Core Flow Blockage Detection and Prevention Strategy

a TerraPower & GE-Hitachi technology

NATD-LIC-PRSNT-0026

Objectives

- Natrium™ reactor overview

Presentation Table of Contents

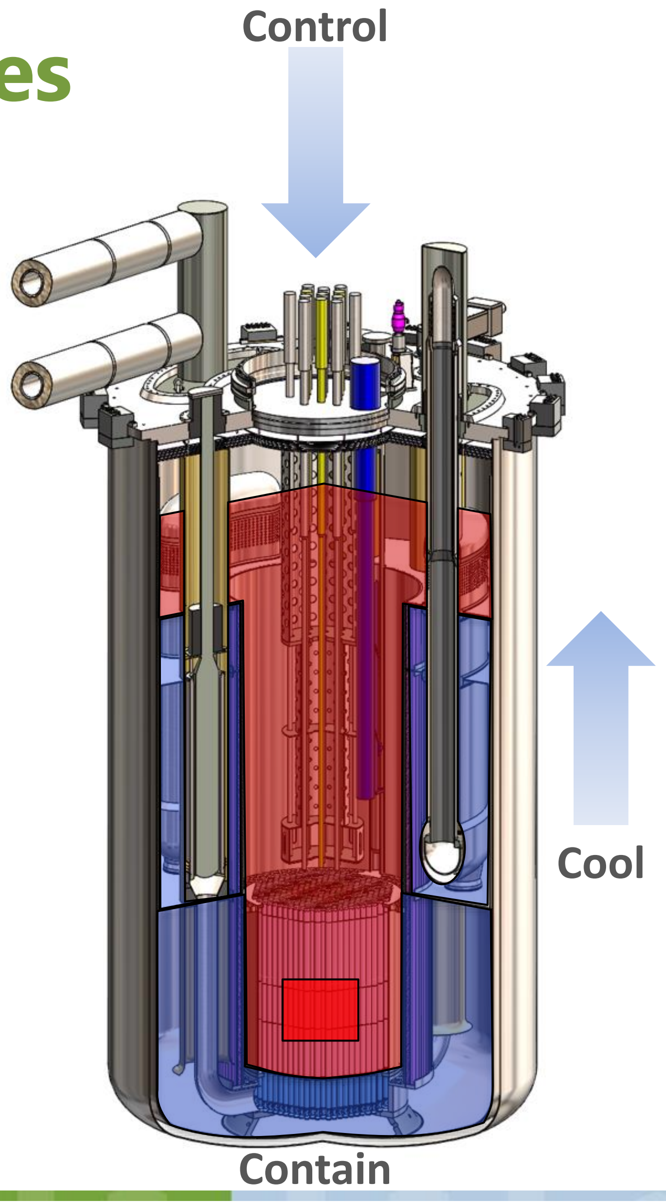
- Historic Core Flow Blockage Accidents & Experiments
- Potential Core Flow Blockage Mechanisms
- Flow Blockage Detection Considerations
- Fuel Failure Monitoring Considerations
- Potential Defense Lines
- Flow Blockage Detection & Prevention Strategy

Natrium Reactor Overview

- Regulatory Engagement Plan was submitted 6/8/2021.
- Construction Permit Application submittal planned for 8/2023.
- Pre-application interactions are ongoing, intended to reduce regulatory uncertainty and facilitate the NRC's understanding of the Natrium advanced reactor and its safety case.
- The Natrium project is demonstrating the ability to design, license, construct, startup and operate the Natrium reactor within a seven-year timeframe.

Natrium Safety Features

- Pool-type Metal Fuel SFR with Molten Salt Energy Island
  - Metallic fuel and sodium have high compatibility
  - No sodium-water reaction in steam generator
  - Large thermal inertia enables simplified response to abnormal events
- Simplified Response to Abnormal Events
  - Reliable reactor shutdown
  - Transition to coolant natural circulation
  - Indefinite passive emergency decay heat removal
  - Low pressure functional containment
  - No reliance on Energy Island for safety functions
- No Safety-Related Operator Actions or AC power
- Technology Based on U.S. SFR Experience
  - EBR-I, EBR-II, FFTF, TREAT
  - SFR inherent safety characteristics demonstrated through testing in EBR-II and FFTF



Control

- Motor-driven control rod runback
- Gravity-driven control rod scram
- Inherently stable with increased power or temperature

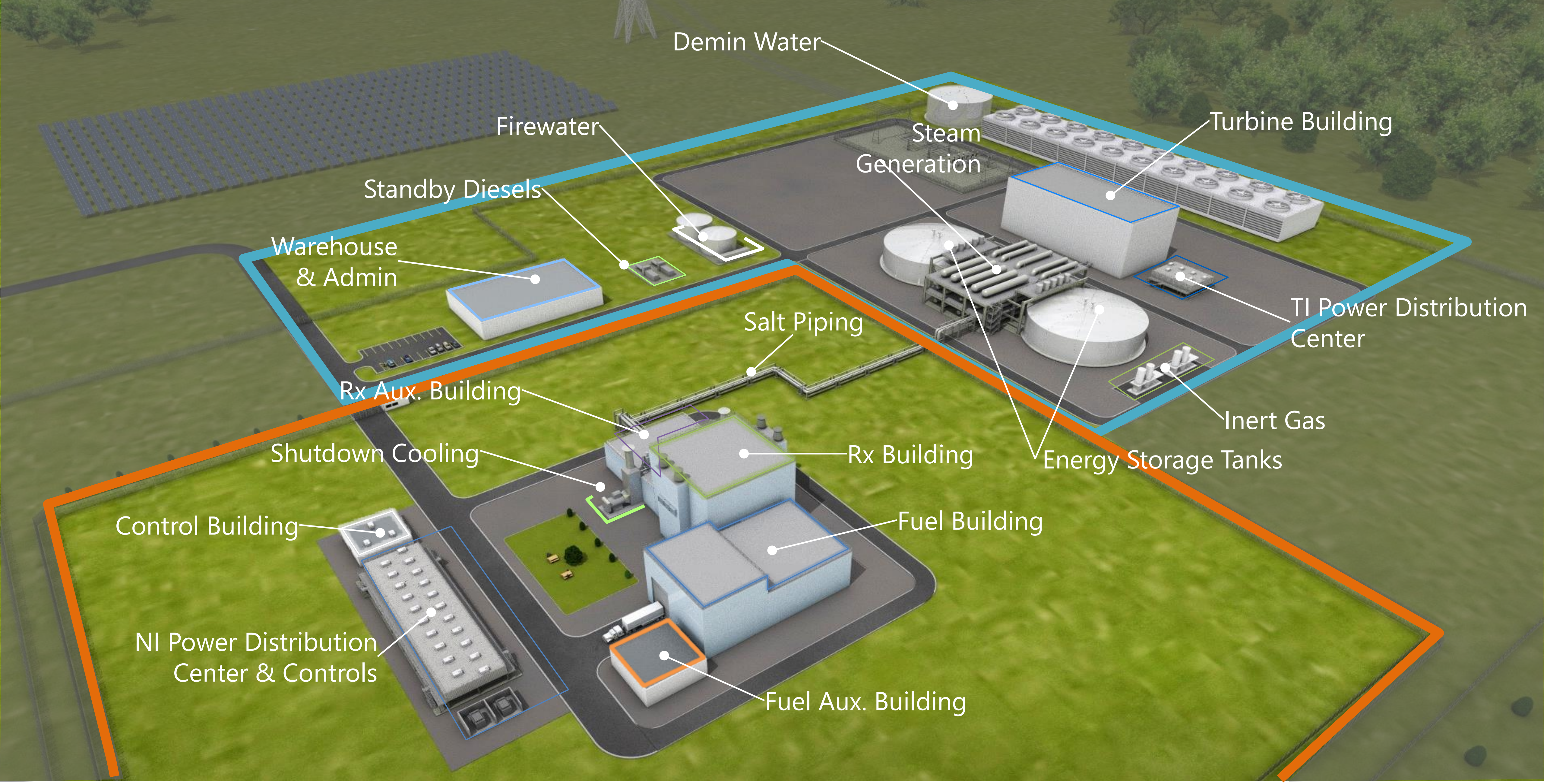
Cool

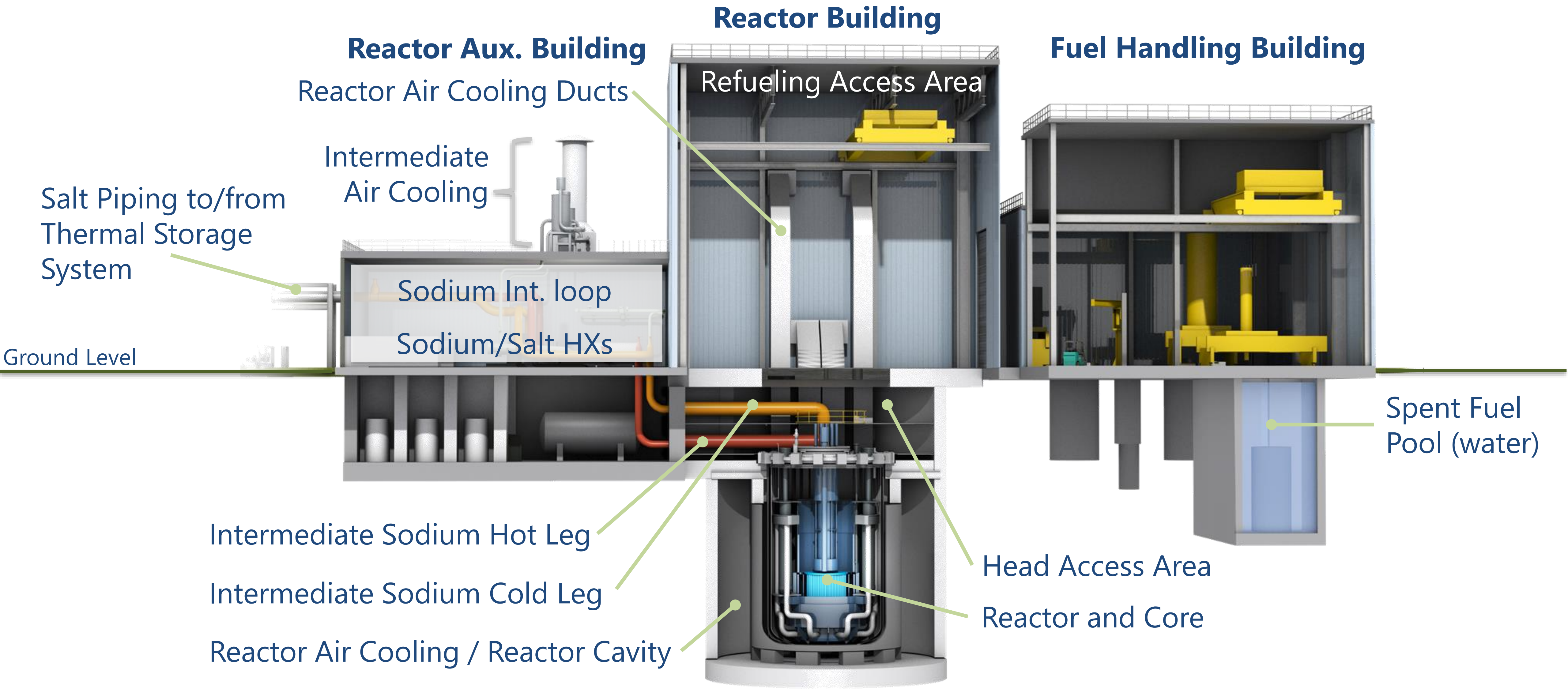
- In-vessel primary sodium heat transport (limited penetrations)
- Intermediate air cooling natural draft flow
- Reactor air cooling natural draft flow – always on

Contain

- Low primary and secondary pressure
- Sodium affinity for radionuclides
- Multiple radionuclides retention boundaries

SUBJECT TO DOE COOPERATIVE AGREEMENT NO. DE-NE0009054


Demin Water
Firewater
Steam Generation
Turbine Building
Standby Diesels
Warehouse & Admin
TI Power Distribution Center
Salt Piping
Rx Aux. Building
Inert Gas
Shutdown Cooling
Rx Building
Energy Storage Tanks
Control Building
Fuel Building
NI Power Distribution Center & Controls
Fuel Aux. Building


Reactor Building
Reactor Aux. Building
Fuel Handling Building
Reactor Air Cooling Ducts
Refueling Access Area
Intermediate
Air Cooling
Salt Piping to/from
Thermal Storage
System
Sodium Int. loop
Sodium/Salt HXs
Ground Level
Spent Fuel
Pool (water)
Intermediate Sodium Hot Leg
Intermediate Sodium Cold Leg
Reactor Air Cooling / Reactor Cavity
Head Access Area
Reactor and Core

Historic Core Flow Blockage Events

Summary of Major Core Flow Blockage Events

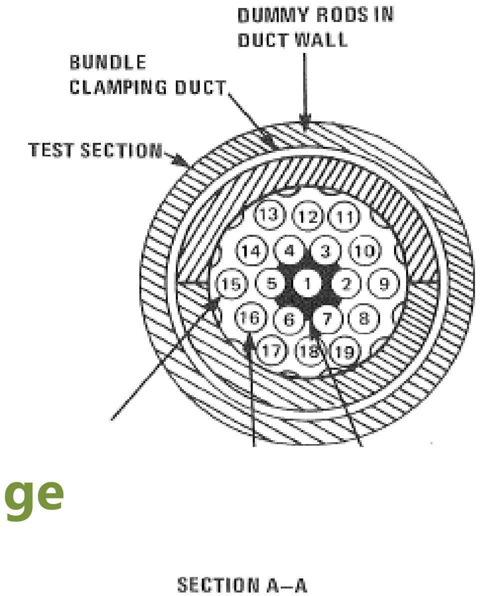
Plant	Event Description	Root Causes	Lessons for Natrium Design
Sodium Reactor Experiment (SRE)	Local fuel melting and cladding failures occurred due to partial blockages in 13 of 43 fuel assemblies	Leaked organic pump coolant formed carbon products to form partial blockages in inlet channels	Pending final design: • Multiple barriers expected to isolate pump fluids • Organic fluids will be avoided if possible
Fermi-I	Local fuel melting occurred due to a total blockage at the core inlet	Loose parts due to flow-induced vibration blocked the single-hole inlet nozzle	• Multiple-hole inlet nozzle • Core strainer • Loose parts prevention
NIST Center for Neutron Research (NCNR)	Fuel plate melting occurred due to a flow diversion that resulted in DNB	A fuel element lifted out due to an inadequate latch system and operation	• No lift-off design features • Operation procedures

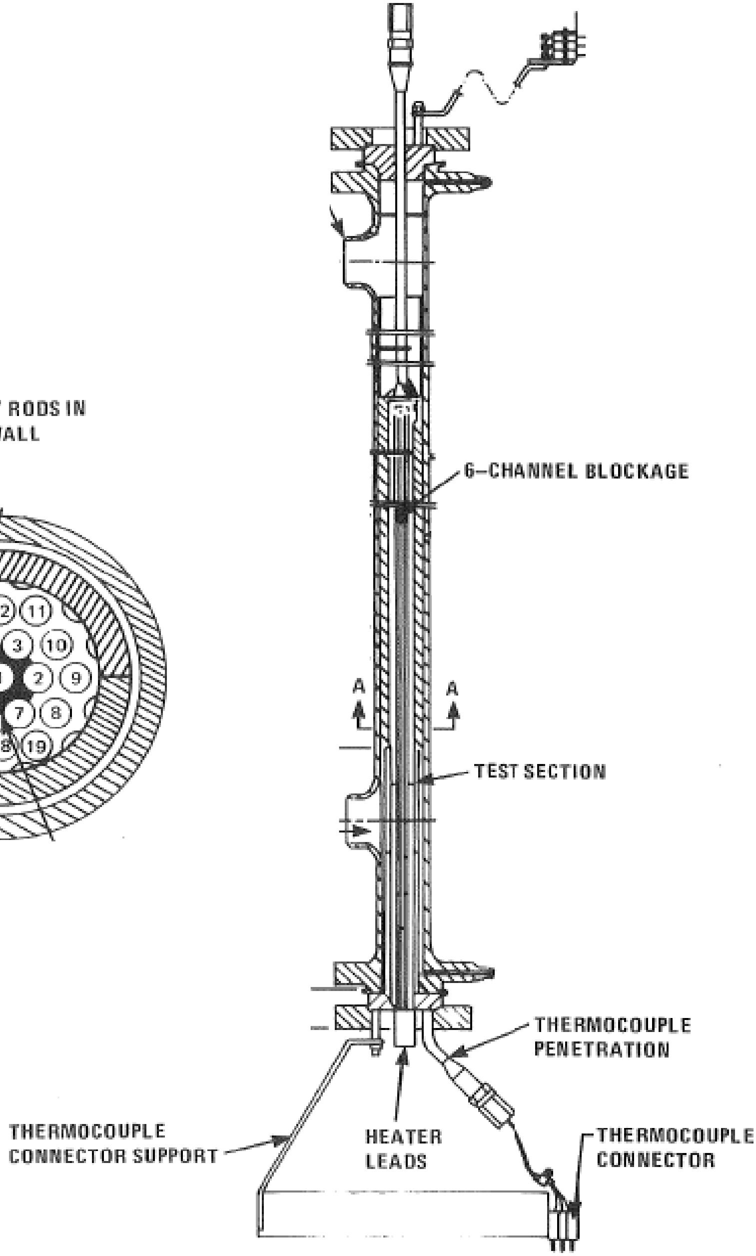
For additional details, see Appendix slides at the end of this presentation.

FFTF Core Flow Blockage Experiments

<u>FFTF FSAR (Appendix C.4.4.1 FFTF-46991, Volume 7)</u>

- ORNL Fuel Failure Mockup (FFM) Test setup
  - Large-scale sodium facility with a 19-pin (.230" OD, .056" wire) bundle simulated by electrical heaters
    - Natrium pin: .290" OD, .056" wire
  - Inlet, in-core, and edge blockages examined
- FFM Test Results
  - The temperature increase due to **50% inlet blockage** was not higher than the variation observed in unblocked bundles.
  - A **planar blockage over six subchannels** could be tolerated at full power and flow without approaching boiling in the wake region.





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FFTF Core Flow Blockage Evaluations

- FFTF FSAR Appendix C.4 describes the formation and consequences of local inlet and outlet blockages of the FTFF coolant flow paths.
  - **Major inlet blockages** were precluded by design, and the formation of local in-core blockages was improbable.
  - Experimental and analytical evidence was presented that even if blockage within the pin bundle should occur, the **consequences would be localized** and would not result in gross boiling or fuel pin failure propagation throughout the bundle.
  - Fuel assembly design margins maintained against large inlet or outlet blockages.

- **Natrium core design features will be similar to those of FFTF, precluding major core flow blockages similar to the events at SRE and Fermi-I.**

- A decision is ongoing to perform similar tests or to qualify historic test data for the Natrium flow blockage analysis.

PRISM PSID RAIs (G.4.6, GEFR-00793 Appendix G)

"The NRC staff's concern is not related to blockages that might develop during power operation, but to fabrication errors that could result in a totally blocked assembly being inserted into the reactor."

- No instrumentation to detect in-core blockages.
- Startup testing procedure to detect a blocked assembly following a refueling outage.

Blockage Type (single assembly)	Probability
Inlet Region	10^{-8}/plant-yr
Outlet	10^{-8}/plant-yr
Active Core Region	10^{-7}/plant-yr
Total Blockage due to Fabrication Defect	10^{-7}/plant-yr

PRISM design features to mitigate flow blockage

- – No drilled flow holes in internal components.
- – 40" long solid shield at the bottom of fuel pin.
- – Gas flow tests prior to insertion in the reactor.

PRISM operation features to mitigate flow blockage

1) Establishing full reactor sodium flow before the withdrawal of control rods and limiting the power ramping rate to less than 1% per minute.
2) Delayed Neutron signals resulting from damaged fuel would alarm, followed by operator action to shut down the reactor to terminate the event with minimal core damage.

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Natrium Flow Blockage Events

Natrium Flow Blockage Mechanisms

The following core flow blockage mechanisms are identified:

1. **Coolant flow hole** blockages by **foreign materials**.
   - Core receptacle or inlet nozzle flow hole blockages by large-size loose parts or debris
   - Core inlet orifice plate blockages by the accumulation of smaller loose parts or debris
   - Handling socket exit flow blockages by loose parts from upper internal structures or fuel handling systems

2. **Core inlet flow** blockage due to **fuel assembly lift-off** (i.e., flow channel mismatch between receptacle and inlet nozzle).
   - Loss of the hydraulic hold-down force due to failed seals or clogged flow paths
   - Incomplete fuel assembly insertion due to high frictions or debris

Natrium Flow Blockage Mechanisms

The following core flow blockage mechanisms are identified:

3. **Fuel assembly subchannel** blockage by lodging of **foreign materials**.
   - Loose parts from failed fuel pins (e.g., wire-wrap, fuel or cladding fragments)
   - Small debris from welded joints or maintenance (e.g., weld spatters, metal chips or turnings)

4. **Fuel assembly subchannel** blockage by excessive **fuel pin deformations**.
   - Inappropriate pin bundle-to-duct interactions (e.g., pin bowing, pinching, bending)
   - Excessive fuel swelling or ballooning (e.g., internal pressure, high strain)

Natrium Flow Blockage Detection Considerations

A flow blockage in a fuel assembly may induce the following effects:

1) Higher coolant temperature
2) Reduced coolant flow rate
3) Fuel pin failure resulting in fission product release and molten fuel

- The magnitude of outlet temperature increment and flow reduction is not detectable unless the blockage is over 80%, according to past experiments. (FFTF FSAR)

- **No individual monitoring is required since the temperature or flow variations due to partial flow blockages will remain within the normal operating range.**
  - The minimum detectable blockage will be precluded by design features (see Slide 20).

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Natrium Fuel Failure Monitoring Considerations

A fuel failure due to a partial flow blockage can be detected by conventional fuel failure monitoring systems based on the size of the damage, types of precursors, or the characteristics of the failed fuel such as burn up, fuel type, or bonding type:

- **Cover gas monitoring system**
  - Detects gaseous fission products
  - Identifies the failure location via **unique tag gases** in the fuel pins
- **Coolant activity monitoring system**
  - Detects solidus fission products via coolant sampling
  - Takes a longer time to analyze
- **No Delayed Neutron Detectors** (DND) will be used

Natrium Failed Fuel Detection Strategy

DND is not credited for any Defense Line Function.

- Individual pin failures fall within SARRDL limits.
- Major flow blockages will be precluded by design features.

1. **Poor Circulation in Pool Reactors**
   - DND has previously been used in loop reactors with oxide fuel. In a pool reactor:
     - The **half-lives of key fission products are too short** to reach a DND in the IHX.
     - Adding DND measurement loops would **negate the leak-proof benefit** of a pool reactor.

2. **Low Release Rate in SFRs**
   - **Fewer radionuclides are released** from metal fuel.
   - Chemical compatibility of metal fuel and sodium precludes major fuel failures (i.e., hydriding).
   - Sodium chemical reactions significantly arrest precursors and radionuclides prior to the DND detector (SRE and EBR-II).

Natrium Failed Fuel Detection Methods

Reactor	Outlet Temperature	Flow measurement	Delayed-neutron detection	Acoustic noise detection (sodium boiling)	Neutron-flux noise measurement	Cover gas monitoring (Tag/Fission)
SNR-300	I	I				
PHENIX	I / G		I / G	G	G	G
Super-Phenix	I / G / FR		I / G	G	G	G
FFTF	I	I	G		G	G
CRBRP	I		G			G
LMFBR	I / FR	G	G	G	G	
Potential NATD (See Next Slide)	P / G	G				I / G

Individual fuel assembly measurement, **G**lobal measurement, **F**ast **R**esponse thermocouple to detect small disturbances, **P**artial

Note: The fast-response thermocouple measurement showed there's very little correlation between neutron power and outlet temperature noise that is produced by turbulent coolant flow and the rapid temperature fluctuation due to partial flow blockages was hard to capture (https://inis.iaea.org/collection/NCLCollectionStore/_Public/14/802/14802898.pdf)

Natrium Flow Blockage Prevention Mechanisms

Potential Defense Lines

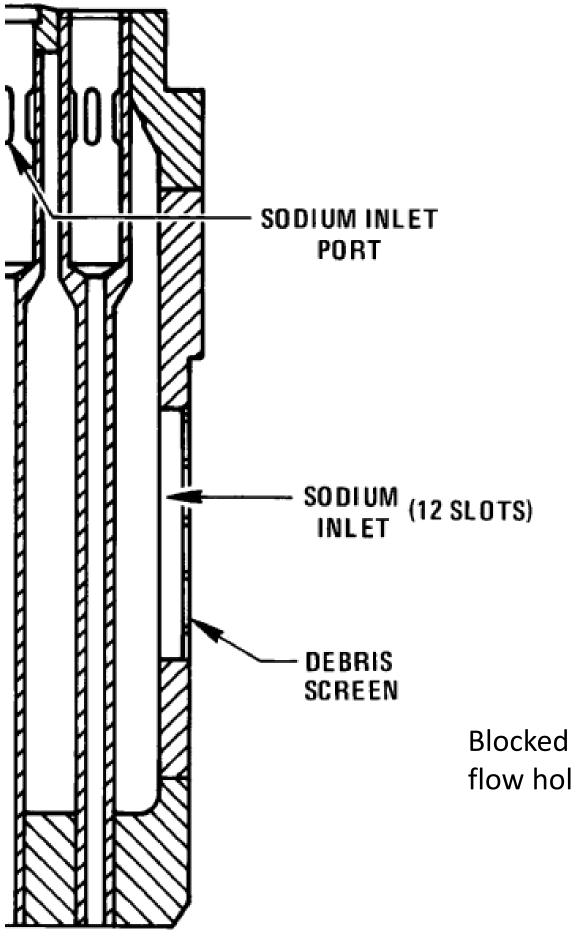
The following primary coolant system components are under consideration to preclude the potential of large-scale core flow blockages:

1) Loose part retention design features on non-welded fasteners (red circles).

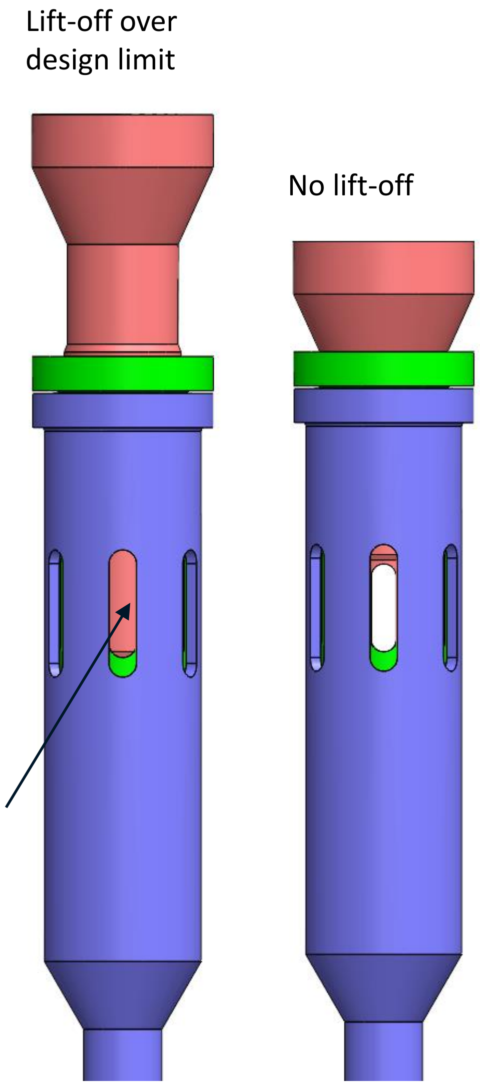
2) Core strainer in the core inlet plenum to limit the size of debris that may create a non-detectable blockage.

3) Multiple flow holes/slots in the receptacle and inlet nozzle prevent the total instantaneous blockage that happened in Fermi-I.

4) Long flow slots to accommodate fuel lift-off due to loss of hydraulic holddown, thermal ratcheting, or incomplete insertion.



FFTF Core Basket Cutaway



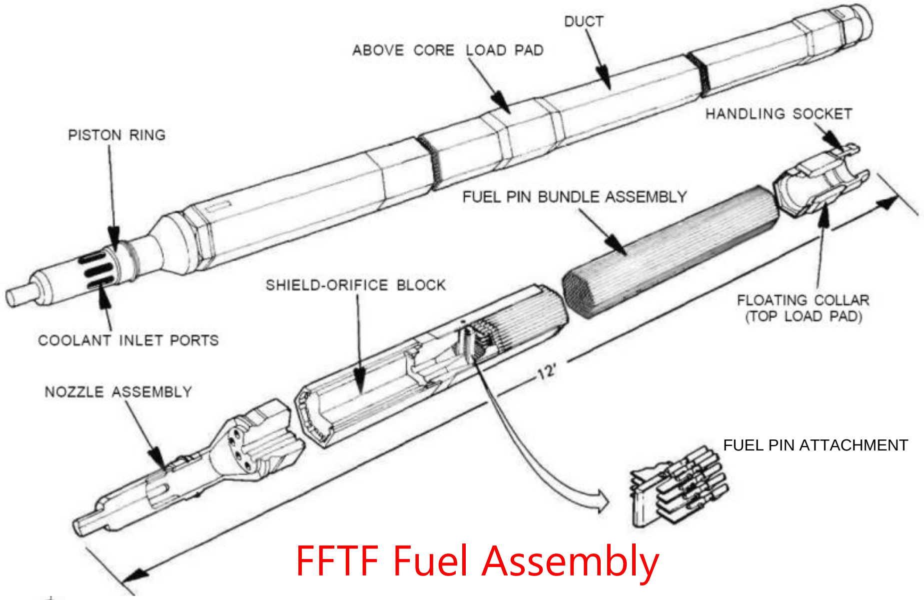
Generic Core Inlet Design Schematic

Potential Defense Lines

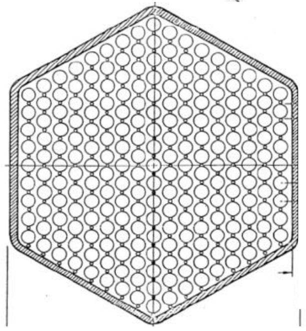
5) Multi-stage fuel pin attachment (pin strip rail, locking plate, end plug) limits the size of debris (e.g., for FFTF, max. diameter in the subchannel=~0.1”).

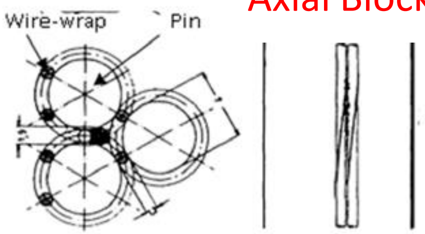
6) Wire-wrapped fuel pin bundle leads to a porous axial blockage formation.

7) Bypass ports provide a minimum coolant flow when a flow blockage occurred at the handling socket.

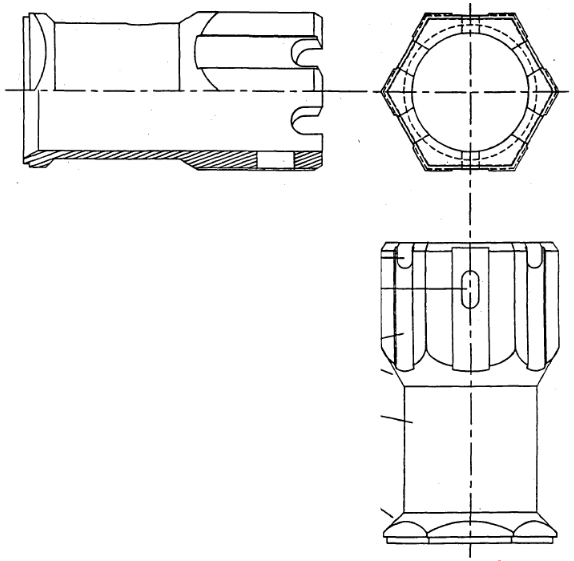


FFTF Fuel Assembly





Axial Blockage


PRISM Handling Socket

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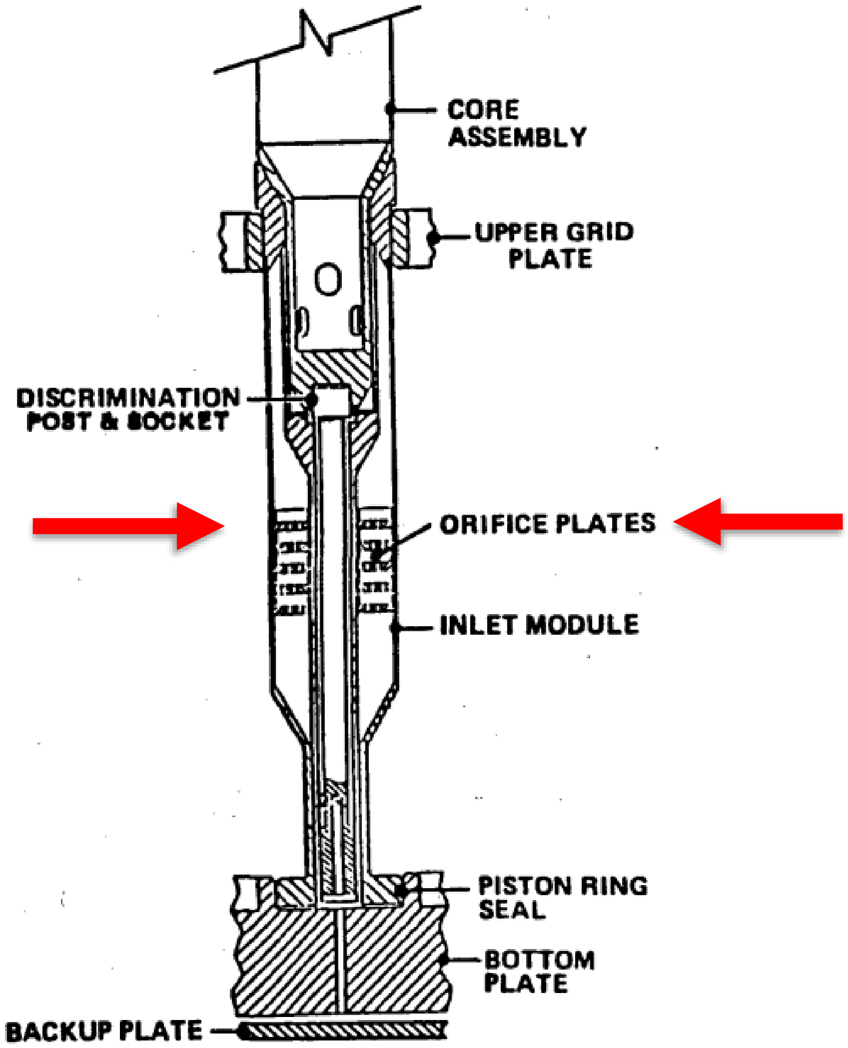
Addressing Orifice Plate Clogging

- **Purpose of orifice plates:** to regulate coolant flow into the assembly.
  - Debris accumulation could block the plates over time.
- The PRISM orifice plates were not preceded by a nozzle inlet strainer, increasing the chance of clogging by debris accumulation.
  - PRISM orifice plates were designed to be replaceable.
  - Flow uncertainty in the hot channel factor would have accounted for small blockages.
- Is it necessary to verify assembly flow during the life of the plant?
  - **In Natrium assemblies, other defense lines suffice to mitigate partial flow blockage.**



ALMR

Programmatic Prevention Programs

1. **Ex-core Foreign Material Exclusion Programs**
   - Core assembly air-flow test at final inspection
   - Fabrication quality control on cleaning, packaging, shipping & handling

2. **In-core Foreign Material Exclusion Programs**
   - Sodium filtering/cleaning operations
   - Reactor cleanup operation with Simulated Core Assembly during hot functional tests
   - FFTF used a 100-micron filter. The Natrium filter design is on-going.

Natrium Flow Blockage Strategy

Natrium Strategy for Core Flow Blockage

Design Features Precluding Major Flow Blockages

- Small Hole Core Strainer
- Multi-flow Hole Core Inlet
- Multi-stage Fuel Pin Attachment
- Exit Flow Drain Ports
- Loose-part Retention Design

Partial Flow Blockage Analysis Methodology

- Establish Acceptable Blockage Size and Detectability
- Evaluate Consequences of Postulated Blockages

Fuel Failure Monitoring Systems

- Limited Individual Fuel Assembly Instrumentations
- Bulk Temperature & Flow Measurement Systems
- Tag-gas & Coolant Activity Monitoring System

Flow Blockage Prevention Programs

- Fabrication Quality Control, Inspection, and Test Program
- In-core and Ex-core Foreign Material Exclusion Program

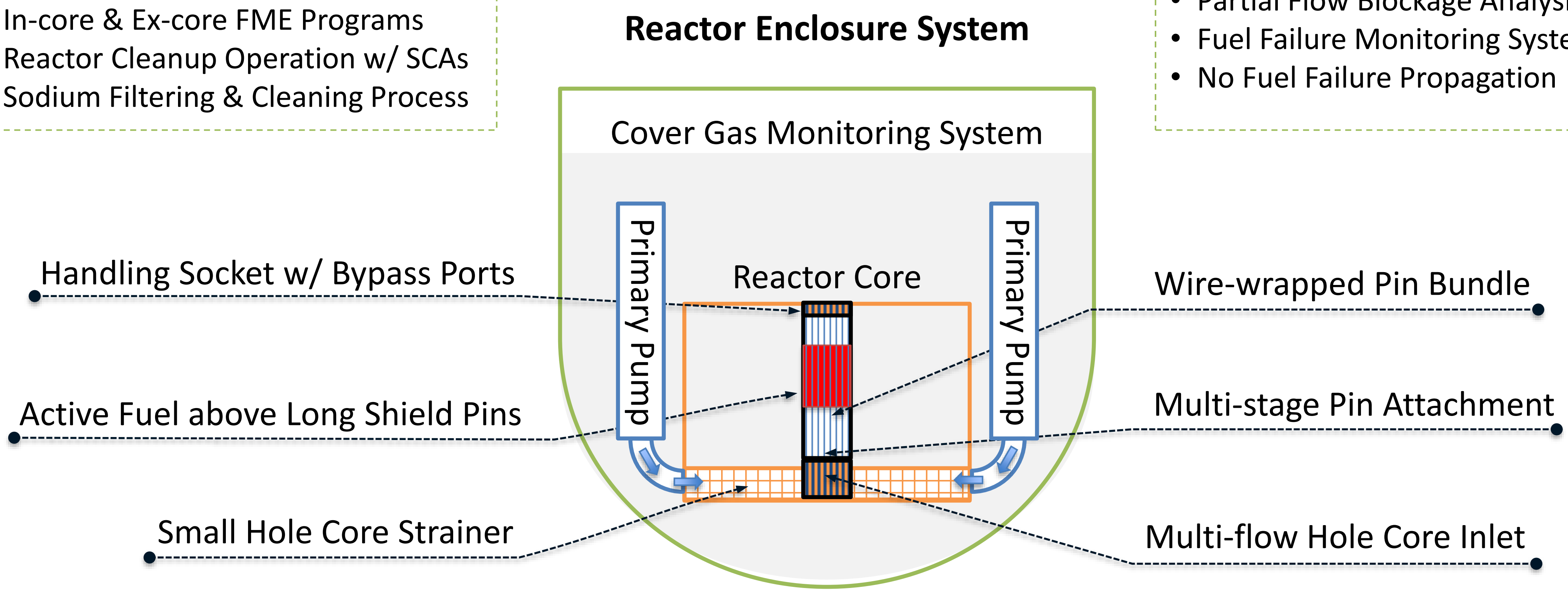
Comparing the Natrium Design to LWRs

Item	Light Water Reactor (LWR)	Natrium Design
Latent debris inclusion during refueling operation	• Reactor head opened during reload • Coolant circulates between the reactor and Spent Fuel Pool (SFP) • Fuel assemblies travel between reactor and SFP	• Reactor head closed all the time • Independent spent fuel pool • Reloaded assemblies stay in the In-vessel Storage (IVS) during refueling
Long-term Core Cooling (LTCC) degradation after a LOCA (GSI-191)	• LOCA-generated debris such as chemical precipitate, fibrous, and particulate debris could flow into the reactor coolant system	• No LOCA concerns • No recirculation or injection • Passive cooling by Reactor Air Cooling (RAC) system
Fuel Failure Propagations	• A fuel pin failure may result in secondary hydriding damage or ballooning → local flow blockage may cause adjacent fuel pin failures • PWR has no duct preventing failure propagation to adjacent assemblies	• No failure propagation was observed from the past accidents or tests • Fuel assembly duct may prevent failure propagations to adjacent fuel assemblies

Multi-Defense Designs for Core Flow Blockages

- NQA-1 Quality Controls
- In-core & Ex-core FME Programs
- Reactor Cleanup Operation w/ SCAs
- Sodium Filtering & Cleaning Process

- Partial Flow Blockage Analysis
- Fuel Failure Monitoring System
- No Fuel Failure Propagation



Multiple defense lines in the Natrium design to prevent a major core flow blockage.

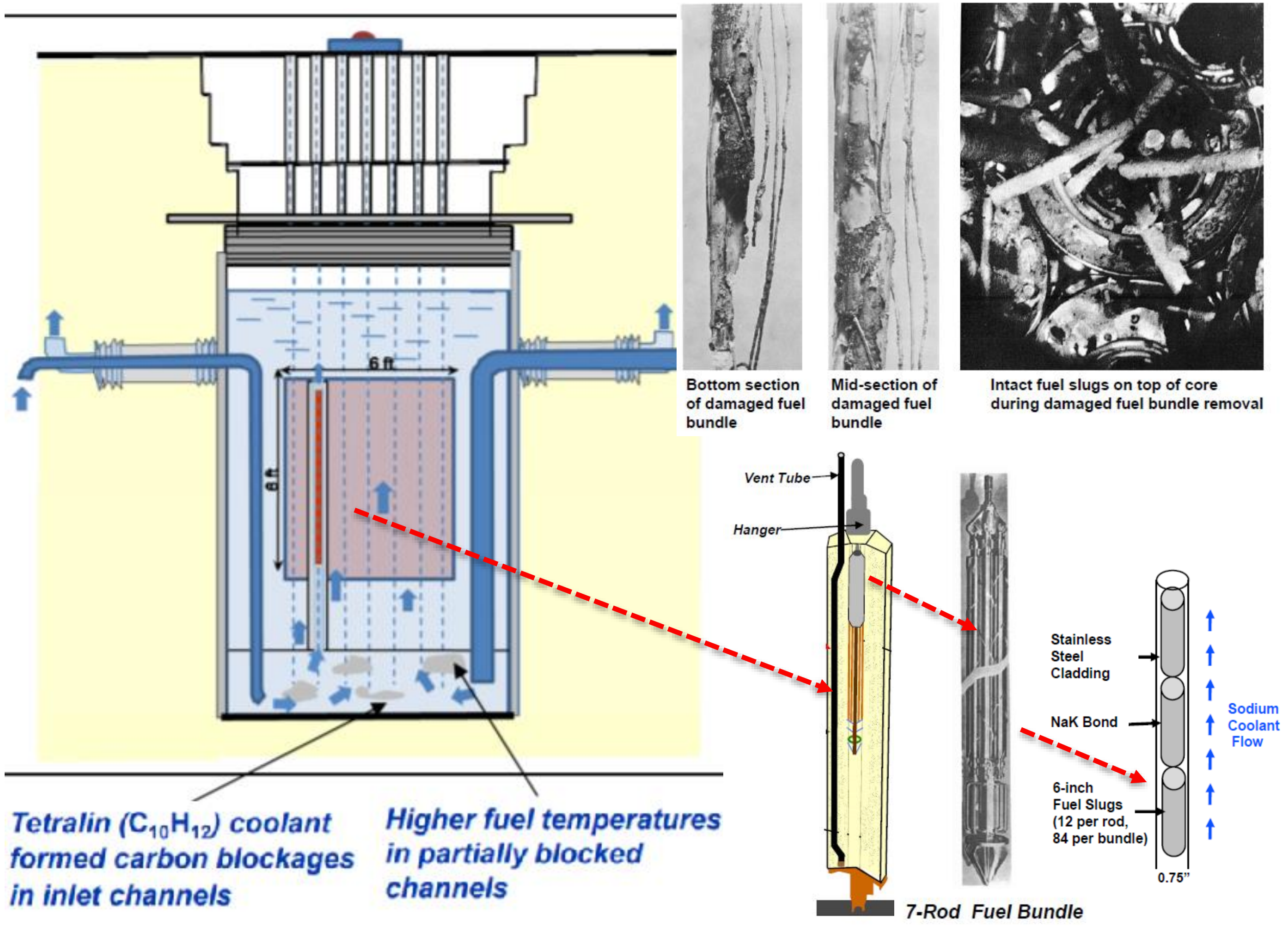

Questions?

Appendix: Historic Events

Historic Core Flow Blockage – Major Accidents

<u>Sodium Reactor Experiment Accident</u>

- Organic pump coolant (Tetralin $C_{10}H_{12}$) leaked into the primary cooling system.
- Decomposed carbon products coated reactor internal components to form partial blockages of the inlet channels of 13 fuel assemblies.
- Damaged fuel bundles showed evidence of local melting and cladding failure.
- Most fuel slugs were still intact (i.e., **had not melted**).

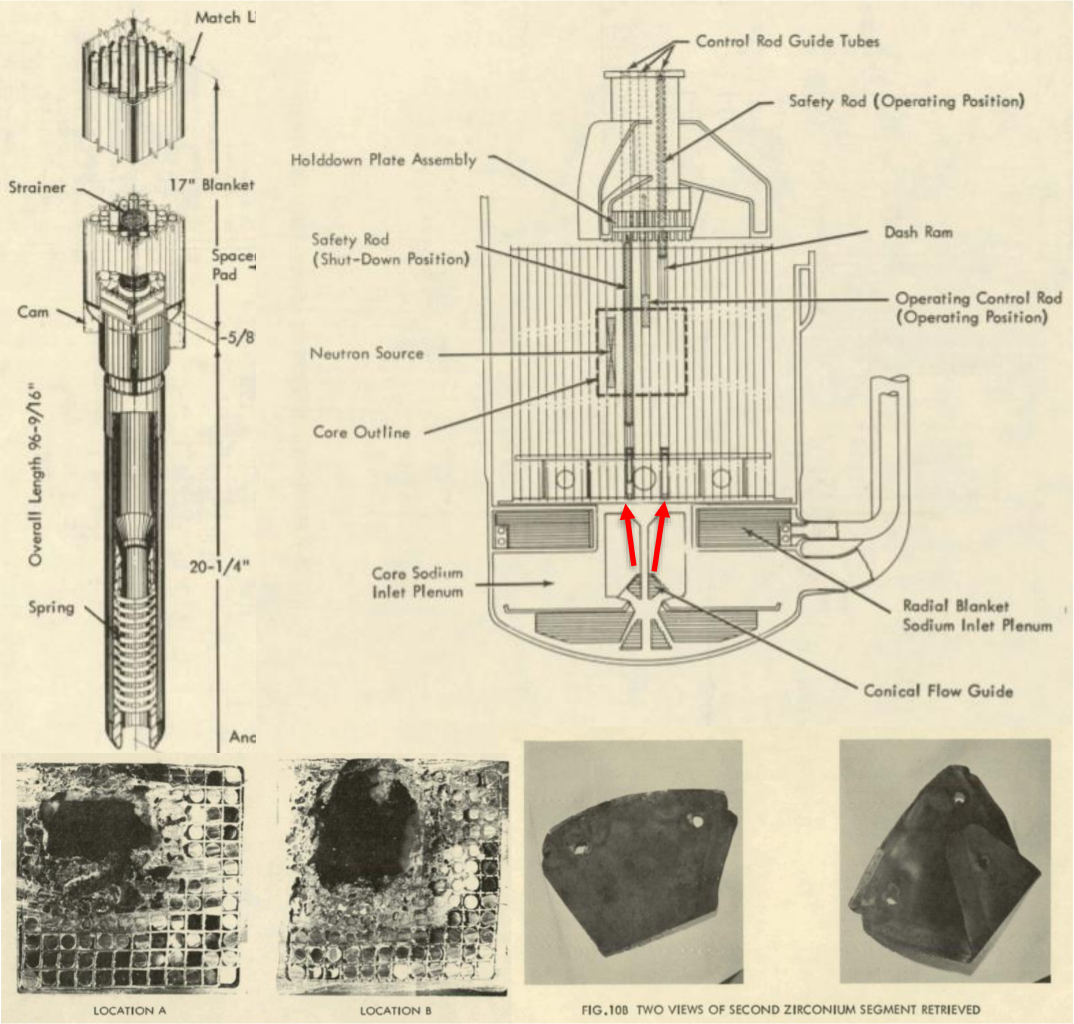


https://www.etec.energy.gov/Library/Main/Pickard%20SRE%20presentation.pdf

Historic Core Flow Blockage – Major Accidents

<u>Fermi-I Accident</u>

- A large size Zr cladding plate on conical flow guides vibrated loose and blocked 4 fuel assemblies.
- The fuel assembly coolant inlet had a single hole in a flat plate, easily blocked by the Zr plate.
- No evidence was found that molten fuel had flowed from one subassembly to the other (i.e., **no propagation**).



https://www.nrc.gov/docs/ML2009/ML20090C309.pdf

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NCNR Fuel Failure (February 2021)

- The neutron source for the NIST Center for Neutron Research (NCNR) is a 20 MW reactor, the National Bureau of Standards Reactor (NBSR).
- An unlatched fuel element was lifted out and caused fuel failures by departure from nucleate boiling due to flow blockages.
- Root causes:
  - Inadequate training and qualification program
  - Inaccurate procedures
  - Un-enforced procedural compliance
  - Inadequate latch system
  - Inadequate management oversight of refueling staffing

https://www.nrc.gov/docs/ML2127/ML21274A019.pdf

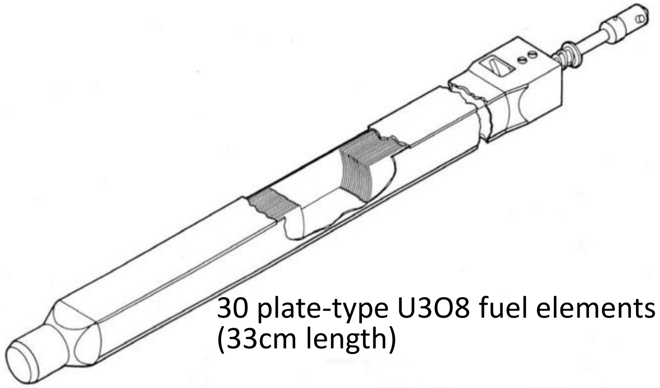

Figure 4. Fuel element head latched into a mockup of the upper grid plate

Figure 6. Mock fuel element head in a "partially latched" position

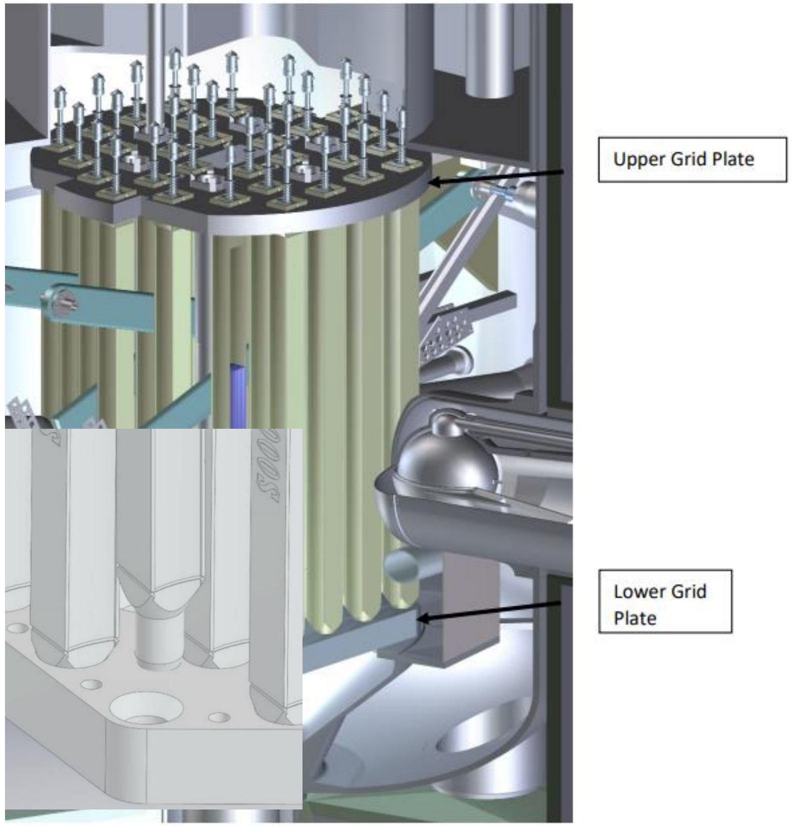

Figure 2. The NBSR core.

Acronym List

CRBRP – Clinch River Breeder Reactor Plant
DOE – Department of Energy
DND – Delayed Neutron Detector
EBR – Experimental Breeder Reactor
FFM – Fuel Failure Mockup
FME – Foreign Material Exclusion
FFTF – Fast Flux Test Facility
FSAR – Final Safety Analysis Report
GSI – Generic Safety Issue
IHX – Intermediate Heat Exchanger
IVS – In-Vessel Storage
LMFBR – Liquid Metal Fast Breeder Reactor
LOCA – Loss Of Coolant Accident
LTCC – Long-term Core Cooling
LWR – Light Water Reactor
NRC – Nuclear Regulatory Commission
NCNR – NIST Center for Neutron Research
NIST – National Institute of Standards and Technology
NSBR – National Bureau of Standards Reactor
ORNL – Oak Ridge National Laboratory
PSID – Preliminary Safety Information Document
RAC – Reactor Air Cooling
REP – Regulatory Engagement Plan
SCA – Simulated Core Assembly
SFR – Sodium Fast Reactor
SFP – Spent Fuel Pool
UIS – Upper Internal Structure