

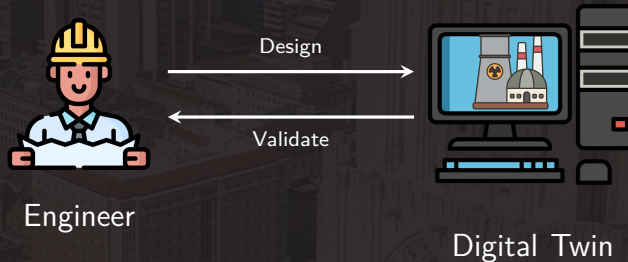
Formally Verified Autonomous Hybrid Control

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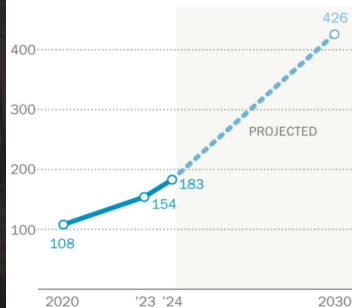
December 13, 2025



The United States stands on the precipice of a severe energy crisis

Electricity consumption at U.S. data centers is expected to more than double by 2030

Total electricity consumption by U.S. data centers (terawatt-hours)



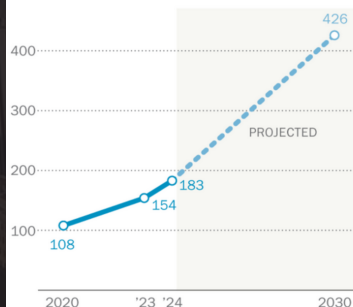
Source: Pew Research Center, Data from IEA

How much baseload power increase is this?

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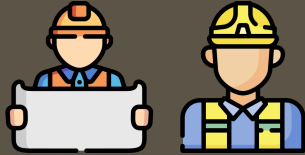
30 gigawatts!

Nuclear reactors are operated with prescriptive handbooks and legacy control technologies



Human reactor operators have key limitations that limit nuclear buildout

Humans cannot meet
labor demand



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Procedures are not formally verified



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Human factors cannot be trained away



The goal of this research is to create verified autonomous control systems

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- 1 Translate written procedures into discrete control logic
- 2 Verify continuous control behavior across discrete mode transitions
- 3 Demonstrate autonomous reactor startup with verifiable safety guarantees

First, we will formalize written procedures into logical statements

APPENDIX 19-1 Plant Startup from Cold Shutdown

I. INITIAL CONDITIONS

1. Cold Shutdown - MODE 5:

- $K_{\text{eff}} < 0.99$
- 0% power
- $T_{\text{avg}} < 200^{\circ}\text{F}$

2. Reactor Coolant System: solid.

3. RCS Temperature: 150 - 160°F.

Note:

Temperature may be less than 150°F depending upon the decay heat load of the core.

4. RCS Pressure: 320 - 400 psig.
5. Steam Generators: filled to wet layup (100% wide-range level indication).
6. Secondary Systems: shutdown, main turbine and feedwater pump turbines on their turning gears.
7. Pre-Startup Checklists: completed.

Westinghouse Technology Systems Manual, Section 19.0 - Plant Operations

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FRET Specification

INITIAL_CONDITIONS shall satisfy:

mode = MODE_5

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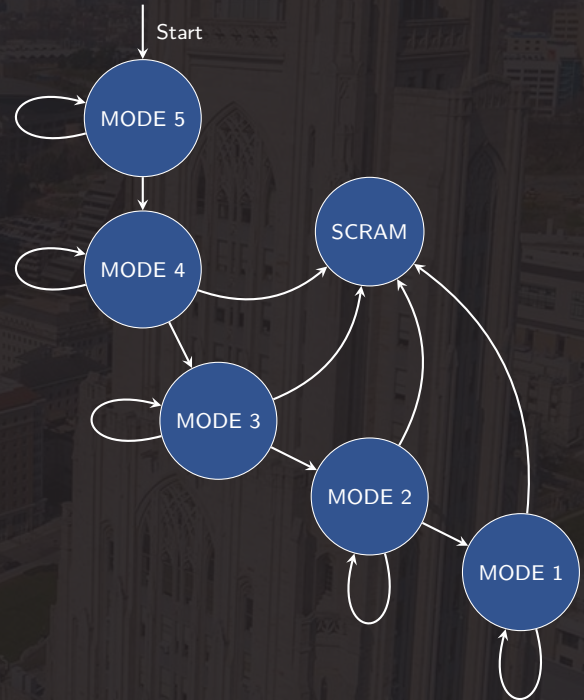
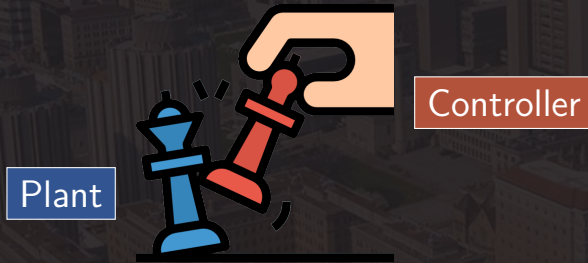
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```
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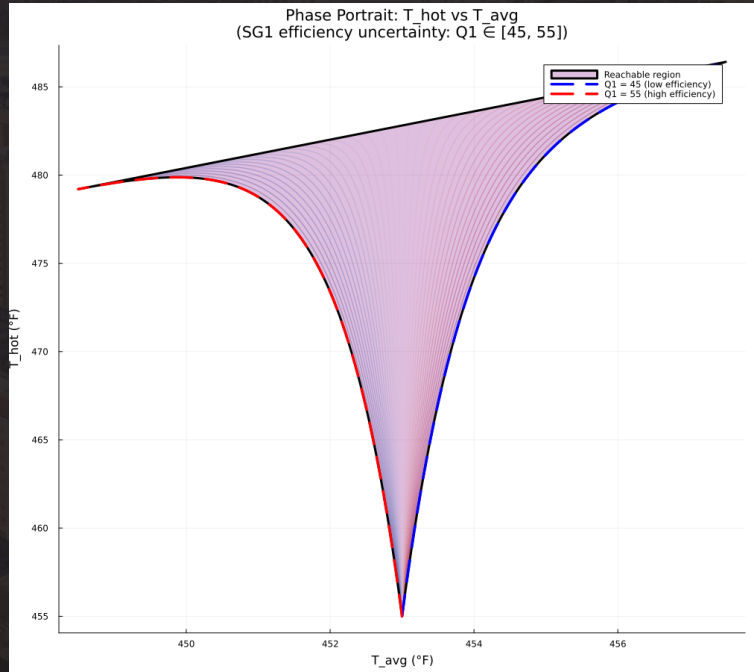
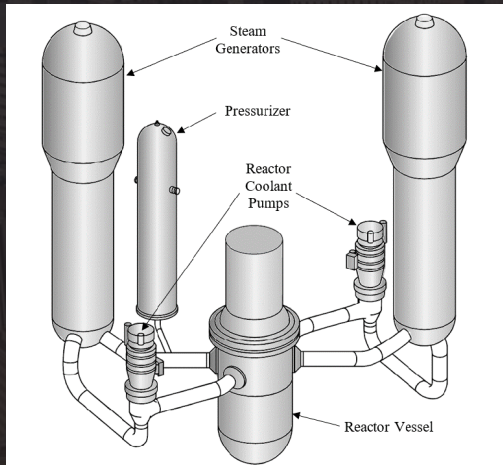
LTL Formula

```
□ (initial → (
    mode_5_active ∧
    k_eff_subcritical ∧
    zero_power ∧
    temp_safe ∧
    ...))
```

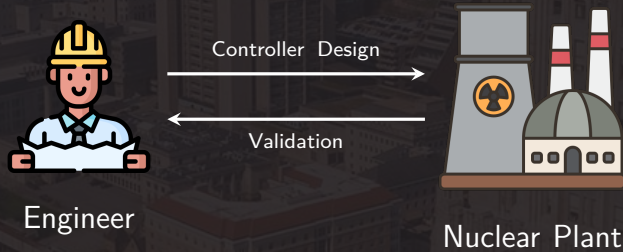
Second, we will use reactive synthesis to convert the logical formulae to generate discrete automata



Finally, we will build continuous controllers with formal methods to ensure transitions between modes



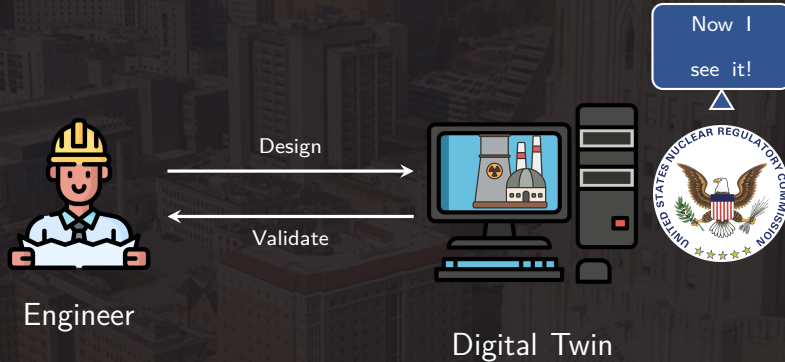
Validating this methodology is not possible using real nuclear plants



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Instead, digital twins will enable controller development and validation before implementation



Success will be measured through Technology Readiness Level (TRL) advancement

TRL Goal

Current: TRL 2-3

Target: TRL 5

TRL 3
Components



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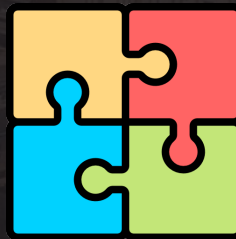
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TRL 4
Integration



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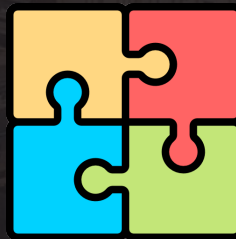
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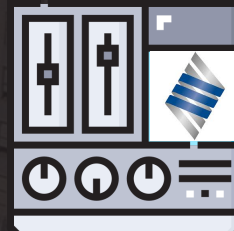
TRL 3
Components



TRL 4
Integration



TRL 5
Hardware



Reducing operations costs for new nuclear power is a billion dollar problem



Formally Verified Autonomous Hybrid Control

Enabling Economic Viability
of Next-Generation Nuclear
Power

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