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Autonomous Control Algorithms to Simulate Boiling Water Reactor Cycle Depletion

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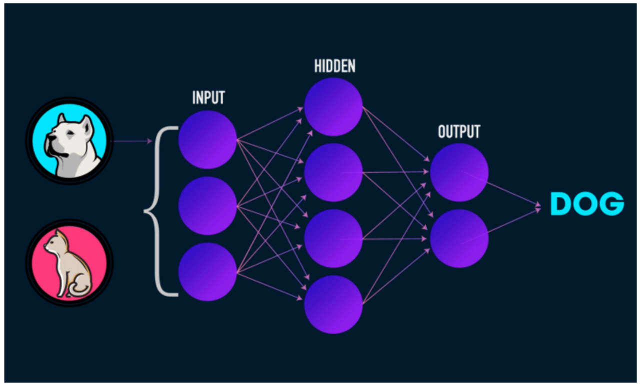
Regulatory Purpose

NRC then

- Reactive
- Plant specific
- Traditional methods

NRC now

- Proactive
- Generic model
- Advanced methods



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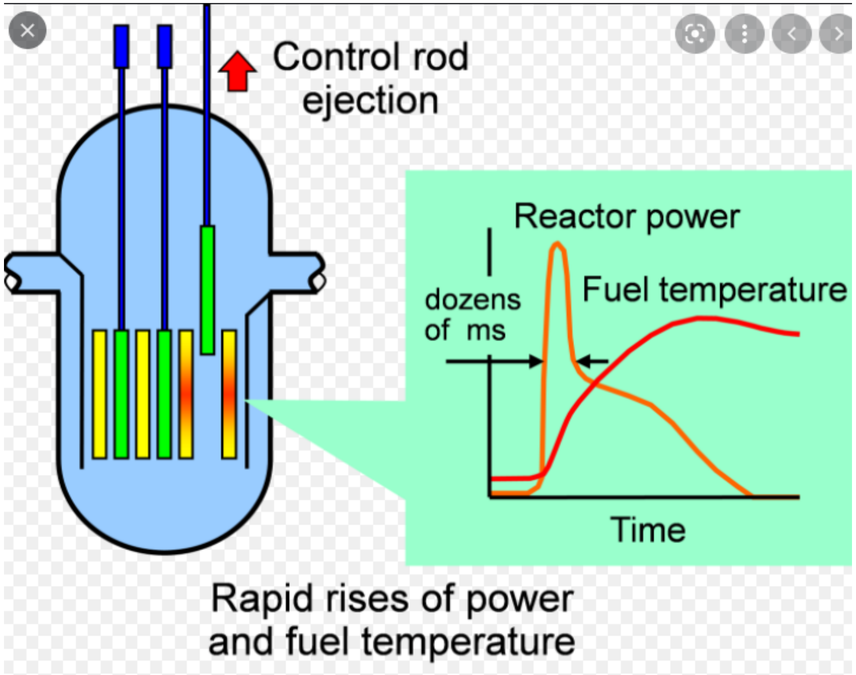
NRC is exploring innovative tools

- Perform independent transients/accidents analysis
- Increase staff efficiency
- Identify/focus safety significant issues
- Boost confidence in licensee results
  - uncertainty high
  - margin low
- Address emergent issues



Motivation

- Automate LWR core/cycle design
- Create models not associated with any specific licensing action
- Use autonomous control methods

RES develops generic LWR TRACE models for accident/transient analysis

Boiling water reactor

- Peter Yarsky (Project Lead, Senior Reactor Systems Engineer, Code And Reactor Analysis Branch)
- Nate Hudson (Reactor Systems Engineer, Code And Reactor Analysis Branch)
- Nazila Tehrani (Reactor Systems Engineer, Accident Analysis Branch)

Pressurized water reactor

- Andy Bielen (Project Lead, Nuclear Engineer (Fuels/Neutronics), Fuel & Source Term Code Development Branch)
- Mike Rose (Reactor System Engineer (Neutronics Analyst, Fuel & Source Term Code Development Branch)
- Alice Chung (Reactor System Engineer (Fuel Analyst), Fuel & Source Term Code Development Branch)

BWR cores are complex to design

Control excess reactivity during cycle

- burnable poisons
- control blades
- flow control windows

Competing goals

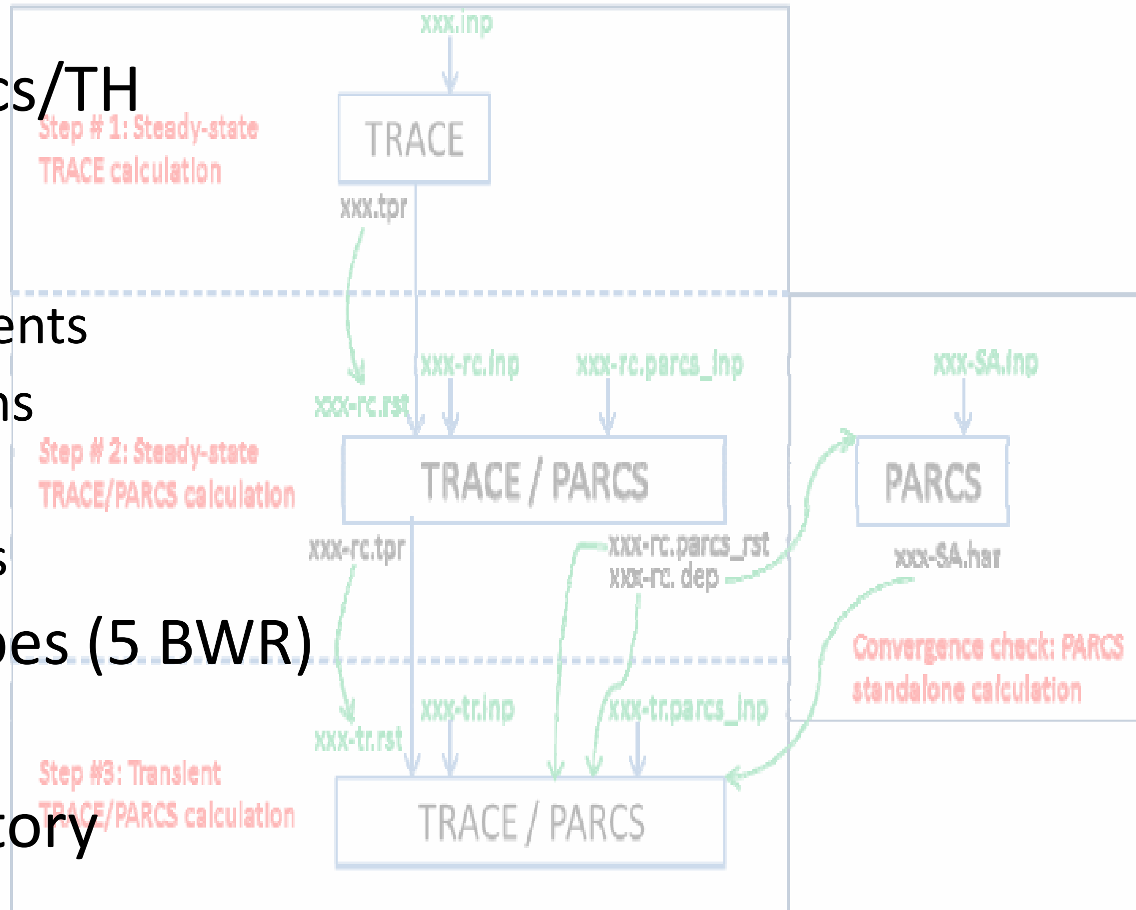
- meeting desired cycle energy
- maintaining safety margins
- minimizing duty related fuel failures

High-dimensionality of BWR cores

- issues with symmetry
- very large number of types of fuel elements

TRACE/PARCS models of PWR/BWR transients/accidents analysis

- Coupled neutronics/TH transient
  - normal
  - anticipated transients
  - accident conditions
  - current reactors
  - advanced reactors
- 12 major plant types (5 BWR)
- Standard models
- Efficient confirmatory calculations



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Necessity

Traditional NRC

- NRC used PARCS to simulate BWR cycle depletion
- calculate cycle power and burnup distributions
- transient analyses need burnup-dependent
  - rod patterns
  - flow rate
  - EOC bundle shuffle sequence

Innovative NRC

- develop an alternative approach for BWR core designs
- generate a BWR equilibrium cycle
  - theoretical concept
  - operate a “typical” plant
  - given fuel design
  - over a long time

Autonomous control algorithms

Literature review

- Proposed micro-reactor
- sense reactor conditions
- sense reactor coolant system
- judge qualification of signals
- evaluate current state of system
- make decisions about actions
- implement actions for operation

NRC goals

- PARCS models
- dynamically adjust
  - fuel loading between cycles
  - control rod pattern
  - flow rate during cycle
- yield all statepoint information over full cycle

Literature Review

Bayesian networks for dynamic (PRA)

Kim, et al.

Annealing method

Hays and Turinsky

DNN to optimize core loading pattern for BWR

Saleem, et al.

Literature Review

Bayesian networks for dynamic (PRA)

- studies evolution of risk during postulated events
- makes decisions during a transient for reducing risk
- artificial reasoning rely on surrogate models
- NRC wants to create surrogate models

Annealing method

- use core simulator
- use sampling of design choices similar to particles distribution at a temperature
- iteratively lowering temperature, algorithm finds optimal solution
- ~100,000 core simulator runs
- NRC wants to optimize loading patterns

DNNs to optimize core loading pattern for BWR

- DNNs trained against core simulator
- artificial reasoning makes decisions about core loading patterns
- meeting power peaking limits
- cycle energy demand
- reasonable computational expense/accuracy
- used to find optimal designs
- ~10,000 simulations to train
- NRC wants to optimize loading patterns

Work to be Performed

- Autonomous control for BWR core/cycle design feasible**?**
  - Apply combination of existing decision-making methods
    - Bayesian
    - Neural Networks
    - Machine Learning
    - etc.
  - Approximate core loading design/control rod sequence
- Contingency (Traditional Methods)
- Need feedback

Definitions

- BWR: Boiling water reactor
- DNN: Deep neural networks
- EOC: End of cycle
- LWR: Light water reactor
- PARCS: NRC Reactor Kinetics code
- PRA: Probabilistic risk assessment
- PWR: Pressurized water reactor
- RES: Office of Nuclear Regulatory Research
- TH: Thermal-Hydraulics
- TRACE: NRC Thermal-Hydraulics code