Environmental Effects in Liquid Metal Systems

December 2019, Todd Allen, Professor & Senior Fellow

FASTEST PATH TO ZERO
UNIVERSITY OF MICHIGAN

LIQUID METAL SYSTEMS

Table 6.1 Operating Conditions Anticipated for Generation IV Reactor Concepts [3]

Reactor Type	Coolant Inlet Temp (°C)	Coolant Outlet Temp (°C)	Maximum Dose (dpa[a])	Pressure (Mpa)	Coolant
Supercritical water-cooled reactor (SCWR)	290	500	15–67	25	Water
Very high-temperature gas-cooled reactor (VHTR)	600	1000	1–10	7	Helium
Sodium-cooled fast reactor (SFR)	370	550	200	0.1	Sodium
Lead-cooled fast reactor (LFR)	600	800	200	0.1	Lead
Gas-cooled fast reactor (GFR)	450	850	200	7	Helium/ SC CO_2
Molten salt reactor (MSR)	700	1000	200	0.1	Molten salt
Pressurized water reactor (PWR)	290	320	100	16	Water

[a]*dpa is displacement per atom and refers to a unit that radiation material scientists used to normalize radiation damage across different reactor types. For one dpa, on average each atom has been knocked out of its lattice site once.*

SODIUM

Outlet temp ~550°C

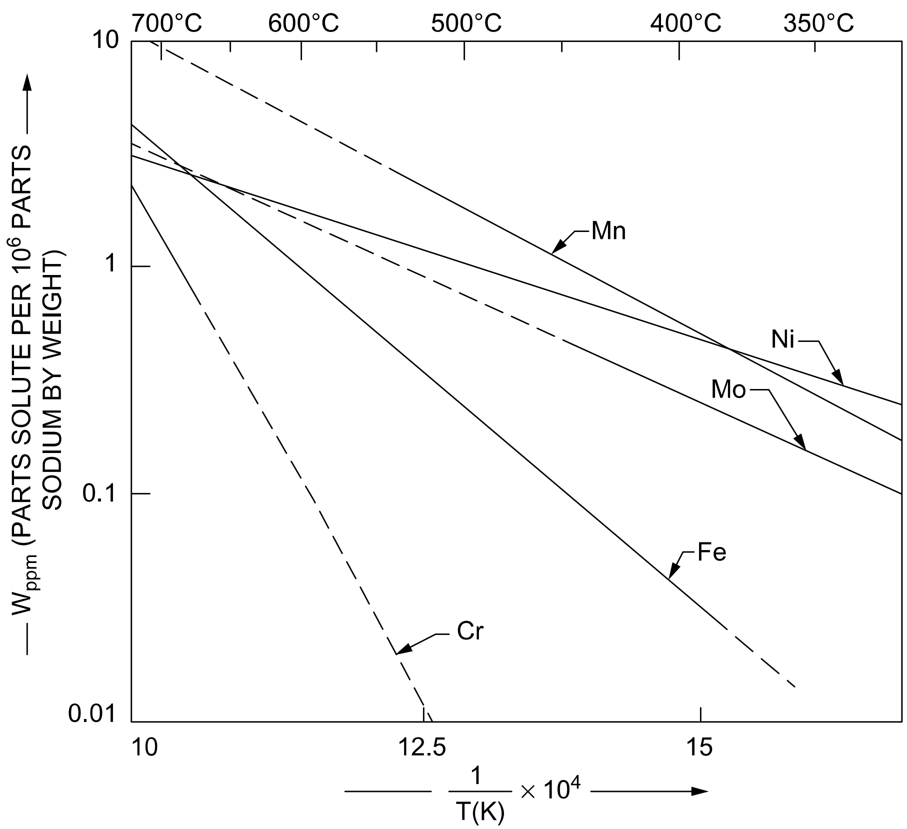


FIG. 6.21

Solubility of the alloying elements of stainless steel in liquid sodium [69].

From C. K. Mathews, Liquid Sodium-The Heat Transport Medium in Fast Breeder Reactors. Bull. Mat. Sci. 16 (6) (1993) 477–489.

SODIUM

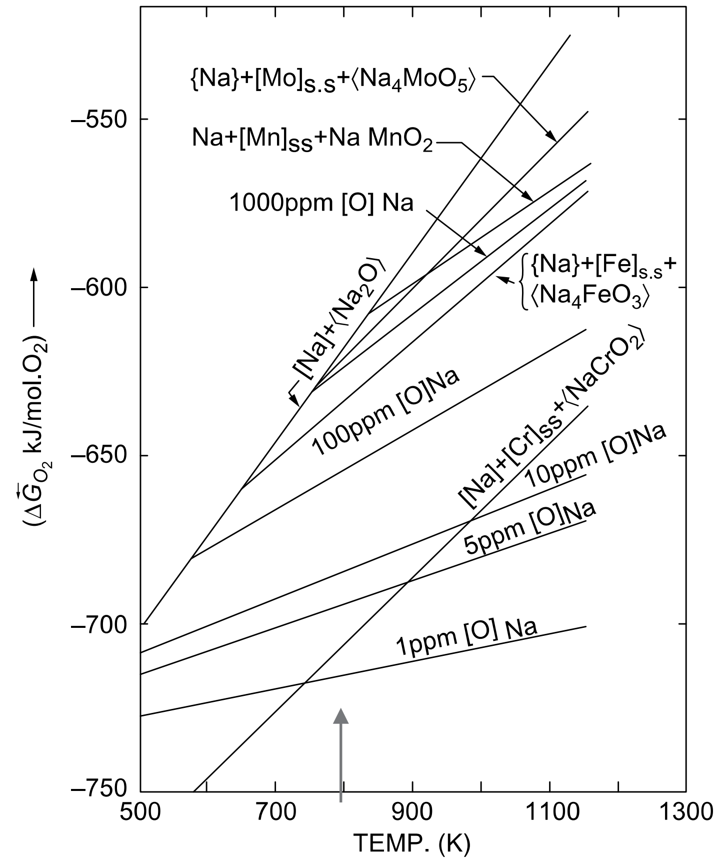


FIG. 6.22

Oxygen potentials for Na-(M)$_{SS}$-NaM$_x$O$_y$ and Na-Na-Na$_2$O systems [70].

From C. W. Mathews Pure & Appl. Chem., Vol. 67, No. 6, pp. 1011–1018, 1995. Printed in Great Britain. 1995 IUPAC.

Operationally oxygen controlled by a cold trap at 2-3 ppm (up to 10 ppm during maintenance)

SODIUM

- Cr has little solubility as a metal and the transport of chromium from the metal surface to form an oxide in the sodium is a stronger driving force.
- Molybdenum is unlikely to form an oxide at typical sodium reactor operating temperatures, and with limited solubility, is likely to stay in the steel.
- Nickel oxides are not thermodynamically stable so Ni loss from the steel surface is driven by the difference in the solubility of nickel in sodium and the amount of nickel in the alloy.
- Iron does not form a thermodynamically favorable oxide yet corrosion data for pure iron indicates that the iron dissolution increases with the square of the oxygen concentration, indicating a kinetic effect in which oxygen promotes the local dissolution of iron into sodium

SODIUM

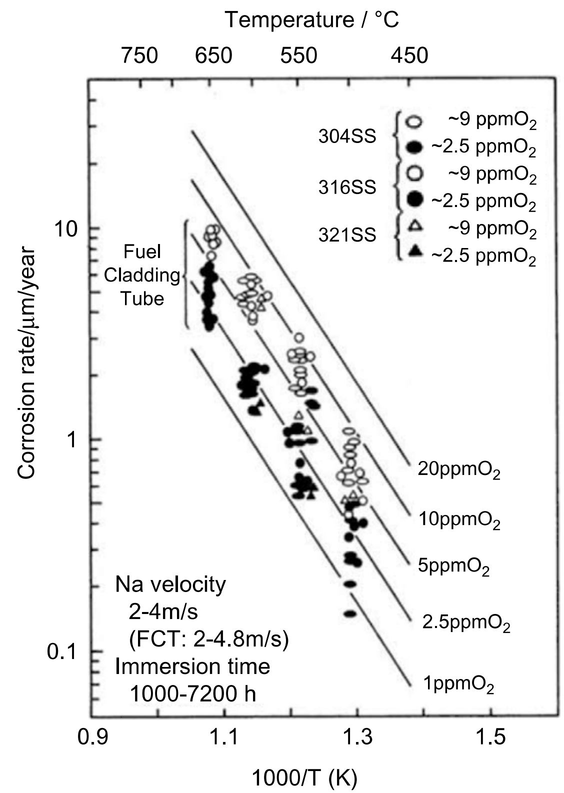


FIG. 6.23

Corrosion rate of austenitic steels in sodium [68].

From T. Furukawa, S. Kato, E. Yoshida, Compatibility of FBR materials with sodium, J. Nucl. Mater. 392 (2009) 249–254.

MONJU adopted corrosion rate

$$\log_{10} R = 0:85 + 1.5 \log_{10} C_o - 3:9 \times 10^3 / (T + 273)$$

SODIUM

An important observation after the sodium was drained from the primary tank was that the condition of the tank and the components submerged in sodium was pristine. There was absolutely no corrosion of the stainless steel after 35 years in contact with hot sodium.

Dr. John Sackett Testimony to the NRC in December 2008

Transport of carbon and nitrogen from the reactor vessel (proposed to be constructed from 316 stainless steel), and associated decrements in strength was noted as an open question for General Electric as part of the Nuclear Regulatory Commission review of the proposed PRISM sodium-cooled reactor design

LEAD ALLOYS

Outlet temp up to ~800°C

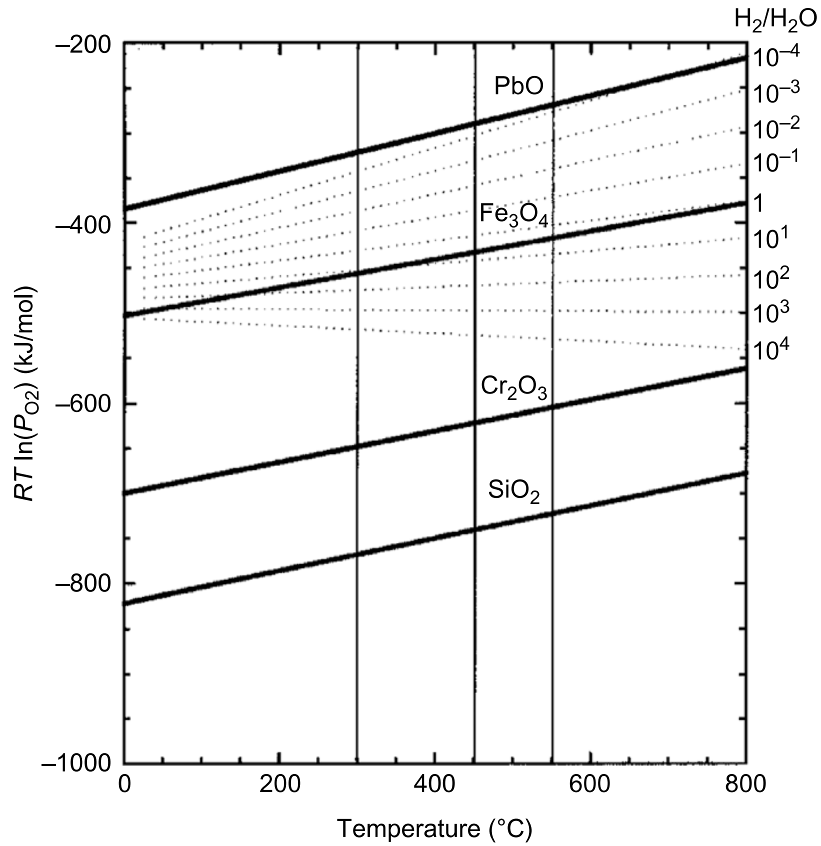


FIG. 6.24

Ellingham diagrams showing the standard Gibbs free energy of formation, ΔG_f°, of oxides of typical steel constituents in comparison to PbO: (A) for liquid Pb; (B) for LBE [83].

LEAD ALLOYS

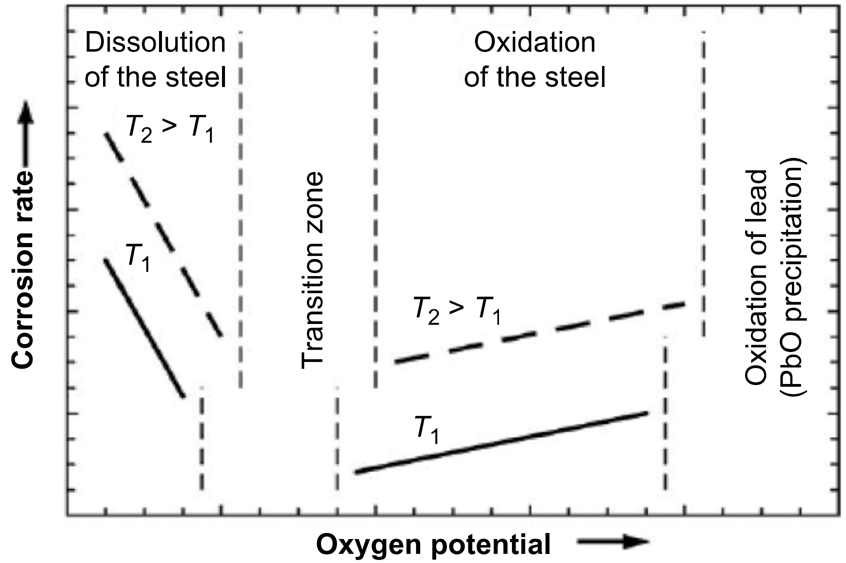


FIG. 6.25

Qualitative performance of steels as a function of oxygen potential in liquid lead alloys [77].

From C. Schroer, O. Wedemeyer, J. Konys, Aspects of minimizing steel corrosion in liquid lead-alloys by addition of oxygen. Nucl. Engin. Des. 241 (2011) 4913–4923.

Pb and Pb-Bi are both in consideration

Si-containing alloys provide a more protective oxide

Al-containing coatings are being studied in Europe for higher temperature application

LEAD ALLOYS

- At very low oxygen, both austenitic and ferritic-martensitic steels are subject to dissolution, even at low temperature.
- From 300°C to 470°C, with sufficient oxygen ($>10_4$ ppm), protective oxide films can be formed on both austenitic and ferritic-martensitic steels.
- For temperatures above 550°C, austenitic stainless steels undergo heavy dissolution and ferritic-martensitic steels form a very thick and potentially unstable oxide. This thick oxide may be susceptible to erosion at high flow rates.
- Between 470°C and 550°C, the corrosion behavior in structural steels appears to make transition from oxidation to dissolution. Furukawa et al. determined that at these higher temperatures, the iron oxide form changed from magnetite to wustite which is less adherent and thus more prone to detachment

LEAD ALLOYS

•Tensile properties appear to be unaffected for both T91 and 316 L steels when exposed to oxidizing LBE but does lose some ductility when exposed to an LBE under reducing conditions.

•Low cycle fatigue in 316 L contacted with LBE shows only a weak damaging effect but T91 shows a decrease in low cycle fatigue resistance. If the T91 is brought to reducing conditions, the decrease in low cycle fatigue growth is greater, supporting the idea that reducing conditions appear to be detrimental to mechanical properties.

•Creep-rupture tests in flowing LBE at 550°C showed a marked acceleration of creep rate at stresses >180 MPa.

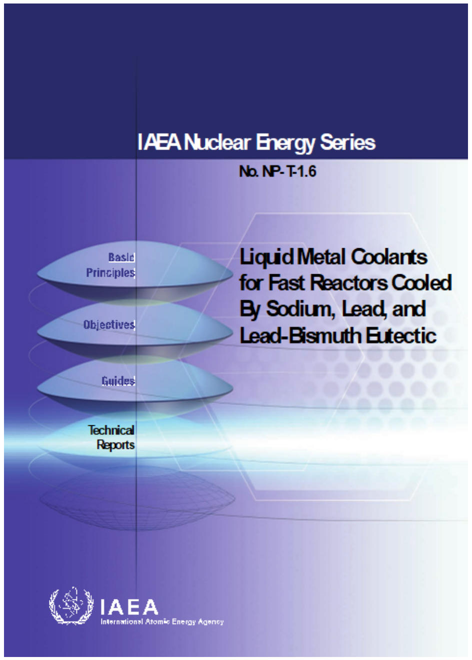
Overall, the mechanical properties of austenitic steels appear to be little affected but those of ferritic-martensitic
steels can be affected and must be chosen carefully.

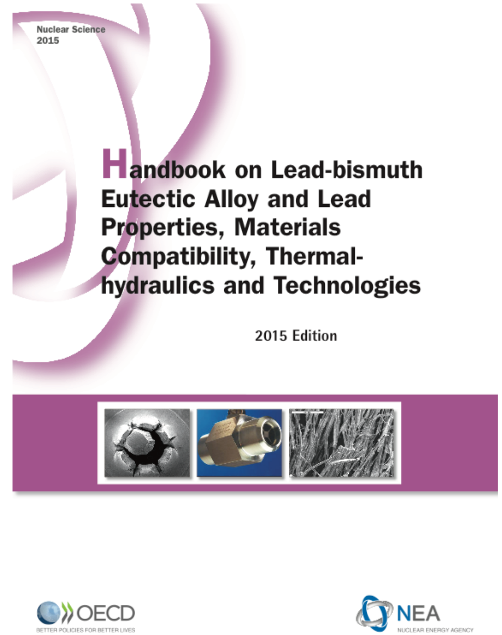
COMPARISON

The U.S. has operated multiple sodium-cooled demonstration plants and environmental effects from the coolant was not limiting. Oxygen control was critical

The U.S. has only operated test loops to understand liquid lead alloy systems but the Russian’s did operate submarines using lead alloys for the coolant.

REFERENCES





In the beginning of the 1950s nearly at the same time the USA and USSR launched the development of the nuclear power installations (NPI) for nuclear submarines (NS). In both countries the work was carried out for two types of NPIs: with pressurized water reactors and reactors cooled by liquid metal coolant (LMC).

In the USA sodium was chosen as LMC as it possessed the better thermo-hydraulic characteristics. The ground-based test facility-prototype of the NPI and the experimental nuclear submarine "Sea Wolf" were constructed. Yet the operation experience has pointed that the choice of coolant which was chemically active with respect to oxygen and water has not justified itself. After several sodium\water interaction, the RI was decommissioned together with the compartment and replaced by the pressurized water RI.

In the USSR the lead-bismuth eutectic alloy was chosen as LMC [1].

In the USA the scientific and research development works were conducted on using lead-bismuth coolant (LBC), but the alternative to solving the problem of corrosion resistance of structure materials and maintenance of coolant quality (the coolant technology) did not give any

BACKUPS

WHAT DOES CORROSION LOOK LIKE

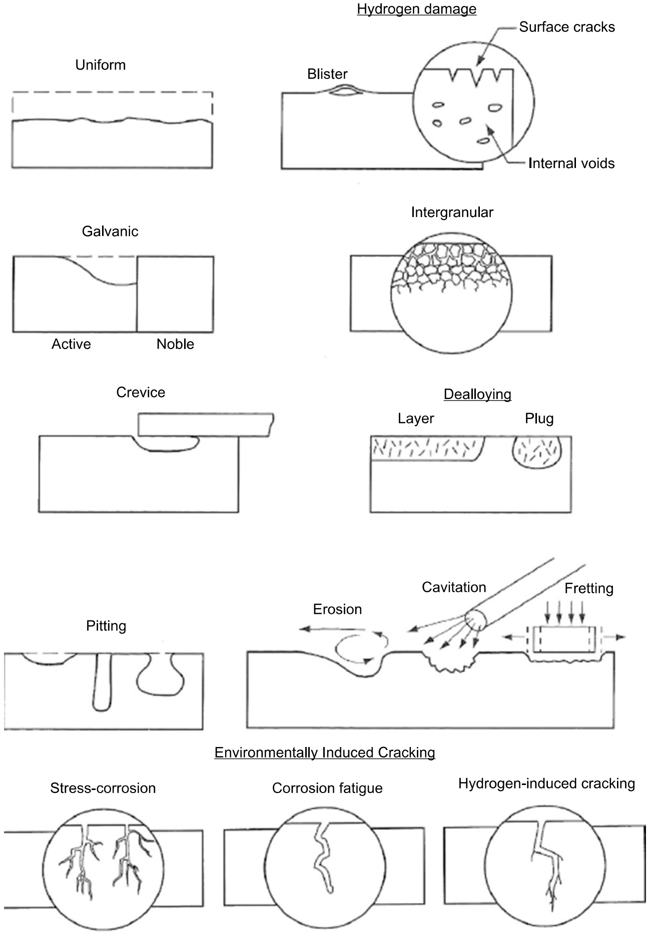


FIG. 6.1

Various forms of corrosion [2].

Redrawn from D. A. Jones, Principles and Prevention of Corrosion, Prentice-Hall, Upper Saddle River, NJ, 1996.