Formally Verified Autonomous Hybrid Control

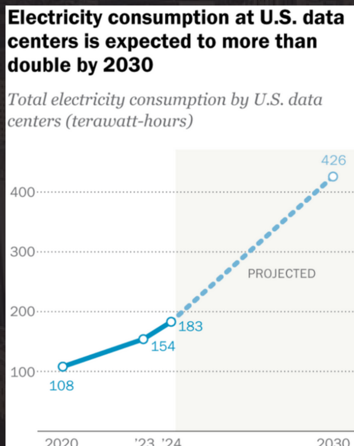
Dane A. Sabo
dane.sabo@pitt.edu

Dr. Daniel G. Cole
dgcole@pitt.edu

University of Pittsburgh

November 30, 2025

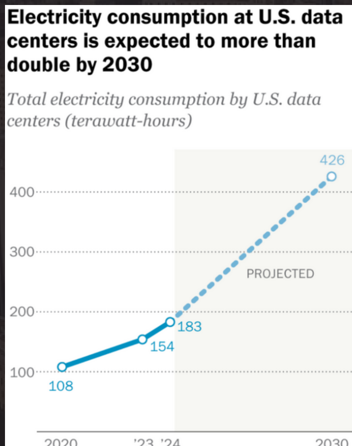
The United States stands on the precipice of a severe energy crises



Source: Pew Research Center, Data from IEA

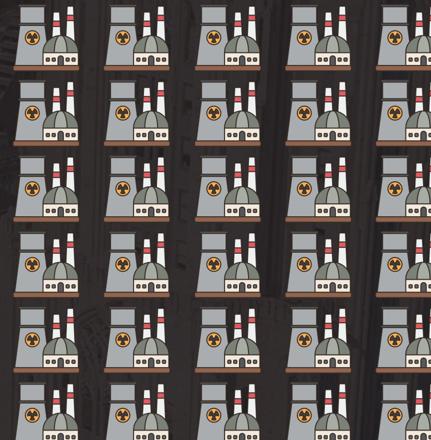
How much baseload power increase is this?

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



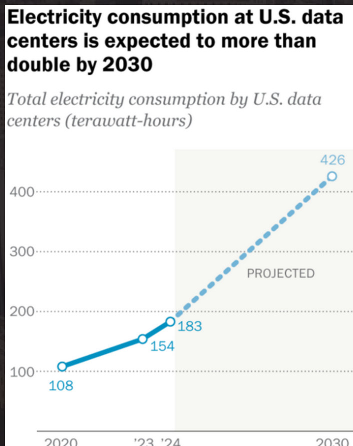
Source: Pew Research Center, Data from IEA

How much baseload power increase is this?



30 gigawatts!

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



Source: Pew Research Center, Data from IEA

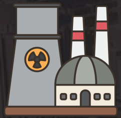
How much baseload power increase is this?

30 gigawatts!

University of Pittsburgh
Cyber Energy Center

Staffing these new reactors will be an incredible challenge

How many reactor operators are required to staff this new fleet?



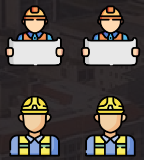
For one Small Modular Reactor (SMR)...

Staffing these new reactors will be an incredible challenge

How many reactor operators are required to staff this new fleet?

For one Small Modular Reactor (SMR)...

One shift requires:

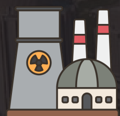


2 Senior Reactor Operators

2 Reactor Operators

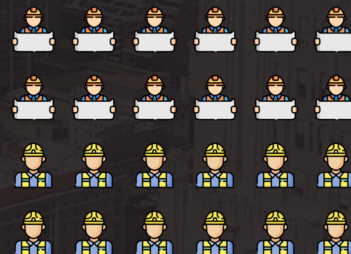
Staffing these new reactors will be an incredible challenge

How many reactor operators are required to staff this new fleet?



For one Small Modular Reactor (SMR)...

24/7 operations require ∼6 shifts:



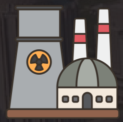
12 SROs

12 ROs

24 licensed operators per reactor

Staffing these new reactors will be an incredible challenge

How many reactor operators are required to staff this new fleet?



For one Small Modular Reactor (SMR)...

24/7 operations require ∼6 shifts:

12 SROs

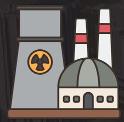
12 ROs

24 licensed operators per reactor

To meet demand we require 2,400 new licensed operators!

Staffing these new reactors will be an incredible challenge

How many reactor operators are required to staff this new fleet?



For one Small Modular Reactor (SMR)...

24/7 operations require ∼6 shifts:

12 SROs

12 ROs

24 licensed operators per reactor

To meet demand we require 2,400 new licensed operators!

We currently have only 3,600 licensed operators total...

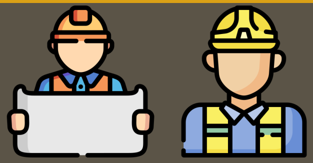
University of Pittsburgh
Cyber Energy Center

Nuclear reactors are operated with prescriptive handbooks and legacy control technologies

University of Pittsburgh
Cyber Energy Center

Human reactor operators have key limitations that limit nuclear buildout

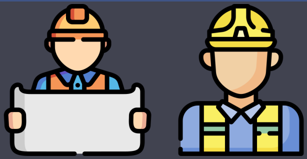
Humans cannot meet labor demand



University of Pittsburgh
Cyber Energy Center

Human reactor operators have key limitations that limit nuclear buildout

Humans cannot meet labor demand



Procedures are not exhaustively verified

Human reactor operators have key limitations that limit nuclear buildout

Humans cannot meet labor demand

Procedures are not exhaustively verified

Human factors cannot be trained away

University of Pittsburgh
Cyber Energy Center

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

If this research is successful, we will be able to do the following:

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

If this research is successful, we will be able to do the following:

1. Translate written procedures into discrete control logic

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

If this research is successful, we will be able to do the following:

1. Translate written procedures into discrete control logic
2. Verify continuous control behavior across discrete mode transitions

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

If this research is successful, we will be able to do the following:

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

University of Pittsburgh
Cyber Energy Center

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:
   - $K_{eff} < 0.99$
   - 0% power
   - $T_{avg} < 200°F$
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.

II. INSTRUCTIONS

A. Heatup from COLD SHUTDOWN to HOT SHUTDOWN (MODE 5 to MODE 4)

1. Permission received from Operations Supervisor for startup.
2. Begin establishing steam generator water levels to 33 ± 5% narrow-range indication.
3. Verify or establish RCP seal injection flow.

> **CAUTION:**
> *Do not exceed a heatup rate of 100°F/hr in the pressurizer or 100°F/hr in the RCS. Do not exceed 320°F ΔT between pressurizer and spray temperature. Use auxiliary spray for pressurizer volume and coolant mixing.*

4. Energize pressurizer heaters and begin pressurizer heatup.
5. Establish a pressurizer steam bubble by;
   a. Increasing pressurizer temperature using pressurizer heaters.
   b. Adjust charging and letdown flow to maintain pressurizer pressure at approximately 320-400 psig while reducing pressurizer level.
   c. As pressurizer temperature approaches 428°F (saturation temperature for 320 psig), reduce pressurizer level toward 25%.

USNRC HRTD 19-12 Rev 0109

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_{eff} < 0.99
   - 0% power
   - T_{avg} < 200°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.

II. INSTRUCTIONS

A. Heatup from COLD SHUTDOWN to HOT SHUTDOWN (MODE 5 to MODE 4)

1. Permission received from Operations Supervisor for startup.
2. Begin establishing steam generator water levels to 33 ± 5% narrow-range indication.
3. Verify or establish RCP seal injection flow.

> **CAUTION:**
> *Do not exceed a heatup rate of 100°F/hr in the pressurizer or 100°F/hr in the RCS. Do not exceed 320°F ΔT between pressurizer and spray temperature. Use auxiliary spray for pressurizer volume and coolant mixing.*

4. Energize pressurizer heaters and begin pressurizer heatup.
5. Establish a pressurizer steam bubble by;
   a. Increasing pressurizer temperature using pressurizer heaters.
   b. Adjust charging and letdown flow to maintain pressurizer pressure at approximately 320-400 psig while reducing pressurizer level.
   c. As pressurizer temperature approaches 428°F (saturation temperature for 320 psig), reduce pressurizer level toward 25%.

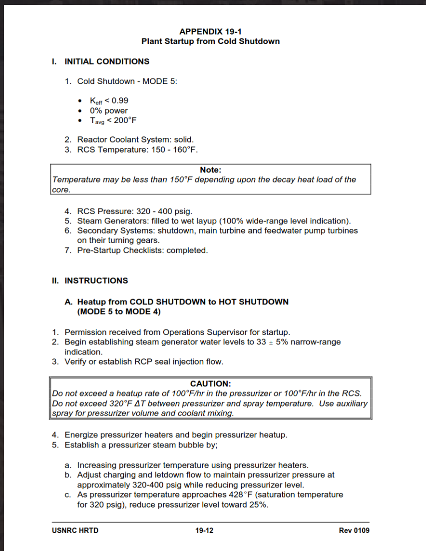
USNRC HRTD 19-12 Rev 0109

FRET Specification

```
INITIAL_CONDITIONS shall satisfy:
      mode = MODE_5
      k_eff < 0.99
      power = 0
      t_avg < 200
      ...
```

University of Pittsburgh
Cyber Energy Center

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:
   - $K_{eff} < 0.99$
   - 0% power
   - $T_{avg} < 200$°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.

II. INSTRUCTIONS

A. Heatup from COLD SHUTDOWN to HOT SHUTDOWN (MODE 5 to MODE 4)

1. Permission received from Operations Supervisor for startup.
2. Begin establishing steam generator water levels to 33 ± 5% narrow-range indication.
3. Verify or establish RCP seal injection flow.

CAUTION:
Do not exceed a heatup rate of 100°F/hr in the pressurizer or 100°F/hr in the RCS. Do not exceed 320°F ΔT between pressurizer and spray temperature. Use auxiliary spray for pressurizer volume and coolant mixing.

4. Energize pressurizer heaters and begin pressurizer heatup.
5. Establish a pressurizer steam bubble by;
   a. Increasing pressurizer temperature using pressurizer heaters.
   b. Adjust charging and letdown flow to maintain pressurizer pressure at approximately 320-400 psig while reducing pressurizer level.
   c. As pressurizer temperature approaches 428°F (saturation temperature for 320 psig), reduce pressurizer level toward 25%.

USNRC HRTD 19-12 Rev 0109

FRET Specification

```
INITIAL_CONDITIONS shall satisfy:
      mode = MODE_5
      k_eff < 0.99
      power = 0
      t_avg < 200
      ...
```

LTL Formula

$$\Box\,(\mathtt{initial} \rightarrow (\mathtt{mode\_5\_active} \wedge \mathtt{k\_eff\_subcritical} \wedge \mathtt{zero\_power} \wedge \mathtt{temp\_safe} \wedge \ldots))$$

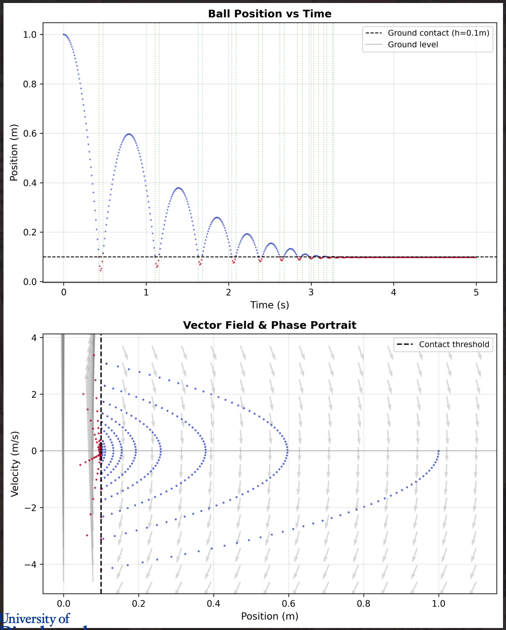
University of Pittsburgh
Cyber Energy Center

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

$$\underbrace{\boxed{\text{LTL Specification}} \longrightarrow \boxed{\text{Parity Game}} \longrightarrow \boxed{\text{Discrete Automata}}}_{\textbf{Reactive Synthesis}}$$

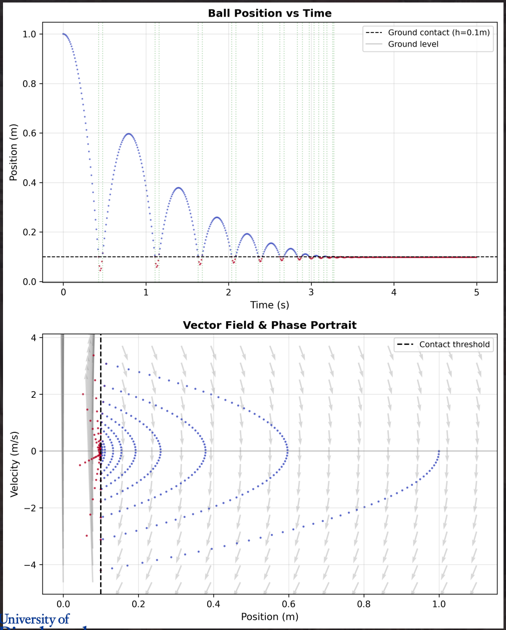
University of Pittsburgh
Cyber Energy Center

Finally, we will build continuous controllers to move between discrete states



University of Pittsburgh
Cyber Energy Center

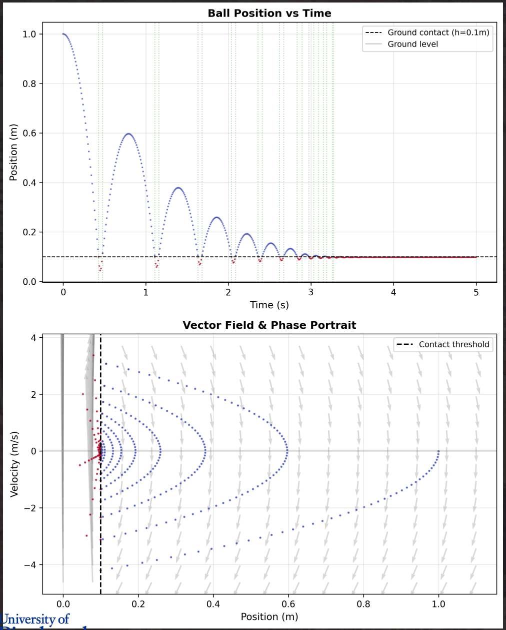
Finally, we will build continuous controllers to move between discrete states



Key Challenge

Verify continuous control behavior across discrete mode transitions

Finally, we will build continuous controllers to move between discrete states



Key Challenge

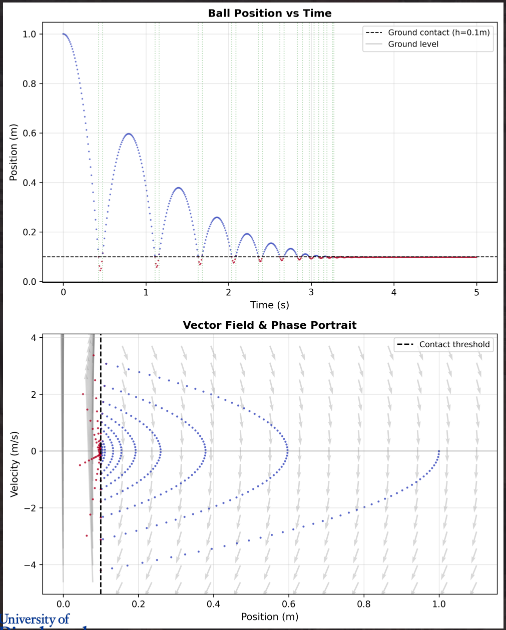
Verify continuous control behavior across discrete mode transitions

Reachable Set

$$\mathcal{R}(t) = \{x(t) \mid x(0) \in X_0, \dot{x} = f(x)\}$$

University of Pittsburgh
Cyber Energy Center

Finally, we will build continuous controllers to move between discrete states



Key Challenge

Verify continuous control behavior across discrete mode transitions

Reachable Set

$$\mathcal{R}(t) = \{x(t) \mid x(0) \in X_0, \dot{x} = f(x)\}$$

Barrier Certificate

$$B(x) > 0 \wedge \nabla B \cdot f(x) \leq 0 \implies x \in \text{Safe}$$

University of Pittsburgh
Cyber Energy Center

Verified autonomous controllers can be created by building this chain of proof of correctness

1. Formalize regulatory procedures into FRET specifications and translate to Linear Temporal Logic (LTL)

Verified autonomous controllers can be created by building this chain of proof of correctness

1. Formalize regulatory procedures into FRET specifications and translate to Linear Temporal Logic (LTL)
2. Synthesize discrete automata from LTL using reactive synthesis

Verified autonomous controllers can be created by building this chain of proof of correctness

1. Formalize regulatory procedures into FRET specifications and translate to Linear Temporal Logic (LTL)
2. Synthesize discrete automata from LTL using reactive synthesis
3. Design continuous controllers for each discrete mode and verify safety across mode transitions using barrier certificates and reachability analysis

University of Pittsburgh
Cyber Energy Center

Verified autonomous controllers can be created by building this chain of proof of correctness

1. Formalize regulatory procedures into FRET specifications and translate to Linear Temporal Logic (LTL)
2. Synthesize discrete automata from LTL using reactive synthesis
3. Design continuous controllers for each discrete mode and verify safety across mode transitions using barrier certificates and reachability analysis

Result: Complete hybrid autonomous system with correctness guarantees by construction

University of Pittsburgh
Cyber Energy Center

Success will be measured through Technology Readiness Level advancement

Why TRLs?

Bridge gap between proof-of-concept and deployment

Measure both rigor and feasibility

TRL 3

Components

Current: TRL 2-3

Target: TRL 5

University of Pittsburgh
Cyber Energy Center

Success will be measured through Technology Readiness Level advancement

Why TRLs?

Bridge gap between proof-of-concept and deployment

Measure both rigor and feasibility

TRL 3
Components

TRL 4
Integration

Current: TRL 2-3
Target: TRL 5

Success will be measured through Technology Readiness Level advancement

Why TRLs?

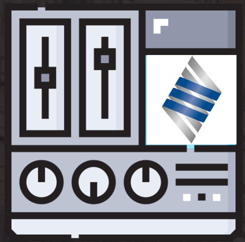
Bridge gap between proof-of-concept and deployment

Measure both rigor and feasibility

TRL 3
Components

TRL 4
Integration

TRL 5
Hardware



Current: TRL 2-3
Target: TRL 5

Four primary risks are identified with clear mitigation and contingency plans

1. Computational Tractability of Synthesis

Four primary risks are identified with clear mitigation and contingency plans

1. Computational Tractability of Synthesis
2. Discrete-Continuous Interface Complexity

Four primary risks are identified with clear mitigation and contingency plans

1. Computational Tractability of Synthesis
2. Discrete-Continuous Interface Complexity
3. Procedure Formalization Completeness

Four primary risks are identified with clear mitigation and contingency plans

1. Computational Tractability of Synthesis
2. Discrete-Continuous Interface Complexity
3. Procedure Formalization Completeness
4. Hardware-in-the-Loop Integration

Broader Impact: Multi-billion dollar O&M cost reduction

The Economic Opportunity

Datacenter electricity demand projected to reach **1,050 TWh/year by 2030**

If supplied by nuclear power:

$$\begin{aligned}\text{Total annual cost} &= 1,050\ \text{TWh/yr} \times \$88.24/\text{MWh} \\ &= \mathbf{\$92.7\ billion/year}\end{aligned}$$

University of Pittsburgh
Cyber Energy Center

Broader Impact: Multi-billion dollar O&M cost reduction

The Economic Opportunity

Datacenter electricity demand projected to reach **1,050 TWh/year by 2030**

If supplied by nuclear power:

$$\begin{aligned}\text{Total annual cost} &= 1,050\ \text{TWh/yr} \times \$88.24/\text{MWh} \\ &= \mathbf{\$92.7\ billion/year}\end{aligned}$$

O&M represents 23-30% of LCOE:

$$\begin{aligned}\text{O\&M costs} &= \$92.7\text{B} \times 0.23\text{-}0.30 \\ &= \mathbf{\$21\text{-}28\ billion/year}\end{aligned}$$

University of Pittsburgh
Cyber Energy Center

Broader Impact: Multi-billion dollar O&M cost reduction

The Economic Opportunity

Datacenter electricity demand projected to reach **1,050 TWh/year by 2030**

If supplied by nuclear power:

$$\begin{aligned}\text{Total annual cost} &= 1,050\ \text{TWh/yr} \times \$88.24/\text{MWh} \\ &= \mathbf{\$92.7\ billion/year}\end{aligned}$$

O&M represents 23-30% of LCOE:

$$\begin{aligned}\text{O\&M costs} &= \$92.7\text{B} \times 0.23\text{-}0.30 \\ &= \mathbf{\$21\text{-}28\ billion/year}\end{aligned}$$

University of Pittsburgh Cyber Energy Center

Beyond nuclear: A generalizable framework for safety-critical autonomy

Why Nuclear First?

- Highest regulatory requirements
- Most safety-critical domain
- Procedures already documented
- Establishes regulatory pathway

Future Applications

- Chemical process control
- Aerospace systems
- Autonomous transportation
- Critical infrastructure

Translate procedures → Synthesize logic → Verify behavior

Applicable to any hybrid system with documented operational requirements

University of Pittsburgh
Cyber Energy Center

Formally Verified Autonomous Hybrid Control

Enabling Economic Viability of Next-Generation Nuclear Power

Dane A. Sabo
dane.sabo@pitt.edu

Advisor:
Dr. Daniel G. Cole
dgcole@pitt.edu

University of Pittsburgh
Department of Mechanical Engineering and Materials Science