Sodium as a Fast Reactor Coolant

Presented by

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U.S. Nuclear Regulatory Commission
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$_2$SO$_4$/ThO$_2$; molten salt: NaF-BeF$_2$-UF$_4$, LiF-BeF$_2$-ZrF$_4$-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<sub>e</sub>
  - PFBR (India) 2010 500 MW<sub>e</sub>
  - BN-800 (Russia)
- China has an ambitious vision to deploy 200 GWe of sodium-cooled fast breeder reactors by 2050 (12% of projected capacity).

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


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


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

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.
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.
- 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:
  - China: HTR-10 (2000/3 – Present)
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

<table>
<thead>
<tr>
<th></th>
<th>Na</th>
<th>Pb</th>
<th>LBE</th>
<th>He</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atomic Weight</strong></td>
<td>22.997</td>
<td>207.21</td>
<td>208</td>
<td>4</td>
</tr>
<tr>
<td><strong>Melting Point (°C)</strong></td>
<td>97.8</td>
<td>327.4</td>
<td>123.5</td>
<td>n/a</td>
</tr>
<tr>
<td><strong>Boiling Point (°C)</strong></td>
<td>892</td>
<td>1737</td>
<td>1670</td>
<td>-267</td>
</tr>
<tr>
<td><strong>Density (kg/m³)</strong></td>
<td>880</td>
<td>10500</td>
<td>10300</td>
<td>0.178</td>
</tr>
<tr>
<td><strong>Specific Heat (J/kg-K)</strong></td>
<td>1300</td>
<td>160</td>
<td>146</td>
<td>5200</td>
</tr>
<tr>
<td><strong>Heat Capacity (MJ/m³-K)</strong></td>
<td>1.14</td>
<td>1.68</td>
<td>1.50</td>
<td>0.0009</td>
</tr>
<tr>
<td><strong>Thermal Conductivity (W/m-K)</strong></td>
<td>76</td>
<td>16</td>
<td>11</td>
<td>0.152</td>
</tr>
<tr>
<td><strong>Viscosity (cP)</strong></td>
<td>0.34</td>
<td>2.0-2.5</td>
<td>1.7</td>
<td>0.018</td>
</tr>
</tbody>
</table>

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:
**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$_2$O.
  - 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:

Dissolution | Protective Oxide Layer | PbO Sludge
---|---|---
Fe₃O₄, FeCr₂O₄ | PbO | Oxygen in LBE
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$_3$O$_4$) undergoes a phase transformation at 570°C.

- Newer solution is to prefer SiO$_2$ and Al$_2$O$_3$ 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

![Graph showing sensitivity of neutron flux to varying parameters.](image)

- **Equivalent Core Diameter (cm)**
- **Average Experimental Fast Flux, Center** $(10^{15}$ n/cm$^2$/s)
- **Legend:**
  - He, Standard (U)
  - He, Standard (Pu)
  - He, Compact (U)
  - LBE, 61-Pin (U)
  - Na, 91-Pin (U)
  - Na, 61-Pin (U)
  - Na, 91-Pin (Pu)
  - LBE, 91-Pin (U)

$D = 119$ cm
Sensitivity of Enrichment to Varying Parameters

The diagram illustrates the sensitivity of fissile enrichment to varying parameters as a function of equivalent core diameter (cm). The different lines and markers represent various combinations of He, Standard (U), He, Standard (Pu), He, Compact (U), LBE, 61-Pin (U), Na, 91-Pin (U), Na, 61-Pin (U), Na, 91-Pin (Pu), and LBE, 91-Pin (U). The x-axis represents the equivalent core diameter, while the y-axis shows the fissile enrichment percentage.
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\textsubscript{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.
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.

<table>
<thead>
<tr>
<th></th>
<th>Sodium</th>
<th>LBE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Power (MW)</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>Coolant Velocity (m/s)</td>
<td>8.3</td>
<td>2.0</td>
</tr>
<tr>
<td>Average Experimental Fast Flux ($10^{15}$ n/cm²/s)</td>
<td>1.83</td>
<td>1.79</td>
</tr>
<tr>
<td>Number of Driver Assemblies</td>
<td>135</td>
<td>237</td>
</tr>
<tr>
<td>Pins per Assembly</td>
<td>91</td>
<td>61</td>
</tr>
<tr>
<td>Equivalent Core Diameter (cm)</td>
<td>119</td>
<td>154</td>
</tr>
<tr>
<td>Active Height (cm)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Fissile Enrichment (%)</td>
<td>18.3</td>
<td>20.0</td>
</tr>
<tr>
<td>Heavy Metal Inventory (kgHM)</td>
<td>5138</td>
<td>5716</td>
</tr>
</tbody>
</table>

- 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: $^{23}\text{Na}(n,\gamma)^{24}\text{N} \quad (t_{1/2} = 15 \text{ hours})$
  - LBE: $^{209}\text{Bi}(n,\gamma)^{210}\text{Bi}, \quad ^{210}\text{Bi} \rightarrow ^{210}\text{Po} \quad (t_{1/2} = 138 \text{ days})$

- Operationally, this requires shielding for primary components.

- Po-210 represents a significant biological hazard, requiring a leak-proof system.
  - $\text{PbPo(s)} + \text{H}_2\text{O} = \text{PbO} + \text{H}_2\text{Po(g)} \quad \text{(volatile alpha-emitting aerosol)}$

- 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/m³).
- Lead: 2005 USGS, 43 – 61 ¢/lb ($15,000/m³).
- 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/m³).
- The Helium Privatization Act of 1996 mandates the price of helium. In 2005, Government price was 1.965 $/m³. Private prices ranged from 2.42 to 2.63 $/m³. At 85 atm, this is roughly $220/m³.

**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**
  - Opaque nature 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 Na₂O 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 Na₂O) react with air (including water vapor and CO₂) to produce NaOH, and Na₂CO₃.
  - Production of NaOH takes a few seconds after particle formation.
  - Na₂CO₃ 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.
- 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

**No adverse effects were reported for operating personnel or surrounding environment**
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:
    \[
    \text{Na} + \text{H}_2\text{O} = \text{NaOH} + \frac{1}{2} \text{H}_2 + 140 \text{ kJ/mole}
    \]
  - In the second stage, chemical interaction takes place between the products of the first stage and excess sodium:
    \[
    2 \text{Na} + \text{NaOH} = \text{Na}_2\text{O} + \text{NaH}
    \]
    \[
    \text{Na} + \frac{1}{2} \text{H}_2 = \text{NaH}
    \]

- 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

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

<table>
<thead>
<tr>
<th>Property</th>
<th>Sodium</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic Weight</td>
<td>22.997</td>
<td>18</td>
</tr>
<tr>
<td>Optical Properties</td>
<td>Opaque</td>
<td>Transparent</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>97.8</td>
<td>0</td>
</tr>
<tr>
<td>Boiling Point (°C)</td>
<td>892</td>
<td>100</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>880</td>
<td>713</td>
</tr>
<tr>
<td>Specific Heat (J/kg-K)</td>
<td>1300</td>
<td>5600</td>
</tr>
<tr>
<td>Heat Capacity (MJ/m³-K)</td>
<td>1.14</td>
<td>4.00</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m-K)</td>
<td>76</td>
<td>0.54</td>
</tr>
<tr>
<td>Viscosity (cP)</td>
<td>0.34</td>
<td>0.1</td>
</tr>
</tbody>
</table>

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

- 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).

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.

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.
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

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.
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.