Shutdown Capability of the NuScale Power Module

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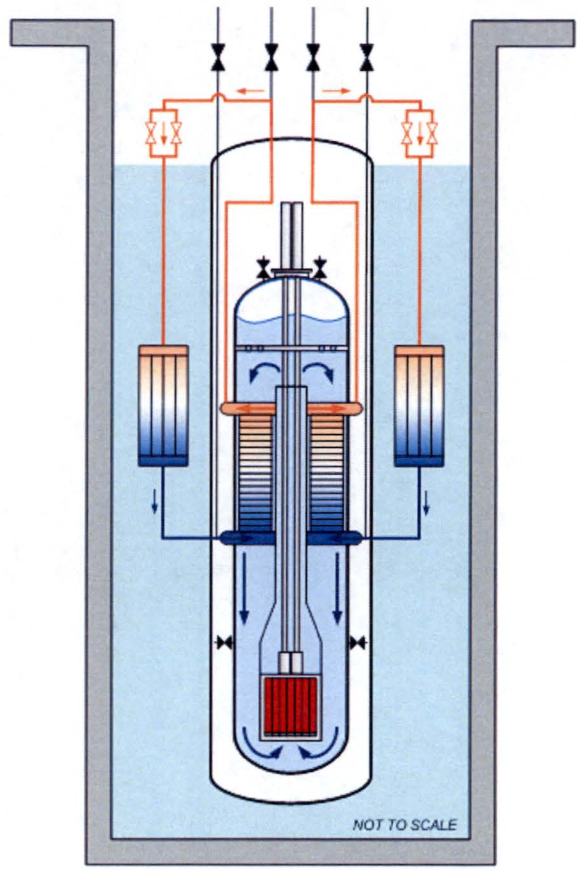
Background: GDC 27 Exemption

- Reactivity control systems are well-matched to the simplicity and passive safety of the NuScale design.
  - Safety-related control rods
  - Nonsafety-related chemical volume and control system (CVCS)
- Small core with higher control rod worth leads to potential for benign, low probability return to power event with highest worth rod stuck out (WRSO) assumption.
- NuScale's white paper on reactivity control (LO-1116-51829, Nov 2016) addressed compliance with GDC 26 and 27, which address two separate reactivity control functions.
  - Protection function: Rapid power reduction to protect fuel
  - Shutdown function: Capability to hold the core subcritical under cold conditions
- NRC staff position (ML16116A083, Sep 2016): required an exemption from GDC 27 to depart from precedent (i.e., long term shutdown with WRSO).

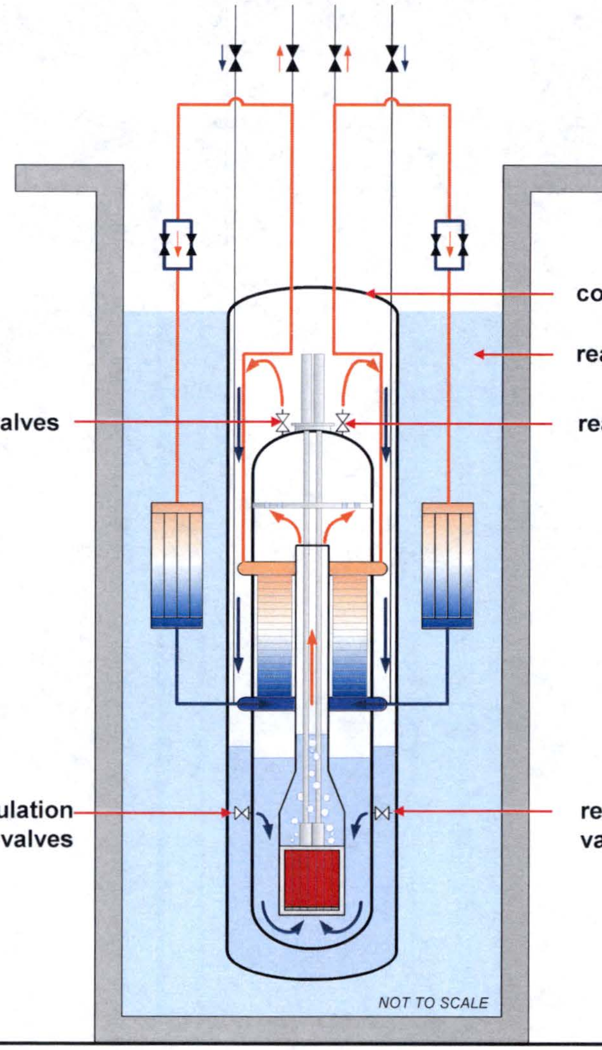
Design Overview: Passive Decay Heat Removal System

- Main steam and main feedwater isolated
- Decay heat removal (DHR) valves opened
- Decay heat passively removed via the steam generators and DHR heat condensers to the reactor pool
- DHR system is composed of two independent and redundant trains (1 of 2 trains needed)



Design Overview: ECCS and Containment Heat Removal

- Adequate core cooling is provided without the need for safety-related injection
- Reactor vent valves and Reactor recirculation valves open on emergency core cooling system (ECCS) actuation signal
- Decay heat removed
  - condensing steam on inside surface of containment vessel
  - convection to the pool fluid on outside vessel wall



Reliable Means for Shutdown

- Protection function: highly reliable safety-related means for achieving rapid reactor shutdown
  - In all cases, reactor immediately shuts down after a trip using control rods, with WRSO
- Shutdown function: under nominal conditions, the reactor remains shut down under cold conditions with reliance only on control rods
  - indefinitely when all control rods are inserted, **or**
  - indefinitely with WRSO during first 70 percent of equilibrium fuel cycle, **or**
  - for 30 days (typical) assuming WRSO while decay heat remains above 100 kW* because of negative reactivity feedback from voiding in the core.
- A return to power is a benign, low probability event that can only occur under a limited set of conditions (e.g., WRSO, loss of power, late in core life, and with low levels of decay heat).

*Depending on core burnup at shutdown, decay heat of 100 kW would be reached at 50 days BOC to 100 days EOC.

Reliable Means for Shutdown

- A return to power is highly unlikely (< 1E-6 per year) and involves
  - the probability of a stuck control rod (2E-4 per demand),
  - the probability of a CVCS failure to insert soluble boron (8E-3 per demand), and
  - the probability that the reactor is in a state that could result in a return to power with a WRSO (4E-2 to 1E-1 per year).

Consequence of a Return to Power

- For licensed designs, a return to power can challenge heat removal system capacity of active safety-related systems, resulting in core damage.
- The capacity of NuScale's passive heat removal systems protects the core, irrespective of control rod performance.
  - Core is protected after a return to power with a WRSO, or even after a failure to trip the reactor (ATWS).
  - Reactor power is limited by negative reactivity feedback while removing heat with DHRS or ECCS.

Consequence of a Return to Power

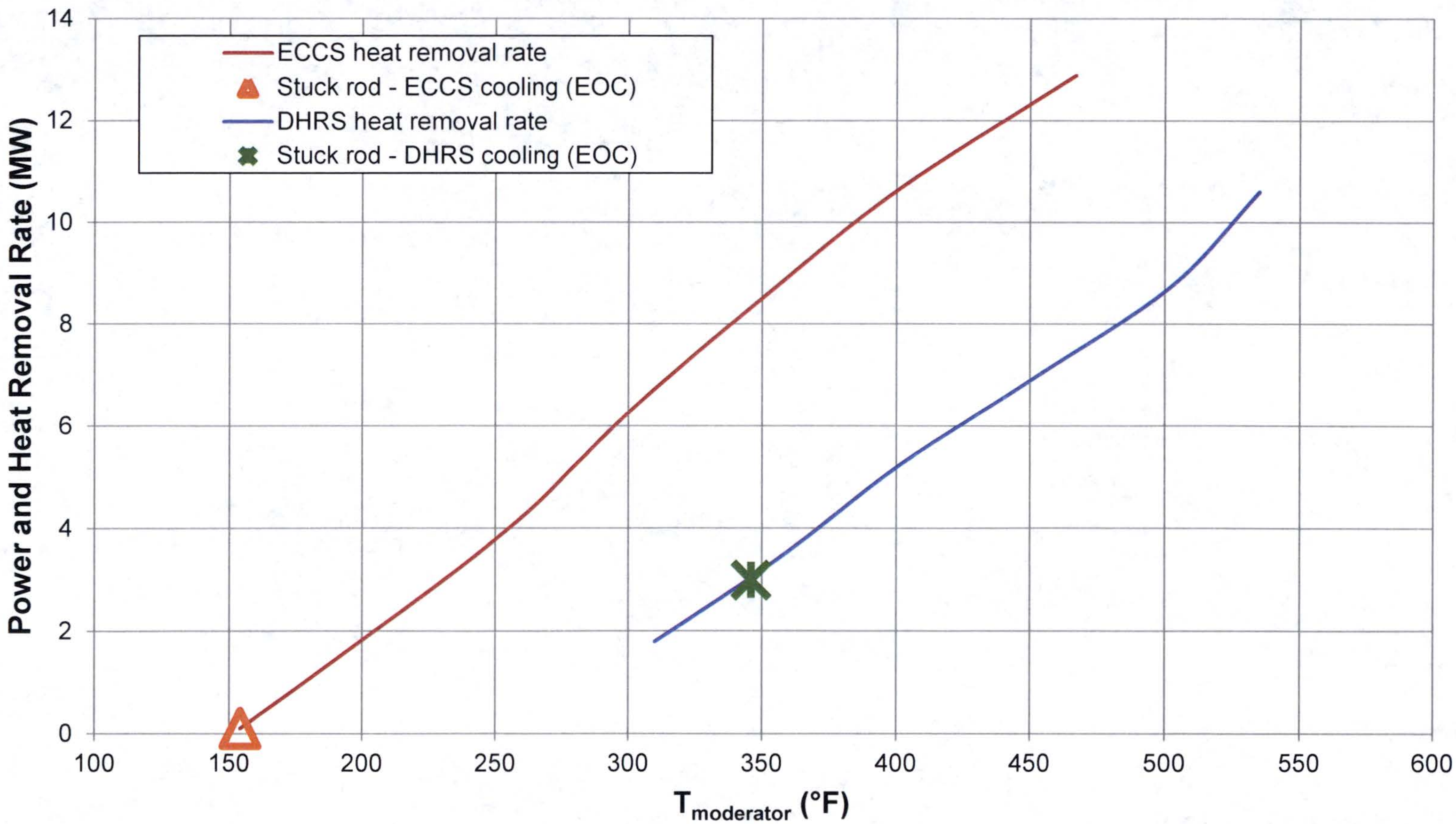
- DHRS heat removal example: Loss of feedwater with WRSO
- DHRS heat removal characteristic in combination with negative moderator coefficient leads to self-limiting condition
  - higher power -> higher moderator temperature -> negative moderator feedback
- DHRS capacity to remove heat is sufficient for power generated with a WRSO
- A return to power with a WRSO while on DHRS is presented in Chapter 15 of the DCA
  - demonstrates that fuel remains protected using conservative deterministic analysis
- Under nominal conditions, a return to power while using DHRS can be avoided

Consequence of a Return to Power

- ECCS heat removal example: RCS depressurization with WRSO
- Depressurization results in shutdown due to voiding, until voiding subsides
- ECCS heat removal characteristic in combination with moderator density decrease due to voiding leads to self-limiting condition
  - higher power -> lower moderator density due to voiding -> negative density feedback
- ECCS capacity to remove heat is sufficient for power generated with a WRSO
- A return to power with a WRSO while on ECCS (<100 kW) is bounded by normal ECCS cooldown with decay heat

Consequence of a Return to Power

- Equilibrium power after return to power with WRSO is within DHRS and ECCS heat removal capacity



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Design Considerations for Shutdown

- The NuScale control rod design utilizes conventional external magnetic jack control rod drives because of extensive operating experience and well-documented reliability.
- The safety-related control rods provide sufficient shutdown capability. An additional separate safety-related reactivity control capability is not needed to ensure overall safety.
  - **Passive system reliability:** Low probability of a stuck rod (2E-4 per demand) compared to typical active ECCS unreliability (1E-2 per demand). After successful control rod insertion, no further operator actions are required to protect the core.
  - **Passive system simplicity:** The design relies on passive control rod insertion. The inclusion of additional safety-related capability will increase design complexity, and introduces additional failure modes that could, for example, result in containment bypass (due to external module piping connections that would be required to open).

Design Considerations for Shutdown

- NuScale design aligns with the NRC's advanced reactor policy statement (73 FR 60612; October 14, 2008) for an advanced reactor design
  - "Highly reliable and less complex shutdown and decay heat removal systems. The use of inherent or passive means to accomplish this objective is encouraged (negative temperature coefficient, natural circulation, etc.)."
  - "Simplified safety systems that, where possible, reduce required operator actions, equipment subjected to severe environmental conditions, and components needed for maintaining safe shutdown conditions. Such simplified systems should facilitate operator comprehension, reliable system function, and more straightforward engineering analysis."
  - "Design features that can be proven by citation of existing technology, or that can be satisfactorily established by commitment to a suitable technology development program."

Precedent for a Return to Power

- GSI-22, Inadvertent Boron Dilution Events
  - 2E-4 per reactor year for a return to power
- NUREG-1449, Shutdown and Low-Power Operation
  - 1E-5 per reactor year for core damage due to rapid boron dilution
- GSI-185, Control of Recriticality Following Small-Break LOCAs
  - 3E-8 per reactor year for core damage due to inadvertent boron dilution during a small-break LOCA transient
- 10 CFR 50.62, ATWS
  - Goal to reduce ATWS CDF to less than 1E-5 per reactor year

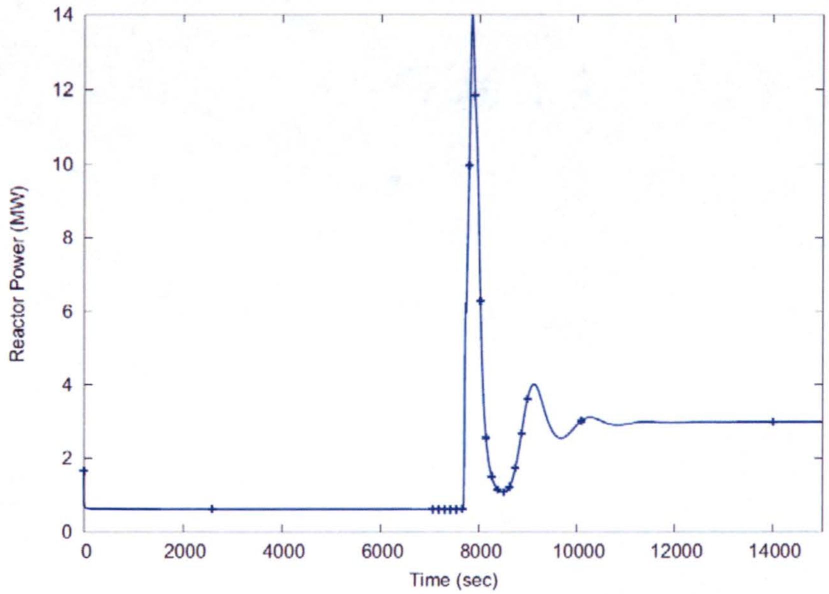
In contrast, a return to power for NuScale is a low probability, low consequence event.

Summary

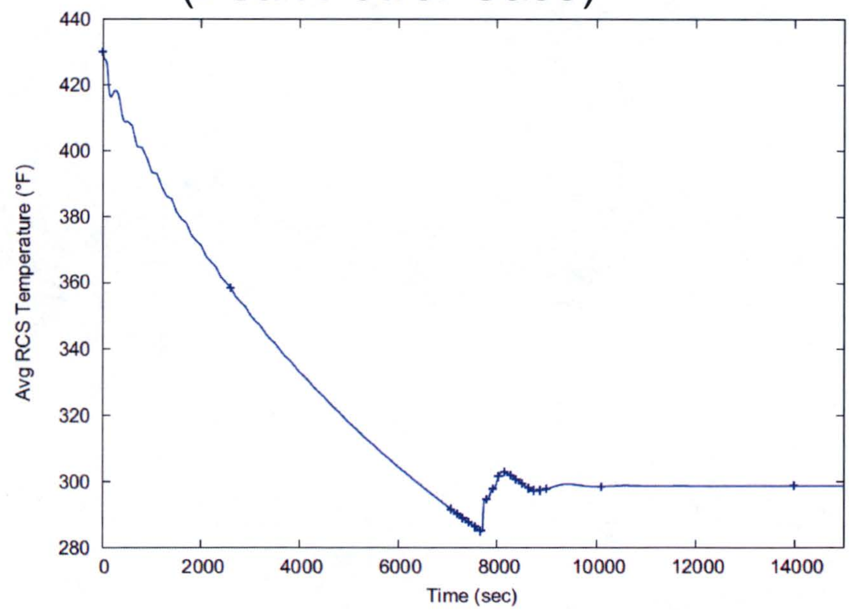
- Reactivity control systems appropriately matched with the simplicity and passive safety of the NuScale design provides:
  - rapid shutdown to protect fuel
  - reliable capability to maintain the reactor subcritical under cold conditions
  - passive heat removal provides protection against control rod malfunctions
- Design of reactivity control systems aligns with the NRC's advanced reactor policy statement (73 FR 26349; October 14, 2008) for an advanced reactor design
- A return to power with a WRSO is a benign event with a lower probability than the core damage frequency of approved designs

Backup Slides

Reactor Power (Peak Power Case, EDSS Available)



RCS Average Temperature (Peak Power Case)



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