SUMMARY OF OPERATIONAL EXPERIENCE FOR ADVANCED NON-LIGHT WATER REACTORS: MATERIALS AND STRUCTURAL INTEGRITY ISSUES

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by

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Introduction

- ***NRC Effort – three main tasks***
  - ***Task 1: Compile compendium of Advanced Non-Light Water Reactor (ANLWR) Operating Experience (OpE)***
    - ***Briefly summarized here***
  - ***Task 2: Based on OpE and other documents develop gap assessment of ASME code for licensing ANLWRs***
    - ***Led to identification of 30 suggestions for enhancement of ASME BPV Division 5 code***
  - ***Task 3: Examine Computational codes necessary to assess ANLWR damage mechanisms and identify gaps necessary to better enable licensing of ANLWRs***
    - ***This effort led to development of road map for ANLWR computational code development and assessment***

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Introduction

- This paper summarizes Operational Experience (OpE) of advanced non-light water reactors (ANLWR) that have been in operation over the last sixty years.
- The focus of this paper is on Sodium Cooled Fast Reactors (SFR) and High Temperature Gas Cooled Reactors (HTGR) with regard to materials and component integrity.
- Operational experience was compiled from numerous journal publications, pertinent books, and publicly available reports, and discussion with operators.

This paper represents a short summary of the report: https://www.nrc.gov/docs/ML1835/ML18353B121.pdf.

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Overview

Issues Summarized

- ***Materials used in both SFRs and HTGRs***
- ***Observed and anticipated material degradation mechanisms***
- ***Component integrity issues and possible solutions to challenges involving materials and component integrity***
- ***Specific issues based on OpE that should be addressed in the development of regulatory infrastructure***
- ***Assessment tools and evaluation techniques (e.g., nondestructive evaluation (NDE)) used to identify and address component integrity issues***

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Sodium Fast Reactors

Reactor	Country	Power (MWt)	Criticality (yr)	Shut Down (yr)	Primary Hot Leg (°C) [°F]	Primary Cold Leg (°C) [°F]
EBR-II	US	62.5	1961	1994	473 [883]	371 [700]
FFTR	US	400	1980	1992	503 [937]	360 [680]
PFR	UK	650	1974	1994	560 [1040]	399 [750]
BN-350	Russia	1,000	1972	1999	430 [806]	280 [536]
BN-600	Russia	1,470	1980	N/A	535 [995]	365 [689]
BN-800	Russia	2,100	2014	N/A	547 [1017]	354 [669]
BOR-60	Russia	55	1968	N/A	530 [986]	330 [626]
BR-10	Russia	8	1958	2003	470 [878]	350 [662]
Joyo	Japan	50–140	1977	N/A	465–500 [869-932]	350–370 [662-698]
Monju	Japan	714	1995	2010	529 [984]	397 [747]
FBTR	India	40	1985	N/A	530 [986]	380 [716]
Phénix	France	563	1973	2009	560 [1040]	395 [743]
Rapsodie	France	40	1967	1983	515 [959]	400 [752]
Superphénix	France	3,000	1985	1998	545 [1013]	395 [743]

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High Temp Gas Cooled Reactors (HTGR)

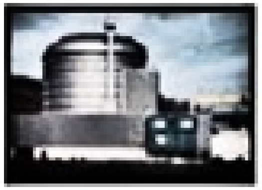
Dragon
20 MWt prismatic
750 C
(UK)
1964-1975

AVR
46 MWt pebble-bed
>900 C
(FRG)
1967-1988

HTTR
30 MWt prismatic
950 C
(Japan)
1998-present

HTR-10
10 MWt pebble-bed
700-950 C
(China)
2000-present

Experimental Reactors



Peach Bottom 1
115 MWt prismatic
~700 C
(USA)
1966-1974

THTR
750 MWt pebble-bed
750 C
(FRG)
1985-1991

Fort St. Vrain
842 MWt prismatic
~800 C
(USA)
1976-1989

Commercial Scale Demonstrations

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Examples: Monju Thermal Couple

(Monju, December 1995):

- After a scheduled shutdown and plant startup, a sodium leak occurred in the secondary heat transport system of pipe loop C (a hot-leg geometry)
- Led to a serious fire when it interacted with oxygen and moisture
- The leak melted steel structures in the room
- Located at a 3 mm diameter thermocouple penetration.
- The well tube failure was caused by high-cycle fatigue from flow-induced vibration caused by vortex shedding in the direction of the sodium flow

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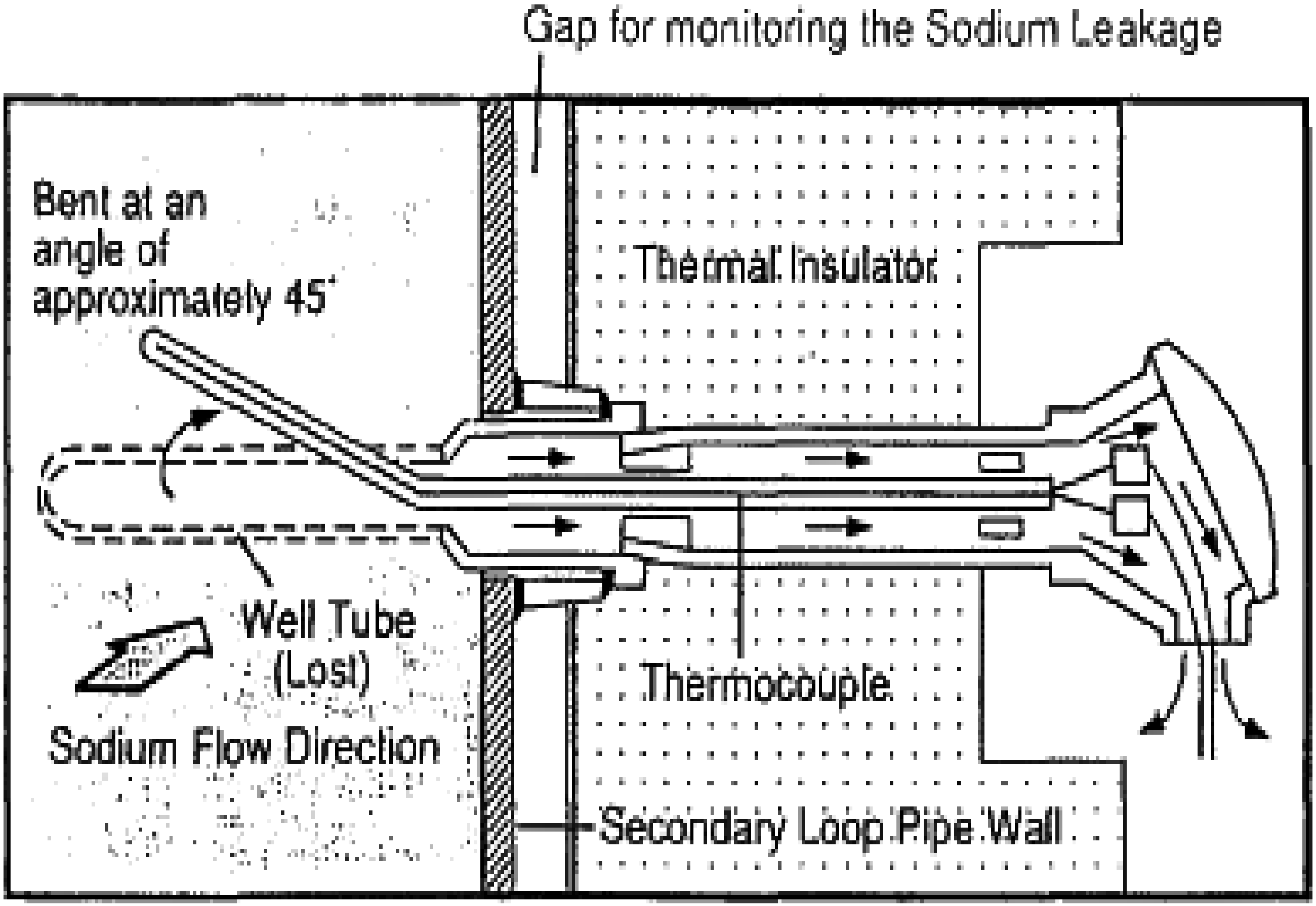
Examples: Monju Thermal Couple



Fracture surface Indicates fatigue striations

Mikami, H., Shono, A., and Hiroi, H., "Sodium Leak at Monju (I)—Cause and Consequences," Reactor and System Engineering Section, Monju Construction Office, Power Reactor and Nuclear Fuel Development Corporation, Japan, 1995.

Examples: Phénix, general

- *Phénix experienced 11 sodium leak in 35 years*
- *These problems were solved using various design modifications*
- *A significant example is a sodium leak into the inner space at the secondary sodium outlet header*
- *Different thermal expansion loads between the inner and outer shells underestimated in the original design*
- *Solution; the redesign improved both the mixing of the secondary sodium outlet from the tube bundle and the flexibility of the IHX hot header between the top closure plate and the inner shell*
- *Control of structural constraints in SFRs in regions of thermal expansion mismatch is an important design feature and must be considered during the license assessment of the plants*

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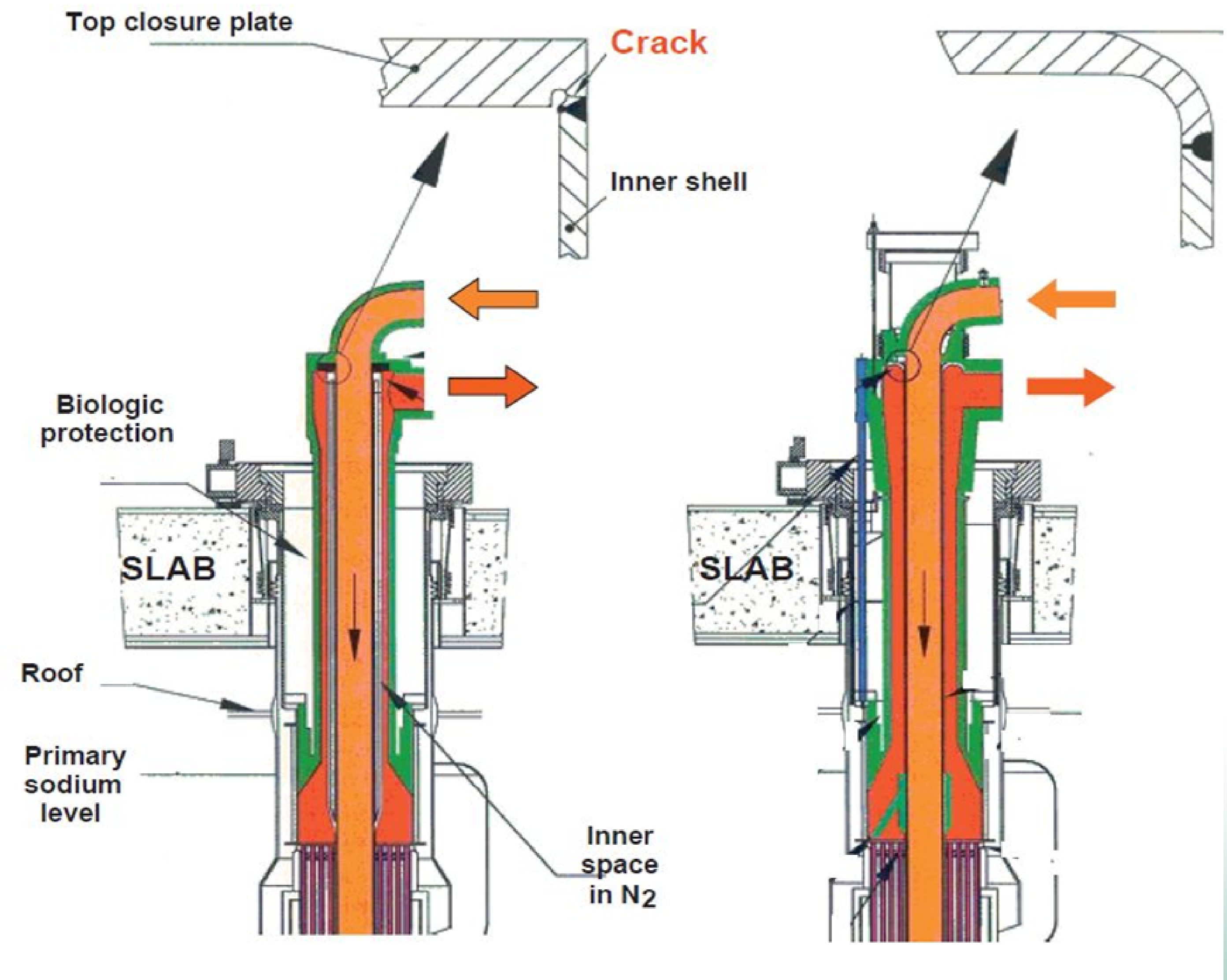
Examples: Phénix, general



Original design Modified design

Sauvage, J.F., "Phénix—30 Years of History: The Heart of the Reactor," EDF report 1979, available at http://fissilematerials.org/library/sau04.pdf.

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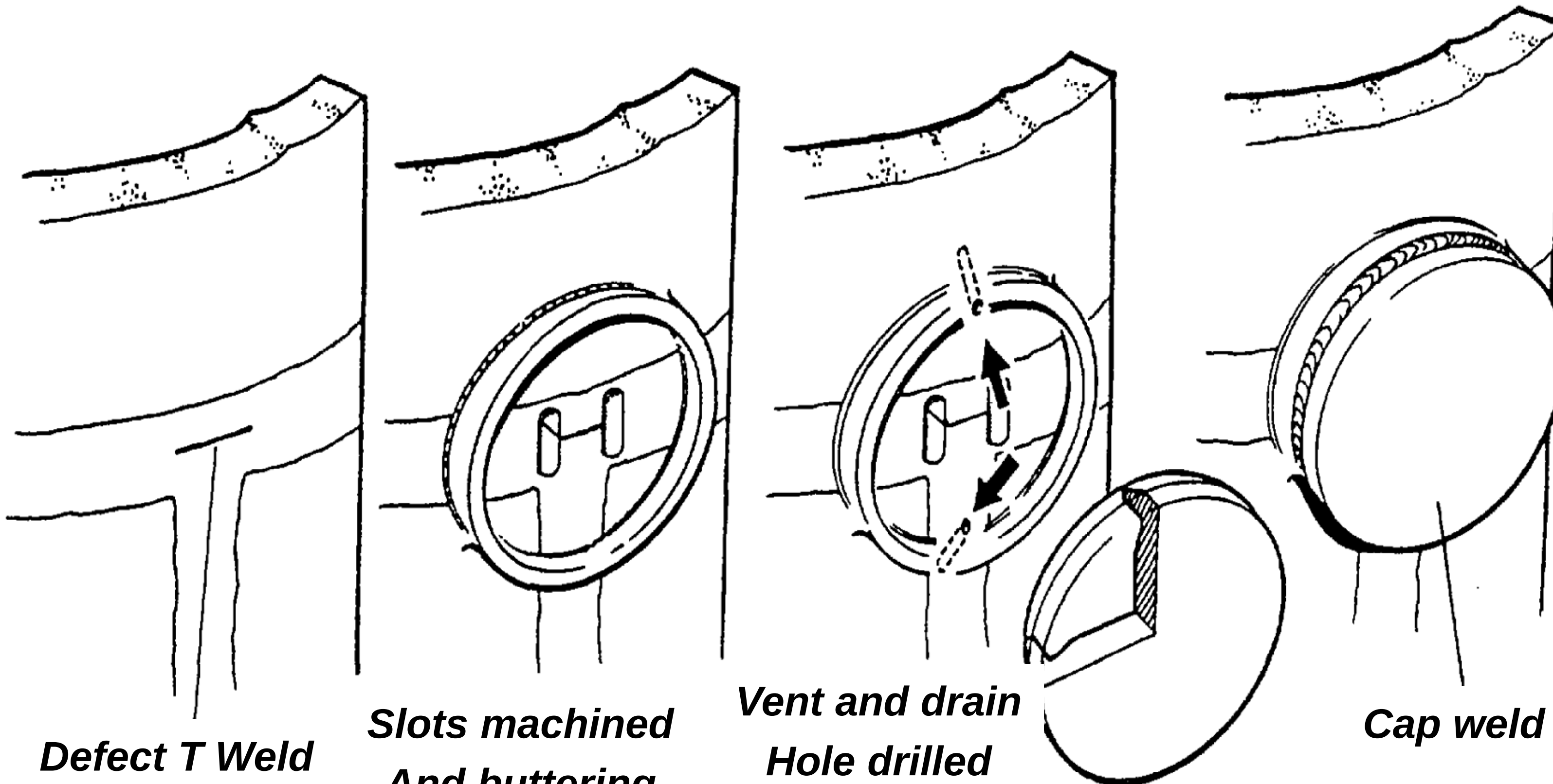
Examples: PFR, general

- *Cracking in PFR SG containment vessels was observed during maintenance activities*
- *Delayed reheat mechanism driven by residual stresses in non-stress-relieved welds initiated cracking in PFR SGs*
- *Weld repairs made during manufacturing gave rise to conditions that favored cracking*
- *Weld residual stresses must be properly managed in systems where creep may occur and where corrosion may take place*

Examples: PFR, general



Cruikshank, A., and Judd, A.M., "https://www-pub.iaea.org/MTCD/Publications/PDF/te_1180_prn.pdf.

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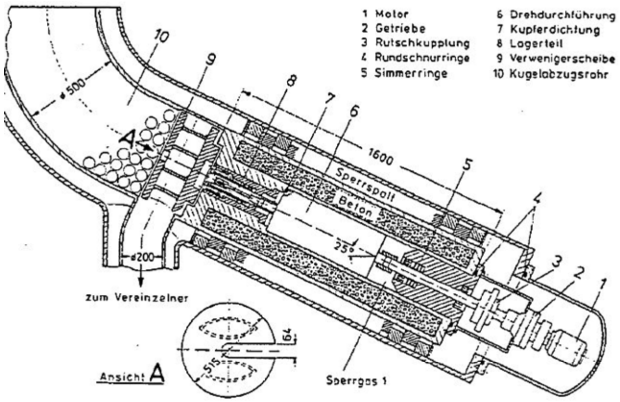
Examples: AVR, 1971-1981

- *Slowly rotating slotted double disk moves fuel pebbles move through the disk and down the pipe*
- *As the disk rotates, the pebbles are statistically distributed into the core.*
- *January 1971, internal friction cause drive motor to fail*
- *October 1974, a drive cam shear failure*
- *July 1976, the bearing shield became loose*
- *August 1976, a feather key sheared off in the reducer drive, stopping the reducer entirely*
- *December 1981, the drive no longer turned because of corrosion caused by water condensation*
- *The repeated failure of the reducer can be attributed to poor design*



Ziermann, E., and Ivens, GNRC Translation 3638, October 1997 (Agencywide Document Access Management System (ADAMS) Accession No. ML082130449).

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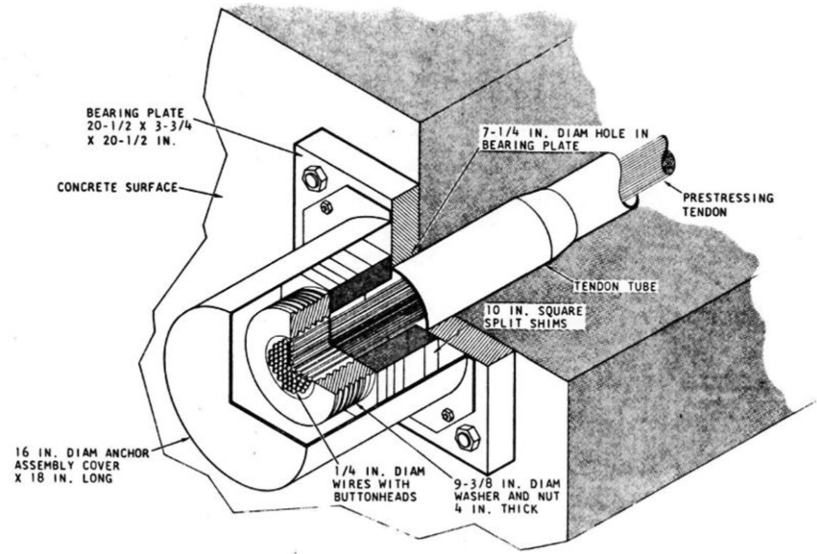
Examples: FSV, 1984

- *The PCRV tendon wires corroded*
- *PCRV: 448 tendons, each 3.87 meters wires*
- *Load cells were used to detect any loss of pre-stress*
- *The licensee found six broken tendons*
- *Tendons are stored in sealed boxes: preventing moisture ingress*
- *Pre-stress produces compression in the PCRV liner*
- *Sulfonate grease used on the tendon wires combined with oxygen from air ingress created acetic acid, corroded the tendons*
- *PCRVs are subject to degradation mechanisms that traditional RPV steels do not encounter in service*



Hildebrand, J.F., Atomic Energy Commission Research and Development Report, Gulf General Atomic, Inc., prepared under Contract AT (04-3)-633, June 22, 1970.

OpE Issues: SFR

- ***Sodium heat-transport systems experienced a significant number of leaks caused by poor weld design and poor weld quality control. Welds should be carefully designed to minimize residual stresses***
- ***Weld repair procedures often lead to tensile weld residual stresses in repair regions. Reheat cracking is a concern in SFR components operating at high temperatures. Weld repairs should be carefully managed because they may give rise to very high tensile residual stresses***
- ***Stresses induced by thermal expansion, particularly in areas of constraint, must be carefully considered for SFRs***

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OpE Issues: SFR

- *Thermal fatigue (thermal striping) in SFRs is a much more significant issue than it is for LWRs*
- *Management of the startup and cooldown transients in SFRs to control vibration, thermal expansion loads, and possible fatigue issues in the components is important*
- *Avoid shrink-fit parts in pumps*
- *Oil-based lubricants should be avoided in SFRs if possible*
- *Valve reliability under operating conditions should be accurately determined*

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OpE Issues: SFR

- ***Austenitic steels may be unsuitable for SFR SGs - risk of caustic stress-corrosion after small leaks***
- ***Confirm the chemical compatibility between molten sodium and insulation material***
- ***SFR design requires complete material databases***
- ***Secondary measurement devices must be designed to prevent leaks - complex fluid flows can cause failure and sodium leaks***
- ***The failure of in-sodium components without means for removal and repair has been costly***

OpE Issues: HTGR

- ***Tensile stresses caused by irradiation swelling can develop in the fuel elements - cracking of graphite fuel elements***
- ***Inaccurate core temperature calculations have led to thermal fatigue and fuel failure in pebble bed HTGRs***
- ***Future HTGRs must be designed to consider all aspects of potential moisture ingress and incorporate methods for removing moisture from the core and primary loop***

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OpE Issues: HTGR

- ***HTGRs must consider the accumulation of cycles during testing***
- ***HTGRs thermal expansion stresses can cause creep cracks***
- ***Abnormal abrasion in helium coolant compressors can degrade the performance of piston-ring seals and cause leakage***
- ***HTGR should be designed to minimize sources of graphite dust (e.g., fretting)***

OpE Issues: HTGR

- ***Control of alloy grain sizes important because alloys with excessive grain sizes may have insufficient toughness***
- ***Oil-based lubricants should be avoided in HTGRs***
- ***The design lesson from the Dragon experience is to ensure that the impact of SG tube ruptures in HTGRs will be limited (design-basis accident control)***
- ***Backup systems must be properly designed to handle overloads and system upsets, such as seismic loads***

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Summary

- *Brief summary OpE for SFRs and HTGRs from publicly available documents*
- *Material and structural degradation issues are the main interest*

https://www.nrc.gov/docs/ML1835/ML18353B121.pdf.

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Summary

Major Findings:

- ***Accidental air and moisture ingress should be expected***
- ***Thermal shock and thermal fatigue are more significant in SFRs***
- ***Weld quality, stress relief and inspection is critical***
- ***Core temperature analyses are problematic in HTGRs***
- ***Pumps and seals are frequent failure points in HTGRs***

https://www.nrc.gov/docs/ML1835/ML18353B121.pdf.

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Summary

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These topics in Draft report under NRC review at present

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Back up

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OpE Issues: SFR

- ***Sodium contamination and the consequent formation of sodium oxide have caused the binding of rotating machinery and control rod drives.***
- ***Better detection methods of corrosion and leaks are necessary, particularly in regions coated with insulation. The design phase should consider sensor placement and reliability under operating conditions. Inadequate or unreliable leak detection systems have caused extensive shutdowns because of sodium contamination and excessive sodium leaks with consequent fires.***
- ***The licensing process needs to scrutinize seismic and external dynamic loading events of SFRs. During an emergency shutdown (scram), the IHX may experience thermal shock caused by the influx of cold sodium. This condition could lead to buckling and structural issues amplified by an external loading.***