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Sodium as a Fast Reactor Coolant

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Topical Seminar Series on Sodium Fast Reactors

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Background

- **Unless new sources of energy are found, the development of nuclear power will necessarily depend on fast reactors.**
    - Fast reactors are not a new technology.
    - Fast reactors have achieved well over 300 reactor-years of operation.

- **To support effective actinide management (as envisioned by GNEP) a fast reactor must have a compact core with a minimum of materials which absorb or moderate fast neutrons. This places a significant heat transfer requirement on the coolant.**

- **The choice of coolant determines the main design approaches and the technical and economic characteristics of a nuclear power plant.**
    - Historically, this requirement has been met by the use of sodium in nearly all fast reactors constructed and operated.
    - The Generation IV International Forum (GIF) identified three fast reactor concepts for potential future development: SFR, LFR, and GFR.

Objectives

- Identify important differences between sodium and other fast reactor coolants (lead/LBE and helium) and why sodium is preferred.
- Characterize the nature of sodium interactions with air and water.
- Understand how differences between sodium and water result in broad design differences between a sodium-cooled fast reactor (SFR) and a light-water reactor.

Topics to be Covered

- **Historical Perspective on Reactor Coolants**
  - Coolants that have been used in the past
  - Coolants for future fast reactors: sodium, lead, helium
- **Comparison of Sodium with other Fast Reactor Coolant Options**
  - Thermophysical properties
  - Material properties
  - Neutronic properties
  - Safety
  - Cost
  - Other issues
- **Sodium Reactivity with Air and Water**
- **Impact of Coolant on SFR and LWR Differences**
  - Operating Pressure
  - Thermal Margins
  - Plant Design
- **Summary**

Historical Perspective on Reactor Coolants

Historical Perspective on Reactor Coolants

- **In the 1950s and 1960s, scientists and engineers considered (and in many cases built) nearly everything imaginable at the time:**
  - Water (light, heavy)
  - Liquid-metal (NaK, sodium, lithium, mercury, rubidium, lead, bismuth, lead-bismuth, gallium, tin, etc. and numerous other alloys)
  - Gas (air, argon, carbon dioxide, helium, hydrogen, nitrogen)
  - Fluid Fuel (aqueous: UO_2/phosphoric acid, $U(SO_4)_2$, UO_2SO_4/ThO_2; molten salt: $NaF\text{-}BeF_2\text{-}UF_4$, $LiF\text{-}BeF_2\text{-}ZrF_4\text{-}UF_4$/FLiBe; liquid metal: U-Bi)
  - Organic (polyphenyls/terphenyls, kerosene, Santowax)
- **Combinations of coolant and moderator were also studied:**
  - Sodium-cooled, graphite moderated (SRE, Hallam)
  - Organic-cooled, heavy water moderated (Whiteshell 1, ESSOR)

Historical Perspective on Fast Reactors

- **Data from IAEA Fast Reactor Database. Does not include submarine (S1G/S2G) or space reactors (SNAP).**
- **More recent fast reactors under construction:**
  - CEFR (China) 2008 25 MW_e
  - PFBR (India) 2010 500 MW_e
  - BN-800 (Russia)
- **China has an ambitious vision to deploy 200 GWe of sodium-cooled fast breeder reactors by 2050 (12% of projected capacity).**

Facility	Country	First Critical	Coolant
Clementine	USA	1946	Mercury
EBR-I	USA	1951	NaK
BR-2	Russia	1956	Mercury
BR-5/BR-10	Russia	1958	Sodium
DFR	UK	1959	NaK
Fermi	USA	1963	Sodium
EBR-II	USA	1963	Sodium
Rapsodie	France	1967	Sodium
BOR-60	Russia	1968	Sodium
SEFOR	USA	1969	Sodium
KNK-II	Germany	1972	Sodium
BN-350	Kazakhstan	1972	Sodium
Phenix	France	1973	Sodium
PFR	UK	1974	Sodium
FFTF	USA	1980	Sodium
BN-600	Russia	1980	Sodium
JOYO	Japan	1982	Sodium
FBTR	India	1985	Sodium
Super-Phenix	France	1985	Sodium
MONJU	Japan	1995	Sodium

Historical Perspective on Sodium

- **Liquid metals in general have received the most attention for fast reactor applications because of their high thermal conductivity, indifference to radiation, and useful temperature range at low pressure.**

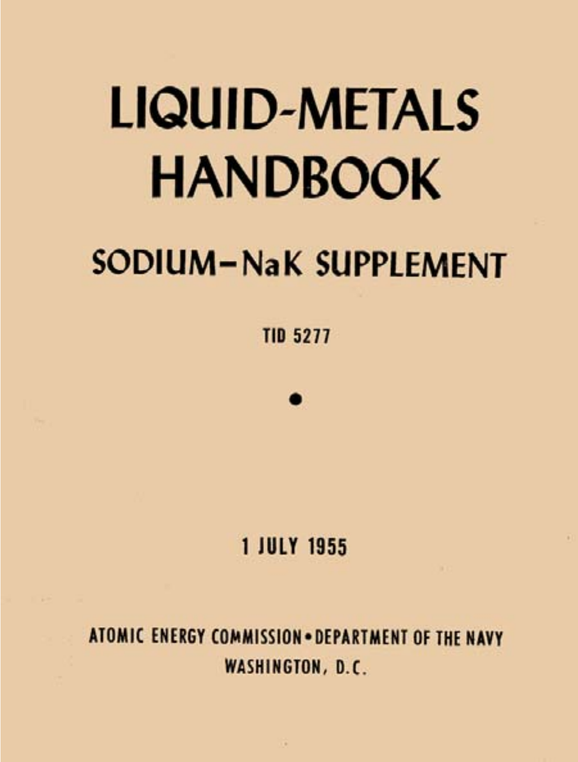
  Liquid-Metals Handbook, NAVEXOS-P-733, US Atomic Energy Commission, US Navy, US Government Printing Office, Washington DC, June 1952. (Revised in 1954)

- **Sodium received so much additional attention, that a supplement to the Liquid-Metals Handbook was published in 1955**

  Liquid-Metals Handbook: Sodium-NaK Supplement, USAEC Report TID-5277, US Atomic Energy Commission, US Navy, US Government Printing Office, Washington DC, July 1955.

- **Numerous additional reports and monographs have been published since. More recently, during the IFR program:**

  J. K. Fink and L. Leibowitz, “A Consistent Assessment of the Thermophysical Properties of Sodium,” *High Temperature and Materials Science*, 1996.



LIQUID-METALS
HANDBOOK

SODIUM–NaK SUPPLEMENT

TID 5277

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1 JULY 1955

ATOMIC ENERGY COMMISSION • DEPARTMENT OF THE NAVY
WASHINGTON, D.C.

Historical Perspective on LBE

- **In the U.S., use of lead/LBE was dismissed early mainly due to high pumping power requirements.**
- **A program for studying compatibility of lead, bismuth, and their alloys with structural materials existed at BNL between 1950 and 1962 as part of the Liquid Metal Fuel Reactor program.**
  - Focus was on development/testing of a natural U-Bi liquid metal fuel.
  - An in-pile liquid-metal fuel loop was constructed and tested in the 1950s
- **Recent interest in lead and LBE developed as part of their application to accelerator-driven systems as target/coolant materials.**
- **The only LBE-cooled reactors are those developed for the Soviet Project 705 (Alfa-class) submarines**
  - Modified November-class (Project 645) commissioned in 1963 to test reactors intended for Alfa-class submarines.
  - Initial prototype (Project 661/Papa Class) commissioned in 1969.
  - Production started in 1974, with first commissioning in 1977. Production ended in 1983 with seven vessels.

Historical Perspective on LBE (continued)

- **Two different reactor designs were used in the Alfa-class submarines: OK-550 and BM-40A.**
  - Significant effort invested to solve the problem of LBE corrosion.
  - Detailed information on the results of Russian LBE testing is difficult to find in the literature.

Project 705 Alfa-class Submarine

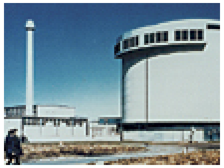
- **First vessel was decommissioned in 1987, with four more by 1992. At least one vessel was refitted with a VM-4 PWR and used for training.**
- **Reactors were single-use designs with HEU and a long core lifetime (up to 15 years)**
  - Coastal facilities were constructed to provide superheated steam during shutdown and maintenance to keep the LBE molten. These proved to be unreliable and completely broke down in the 1980s.
  - Reactors were kept running even while in harbor, and significant maintenance became impossible.
  - Reactor failures and coolant leaks led to a number of fatalities.

Historical Perspective on Helium

- **No gas-cooled *fast* reactors have ever been constructed**
  - GA led efforts to develop a gas-cooled fast breeder reactor in the 1970s.
- **Most early gas-cooled reactors were CO_2 cooled, graphite moderated, natural uranium reactors developed primarily for plutonium production (mainly in UK and France)**
- **Vast majority of currently-operating gas-cooled reactors use CO_2 for coolant (UK: 14 AGR, 8 Magnox)**
- **Helium-cooled *thermal* power reactors (using enriched uranium) include:**
  - USA: Peach Bottom 1 (1967 – 1974),
    Fort St. Vrain (1974/9 – 1989)
  - UK: Dragon (1966 – 1976)
  - Germany: AVR/Jülich (1967 – 1988)
    THTR-300 (1985 – 1988)
  - Japan: HTTR (1998/2002 – Present)
  - China: HTR-10 (2000/3 – Present)

Peach Bottom

Fort St. Vrain



Dragon

THTR

Properties of Fast Reactor Coolants: Sodium, Lead/LBE, and Helium

Coolant Criteria

- **Thermophysical Properties:**
  - Excellent heat transfer
  - Low vapor pressure
  - High boiling point
  - Low melting point
- **Material Properties:**
  - Thermal stability
  - Radiation stability
  - Material compatibility
- **Neutronic Properties:**
  - Low neutron absorption
  - Minimal induced radioactivity
  - Negligible moderation
- **Support Passive Safety**
- **Cost:**
  - Initial inventory
  - Make up inventory
  - Low pumping power
- **Hazards:**
  - Non-toxic
  - Non-reactive

Thermophysical Properties for Fast Reactor Coolants

	Na	**Pb**	**LBE**	**He**
Atomic Weight	22.997	207.21	208	4
Melting Point (°C)	97.8	327.4	123.5	n/a
Boiling Point (°C)	892	1737	1670	-267
Density (kg/m^3)	*880*	*10500*	*10300*	0.178
Specific Heat (J/kg-K)	*1300*	*160*	*146*	5200
Heat Capacity (MJ/m^3-K)	*1.14*	*1.68*	*1.50*	0.0009
Thermal Conductivity (W/m-K)	*76*	*16*	*11*	0.152 *0.238*
Viscosity (cP)	*0.34*	*2.0-2.5*	*1.7*	0.018 *0.031*

Values at STP. *Italic = Evaluated at ~300°C*

Thermophysical Properties

- **Despite very different densities and specific heat, sodium and LBE have similar volumetric heat capacities.**
  - Similar volumetric flow rates
  - For identical flow geometries, similar flow velocity. But LBE will have a significantly higher pressure drop and pumping requirements.
  - LBE will develop slightly higher natural circulation velocity, but at the expense of somewhat higher cladding temperatures.
- **Relatively low thermal conductivity of LBE (combined with low flow velocity) affects heat transfer from cladding to coolant.**

- **Specific heat of helium is high, but density is very low. Requires a high pressure system (~85 atm) and high coolant velocity (~100 m/s). Introduces risk of flow-induced vibrations.**
- **Low thermal conductivity of helium results in poor heat transfer even at high coolant velocity. Cladding surfaces can be roughened to improve heat transfer (4x), but it is still 8-9x lower than for sodium.**

Material Properties

- **Sodium, LBE, helium have excellent thermal and radiation stability.**
- **Compatibility of coolants with available structural, heat exchanger, and pump materials is a key criteria for selection.**
  - Helium is chemically inert, but low molecular weight leads to diffusive losses at seals and valves. Impurities (especially moisture) can lead to corrosion.
  - Liquid metals may selectively deplete constituents from, and impurities may chemically react with, structural materials
  - Chemistry control will be required for all coolants.
- **Standards for sodium:**
  - *ASTM C 1051–85*: “Standard Specification for Sodium as a Coolant For Liquid Metal-Cooled Reactors” (withdrawn in 2000).
  - *ASTM C 997–83*: “Standard Test Methods for Chemical and Instrumental Analysis of Nuclear-Grade Sodium and Cover Gas” (withdrawn in 1999).

Material Properties (Sodium)

- **Primary issue with sodium is its chemical reactivity in air and water.**
- **Sodium is inherently compatible with stainless steels, requiring no special corrosion protection measures**
  - Oxygen preferentially reacts with sodium, forming Na_2O.
  - Oxygen impurity can readily be maintained well below 10 ppm using a cold trap.
  - No difference between high-purity sodium and helium when comparing strain-rate and creep-rupture data for austenitic steels. No indication of liquid metal embrittlement.
  - Based on long-term corrosion testing in BR-10, “the operating service life of sodium equipment in fast reactors can be increased to 60 yr and longer.”
- **Fuel-coolant interactions are benign for metallic fuel.**
- **Many fission products are soluble in sodium and can be filtered out in the cold trap.**
- **Database for sodium compatibility is extensive, with information available in the open literature.**

Material Properties (LBE)

- **Prior to 1998, material database relied mainly on anecdotal information from Russian sources.**
- **Solubility of steels in LBE is generally higher than in lead (due to Bi). Solubility of Ni is of particular concern (Ni ~37000 ppm at 600°C).**
- **Russian approach is to maintain a protective oxide layer on structural components (particularly cladding) and minimize coolant flow velocities.**
  - Applicable to ferritic-martensitic steels.
  - Above 550°C, oxide layer can become thick and unstable
  - Oxygen control is a dynamic equilibrium: thickness of oxide layer stabilizes, but structural (cladding) weight loss continues.
  - Coolant velocity and high shear stress (viscosity) results in erosion.
  - Oxide layer impacts heat transfer from cladding to coolant.
- **Oxide control:**

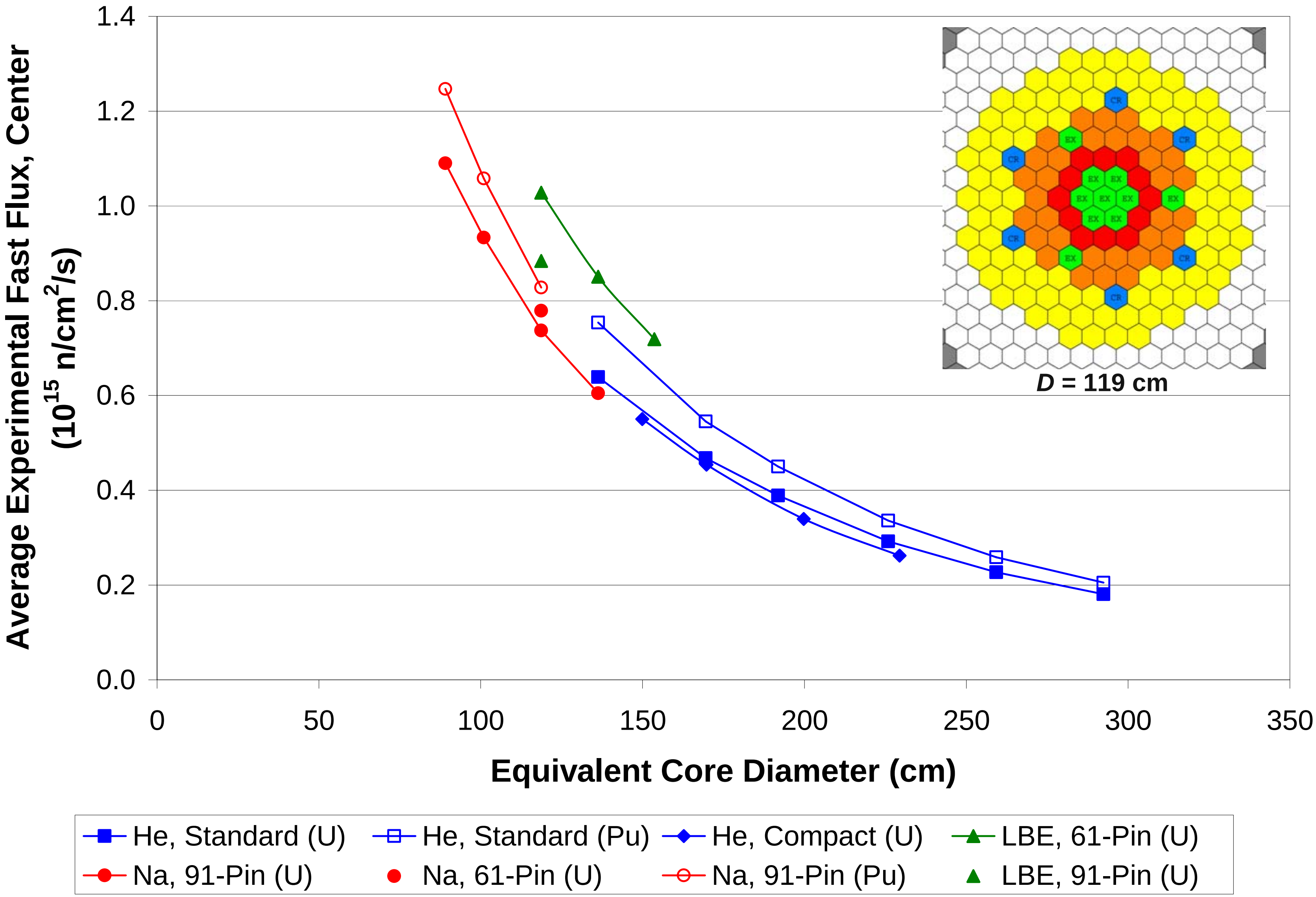
Oxide Control in LBE Systems

- **Oxygen is controlled by constant addition (e.g. flow over PbO “balls”) and subtraction (e.g. bubbling hydrogen gas in a helium carrier to form water).**
- **Problems with oxygen control:**
  - Non-homogeneous oxygen distribution in real systems results in non-uniform coatings. Crevice corrosion and dissolution of occlusions can occur.
  - Magnetite (Fe_3O_4) undergoes a phase transformation at 570°C.
- **Newer solution is to prefer SiO_2 and Al_2O_3 based oxide layers.**
  - Oxide layer forms at lower oxygen concentrations.
  - No phase transformation.
  - EP-823 (Russian steel similar to HT-9 but with higher Si content).
  - Silicon degrades mechanical properties (ductility) and reduces irradiation performance.
  - Some interest in oxide dispersion strengthened (ODS) steels. Irradiation performance and cost are not well known.

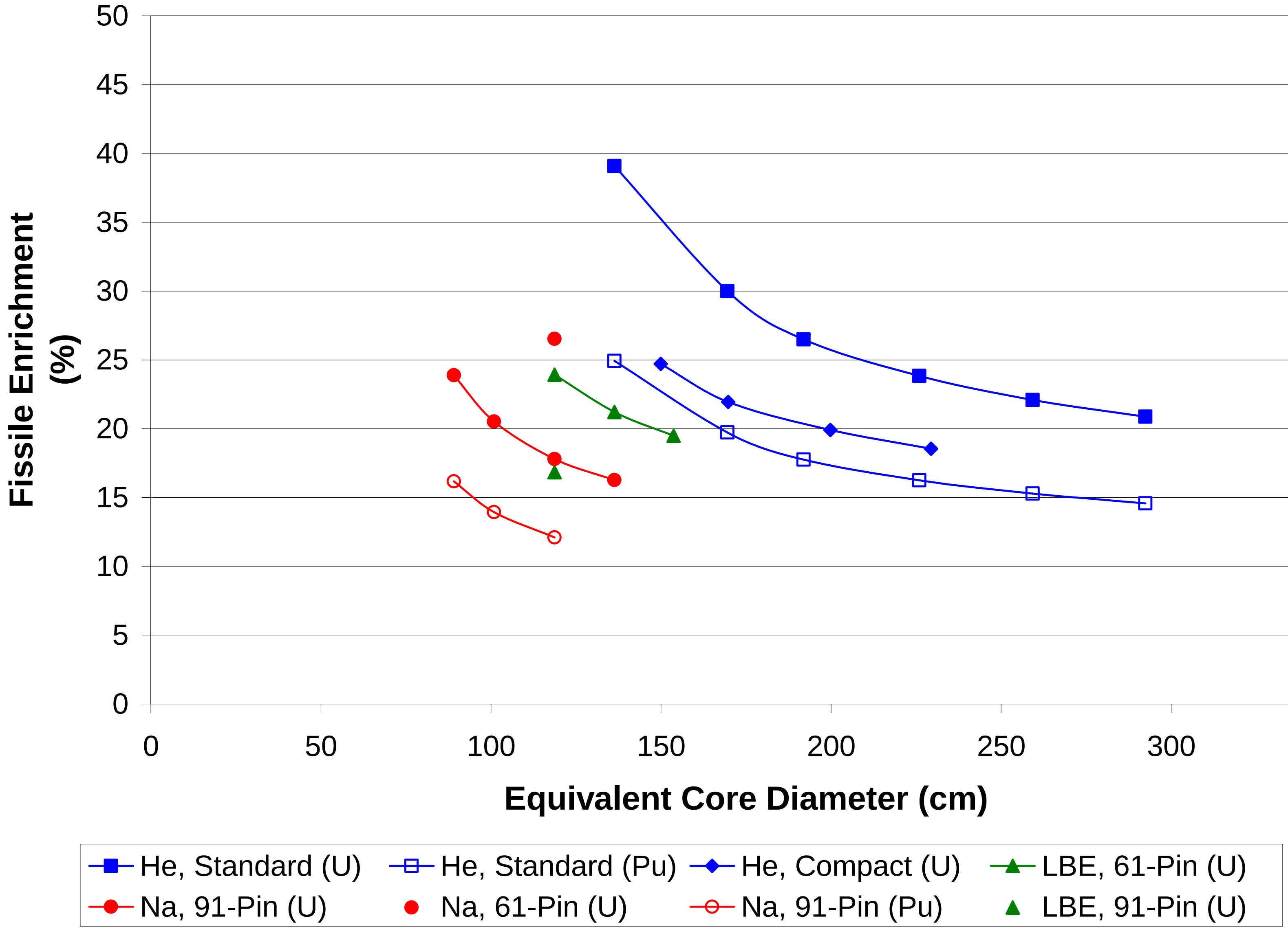
Neutronic Characteristics

- **Sodium, Lead, LBE, and Helium are all suitable for fast reactor applications**
  - Sodium and LBE both introduce a small amount of parasitic absorption.
  - Reduced neutron leakage in an LBE system allows for a higher coolant volume fraction.
  - Helium is transparent to neutrons, and the relatively low density leads to negligible moderation, but this leads to a higher neutron leakage fraction.

Sensitivity of Neutron Flux to Varying Parameters

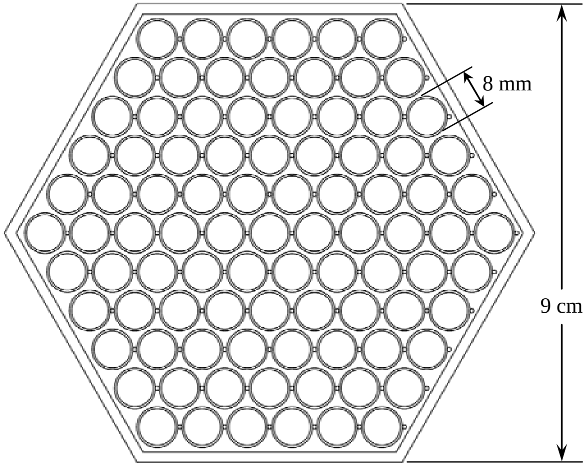


Sensitivity of Enrichment to Varying Parameters

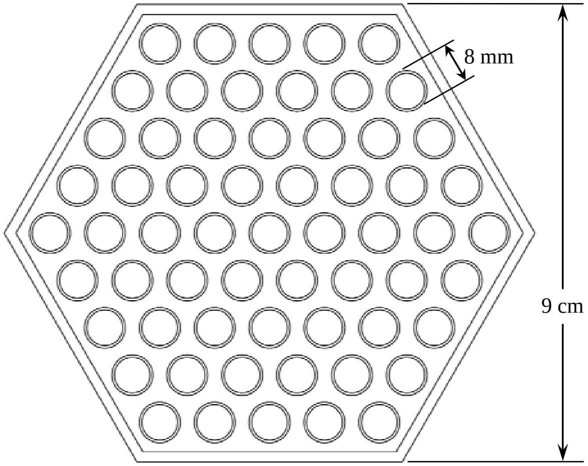


Scaling to Higher Power

- **When comparing sodium and LBE designs with identical geometries, LBE:**
  - Requires a slightly lower enrichment
  - Can produce a higher fast flux
  - Results in a lower fissile inventory.
- **Use of identical geometries does not account for optimization based on individual coolant properties**
- **250 MW_{th} options for sodium and LBE were evaluated to assess more realistic core designs.**
  - Additional constraint on fissile uranium enrichment: < 20% U-235 (LEU)
  - Coolant velocity limit (2 m/s) imposed on LBE to limit erosion.
  - Core designs were adjusted to achieve similar experimental flux levels.



Sodium Concept



LBE Concept

Scaling to Higher Power

- **Sodium coolant results in a smaller core with higher power density, lower enrichment, fewer driver assemblies, and lower heavy metal inventory**

	Sodium	**LBE**
Thermal Power (MW)	250	250
Coolant Velocity (m/s)	8.3	2.0
Average Experimental Fast Flux (10^{15} n/cm^2/s)	**1.83**	**1.79**
Number of Driver Assemblies	**135**	**237**
Pins per Assembly	91	61
Equivalent Core Diameter (cm)	**119**	**154**
Active Height (cm)	100	100
Fissile Enrichment (%)	**18.3**	**20.0**
Heavy Metal Inventory (kgHM)	**5138**	**5716**

- **Sodium case still has room for further optimization**

Coolant Activation

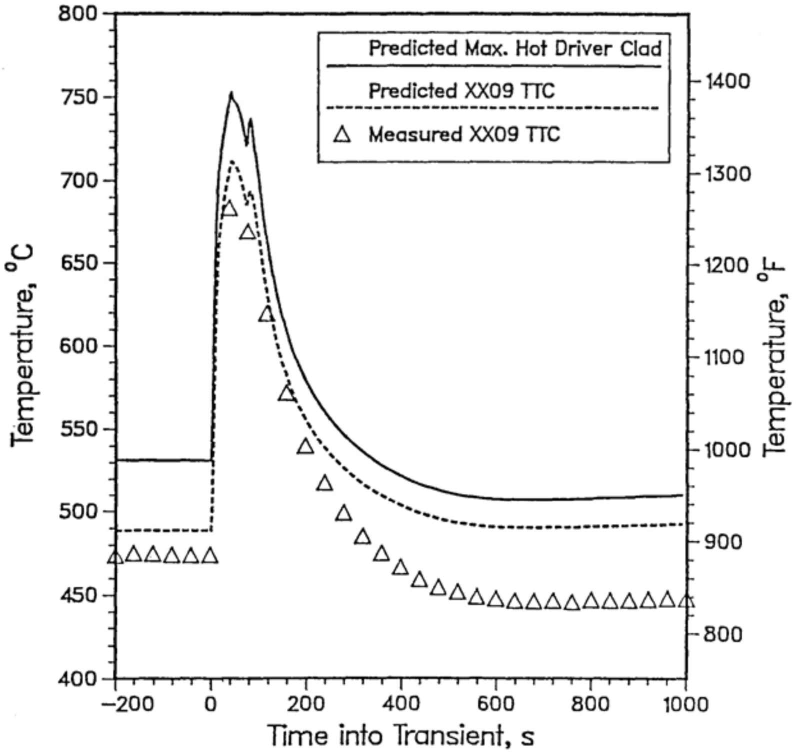
- **Coolant activation results in radioactive isotopes circulating through the primary loop.**
  - Helium yields no activation products unless impurities are present.
  - Sodium: $^{23}Na(n,\gamma)^{24}N$ ($t_{1/2}$ = 15 hours)
  - LBE: $^{209}Bi(n,\gamma)^{210}Bi$, $^{210}Bi \rightarrow {}^{210}Po$ ($t_{1/2}$ = 138 days)
- **Operationally, this requires shielding for primary components.**
- **Po-210 represents a significant biological hazard, requiring a leak-proof system.**
  - $PbPo(s) + H_2O = PbO + H_2Po(g)$ (volatile alpha-emitting aerosol)
- **Estimates of cool-down time to meet the IAEA "exemption" criteria (to be freely used for other industrial purposes):**
  - Sodium (pure): ~7 years
  - Sodium (with impurities): 50-100 years
  - LBE: ~100,000 years
- **Experience exists for processing large quantities of primary sodium coolant for disposal (EBR-II).**

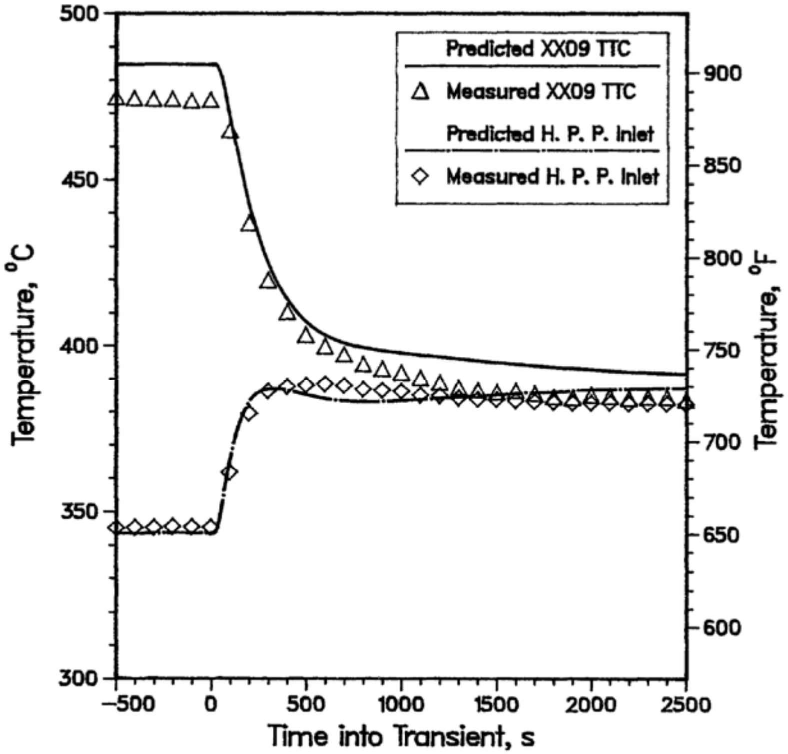
Passive Safety (Liquid Metals)

- **Heat capacity and high thermal conductivity of liquid-metal coolants provides large thermal inertia against system heating during loss-of-flow accidents.**
  - Combined with favorable reactivity feedback (core design/fuel choice) sufficient cooling is available to support passive shutdown.
  - Full-power unprotected loss of flow and loss of heat sink accidents demonstrated in EBR-II in 1986. Similar tests (at 50% power) demonstrated passive response in FFTF
- **Response of lead/LBE systems to seismic events will pose design challenges.**
  - For medium-sized plant, one can expect primary coolant alone to weigh ~10,000 metric tons.
  - Structural design of primary system becomes a significant challenge.

Passive Safety (Demonstrated in EBR-II in 1986)

- Unprotected (no scram) Loss of Flow (ULOF) results in brief temperature rise which is terminated by negative reactivity feedback effects
- Unprotected Loss of Heat Sink (ULOHS) causes increase in inlet temperature which introduces negative reactivity feedback effects.





Passive Safety (Helium-Cooled Fast Reactor)

- **In gas-cooled thermal reactors, graphite moderator provides a large heat capacity against excessive temperature rises. Not present in a fast reactor.**
- **Low thermal conductivity of helium coolant minimizes thermal shock during transients.**
  - Thermal transients do not propagate to structural materials rapidly. Heat is deposited in the fuel.
  - Despite minimal thermal shock, power-to-flow mismatches may be a significant safety concern for gas-cooled fast reactors.
- **GFR relies on secondary vessel/containment to limit pressure loss.**
  - May be able to support decay heat removal, but not full-power transients.
  - Adequate decay heat removal may not be possible under loss of pressure scenarios.

Coolant Cost

- **Direct cost**
  - Sodium: On a volume basis, it is generally the cheapest of all metals, and is among the most abundant elements in the earth's crust. 2006 price from DuPont (reactor grade/Niapure™) is \$1.58/lb (\$3400/m^3).
  - Lead: 2005 USGS, 43 – 61 ¢/lb (\$15,000/m^3).
  - Bismuth: U.S. ceased domestic production in 1997 and is highly dependent on imports. By the end of 2005, USGS-tracked price had increased to >\$4/pound (\$86,000/m^3).
  - The Helium Privatization Act of 1996 mandates the price of helium. In 2005, Government price was 1.965 \$/m^3. Private prices ranged from 2.42 to 2.63 \$/m^3. At 85 atm, this is roughly \$220/m^3.
- **Indirect costs**
  - Coolant chemistry/purification, inventory makeup (helium).
  - Pumping requirements.
  - Core and primary system size.
  - Component lifetime.
  - Passive safety and safety-related systems.

Other Considerations

- **Component Technology R&D**
  - Regardless of coolant, component testing will be required.
  - 50+ years of sodium component development, testing, and operation.
- **Fuel handling**
  - Opaqueness of sodium and lead/LBE affects fuel handling.
  - Need to maintain pressure boundary with helium also affects fuel handling.
  - Must be able to remove residual coolant from spent fuel or test assemblies.
  - Significant experience exists for “washing” sodium from spent fuel with steam or moist air.
  - Removing LBE from spent fuel may require an acidic “brew” or boiling in glycerin. Sodium may be used, but it will also remove surface oxides.

Sodium as a Fast Reactor Coolant

- **Thermophysical and thermal-hydraulic properties of sodium are superior to lead or helium.**
  - Smaller core with higher power density, lower enrichment, and lower heavy metal inventory. Demonstrated passive safety performance.
  - Use of sodium codified in ASTM standards.
- **Extensive testing of coolants lead to nearly all (land-based) fast reactors constructed during the last 50 years using sodium as the primary coolant.**
  - Current fast reactor construction projects use sodium as the primary coolant.
  - LBE-cooled reactors limited to Russian Alfa-class submarine experience.
  - No He-cooled (or gas-cooled) fast reactors.

Thermophysical Properties:	
Excellent Heat Transfer	✓+
Low Vapor Pressure	✓+
High Boiling Point	✓+
Low Melting Point	✓
Material Properties:	
Thermal Stability	✓+
Radiation Stability	✓+
Material Compatibility	✓+
Neutronic Properties:	
Low Neutron Absorption	✓+
Minimal Activation	✓
Negligible Moderation	✓+
Supports Passive Safety	✓+
Cost:	
Initial Inventory	✓+
Make-Up Inventory	✓+
Low Pumping Power	✓+
Hazards:	
Sodium reacts with air and water (next)	

Sodium Reactivity with Air and Water

Sodium Reactivity with Air

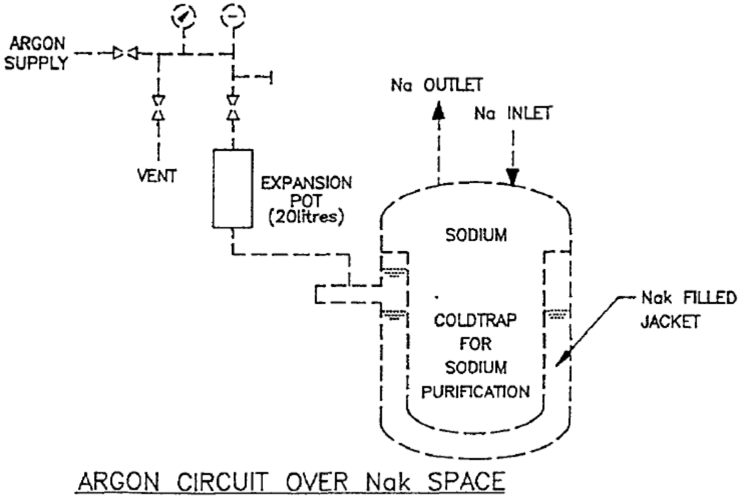
- **Burning reaction is characterized by a zone of small (few cm) flames at the sodium-air interface, formation of Na_2O on the surface, and vigorous emission of oxide fumes.**
- **Sodium reaction with air is slow and causes relatively low heat release**
  - Sodium has a high latent heat of vaporization and high boiling temperature.
    - *This results in a low evaporation rate during combustion.*
    - *Gasoline will burn approximately 4 times faster than sodium*
  - Sodium-air heat of reaction is one-fourth that of burning gasoline.
    - *Energy released during sodium burning is approximately a factor of 15 lower than in the case of gasoline.*
  - In one series of tests, temperature 1 meter above a 1 square meter pool of burning sodium was less than 100°C.
  - For gasoline, the flame zone extended as high as 4 meters and the average temperature 2 meters above the pool exceeded 600°C.

Sodium Reactivity with Air

- **Sodium aerosols (NaO and Na_2O) react with air (including water vapor and CO_2) to produce NaOH, and Na_2CO_3.**
  - Production of NaOH takes a few seconds after particle formation.
  - Na_2CO_3 formation can take several minutes.
- **Aerosols deposit on the floor, walls, and ceiling.**
  - Aerosol particles can cause equipment damage (electrical and instrumentation)
  - Highly toxic
- **Sodium leaks can be detected through gas sampling techniques**
  - Ability for detection means leaks can be readily identified.

Sodium Leaks

- **Most sodium leaks have been small and were the result of design and/or fabrication deficiencies.**
- **E.g. leak from the secondary cold trap at the Fast Breeder Test Reactor:**
  - During initial commissioning, preheating of the cold trap led to over-pressurization of the NaK “jacket” due to inadequate expansion space.
  - 2.5 liters of NaK leaked through a spark-plug type high-level probe.
  - A 20 liter expansion “pot” was added to the argon supply line to prevent overpressurization.

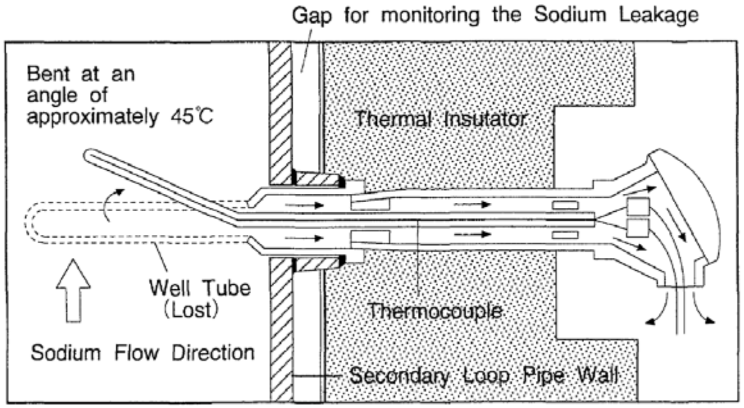


Source: Figure 5 from R.P. Kapoor, et al., “Unusual Occurrences in Fast Breeder Test Reactor," *Unusual Occurrences During LMFR Operation*, IAEA-TECDOC-1180, October 2000. Used with permission.

- **Of the 27 leaks at BN-600, the main causes have been identified as**
  - Inadequate valve design.
  - Insufficient thermal compensation and manufacturing faults.
  - Loss of leak-tightness in sodium reception from tanker cars.
- **Causes for leaks are known.**

Significant Sodium Leaks *

- **BN-600**
  - 1981: Flange joint failure in SG valve seal (300 kg)
  - 1990: Manufacturing defect in SG drain pipeline (600 kg)
  - 1993: Thermal expansion induced failure in primary sodium purification system (1000 kg, ~10 Ci)
  - 1994: Staff error, pipeline cutting before sodium was frozen (650 kg)
- **Monju (8th December, 1995) secondary sodium leak (~640 kg)**
  - 19:47 – Off-scale sodium temperature alarm at IHX outlet, followed by fire alarm, and sodium leak alarm
  - 20:00 – Reactor power-down begins
  - 21:20 – Reactor manually tripped due to observation of increased fumes
  - 22:55 – Began draining secondary sodium circuit
  - 00:15 – Draining operations completed



Source: Figure 4 from A. Miyakawa,et al., "Sodium Leakage Experience at the Prototype FBR Monju," *Unusual Occurrences During LMFR Operation*, IAEA-TECDOC-1180, October 2000. Used with permission.

- **No adverse effects were reported for operating personnel or surrounding environment**

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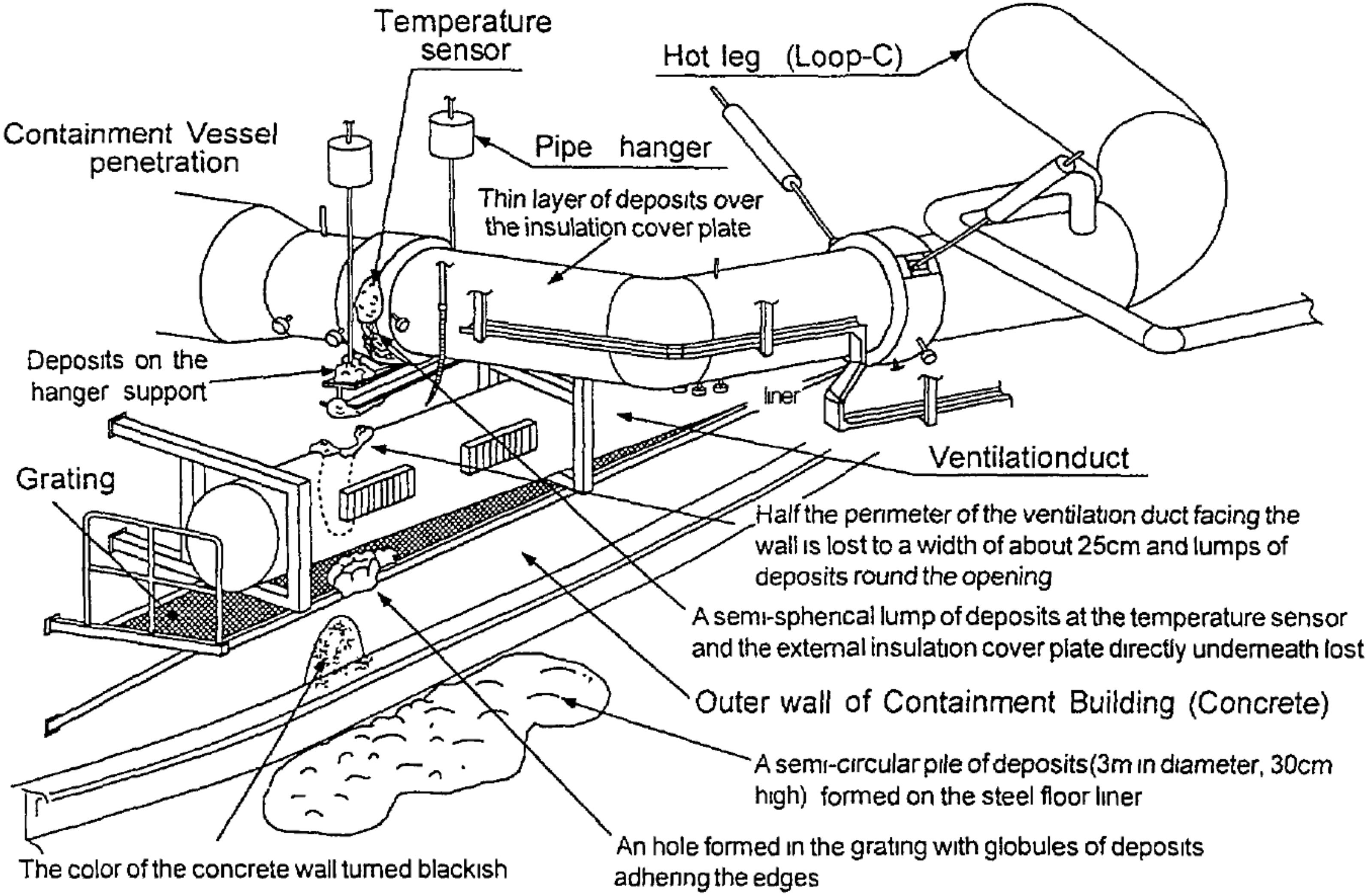
* IAEA-TECDOC-1180: *Unusual Occurrences During LMFR Operation*, October 2000

Consequences of the Sodium Leak at Monju



Source: Figure 2 from A. Miyakawa,et al., “Sodium Leakage Experience at the Prototype FBR Monju," *Unusual Occurrences During LMFR Operation*, IAEA-TECDOC-1180, October 2000. Used with permission.

Sodium Reactivity with Water

- **Sodium-water chemical interactions take place in two stages.**
- **In the first stage, the reaction proceeds at a high rate with release of gaseous hydrogen:**

  $Na + H_2O = NaOH + ½\ H_2 + 140\ kJ/mole$

- **In the second stage, chemical interaction takes place between the products of the first stage and excess sodium:**

  $2\ Na + NaOH = Na_2O + NaH$

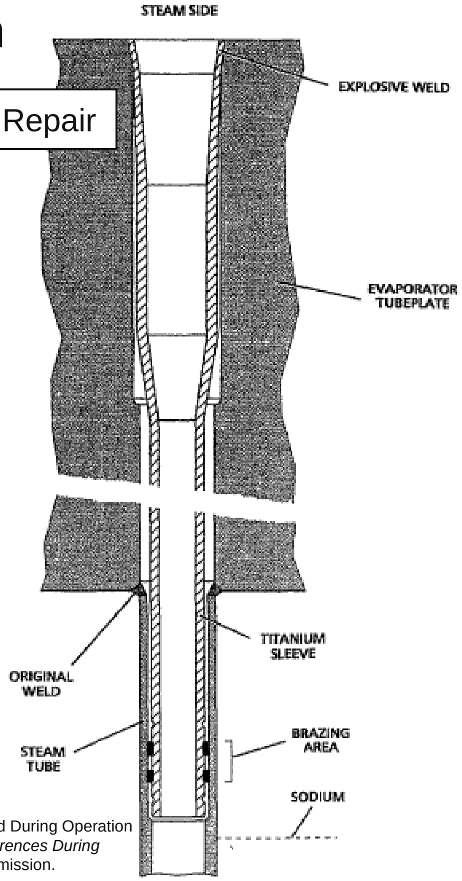
  $Na + ½\ H_2 = NaH$

- **Hydrogen detection plays a key role in leak detection**
  - Diffusion method uses a metal membrane permeable to hydrogen.
  - E.g. diffusion of hydrogen through a nickel membrane into a vacuum cavity coupled to a magnetic discharge pump.
  - Capable of detecting 10 – 30 gram water leak into 100 tons of secondary sodium.
- **Acoustic detection techniques are also being developed.**

Sodium Reactivity with Water

- **Potential for sodium/water interactions requires separation of steam cycle from primary system: an intermediate sodium loop is used.**
- **Lack of fabrication experience in early sodium/water steam generators resulted in a number of large and small water leaks into the sodium.**
  - 33 gas-space leaks in PFR SGs were all associated with cracking of the tube-to-tubeplate welds due to lack of post-weld heat treatment.
  - Large ingress of water does not lead to catastrophic consequences. (One incident at BN-350 leaked 800 kg of water into secondary sodium.)
  - Components remained repairable.
- **Steam generators can be designed to minimize the impact of leaks on the operation of the plant as a whole.**
  - Minimize weld joints and prevent flow-induced vibrations
  - Proper selection of tube materials, thickness, spacing
  - Use of expansion volumes, rupture disks
  - Accommodate leak detection

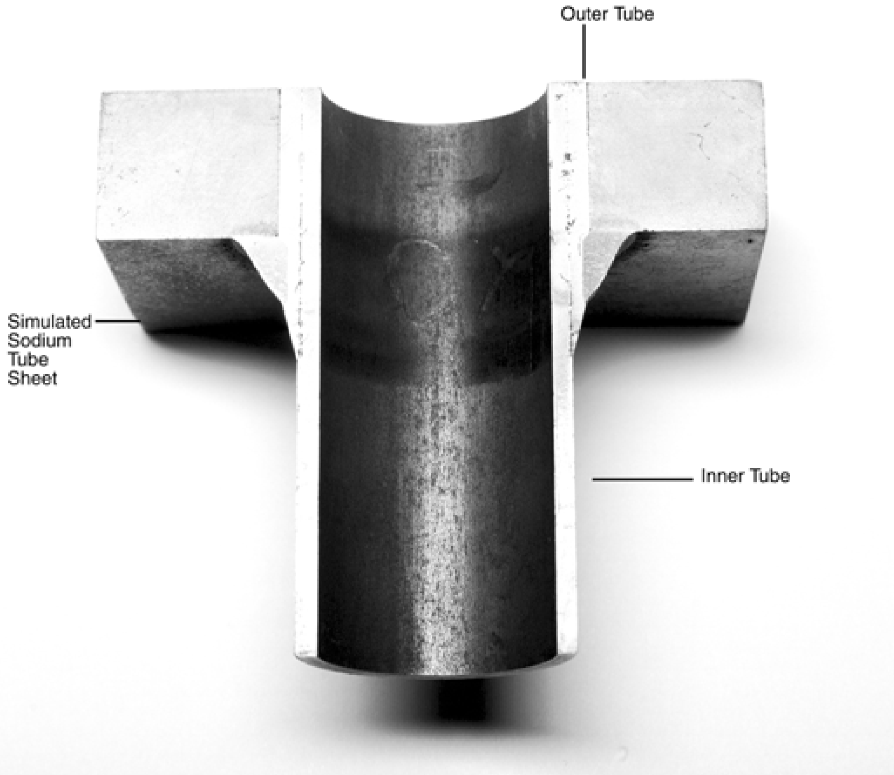
PFR Weld Repair



Source: Figure 1.4 from A. Cruickshank, et al., “Problems Experienced During Operation of the Prototype Fast Reactor, Dounreay, 1974-1994,“ *Unusual Occurrences During LMFR Operation*, IAEA-TECDOC-1180, October 2000. Used with permission.

EBR-II Steam Generator Experience

- **No *tube* leaks occurred during the 30 years of operation of EBR-II.**
- **No sodium leaks occurred at the tube-to-sodium tube sheet welds.**
- **One water/steam leak occurred at the tube-to-steam tube sheet.**
  - Steam leaked into the space between the two tube sheets.
  - This weld was repaired (only one tube-to-tube sheet weld was involved) and the unit was returned to service.
  - Repaired unit operated satisfactorily for the life of the plant.
- **The EBR-II objective was achieved: sodium and water never came in contact during the operating lifetime of the plant.**



Source: Figure C-30 from L. J. Koch, *Experimental Breeder Reactor-II (EBR-II) An Integrated Experimental Fast Reactor Nuclear Power Station*, © 2008 by the American Nuclear Society, La Grange Park, IL. Used with permission.

Impact of Coolant on SFR and LWR Differences

Coolant Choice Affects Design Differences

- **The choice of sodium has broad consequences in reactor design**
  - Absence of high pressure in the primary system
  - Higher operating temperatures with significant thermal margins
  - More compact fuel assembly designs
  - Incorporation of an intermediate loop
  - Different arrangements for fuel handling

Selected Properties of Sodium and Water

	Sodium	**Water**
Atomic Weight	22.997	18
Optical Properties	Opaque	Transparent
Melting Point (°C)	97.8	0
Boiling Point (°C)	892	100
Density (kg/m^3)	*880*	*713*
Specific Heat (J/kg-K)	*1300*	*5600*
Heat Capacity (MJ/m^3-K)	*1.14*	*4.00*
Thermal Conductivity (W/m-K)	*76*	*0.54*
Viscosity (cP)	*0.34*	*0.1* (~1)

Values at STP. *Italic = Evaluated at ~300°C (and 2000 psi for water)*

Sodium Allows Operation at Low System Pressure

- **While PWRs operate at system pressures in excess of 2000 psi, the inert cover gas in a sodium-cooled fast reactor is near atmospheric pressure.**
- **This difference impacts several design features:**
  - Vessel Thickness: PWR ~10 inches, SFR ~ 1 inch
  - No need for pressurization of SFR fuel pins.
- **Low system pressure offers advantages in terms of safety:**
  - Minimal pressure loading on the coolant boundary.
  - In a high-pressure system, coolant pipe breaks are a concern.
  - In a low-pressure system, coolant leaks are unlikely to propagate to a large-scale failure.
  - No need for high-pressure injection cooling.

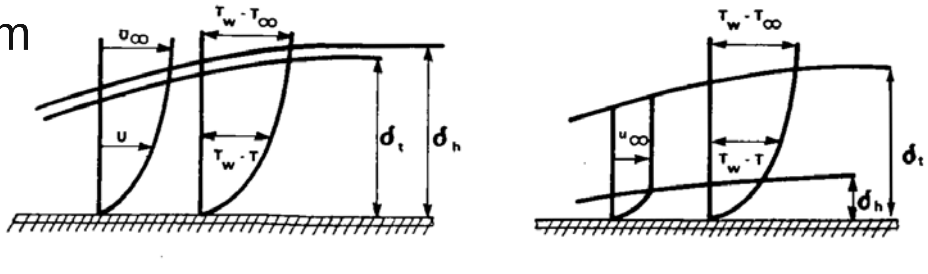
Sodium Provides a Large Margin to Coolant Boiling

	PWR (2200 psi)	SFR
Inlet Temperature (°C)	300	355
Core ΔT (°C)	30	155
Outlet Temperature (°C)	330	510
Boiling Temperature (°C)	345	>892
Margin to Boiling (°C)	15	>380

- Some nucleate boiling in a PWR is desirable, and the margin to boiling does not represent a real limit. Instead, the limit is defined by the departure from nucleate boiling, which can result in cladding burnout.
- Boiling in an SFR significantly impairs heat transfer and must be avoided.

Sodium Possesses High Thermal Conductivity

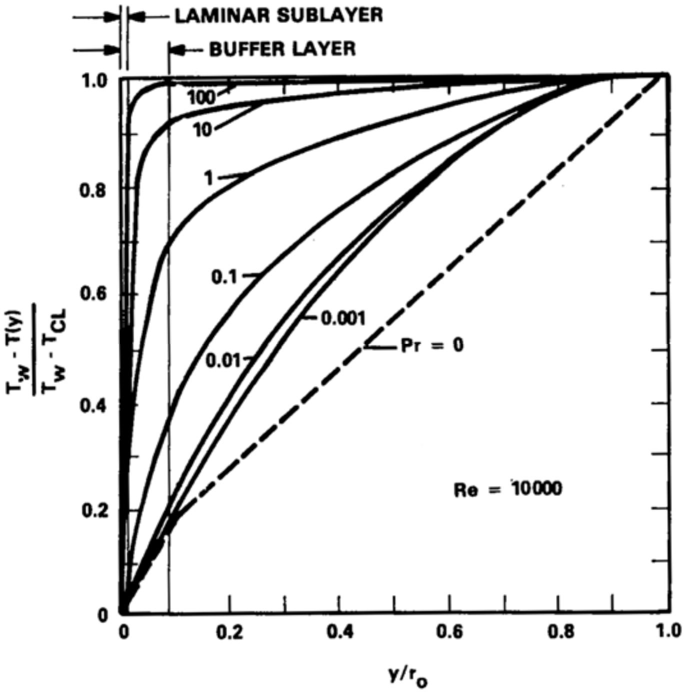
- **In sodium, the thickness of the thermal boundary layer is significantly larger than the thickness of the hydrodynamic boundary layer.**
  - Heat transfer coefficient for sodium is independent of viscosity (which is temperature dependent)



(a) ORDINARY FLUID

(b) LIQUID METAL

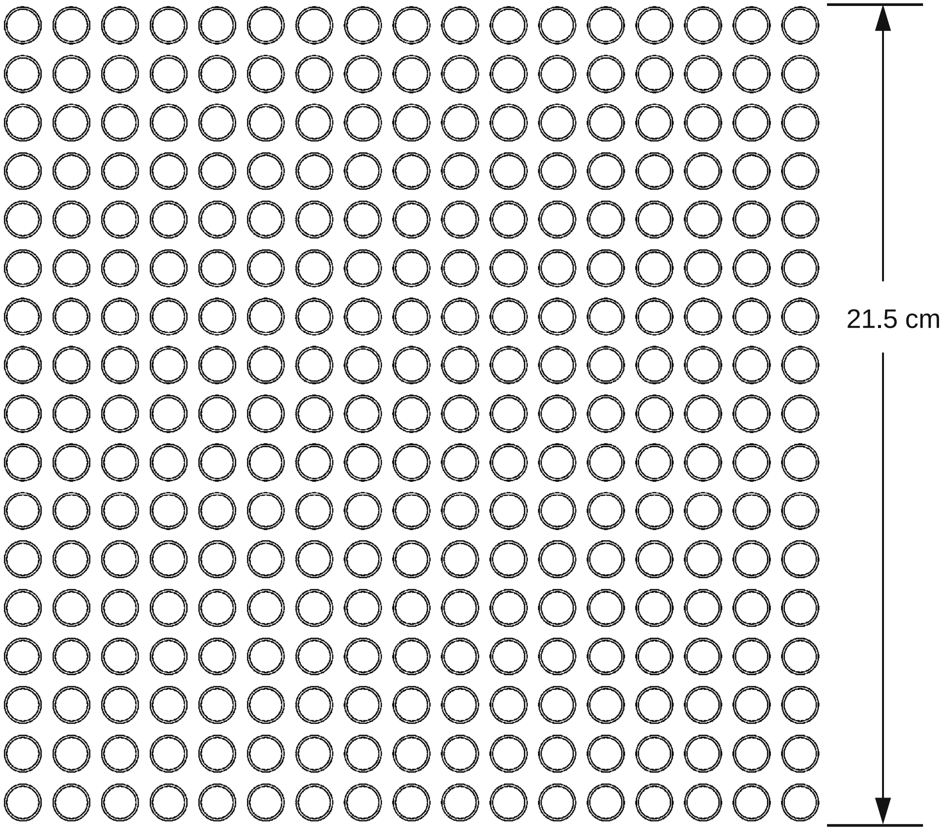
FIGURE 9-15. Comparison of thermal (δ_t) and hydrodynamic (δ_h) boundary layers for ordinary fluids vs liquid metals.



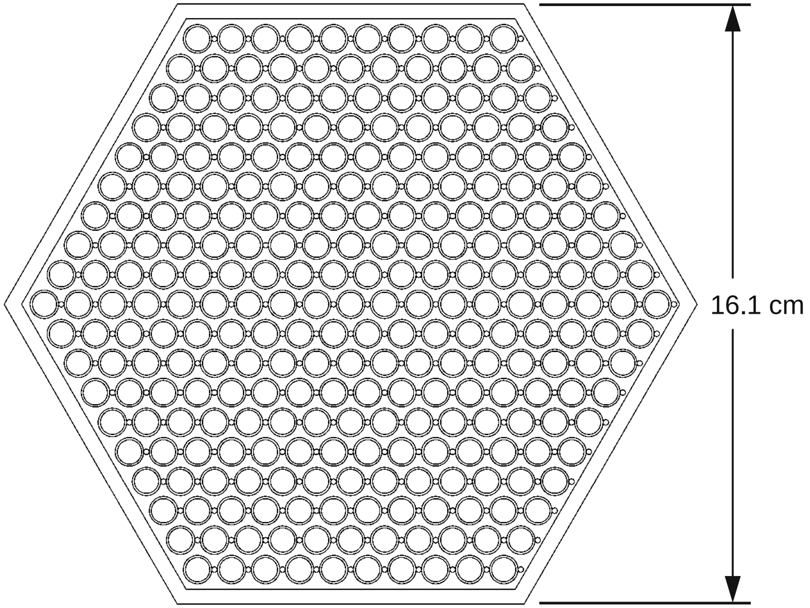
Source: Figure 9-15 (upper right) and Figure 9-16 (above) from A. E. Waltar and A. B. Reynolds, *Fast Breeder Reactors*, Pergamon Press, New York, 1981. Used with permission.

- **In turbulent flow, there is a high resistance to heat transfer in the laminar and buffer sublayers for ordinary fluids (Pr ~ 1).**
  - Critical heat flux determines minimum pin diameter.
  - Moderator-to-fuel ratio impacts core size.
- **For sodium (Pr < 0.01) resistance to heat transfer is distributed throughout the flow channel.**
  - No thermal limit on pin diameter.

Thermal Hydraulics and Neutronics Affect Assembly Design



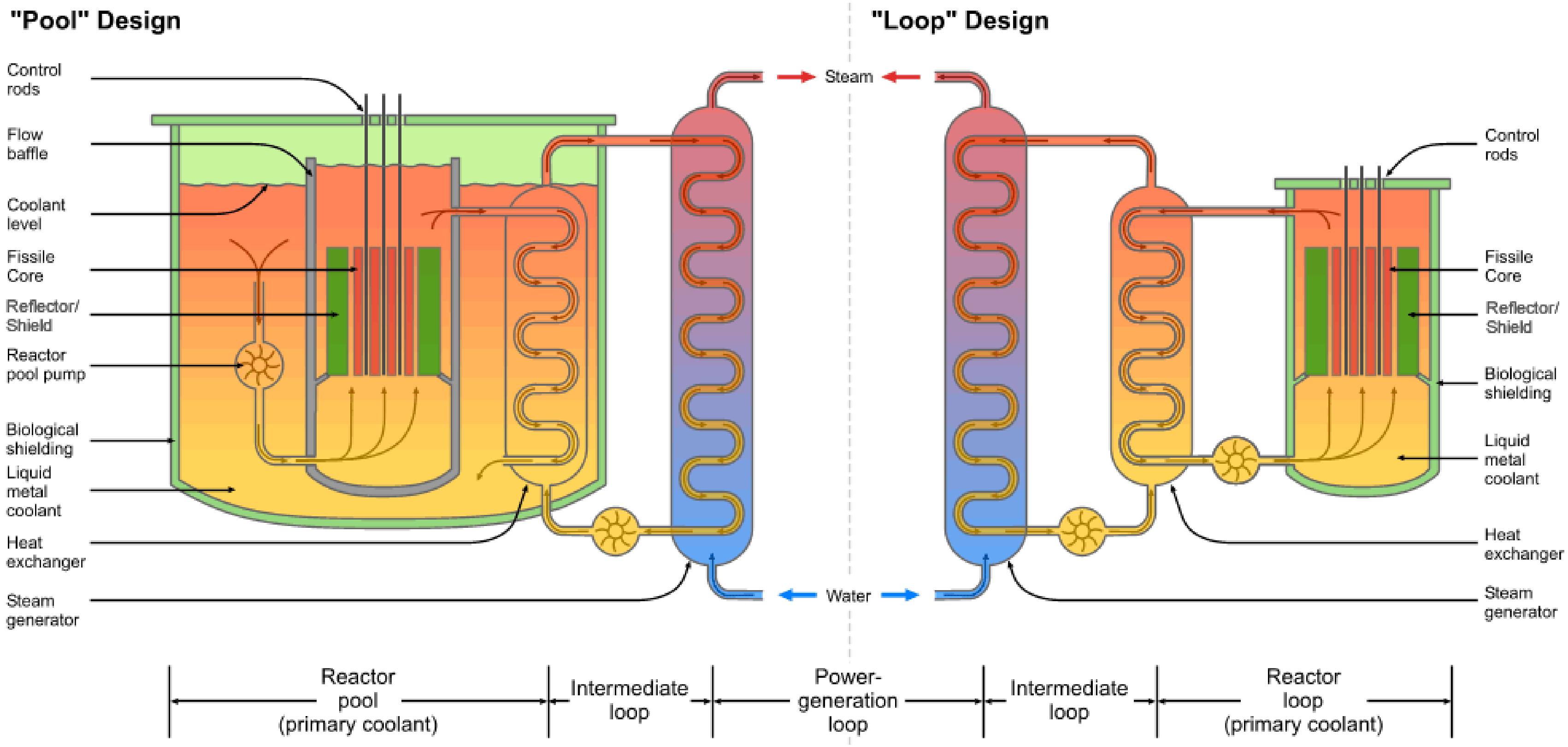
Typical PWR Assembly (289 pin locations)
Pin Diameter = 9.4 mm
Pin Pitch = 12.5 mm



“Typical” SFR Assembly (271 pins)
Pin Diameter = 7.4 mm
Pin Pitch = 8.9 mm

Sodium Coolant Needs an Intermediate Coolant Loop

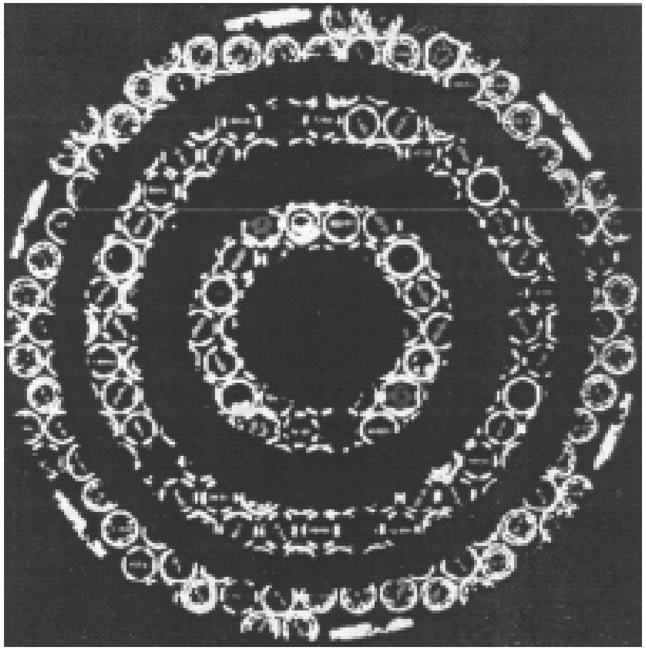
- **Because of coolant activation, the potential for sodium/water interactions between high-pressure steam and a low-pressure sodium loop, an intermediate coolant loop is used.**
- **This leads to two fundamental design choices: Pool vs. Loop**



Source: http://en.wikipedia.org/wiki/Image:LMFBR_schematics.png. Used under Creative Commons License.

Opaqueness of Sodium

- **The opaqueness of sodium has never been an issue for the safe operation of sodium fast reactors.**
- **Fuel handling requires careful tracking and positioning since visual inspections cannot be made under sodium.**
- **Dimensional gauging: A probe (or the fuel handling mechanism) can be used to identify and measure predefined index points to check the integrity of reactor internal structures**
- **Under-sodium viewing (USV):**
  - Ultrasonic imaging technique
  - Developed as early as the late 1960s
  - Can suffer from specular reflection effects
  - Presently limited to a research area. Not essential for operation.



Source: Figure 6.20 from *Status of Liquid Metal Cooled Fast Reactor Technology*, IAEA-TECDOC-1083, April 1999. Used with permission.

USV Images from PFR

Summary

- **Extensive testing of a wide variety of coolants in the 1950s and 1960s.**
- **Nearly all fast reactors constructed have used sodium coolant.**
  - 50+ years of sodium component development, testing, and operation.
  - Current fast reactor construction projects also use sodium.
  - Very limited experience with LBE coolant, and no experience with lead or helium-cooled fast reactors.
- **Thermophysical and thermal-hydraulic properties of sodium are superior to lead or helium.**
  - Smaller core with higher power density, lower enrichment, and lower heavy metal inventory.
  - Use of sodium codified in ASTM standards.
- **Issues of sodium reactivity must be addressed through proper component design, fabrication, and testing.**
- **There are important differences in reactor design introduced by the use of sodium.**
  - Low system pressure, high thermal conductivity, large safety margins.
  - Demonstrated capability for passive shutdown and decay heat removal.