# OPERATIONAL CONSIDERATIONS

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# OBJECTIVES

- Understand typical SAFDLs
- Understand the role of “cleanup” systems
- Understand the monitoring of failed fuel
- Understand the prevention and mitigation of sodium leaks
- Understand the prevention and mitigation of sodium-water interactions
- Discussion of other considerations

**SAFDL**

**Cleanup Systems**

**Failed Fuel Monitoring**

**Sodium Leaks**

**Sodium/Water Interactions**

***SAFDL***

***Cleanup Systems***

***Failed Fuel Monitoring***

***Sodium Leaks***

***Sodium/Water Interactions***

# SPECIFIED ACCEPTABLE FUEL DESIGN LIMITS

- SAFDLs
  - SAFDLS are established to ensure that fuel is not damaged during normal operation or anticipated operational occurrences (AOOs)
  - Many of the ARDCs/SFR-DCs reference the SAFDLs (RG 1.232)

| Criterion | SFR-DC Title and Content |
|---|---|
| **10** | *Reactor design.*<br>Same as GDC<br>The reactor core and associated coolant, control, and protection systems shall be designed with appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences. |

| | |
|---|---|
| **12** | *Suppression of reactor power oscillations.*<br>Same as ARDC<br>The reactor core; associated structures; and associated coolant, control, and protection systems shall be designed to ensure that power oscillations that can result in conditions exceeding specified acceptable fuel design limits are not possible or can be reliably and readily detected and suppressed. |

| Criterion | SFR-DC Title and Content |
|---|---|
| **20** | *Protection system functions.*<br>Same as GDC<br>The protection system shall be designed (1) to initiate automatically the operation of appropriate systems including the reactivity control systems, to assure that specified acceptable fuel design limits are not exceeded as a result of anticipated operational occurrences and (2) to sense accident conditions and to initiate the operation of systems and components important to safety. |

# SPECIFIED ACCEPTABLE FUEL DESIGN LIMITS

- NUREG-800, Section 4.2 states that design criteria should address the following:
  - Fuel System Damage
    - Stress, strain, loading, etc.
    - Fatigue cycles
    - Fretting and wear
    - Oxidation, hydriding, and crud
    - Dimensional changes
    - Internal gas pressure
    - Unseating
  - Fuel Rod Failure
    - Hydriding
    - Cladding collapse
    - Overheating of cladding
    - Excessive fuel enthalpy
    - Pellet/clad interaction
    - Bursting
    - Mechanical fracturing

A central T-H concern that is addressed through DNBR/CHF/MCPR for LWRs

# SPECIFIED ACCEPTABLE FUEL DESIGN LIMITS

## Metal Fuel Criteria

- Cumulative damage fraction (CDF)
- Plastic diametral strain
- No bulk fuel melting
- Limits on eutectic interaction between cladding and fuel
- Hoop stress limits

## EBR-II Example Values

| Criteria | Normal Operation Limits |
|---|---|
| Cumulative Damage Fraction | <0.05 |
| Plastic Diametral Strain | <1% |
| Bulk Fuel Melting (Fuel Temp) | ~1100ºC |
| Eutectic Interaction (Fuel/Clad Interface Temp) | ~ 700ºC |
| Hoop Stress (Internal Pin Pressure) | $\overline{\sigma_H}$<150MPa |

# SPECIFIED ACCEPTABLE FUEL DESIGN LIMITS

## Plastic Diametral Strain

- Unrecoverable change in cladding diameter due to stresses
- Volumetric swelling and irradiation creep
- For HT9 cladding, testing failures typically occurred at >2%

## Cumulative Damage Fraction (CDF)

- Necessary to capture time-at-temperature dependence
- Method for predicting failure for components subject to creep damage at elevated temperatures
- ***NOT*** a probability of failure
- Failure assumed when CDF = 1.0 (on average)
- Utilizes rupture time data from creep tests at constant stress/temperature and translates it to time-varying stress/temperature situations
- Approach has been validated by variable stress/temperature tests
- CDF is not independent of other criteria

$$CDF = \int_{t=0}^{t} \frac{dt}{t_R(\sigma, T)}$$

$t$ – Time

$t_R$ –Rupture time

$\sigma$ – Hoop Stress

$T$ – Temperature

- ***SAFDL***
- ***Cleanup Systems***
- ***Failed Fuel Monitoring***
- ***Sodium Leaks***
- ***Sodium/Water Interactions***

# PRIMARY SODIUM PURIFICATION SYSTEM

## Purpose:

- Remove or limit impurities in the primary sodium, including:
  - Oxygen
  - Hydrogen
  - Corrosion products
  - Fission products
  - Other impurities present in acquired sodium or introduced from maintenance activities and refueling

## Impurity Risks

- Oxygen can increase corrosion (forming radioactive corrosion products) and cause plugging in subcooled areas due to solidification of sodium oxides
- Radioactive corrosions products and fission products from failed fuel can increase system and component dose rates, complicating reactor operations and maintenance activities
- Minimizing hydrogen helps control tritium and aids in the identification of sodium-water interactions (on the secondary/intermediate circuit) through hydrogen sensors

# **PRIMARY SODIUM PURIFICATION:** METHODS

## ■ Cold Traps

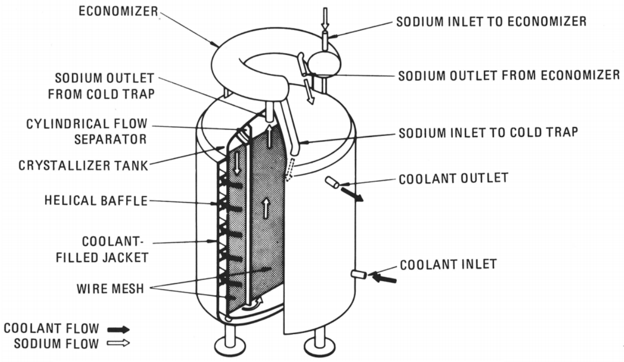
- Cools sodium below saturation temperature of impurities allowing them to crystallize on the cold trap vessel or internal meshes
- Main purpose is to remove oxygen, but can also remove hydrogen (and tritium), carbon, and some corrosion products

## ■ Hot Traps

- Removal of impurities at or above operating temperatures through the use of “getter traps” that form compounds with certain impurities
- Can achieve very low levels of oxygen, but are typically not necessary for sodium reactors

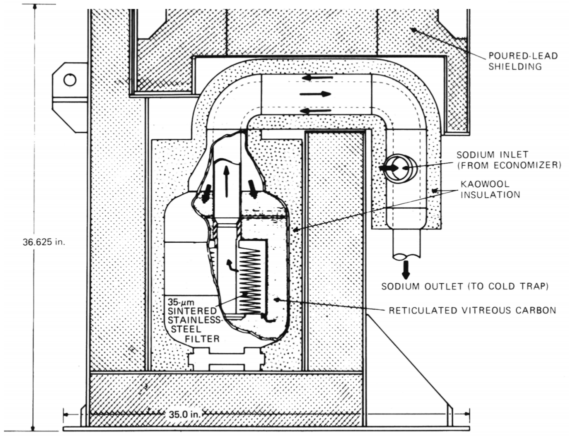
## ■ Cesium Traps

- Cold traps are inefficient at removing cesium (an alkali metal like sodium)
- Reticulated vitreous carbon (RVC) or graphite filters have been used at EBR-II and FFTF to capture cesium

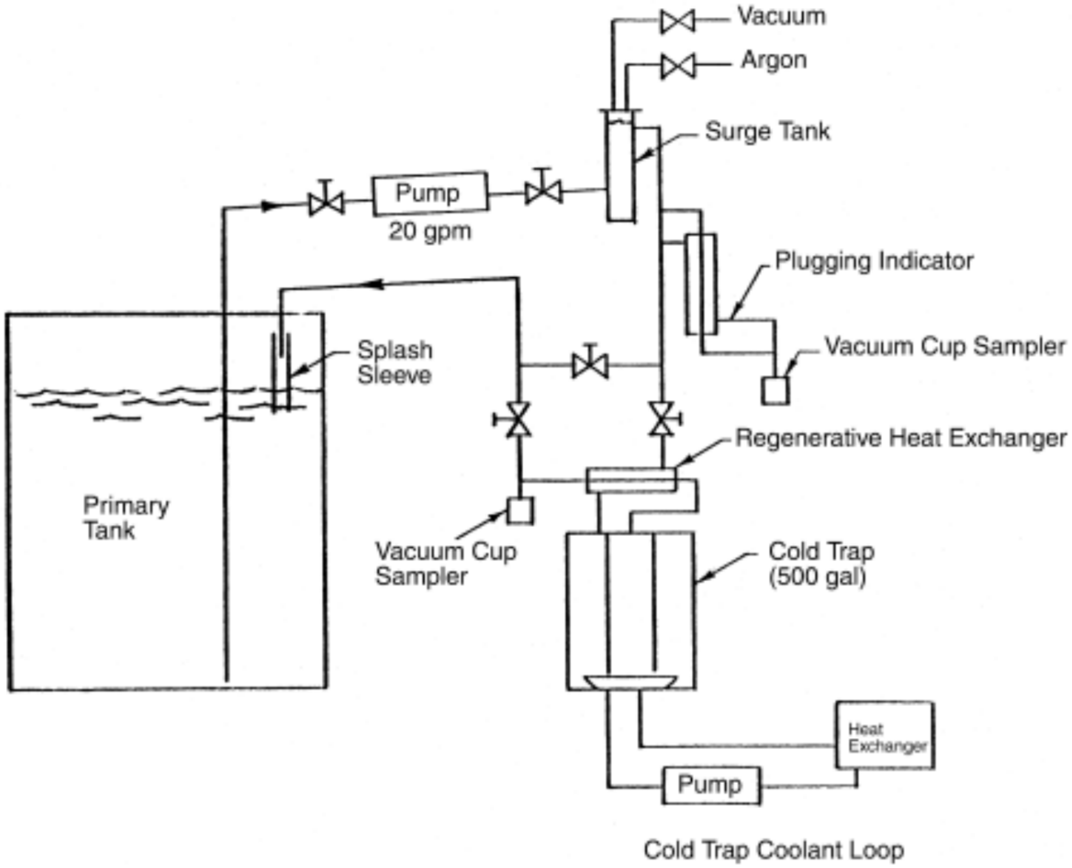



***EBR-II Cold Trap***

***EBR-II Cesium Trap***



# **PRIMARY SODIUM PURIFICATION:** EBR-II DESIGN




** Before installation of cesium trap*

# COVER GAS PURIFICATION SYSTEM

## Purpose:

- Remove or limit impurities in the reactor cover gas (typically argon or helium), including:
  - Xenon
  - Krypton
  - Cesium
  - Sodium aerosols/vapor
  - Other impurities introduced from maintenance activities and refueling
- Identify fuel pin failures (discussed later in presentation)

*Fission products from failed fuel pins or tramp uranium*

## Impurity Risks

- Radioactive xenon and krypton may transport through leakage pathways to areas within containment, increasing dose rates and complicating reactor operation and maintenance activities
- Cesium vapors may condense onto colder surfaces on the reactor head and auxiliary systems, increasing dose rates and complicating maintenance activities
- Sodium aerosols and vapor condense/settle/deposit on surfaces causing plugging and binding of equipment (rotating head, control rod drive mechanisms, etc.) due to formation of sodium oxides

# COVER GAS PURIFICATION: METHODS

## Sodium Removal

- Sodium aerosol and vapor removal is typically performed first in the purification system to prevent sodium from plugging subsequent system piping and equipment
- One method is to heat the sampled cover gas to vaporize all entrained sodium, then pass into a low temperature tank to condense sodium and drain
- Some systems also use filters to retain any residual sodium aerosols after condensation

## Charcoal Adsorbers

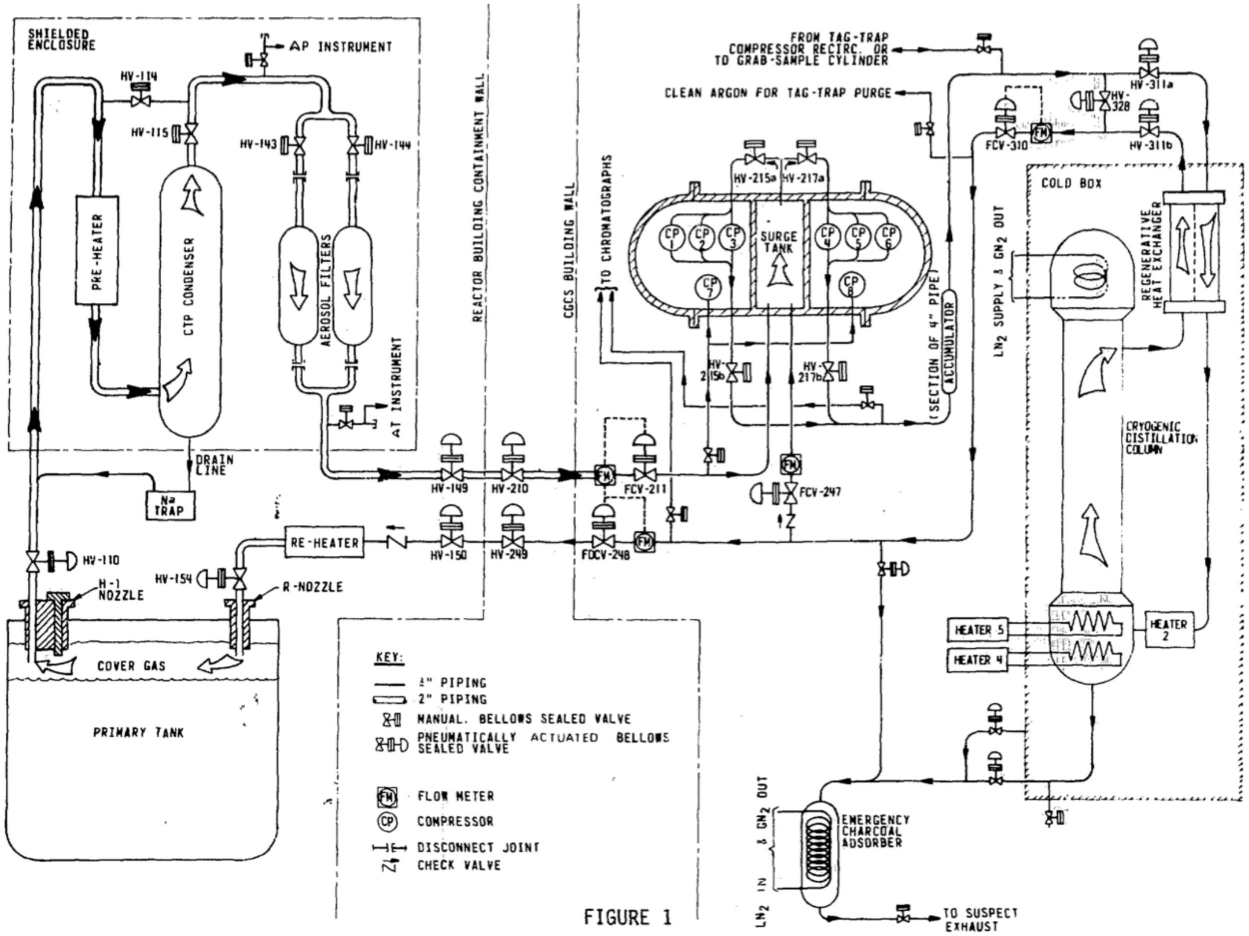
- May be cooled or operated at “room” temperature
- Used for hold up of fission products to allow for decay
- Xenon and krypton have higher affinity to adsorb than argon

## Cryogenic Distillation

- Liquid nitrogen is used to cool argon to -182ºC, which is below boiling point of xenon and krypton, but above boiling point of argon
- Radioactive xenon and krypton is stored for decay
- Method also removes oxygen and hydrocarbons

# COVER GAS PURIFICATION: EBR-II DESIGN

Sodium vapor and aerosol removal




Xe/Kr Removal

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- ***SAFDL***
- ***Cleanup Systems***
- ***Failed Fuel Monitoring***
- ***Sodium Leaks***
- ***Sodium/Water Interactions***

# FAILED FUEL MONITORING

## Purpose

- Recognize when fuel pin failure has occurred
- Identify fuel assembly where failure has occurred
- For oxide fuel, goal to reduce time of interaction between fuel and sodium
- May not be necessary for a commercial, metal fuel SFR due to compatibility between sodium and fuel, which has been demonstrated in run-beyond-cladding-breach tests

## Many Different Techniques

- Delayed neutron detectors sampling the cover gas are typically used to recognize when fuel pin failure occurs by detecting Xe/Kr
- Many different methods have been utilized to identify the assembly where failure has occurred (see table)
- Gas tagging is now the preferred choice for failure identification

TABLE I. Methods Used to Identify Sources of Fission-product Releases in EBR-II

| Method | Purpose | Advantages | Disadvantages |
|---|---|---|---|
| 1. Fission-gas volume | Identifies suspects by gas release | Eliminates low-burnup suspects | Usually limited applicability |
| 2. Ratio $^{134}Xe/^{133}Xe$ | Discriminates between metal and oxide | Identifies type and burnup of suspect | Ratio changes for same element; affected by fuel and breach geometry |
| 3. Normalized excursion parameter | Discriminates betweem metal and oxide | Rapid | Empirical; uses release characteristics that may give ambiguous results |
| 4. $^{135m}Xe$ behavior | Indicates release of bond sodium | Rapid | None; occasionally overlooked |
| 5. Weibull failure analysis | Ranks suspects by failure probability | Predicts breach in advance; helps rank otherwise equal suspects | Assumes common mode of failure; limited by previous experience |
| 6. Flux-tilting test | Narrows down suspects to a section of the core | Easy to perform | Suspect must be adjacent to control rod; only positive response is meaningful |
| 7. Ratio $^{134}Xe/^{128}Xe$ | Determines burnup level of untagged element | Eliminates suspect with too high or low burnup | For small release, natural background contamination can be significant |
| 8. Ratio $^{131}Xe/^{134}Xe$ | Discriminates between metal and oxide | Uses stable high-yield isotopes of xenon | Can be affected by tag in low-burnup elements |
| 9. Xenon tag | Identifies suspects by tag composition | Limits choice to one to three suspects | Exposure changes in tag; sometimes small tag releases; contamination |
| 10. Fission-gas and tag volumes | Discriminates suspects with similar tag compositions | Ranks xenon-tag suspects | As above; also, early tag volumes were variable |
| 11. Lift-and-hold test | Identifies suspects by gas release | Confirms suspect subassembly in fuel handling | Shutdown required; only positive response meaningful; time-consuming |
| 12. FUM isolation test | Identifies suspects by gas release | Confirms suspect subassembly at operator's convenience; minimizes interference from cover-gas activity | As above; can tolerate only low decay-heat level in discharged subassembly |

# FAILED FUEL MONITORING: GAS TAGGING

■ Method

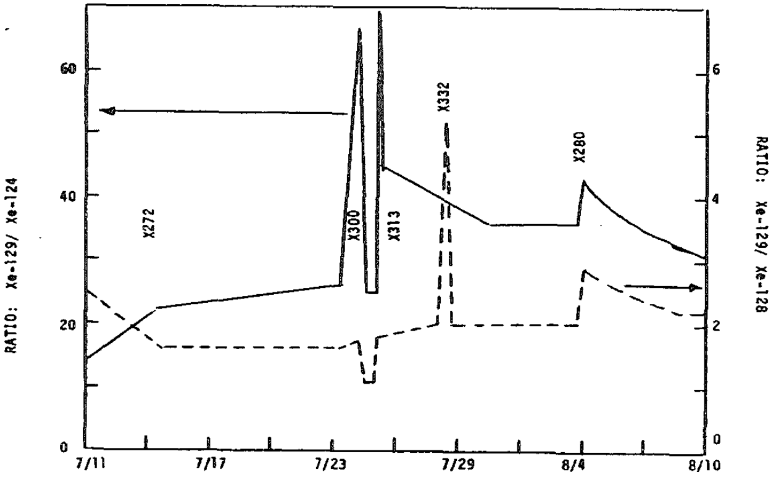
- All pins within an assembly are pre-filled with a unique noble gas composition
- If a pin failure occurs during operation, the noble gases are released from the fuel pin and enter the cover gas region (noble gases do not interact with sodium)
- A mass spectrometer is utilized to sample the cover gas and identify the gas composition

■ Isotopes Utilized

- Xe-124, Xe-126, Xe-128
- Kr-78, Kr-80, Kr-82

■ EBR-II Experience

- 1mL of tag gas in each pin
- 140 unique tags were created using different ratios of only three xenon isotopes
- Mass spec could identify 0.002mL tag gas in ~$10^7$mL cover gas volume




***Identification of 5 fuel pin failures in 3 Weeks (EBR-II 1980)***

- ***SAFDL***
- ***Cleanup Systems***
- ***Failed Fuel Monitoring***
- ***Sodium Leaks***
- ***Sodium/Water Interactions***

# SODIUM LEAKS

## ■ Primary System Leaks

- For pool-type SFRs, primary sodium leaks are extremely unlikely due to the dual vessel design (reactor vessel and guard vessel with inert gas space in-between) and lack of vessel penetrations below the sodium level
- Guard vessel spacing is purposefully designed to ensure that a reactor vessel leak does not reduce the primary sodium level below critical components, such as heat exchangers and the core
- Leaks from systems that interface with the primary sodium, such as the primary sodium purification system, are a possibility
  - Activated sodium is a dose concern
  - Syphon breaks prevent the inadvertent extraction of sodium from the primary pool

## ■ Secondary (Intermediate) and Auxiliary System Leaks

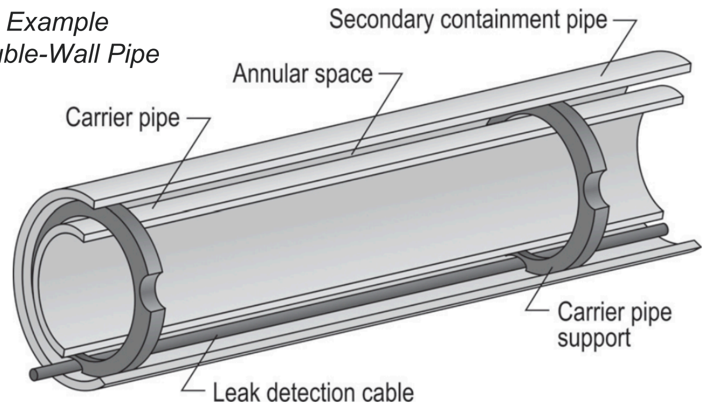
- Sodium leaks from the secondary/intermediate piping and auxiliary systems are a possibility
  - Typically an operational concern or maintenance event
  - Lower sodium activation levels for secondary/intermediate sodium
  - Exception for leaks that could impact safety functions
- There are many different methods utilized to prevent, detect, and mitigate sodium leaks…

# SODIUM LEAKS

## ■ Prevention

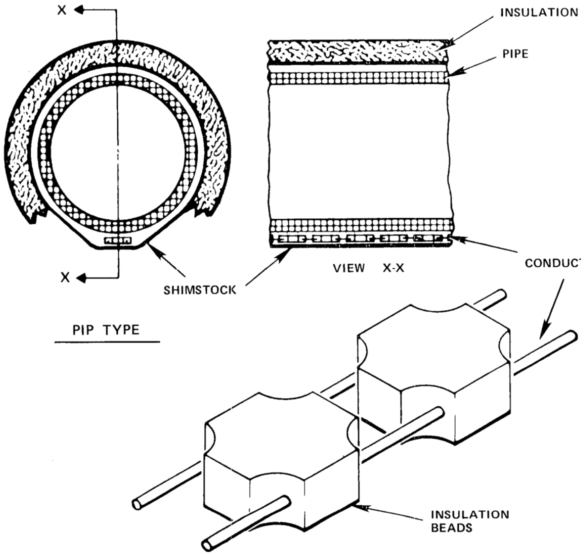
- Low pressure systems
- High quality, code-qualified piping materials
- Potential use of double-walled piping for certain areas (with leak detectors in gap)
- “Leak before break” methodology
  - Due to low pressure, sodium leaks are generally small and can be detected before larger piping breaks occur
- Separation of routing of water systems

*Example Double-Wall Pipe*




## ■ Detection

- Smoke detectors
- Contact detectors (spark plugs)
- Cable detectors
- Aerosol monitors
- Inspections




*Example Contact Detector*



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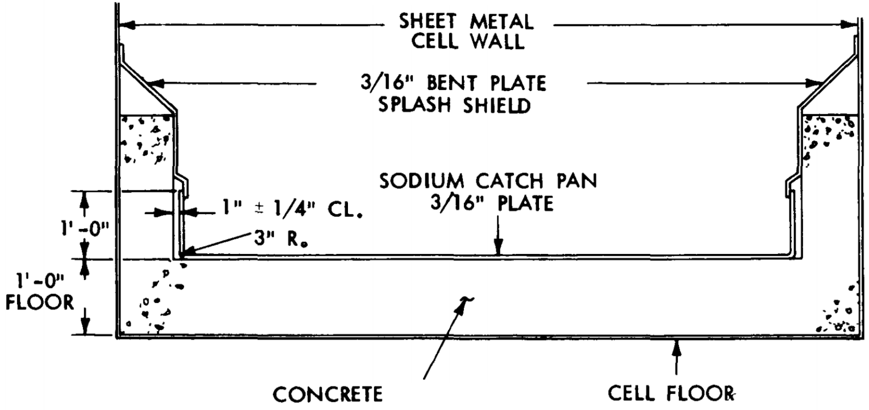
# SODIUM LEAKS

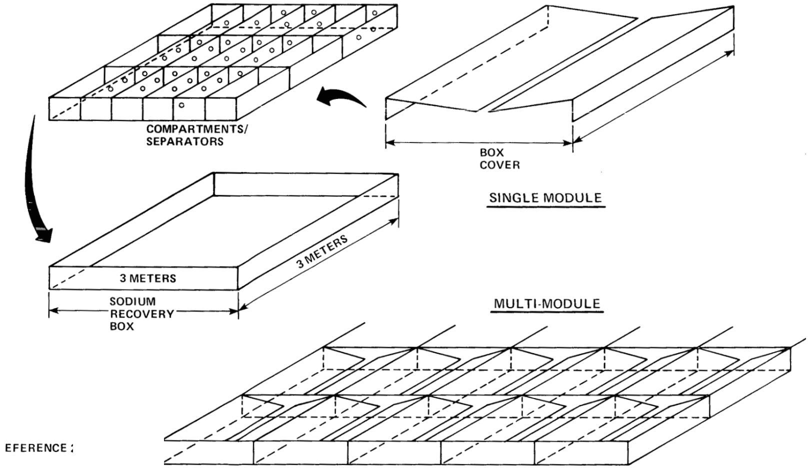
## ■ Mitigation

- Isolation and dump tank systems on loops to limit amount of sodium released
- Locating certain sodium systems within inerted rooms
- Steel liners are used below sodium piping to protect concrete from potentially interacting with sodium
- Suppression decking is used to funnel leaked sodium into channels that limit the surface area exposed to air
- Gas suppression systems, which would limit available oxygen, have been considered
- Oxygen depletion – segmentation/compartmentalization of rooms to limit available oxygen

*Example Concrete Liner*




*Example Suppression Deck*



- SAFDL
- Cleanup Systems
- Failed Fuel Monitoring
- Sodium Leaks
- **Sodium/Water Interactions**

# SODIUM-WATER INTERACTIONS

## ■ Steam Generator Design

- The steam generator serves as the interface between the secondary (intermediate) sodium and the water cycle
- Due to the energetic reaction between sodium and water, sodium-water interactions are both an operational and safety concern
- Many systems are in place to prevent, detect, and mitigate the effects of a steam generator tube leak/rupture

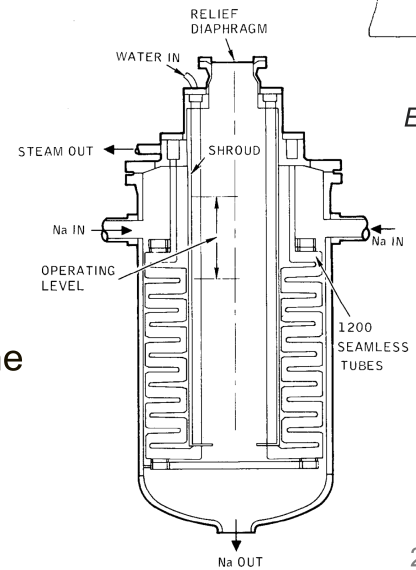
## ■ Prevention

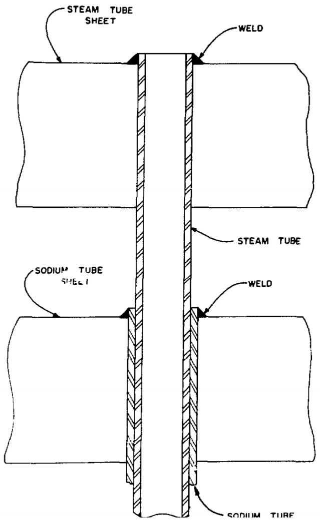
- High quality, code-qualified materials and welding
- Potential use of double-walled steam generator tubes and tubesheets

## ■ Detection

- Hydrogen sensors in the gas space above the sodium in the steam generator monitor for the product of sodium/water reactions
- Acoustic sensors monitor for the noise created by bubble formation during sodium/water reactions

*FERMI-1*
*Steam Generator*

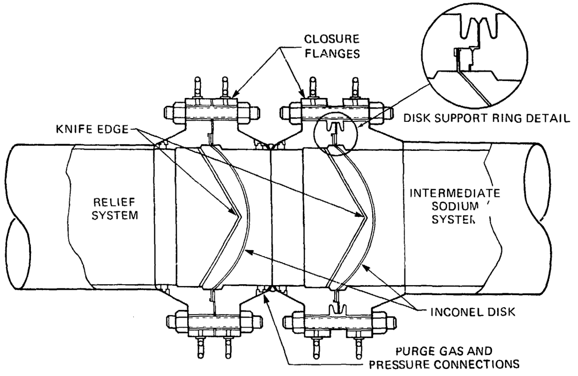


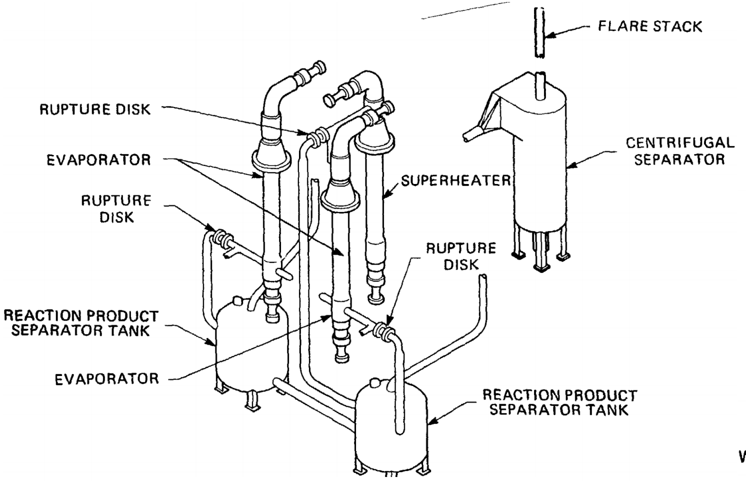

*EBR-II Double Wall Tube Design*

# SODIUM-WATER INTERACTIONS

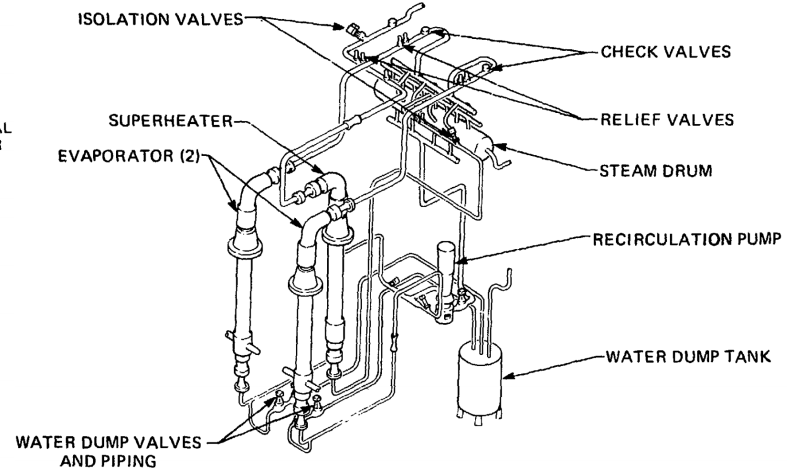
- Mitigation
  - If a sodium/water reaction is detected, steam generator isolation valves are closed (both the sodium and water inlet/outlet piping) and the steam generator contents are discharged to a dump tank
  - Rupture disks, which break at a specified pressure, are also located on the steam generator system to relieve any pressure spikes caused by the reaction to prevent breaks in intermediate system piping, such as the intermediate heat exchanger




*CRBR Rupture Disk Design*




*CRBR Steam Generator (Sodium Side)*




*CRBR Steam Generator (Water Side)*

# OTHER OPERATIONAL CONSIDERATIONS

# OTHER CONSIDERATIONS

## Sodium Freeze/Thaw

- Thawing and freezing of sodium must be completed in a specific way to avoid stresses that can cause piping or component breaks or fatigue issues

## Thermal Stratification

- Although sodium has high thermal conductivity, stratification can occur in low flow conditions, which can impact heat transfer in heat exchangers and natural circulation development

## Thermal Striping

- Due to large $\Delta T$ of system, flow oscillations between hot and cooler sodium can quickly fatigue structures and components

# QUESTIONS?

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