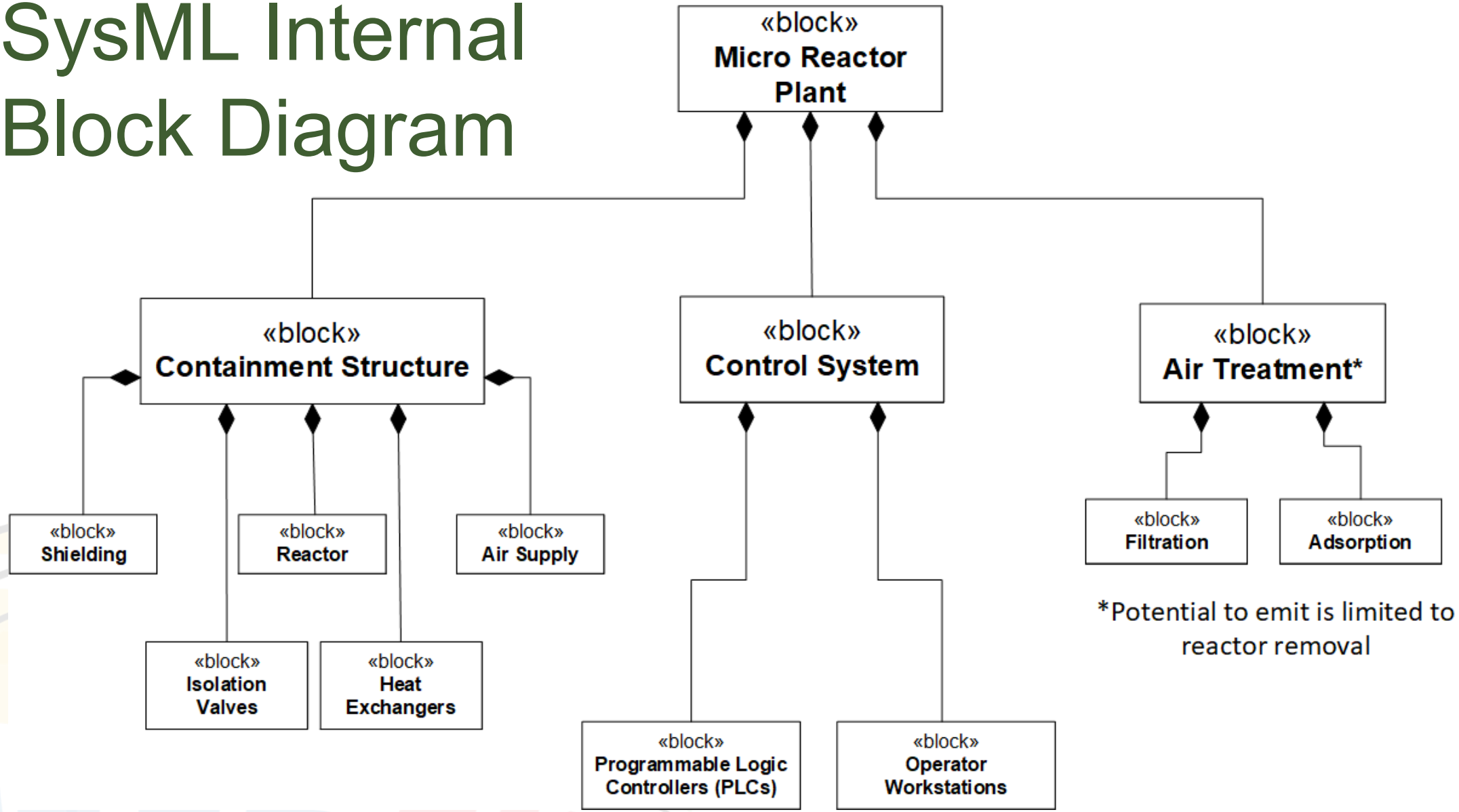
Create Standard Modules for Trade Studies



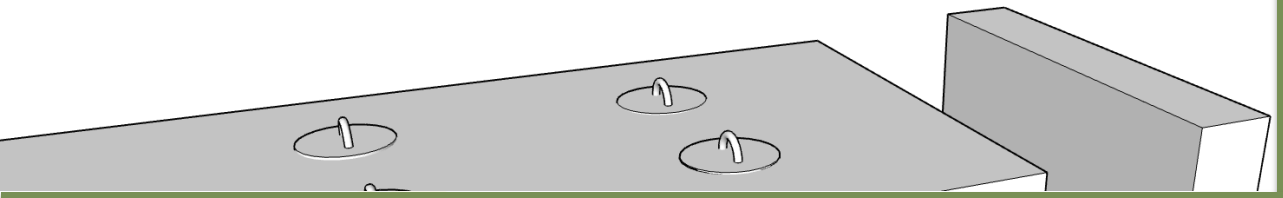
Standard Pattern: System Engineering Vee



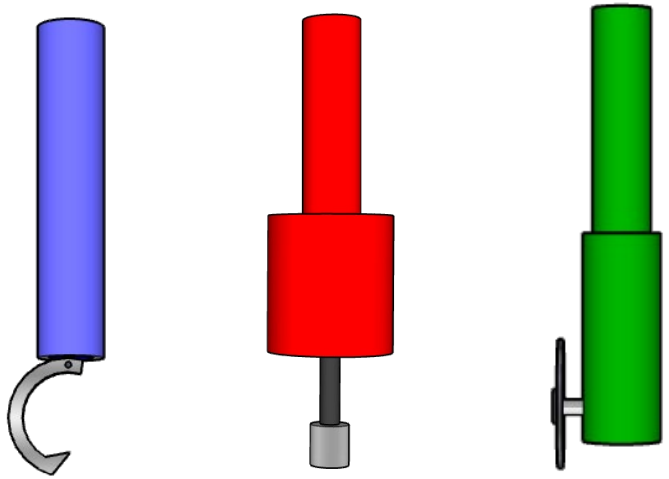
SysML Internal Block Diagram



Reactor Removal



Select a tool



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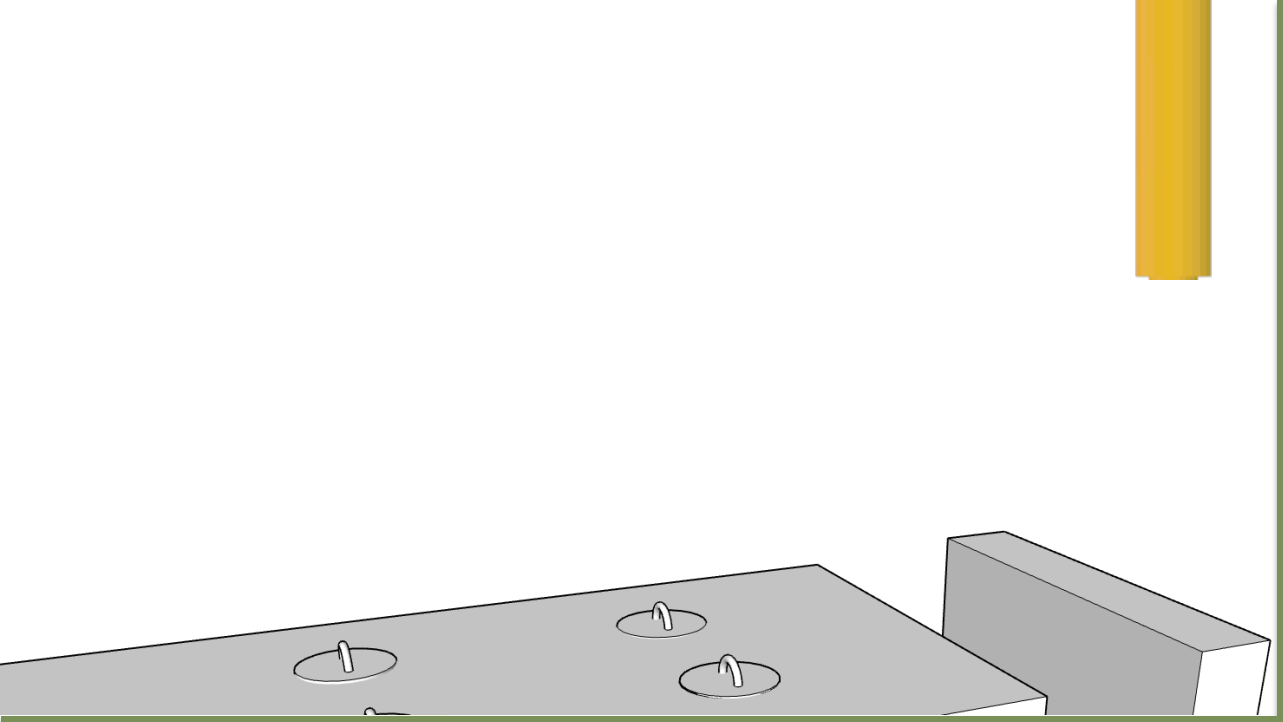

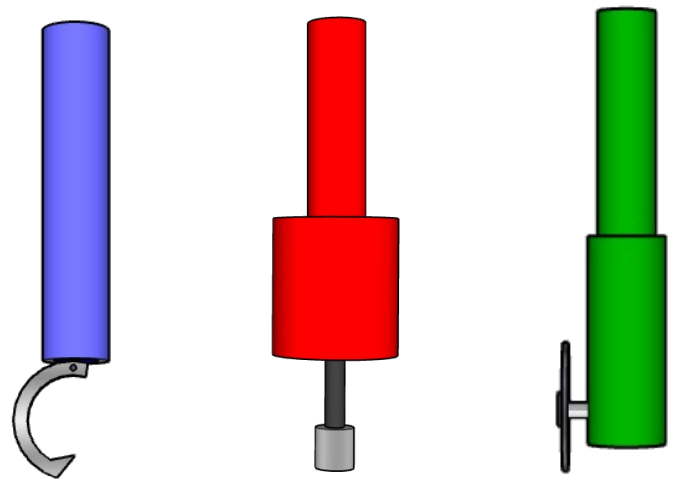

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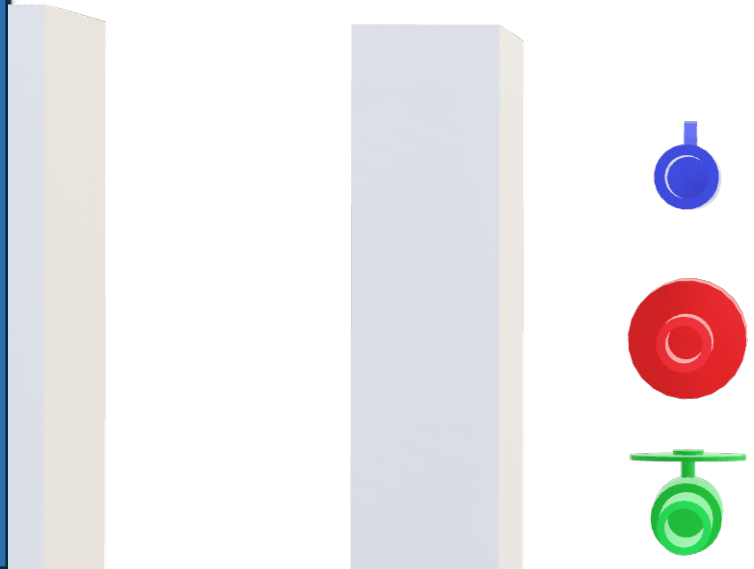

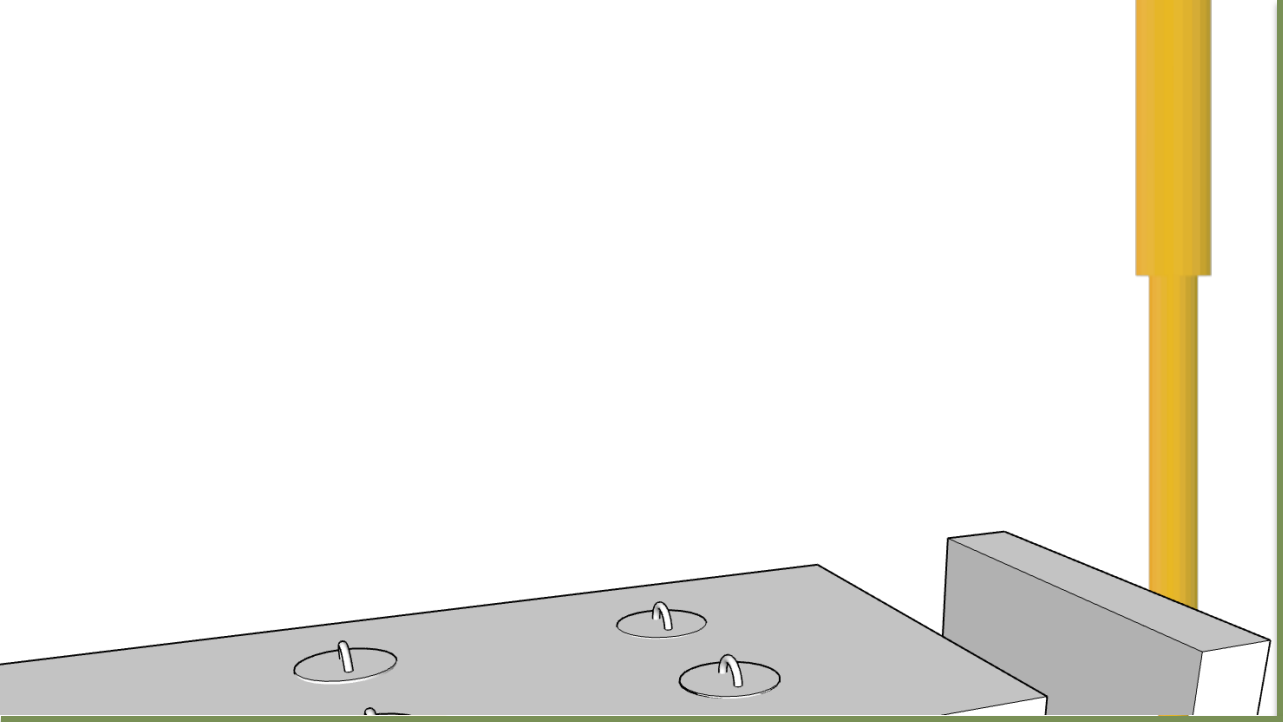

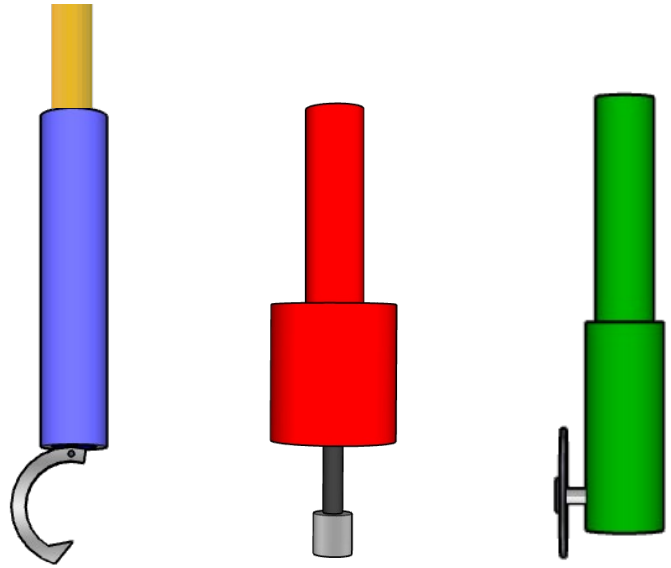

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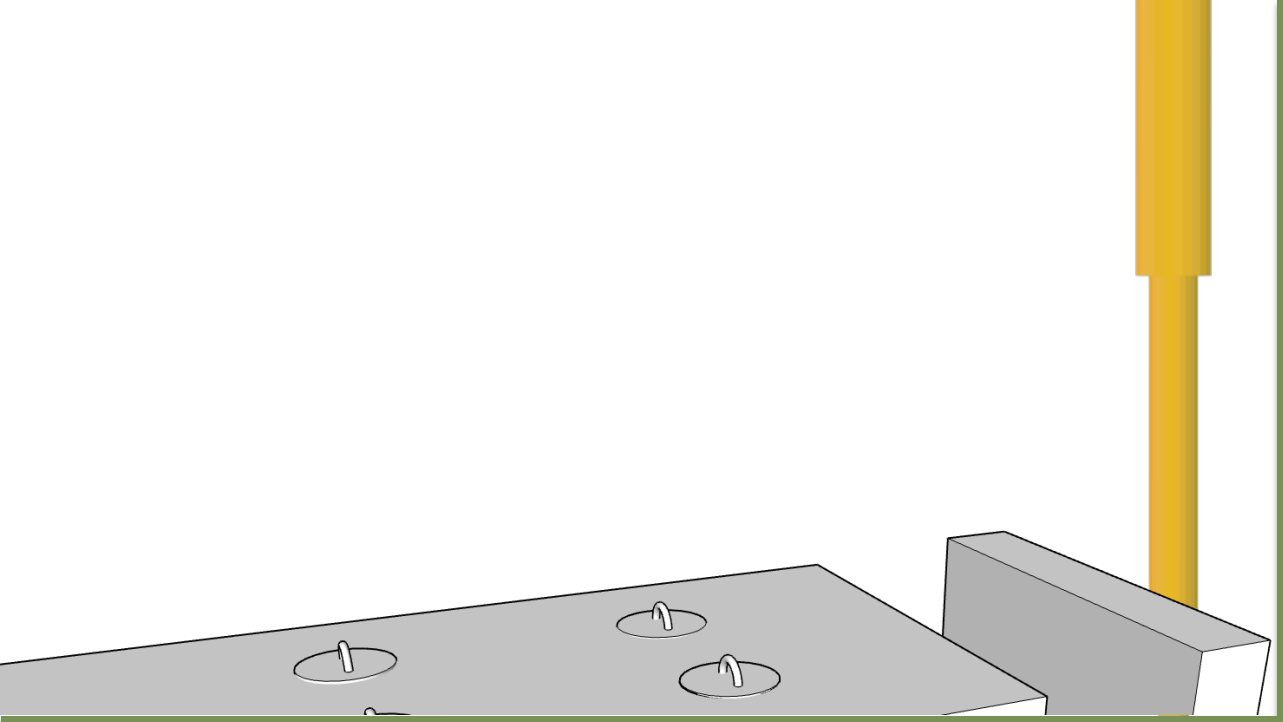

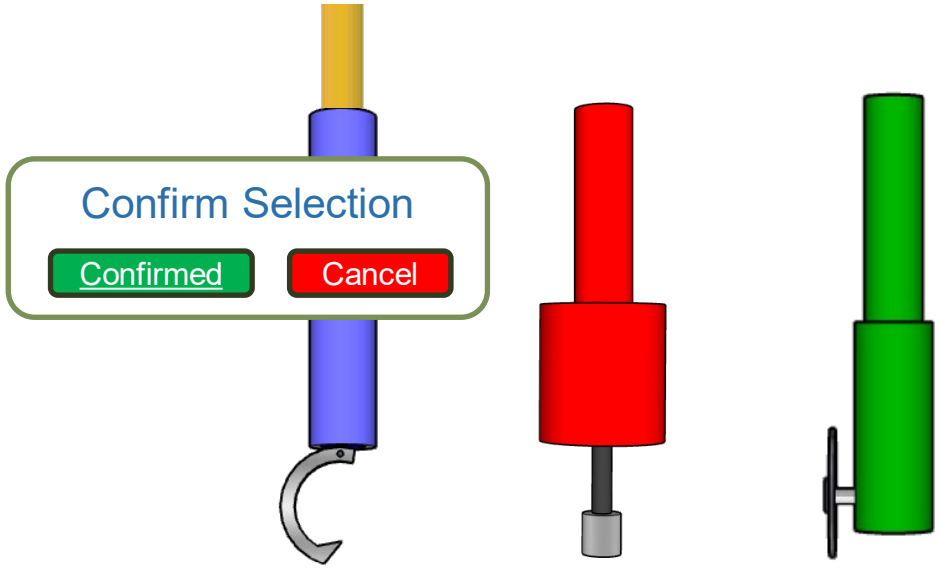

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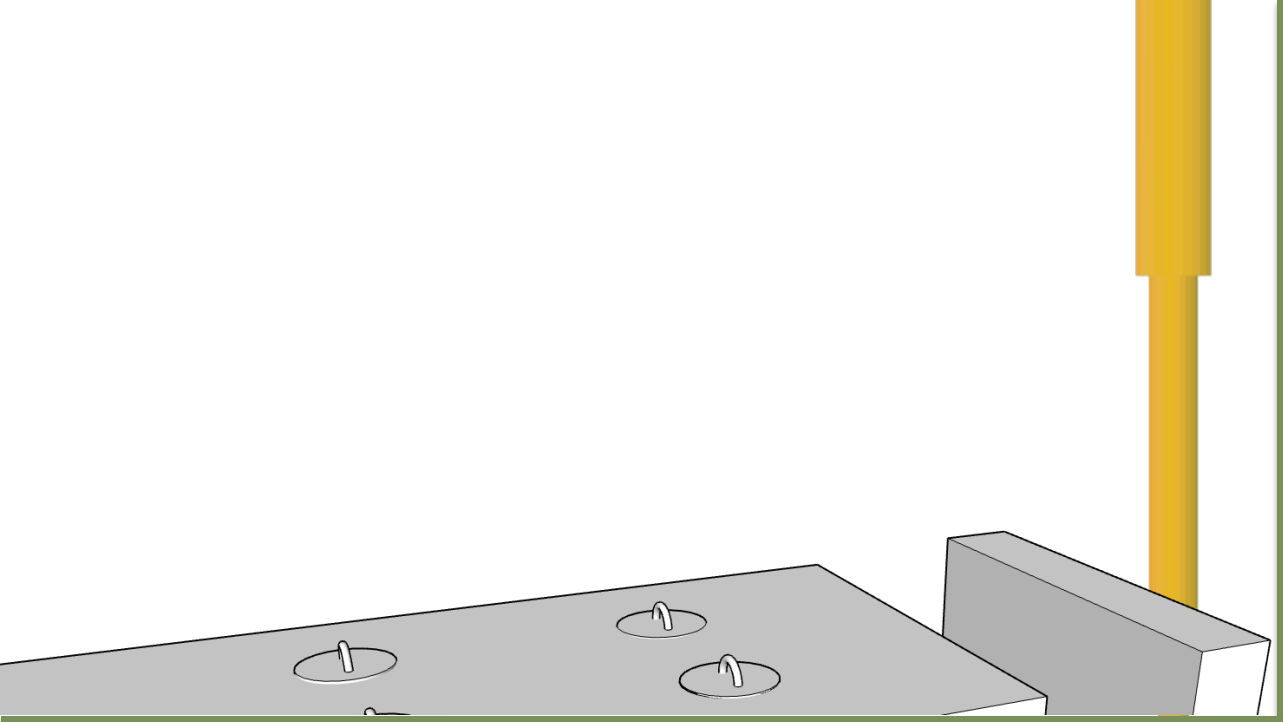

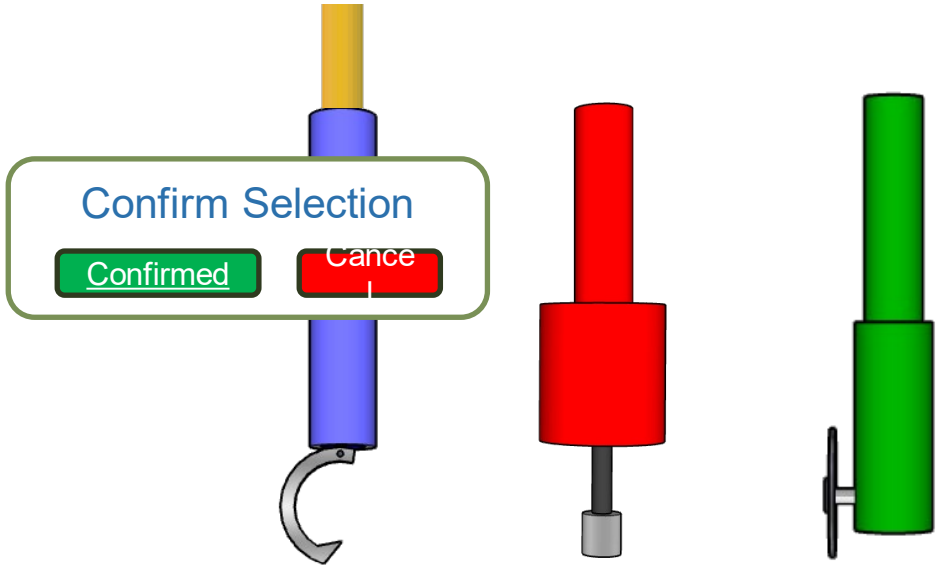

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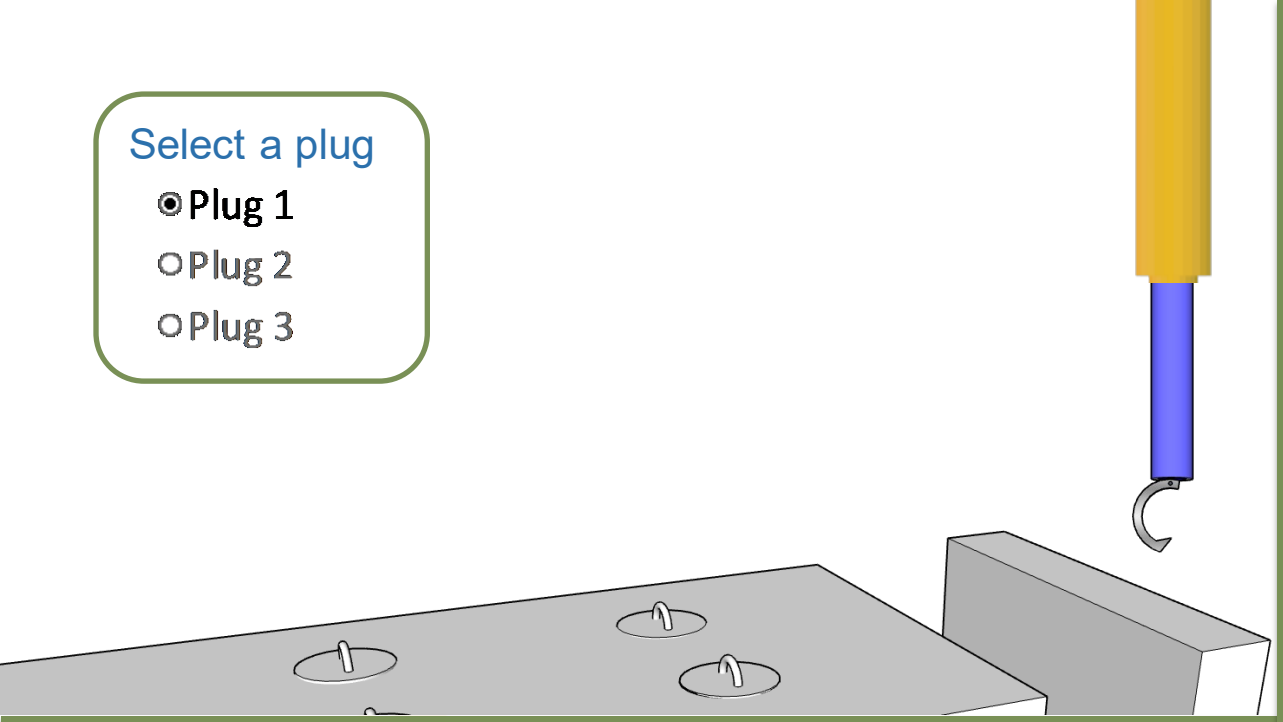
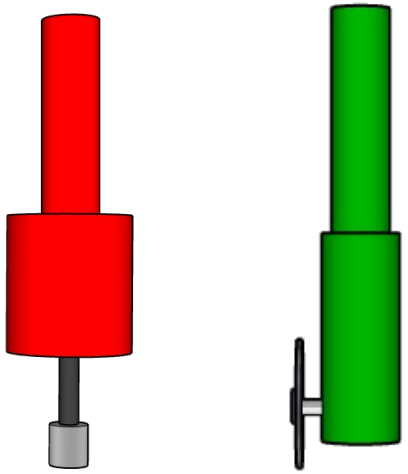
Select a plug

- (•) Plug 1
- ( ) Plug 2
- ( ) Plug 3





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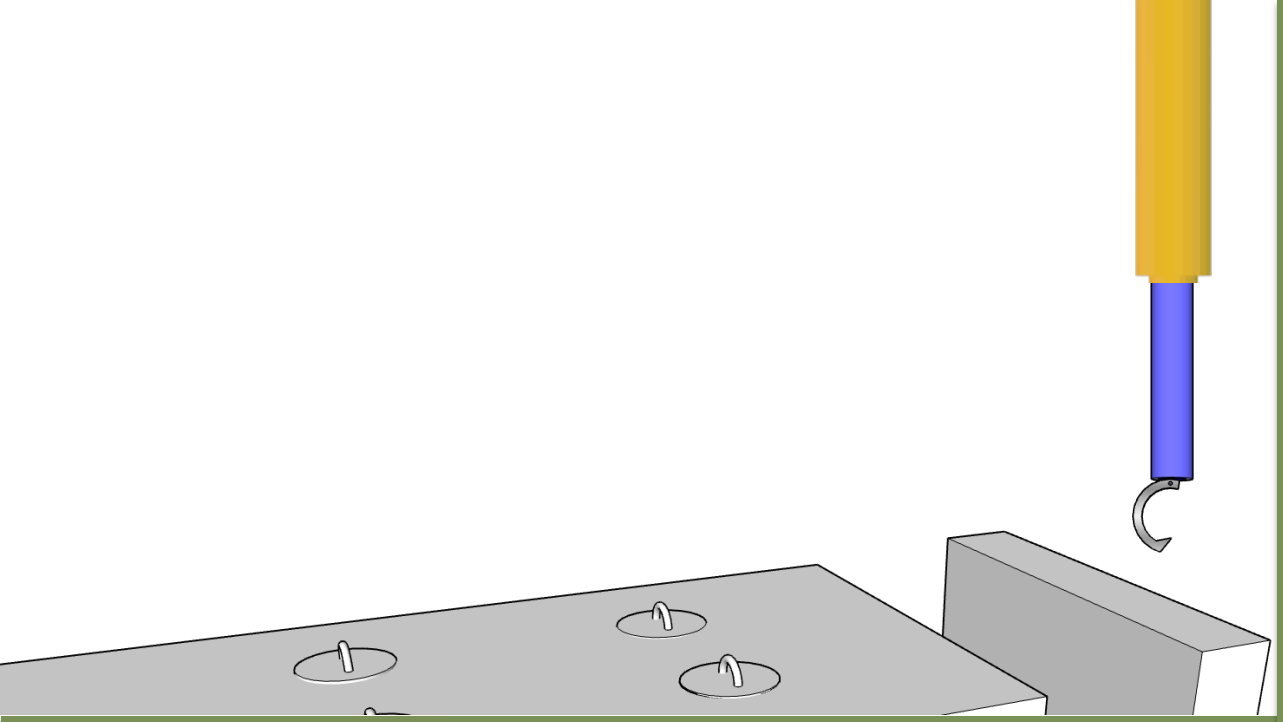
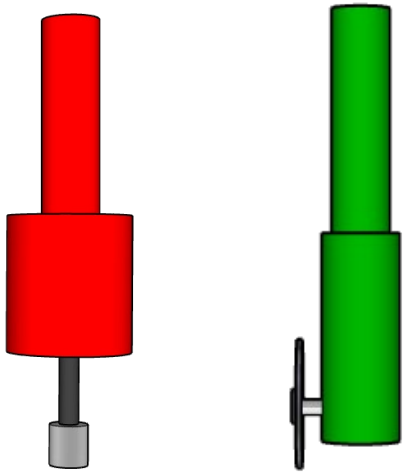




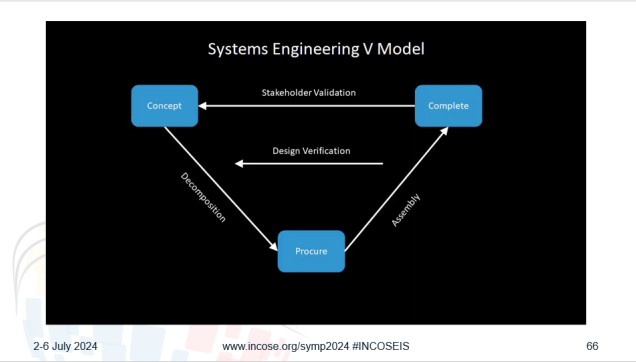
Inside the shielding

Patterns

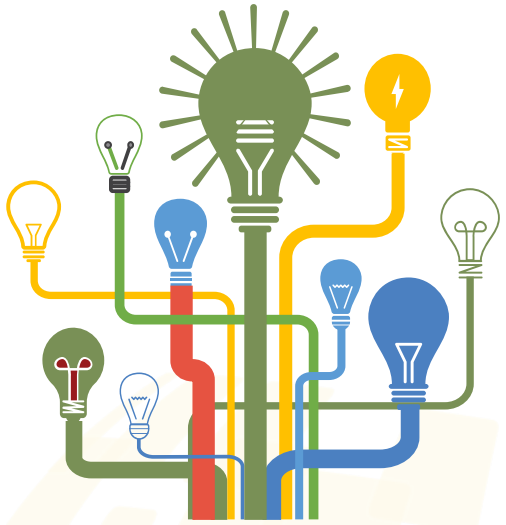
Standard Classification System

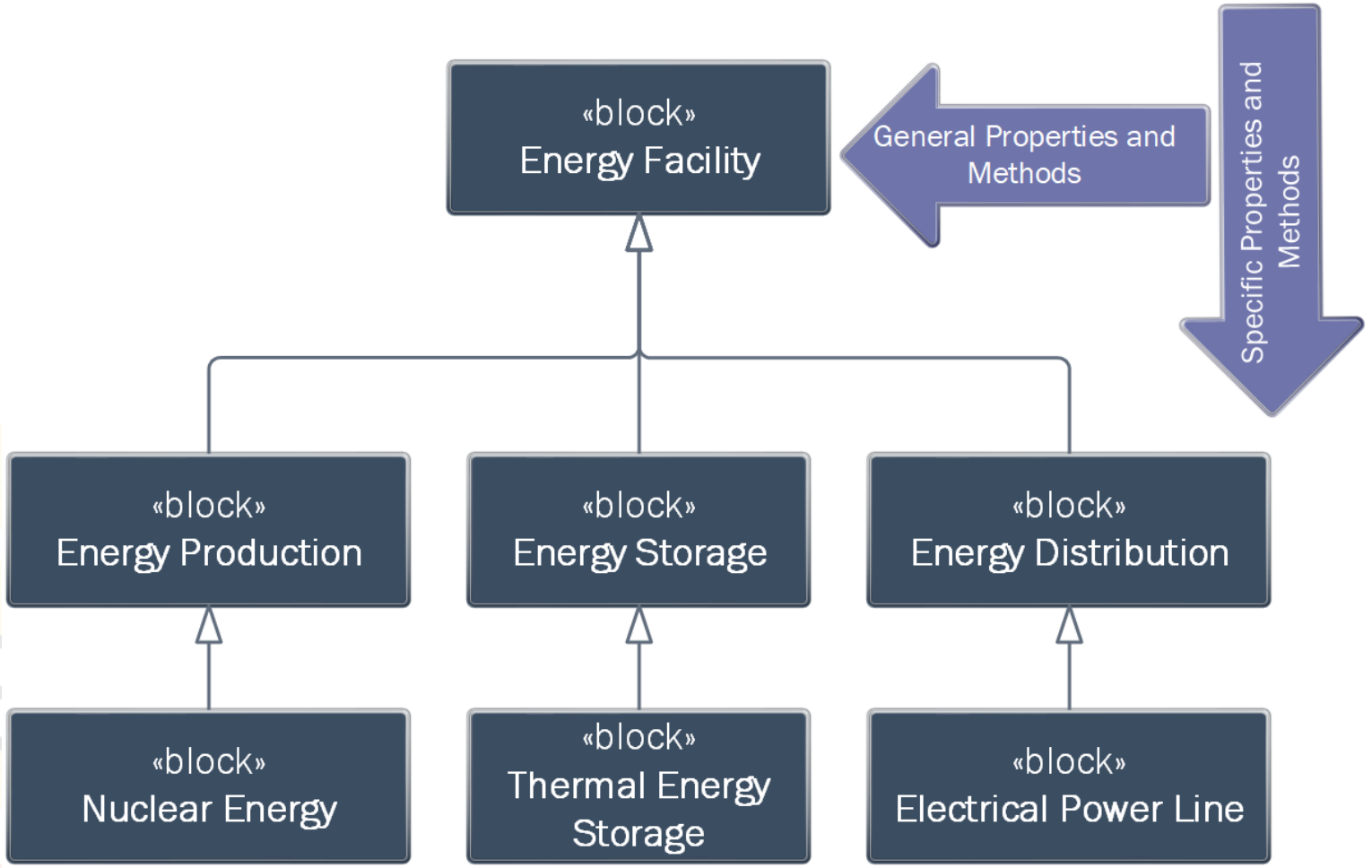
Every Model Needs a Classification System

- Usually created using an iterative process like the development of the Systems Engineering Vee Model.
- The OmniClass classification system is a mature pattern used by construction projects worldwide.
- Can be used as the basis for regenerative AI.

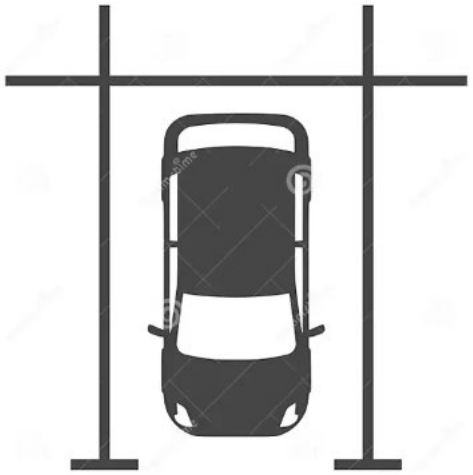


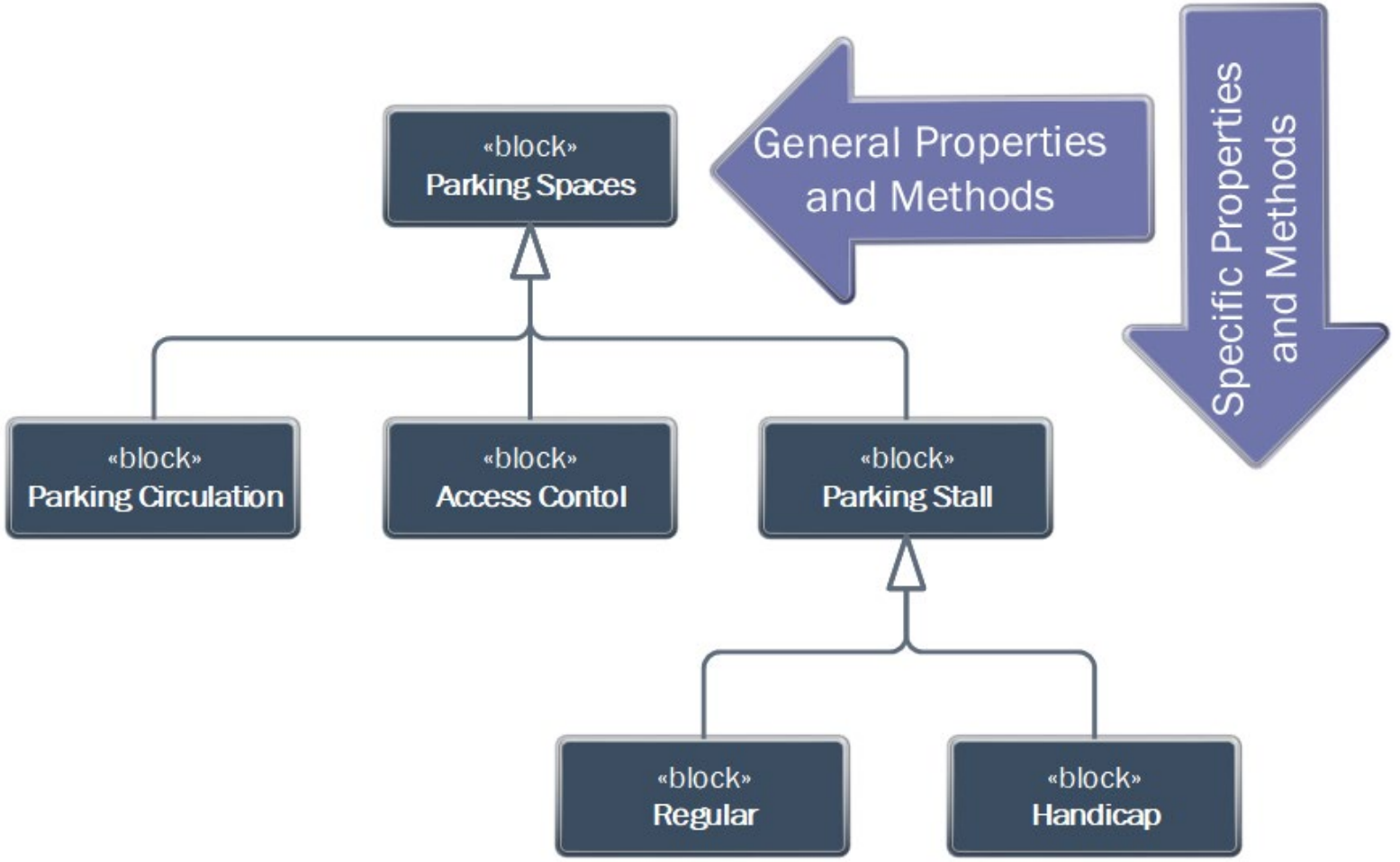
OmniClass Table 11: Entities by Function



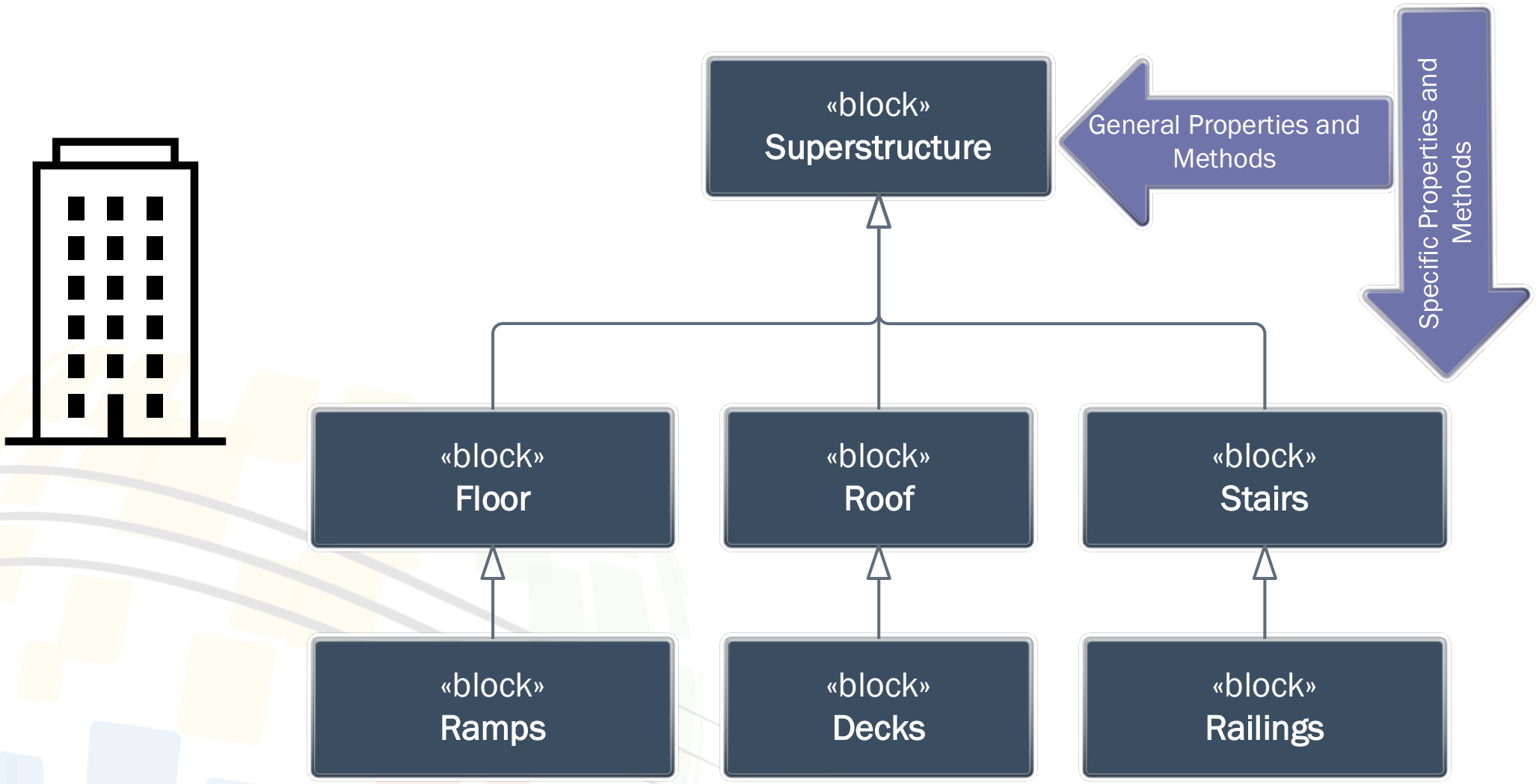


OmniClass Table 13: Spaces by Function

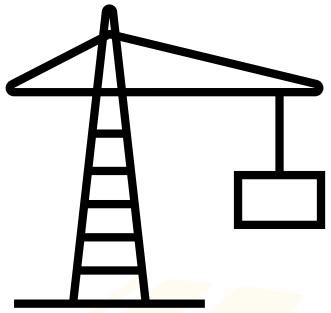


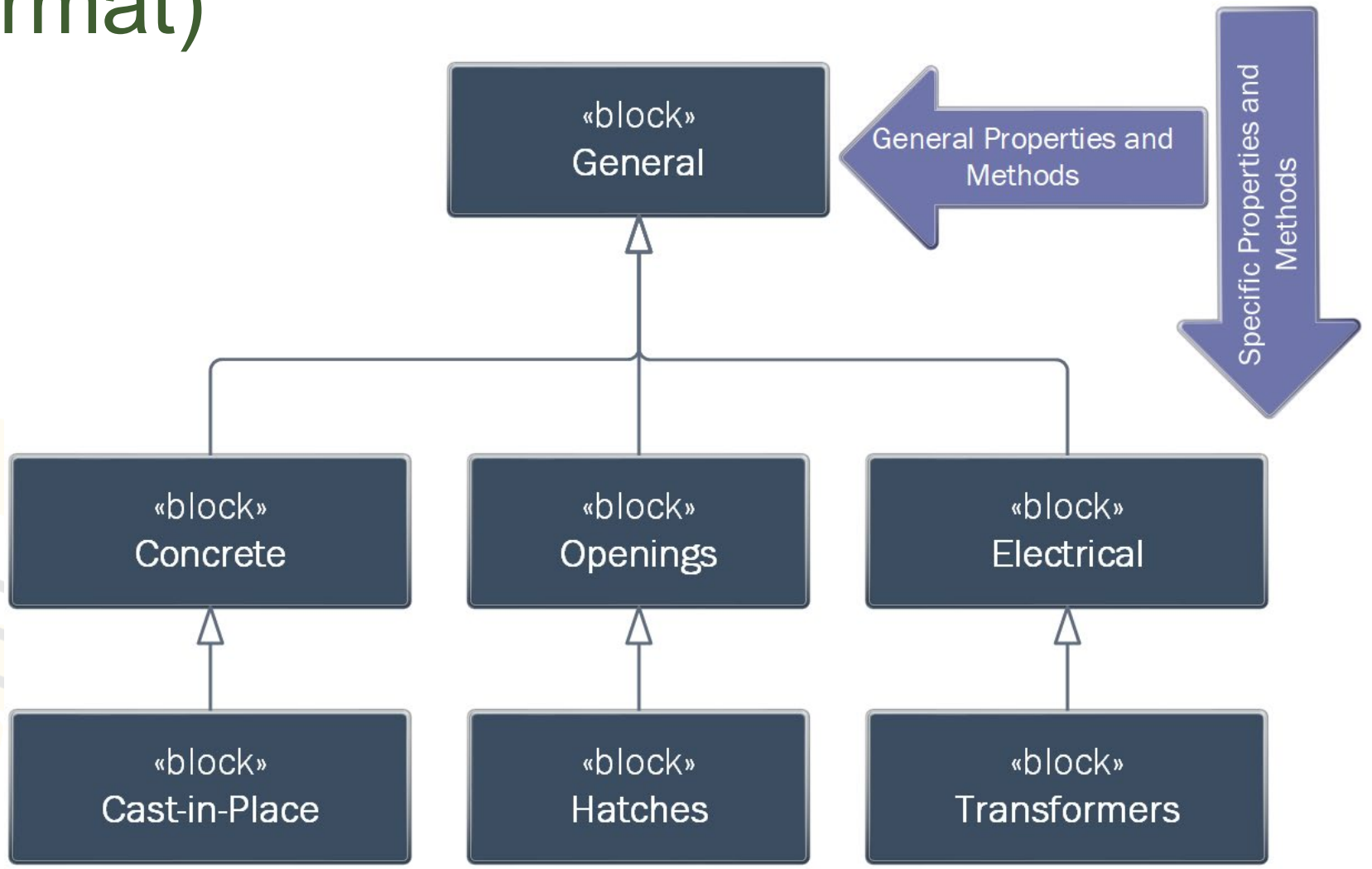


OmniClass Table 21: Elements (UniFormat)

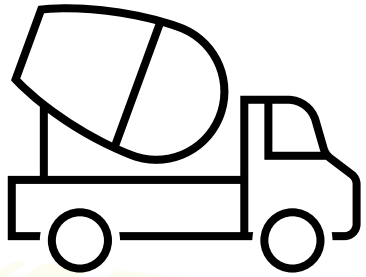


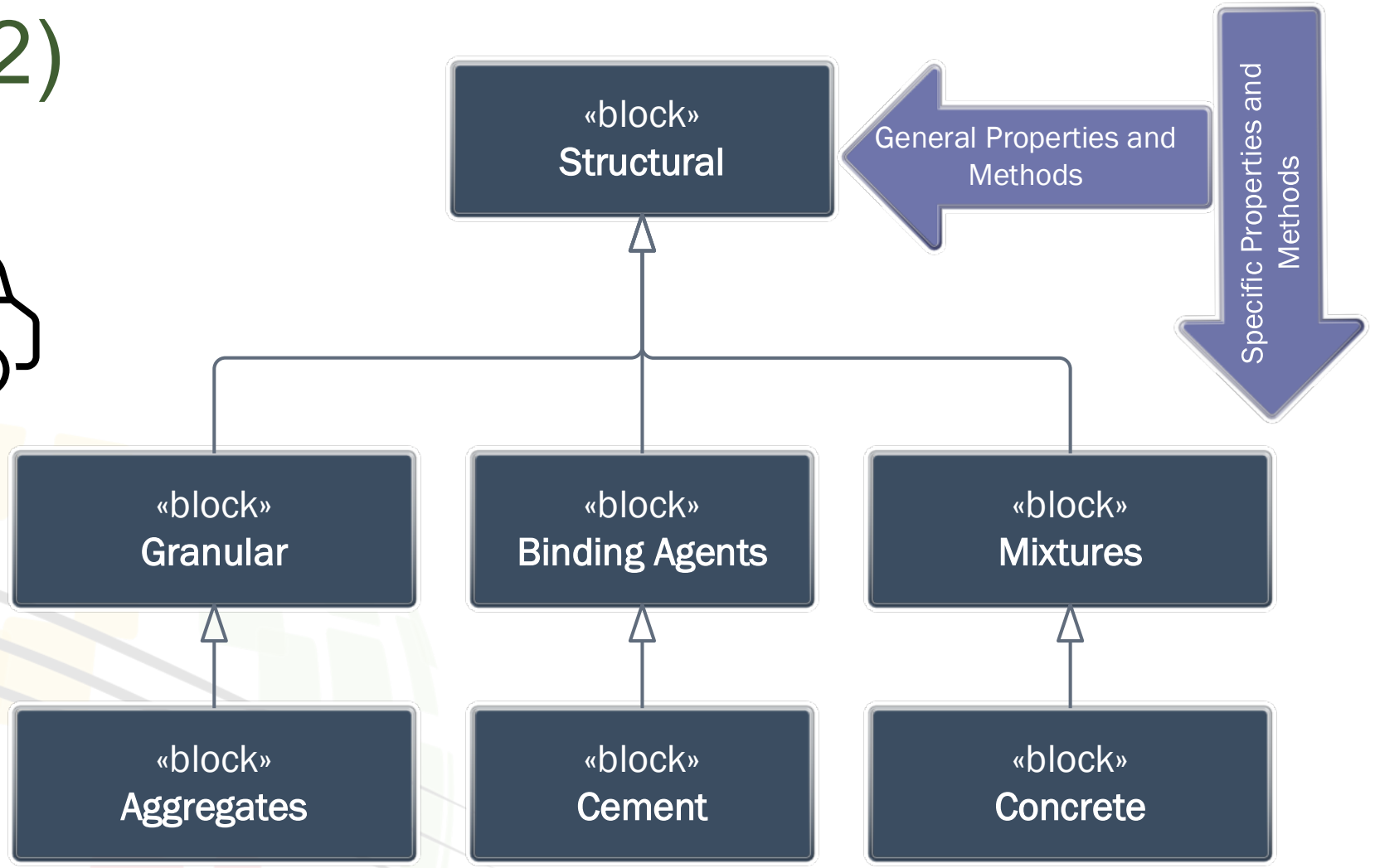
OmniClass Table 22: Work Results (MasterFormat)





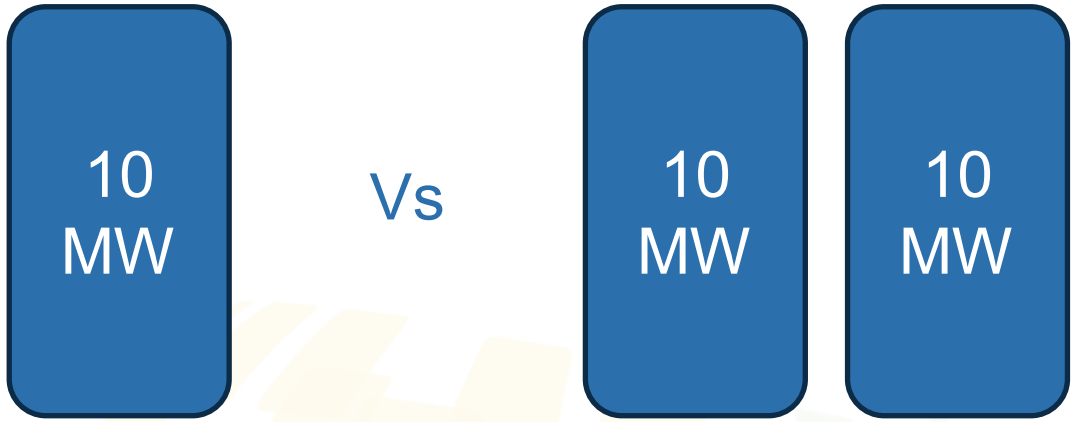
OmniClass Table 23: Products (Construction Spec Part 2)





Tables Missing from OmniClass

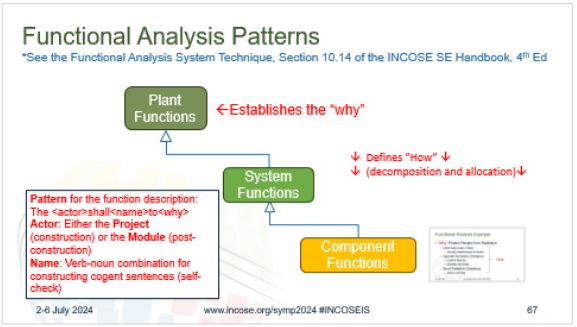
Missing Sizing Parametrics



How does the NPP change when the required capacity changes?

- Increase the number of reactors
- Common facilities such as the control room might retain the same footprint.

Missing a Functional Hierarchy



2

Performance Requirements

Top Down

I know everything!

1

Functional Analysis and Allocation

Middle Out

3

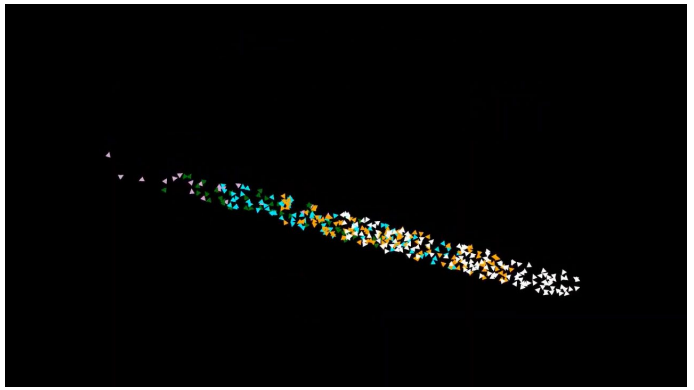
Design

Bottom Up

Why do we have this widget?

Functions are important, often discounted

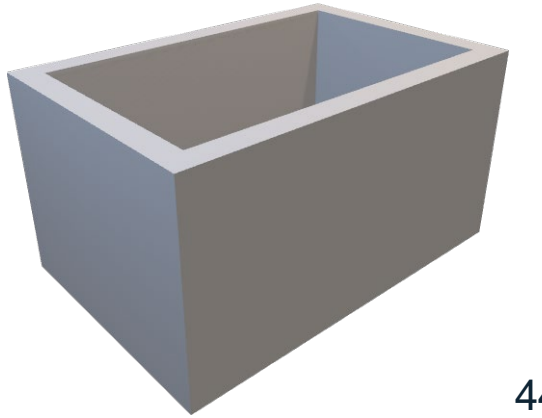
Without any constraints, engineering disciplines will create an amorphous collection of requirements. No way to tell if the collection is necessary or sufficient.



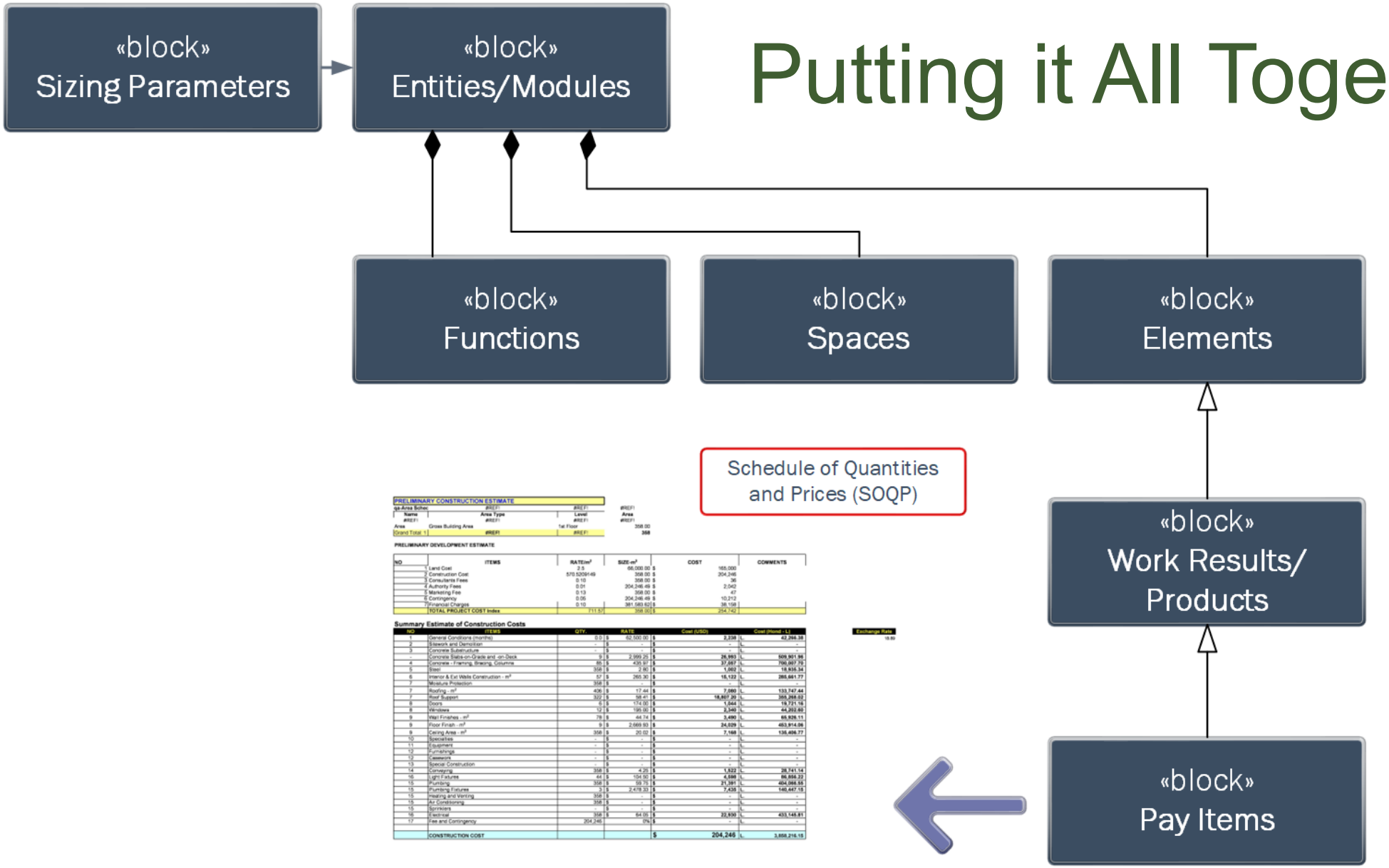
Value Engineering requires a functional analysis to illustrate opportunities for optimization. For example, using one space to perform two functions reduces cost which adds value.

Fuel Rx

Cask Rx



Putting it All Together



Additional Views of the Data

Design Basis Reports[1]

- Architectural Basis of Design
- Structural Basis of Design
- Services Basis of Design
- Sitework Basis

[1]Following OmniClass Table 21, Elements

System Design Descriptions[2]

1. **System Identification**: Identifies the scope of each module.
2. **System Functions**: Functionality of each module as derived from the functional analysis.
3. **System Requirements**: How well each function is performed (Performance Requirements)
4. **System Description**: Objective evidence describing how each requirement is met.

[2]Following DOE-STD-3024

Other Established Patterns

Building Information Management (BIM)

Level of Development (LOD)

BIM Forum Level of Development (LOD) Specification

- LOD 100: Rough (order of magnitude) estimate
- LOD 200: Approximate quantities, size, shape, location
- LOD 300: Specific quantities, size, shape, location
- LOD 400: Sufficient detail for fabrication, assembly, and installation

Conclusion: As s standard product line, the design basis model is at or near LOD 400

BIM Dimensions

United BIM: *What are BIM Dimensions*

Dimension	Quantity	Output
3D	Geometry	3-dimensional (x, y, z) geographical structure.
4D	Time	Timeline, scheduling, and duration
5D	Money	Cost estimate, payment
6D	Sustainability	Sustainable & Energy Efficient
7D	Maintainability	Facility (Asset) Management Information

Design Basis Model and BIM Dimensions

- 3D: The standard modules are all designed in 3D
- 4D: Approximated by the Elements

- 5D: Costs are well established in the SOQP
- 6D: Underpinned by heat transfer calculations
- 7D: Trade studies to optimize maintainability; Commercial Grade Dedication to establish reliability for safety items; commercial databases to estimate RAMI figures of merit.

Conclusions

Conclusions

- Nuclear energy could play an important role toward net-zero carbon emissions if only current risks can be reduced.
- Risks can be reduced by developing and testing modules that consist primarily of standard, commercial components and the application of well-established construction patterns.
- The National Reactor Innovation Center at the Idaho National Laboratory (USA) is demonstrating this approach.

Acknowledgements

From the Idaho National Laboratory

- Aaron Balsmeier, Review
- Dr Rami Saeed, Thermal Energy Storage Concept
- Garrett Holmes, Thermal Energy Storage 3D Graphics

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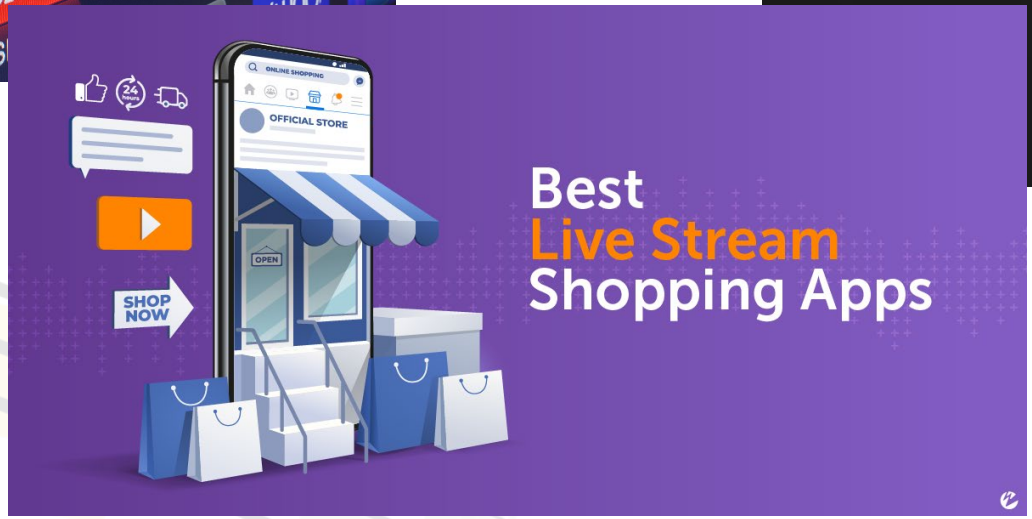
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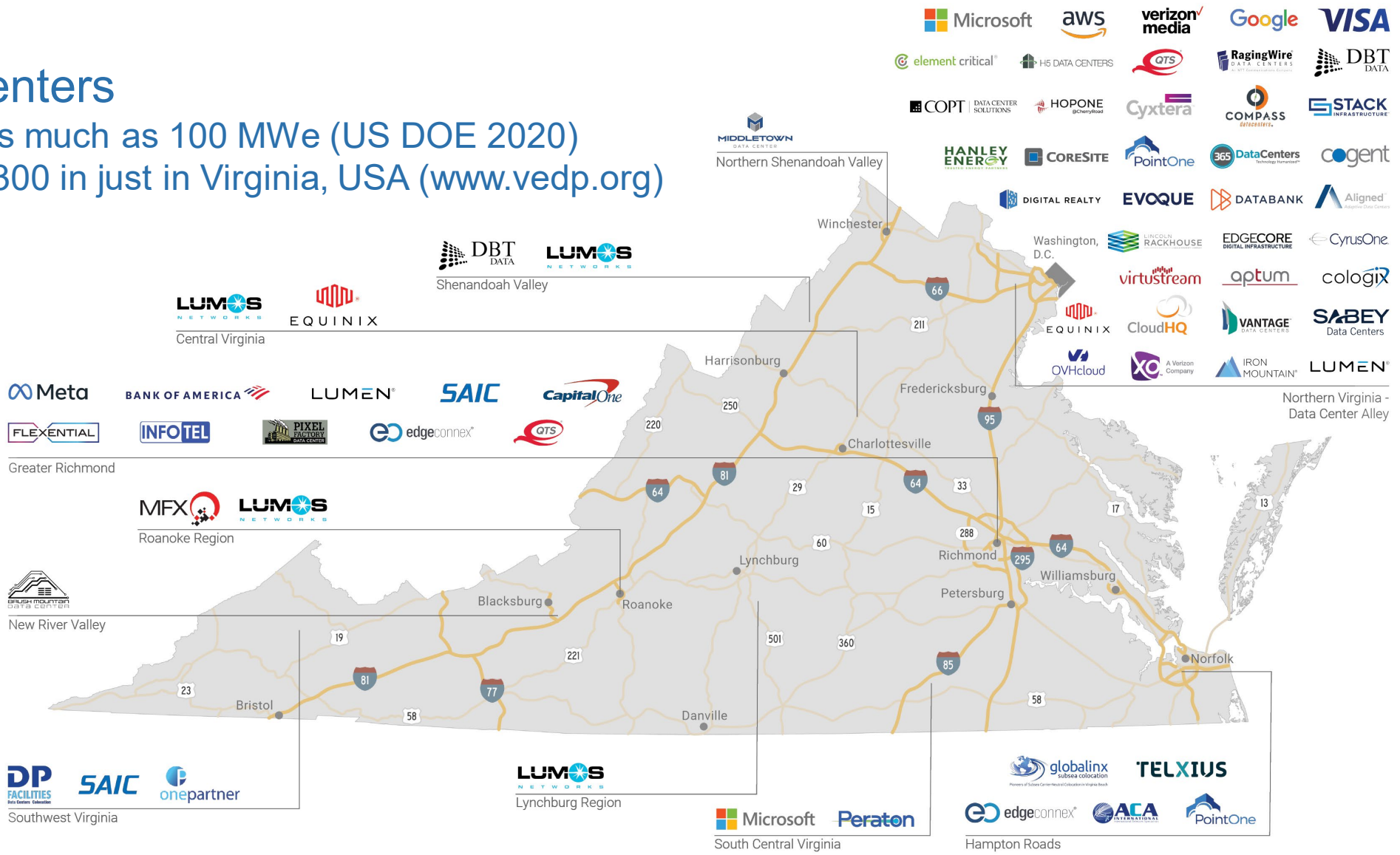
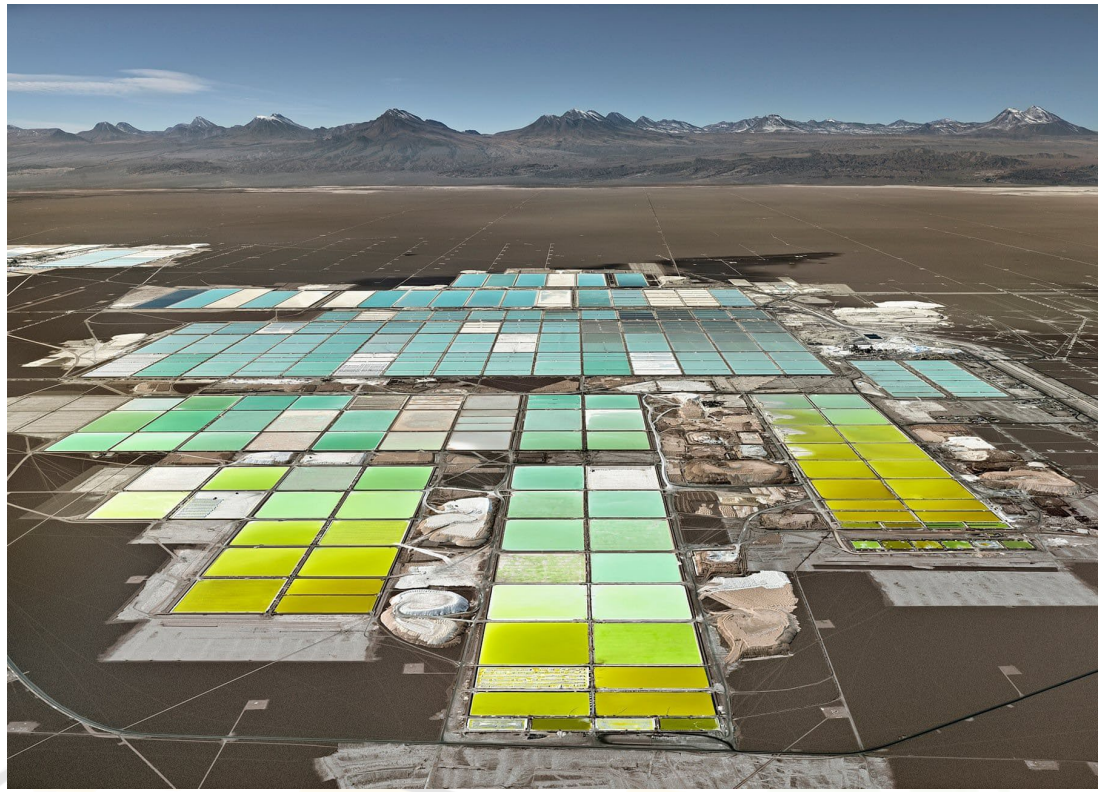
Datacenters

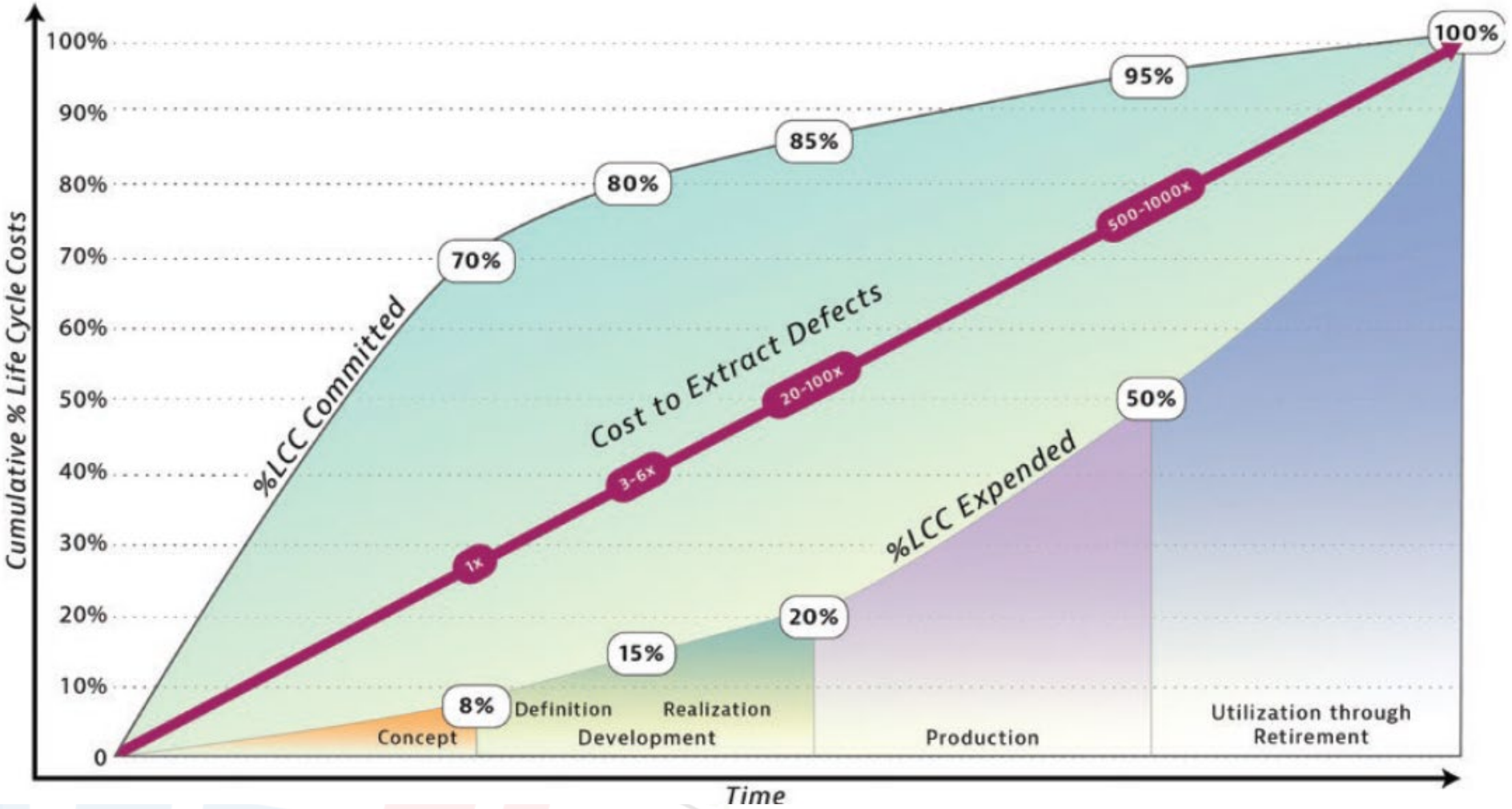
- Use as much as 100 MWe (US DOE 2020)
- Over 300 in just in Virginia, USA (www.vedp.org)





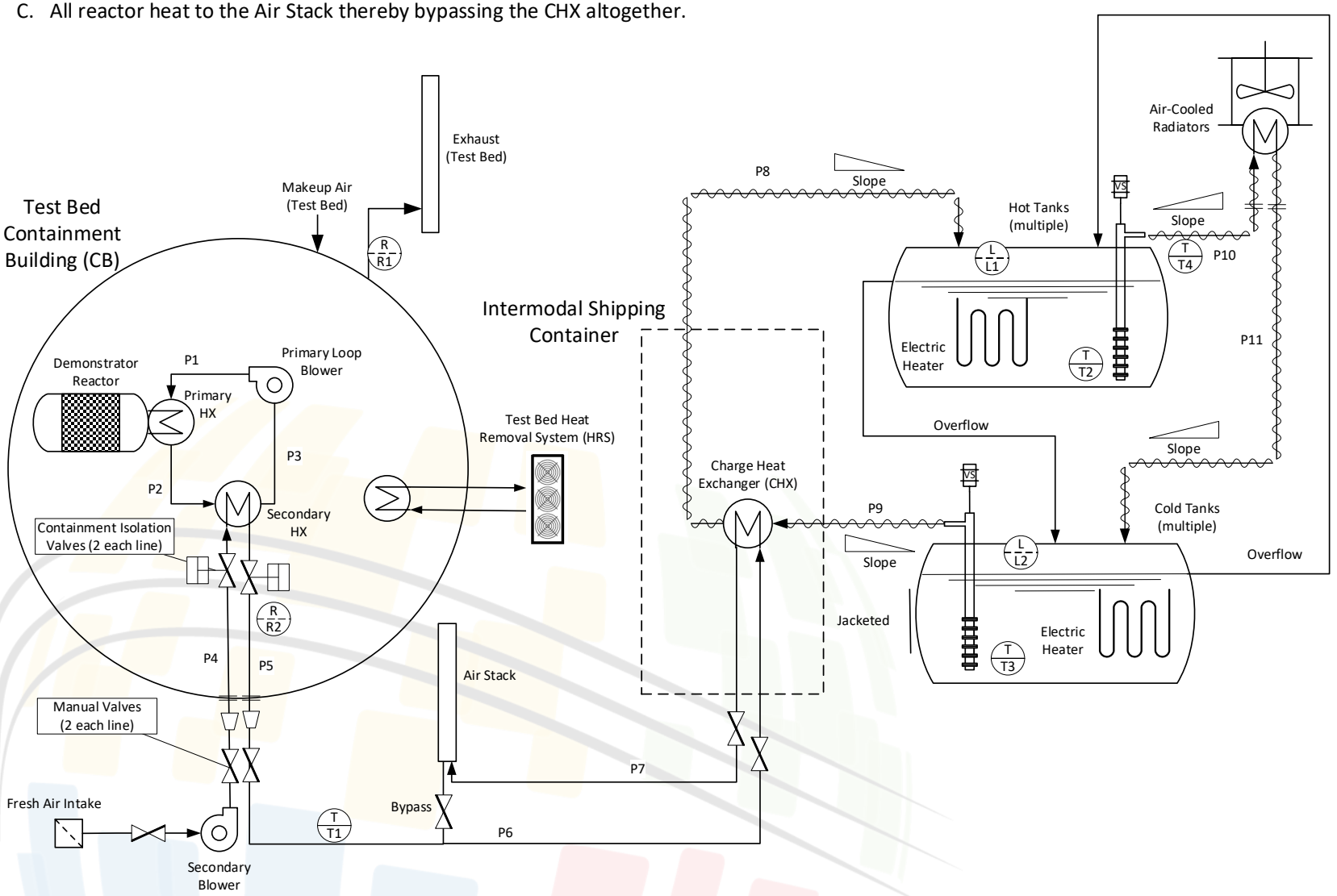

Electric Highway
Electric Highway
Electric Highway

Typical Impact of Changes



Operating Configurations:

A. All reactor heat through the Charge Heat Exchanger (CHX).
B. A portion of the reactor heat through the CHX; Release the balance to the Air Stack.
C. All reactor heat to the Air Stack thereby bypassing the CHX altogether.



Integrated Energy Storage

Modular Integrated Energy Storage

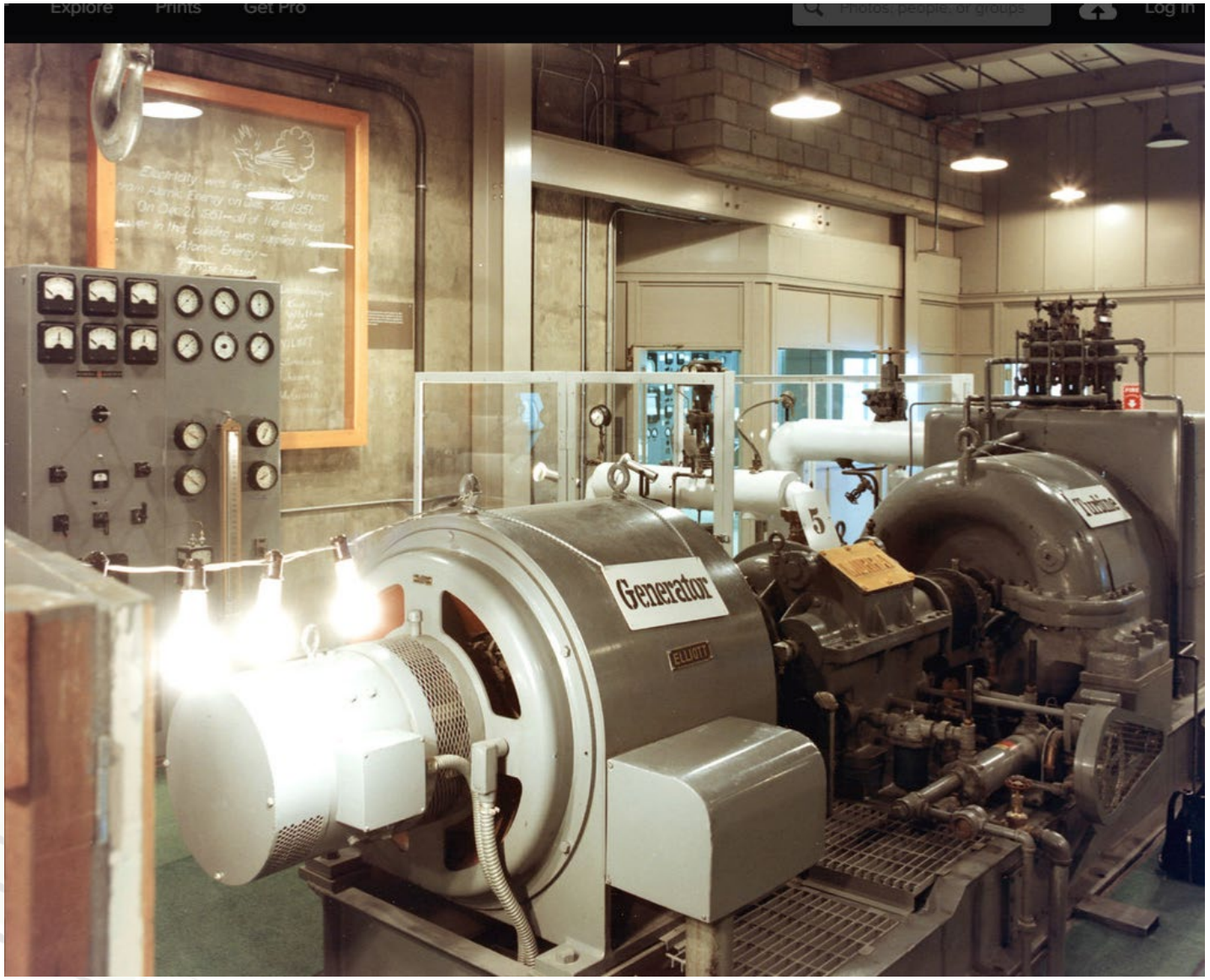
All modules constrained to the size of an intermodal shipping container

Modular Integrated Energy Storage

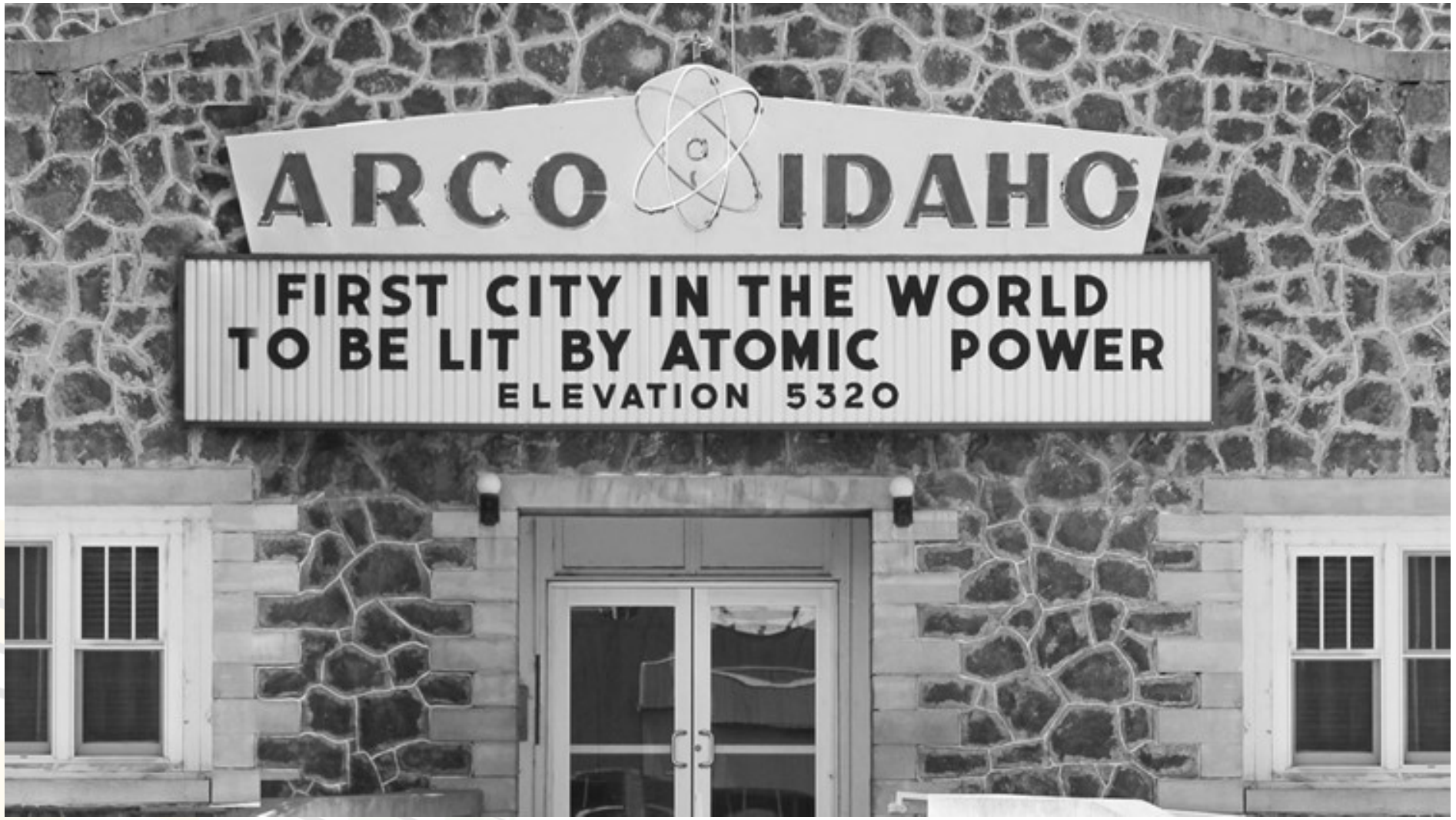
All modules constrained to the size of an intermodal shipping container

Dec. 20, 1951, at 1:23 p.m., "… electricity flows from atomic energy."

Walter Zinn's logbook from that day

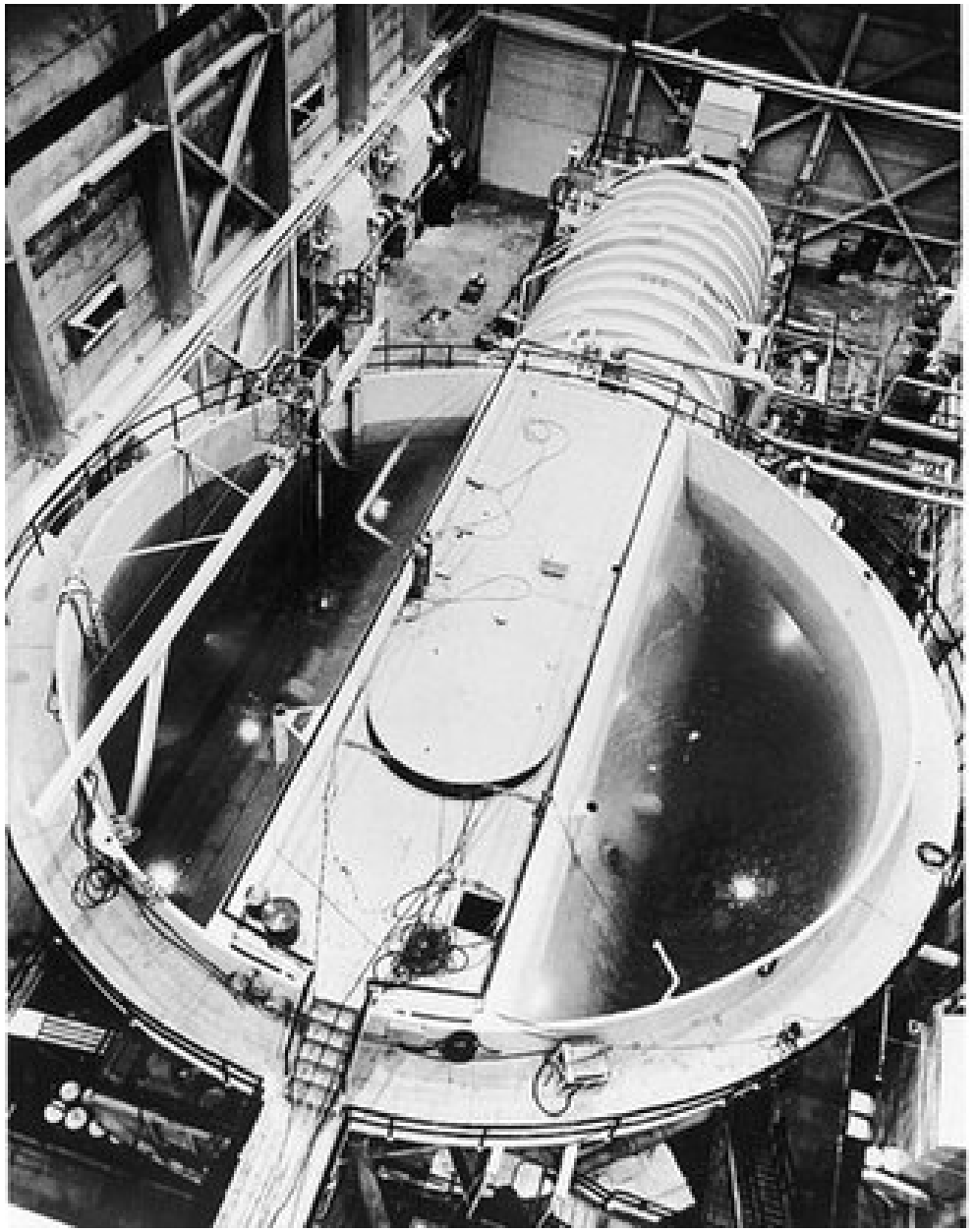


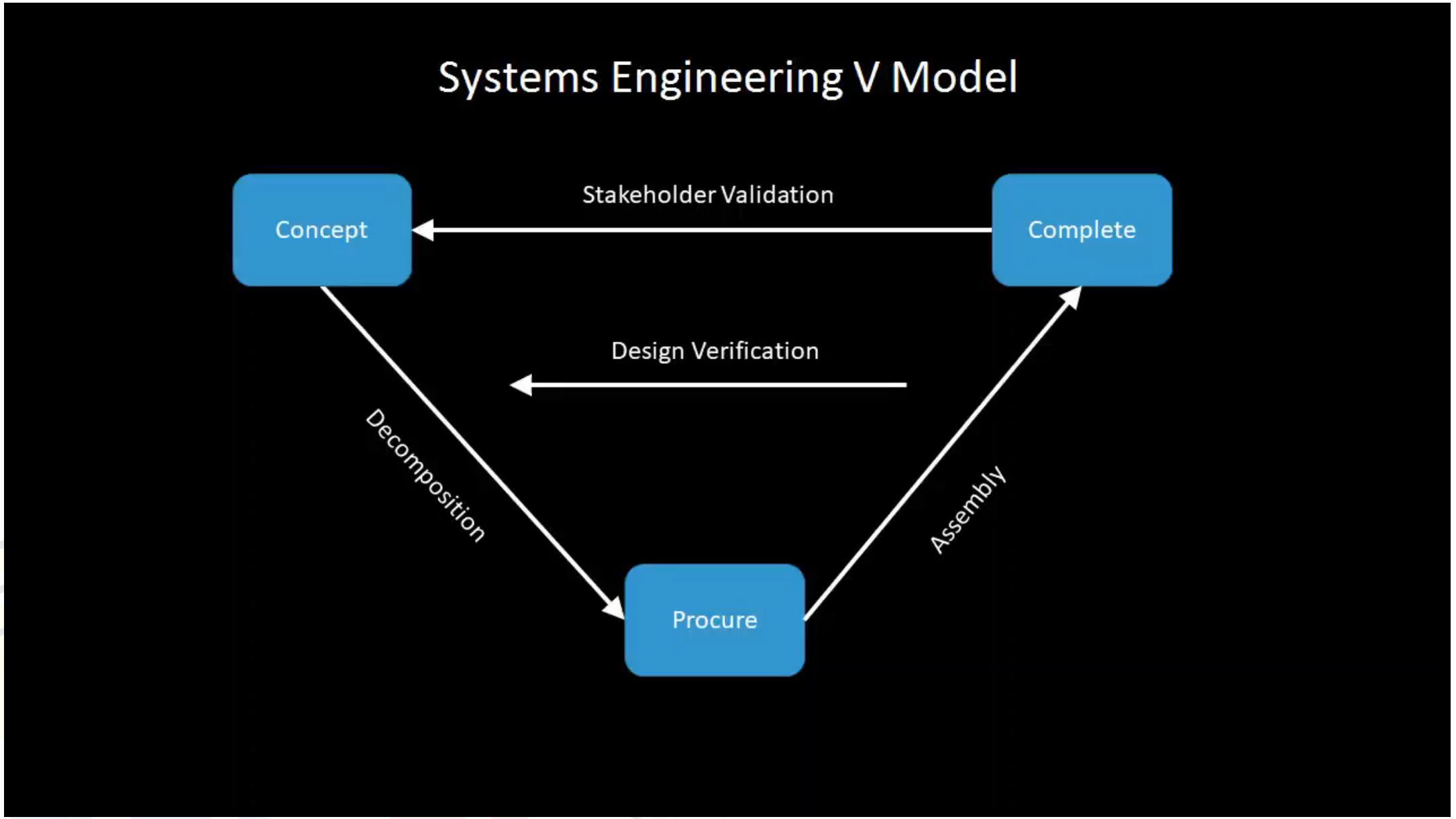
July 17, 1955


ARCO IDAHO
FIRST CITY IN THE WORLD
TO BE LIT BY ATOMIC POWER
ELEVATION 5320

Prototype for USS Nautilus

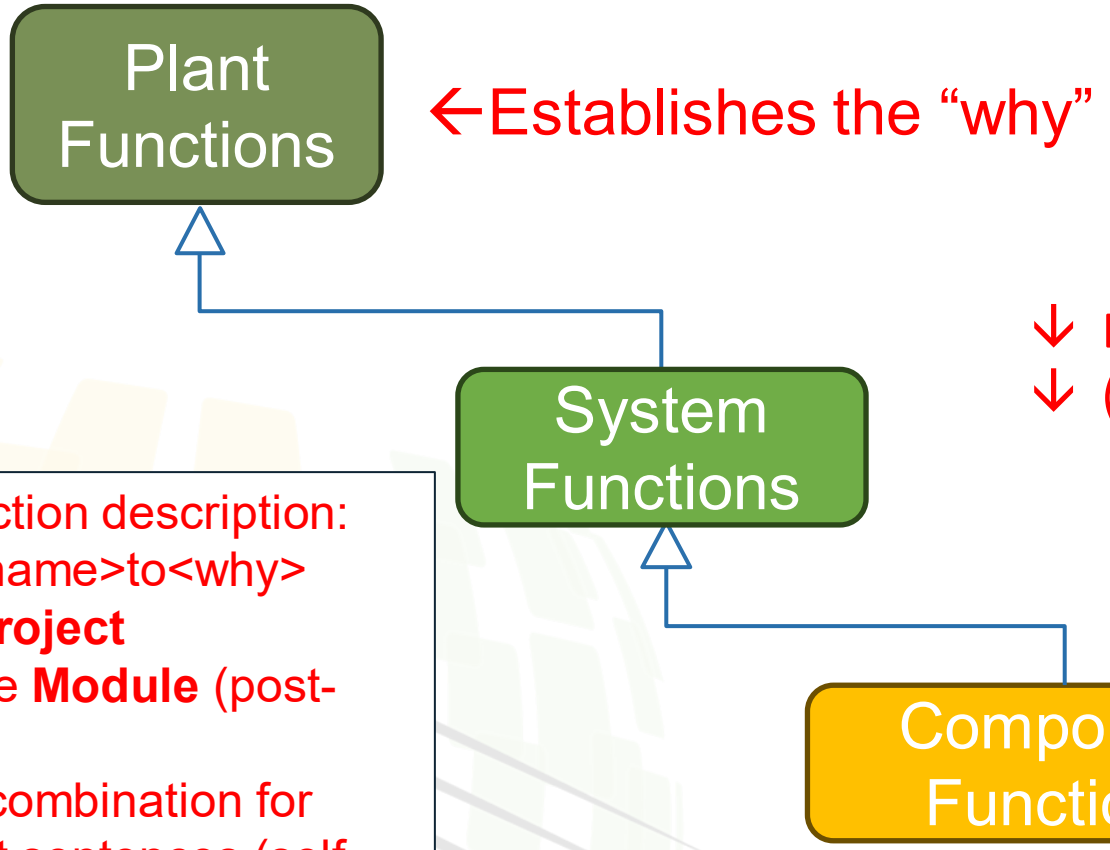
First nuclear-powered submarine of the US Navy, in service from 1954 to 1980



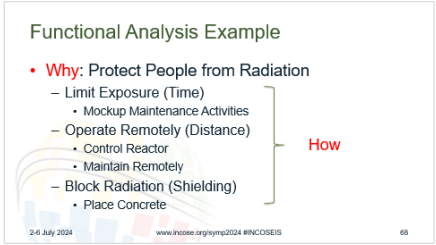

Systems Engineering V Model
Concept
Stakeholder Validation
Complete
Design Verification
Decomposition
Assembly
Procure

Functional Analysis Patterns

*See the Functional Analysis System Technique, Section 10.14 of the INCOSE SE Handbook, 4th Ed



Pattern for the function description:
The <actor>shall<name>to<why>
Actor: Either the **Project** (construction) or the **Module** (post-construction)
Name: Verb-noun combination for constructing cogent sentences (self-check)


Functional Analysis Example

- Why: Protect People from Radiation
  - Limit Exposure (Time)
    - Mockup Maintenance Activities
  - Operate Remotely (Distance)
    - Control Reactor
    - Maintain Remotely
  - Block Radiation (Shielding)
    - Place Concrete

How

Functional Analysis Example

- Why: Protect People from Radiation
  - Limit Exposure (Time)
    - Mockup Maintenance Activities
  - Operate Remotely (Distance)
    - Control Reactor
    - Maintain Remotely
  - Block Radiation (Shielding)
    - Place Concrete

How

Using Elements to Approximate the Construction Timeline