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3. PHYSICAL AND CHEMICAL PROPERTIES OF REACTOR COOLANTS

3.1. PHYSICAL PROPERTIES

The highest purity extent of commercial-grade sodium is 99.8%, this value corresponding to the purity of sodium that passed through the cold or hot traps [3.1, 3.2]. However, sodium of 99.995% purity can be obtained using distillation.

Sodium has one stable isotope, namely: ^{23}Na. Characteristics of other isotopes of sodium are presented in Table 3.1. The main isotopes result from the following reactions:

$$^{23}\text{Na}(n, 2n) \rightarrow {}^{22}\text{Na}(\beta^{+},\gamma);$$

$$^{23}\text{Na}(n) \rightarrow {}^{24}\text{Na}(\beta^{-},\gamma) \rightarrow {}^{24}\text{Mg}.$$

It is just ^{24}Na isotope that determines the main contribution to the radioactivity of the coolant flowing in the circuit.

Crude lead contains 93–99% of the basic metal. Among the basic impurities are Cu (1–5%), Sb, As, Sn (0.5–3%), Bi(0.05–0.4%), Al and Au. The highest purity extent of lead is 99.992%. Lead has four stable isotopes, namely: 204, 206, 207 and 208. The last three are the products of U, Ac and Th decay. Characteristics of lead isotopes are given in Tables 3.2 and 3.3.

The main thermophysical properties of sodium, lead, bismuth and lead-bismuth eutectic alloy (44.5% Pb-55.5% Bi) are presented in the Table 3.4. [3.3]

Other thermophysical properties of these materials vs temperature are given in Tables 3.5–3.7 [3.3; 3.4].

The main thermophysical properties of basic sodium compounds are given in Table 3.8. [3.2].

TABLE 3.1. SODIUM ISOTOPE CHARACTERISTICS

Isotopes	Atomic mass	$T_{1/2}$	Energy, MeV
20	19.99	0.4 s	β^+ (5.5; 7.15; 11.2)
21	20.99	23 s	β^- (2.5)
22	21.99	2.6 years	90% β^+ (0.54; 2.8;); 10% (ec) γ
23	22.99	-	-
24	23.99	14.97 h	β^- (5.5); γ (1.38; 2.76)
25	24.99	60 s	β^- (3.7; 4.0); γ (0.37; 0.58; 0.98)

TABLE 3.2. STABLE LEAD ISOTOPES

Pb isotopes	Content, % mass	Neutron capture cross section, barn	Integral resonance, barn
204	1.48	0.661±0.070	1.7±0.5
206	23.6	0.0305±0.008	0.2±0.1
207	22.6	0.0709±0.010	0.4±0.2
208	52.3	0.487±0.030	-
Natural Pb		0.170±0.002	0.16±0.05

TABLE 3.3. UNSTABLE LEAD ISOTOPES

Isotopes	$T_{1/2}$	Energy, MeV
205	1.5×10^7 years	
209	3.3 hours	β^- (0.6)
210	22 years	β^- (0.029); γ (0.046)
211	36 min	β^- (1.35); γ (0.065–1.265)
212	10.64 hours	β^- (0.16–0.58); γ (0.1–0.3)
214	26.8 min	β^- (0.65–1.03); γ (0.53–0.35)

TABLE 3.4. THERMOPHYSICAL PROPERTIES OF SODIUM, LEAD, BISMUTH AND LEAD-BISMUTH EUTECTIC ALLOY (44.5% PB; 55.5% BI)

Properties	Na	Pb	Bi	PbBi
Atomic number	11	82	83	-
Atomic mass	22.99	207.2	208.98	-
Melting temperature, ^{o}C	98	327.4	271.4	125
Boiling temperature, ^{o}C	883	1745	1552	1670
Heat of melting, kJ/kg kJ/mole	114.8 2.6	24.7 5.1	54.7 11.4	38.8 8.07
Heat of vaporisation, kJ/kg kJ/mole	3871 89.04	856.8 178	852 178	852 178
Density, kg/m^3 at 20^{o}C (solid) at 450^{o}C (liquid)	966 845	11340 10520	9780 9854	10474 10150
Heat capacity, kJ/kg K at 20^{o}C (solid) at 450^{o}C (liquid)	 1.230 1.269	 0.127 147.3	 0.129 150	 0.128 146
Thermal conductivity, W/m K at 20^{o}C (solid) at 450^{o}C (liquid)	 130 68.8	 35 17.1	 8.4 14.2	 12.6 14.2
Kinematic viscosity, m^2/s at 450^{o}C	$3 \cdot 10^{-7}$	$1.9 \cdot 10^{-7}$	$1.3 \cdot 10^{-7}$	$1.4 \cdot 10^{-7}$
Prandtl number at 450^{o}C	0.0048	0.0174	0.0135	0.0147
Surface tension, mN/m at 450^{o}C	163	480	370	392
Volume change with melting,%	+2.65	+3.6	–3.3	~ +0.5

TABLE 3.5. THERMOPHYSICAL PROPERTIES OF LEAD

t, ^{0}C	ρ, (x10^3) kg/m^3	C_p, J/kg·K	λ, W/m·K	a, (x10^{-6}), m^2/s	ν, (x10^{-7}), m^2/s	Pr, (x10^{-2})	σ, (x10^{-3}), N/m	ρ_e, (x10^{-8}), Ohm·m
330	10.67	147.30	15.83	10.07	23.90	2.37	445.81	93.77
400	10.58	147.30	16.58	10.64	20.99	1.97	441.33	97.02
500	10.46	147.30	17.66	11.46	17.63	1.54	434.93	101.67
600	10.34	147.30	18.74	12.31	15.19	1.23	428.53	106.32
700	10.21	147.30	19.82	13.18	13.69	1.04	422.13	110.97
800	10.09	147.30	20.90	14.07	13.13	0.93	415.73	115.62

TABLE 3.6. THERMOPHYSICAL PROPERTIES OF PBBI EUTECTIC

t, ^{0}C	ρ, (x10^3) kg/m^3	C_p J/kgK·	λ, W/m·K	a, (x10^{-6}), m^2/s	ν, (x10^{-7}), m^2/s	Pr, (x10^{-2})	σ, (x10^{-3}), N/m	ρ_e, (x10^{-8}), Ohm·m
130	10.55	146.00	11.0	7.17	29.41	4.10	415.65	104.41
200	10.46	146.00	11.7	7.68	24.85	3.24	410.73	108.07
300	10.33	146.00	12.7	8.43	19.52	2.32	403.70	113.30
400	10.21	146.00	13.7	9.20	15.58	1.69	396.67	118.53
500	10.08	146.00	14.7	9.99	13.03	1.30	389.64	123.76
600	9.96	146.00	15.7	10.80	11.87	1.10	382.61	128.99
700	9.83	146.00	16.7	11.63	12.10	1.04	375.58	134.22
800	9.71	146.00	17.7	12.48	13.72	1.10	368.55	139.45

TABLE 3.7. THERMOPHYSICAL PROPERTIES OF SODIUM

t, ^{0}C	ρ, (x10^3) kg/m^3	C_p, J/kg·K	λ, W/m·K	a, (x10^{-6}), m^2/s	ν, (x10^{-7}), m^2/s	Pr, (x10^{-2})	σ, (x10^{-3}), N/m	ρ_e, (x10^{-8}), Ohm·m
100	0.925	1382.3	84.92	66.42	7.367	1.11	200.06	9.49
200	0.904	1343.3	81.02	66.68	5.001	0.75	189.19	12.8
300	0.881	1309.4	77.12	66.85	3.876	0.58	178.86	16.6
400	0.856	1282.6	73.19	66.64	3.238	0.49	168.96	20.8
500	0.832	1263.9	69.28	65.91	2.836	0.43	159.40	25.6
600	0.808	1253.5	65.37	64.57	2.562	0.40	150.07	31.1
700	0.784	1251.7	61.46	62.62	2.368	0.38	140.88	37.2
800	0.761	1258.6	57.55	60.10	2.226	0.37	131.73	44.3

TABLE 3.8. THERMOPHYSICAL PROPERTIES OF BASIC SODIUM COMPOUNDS

Compounds	Properties					
	Temperature, ^{0}C		Heat of formation, kJ/mole	Density, kg/m^3 at 20^{o}C	Heat capacity, J/mole·K	Heat of melting, kJ/mole
	melting	boiling				
NaH	420	decom-position	65.8	1400	–	–
Na_2O	1350	decom-position	420	2270	70	29.7
Na_2O_2	596		596	2600	–	16.7
NaOH	318		426	2130	59.5	6.4
NaCl	801	1390	410	2165	50.5	28
Na_2CO_3	858	1490	1129	2530	112.3	28
Na_2S	1168	decom-position	359	1856	79.5	30
Na_2SO_4	884	890	1388	2663	118	24.3

3.2. CHEMICAL PROPERTIES OF SODIUM

Sodium is the most electropositive metal. Since it is ahead of hydrogen in electric tension row, Na displaces H_2 out of water with production of hydroxide: NaOH. When interacting with dry hydrogen sodium forms NaH hydride, which is soluble in sodium:

$$2Na(s) + H_2(g) \rightarrow 2NaH(s) + 57.4 \text{ kJ/mole},$$

At the temperature of 420°C NaH is decomposed with release of hydrogen. This fact should be taken into account when gas-tight vessel is heated.

When sodium interacts with the small amount of oxygen, Na_2O oxide is produced, whereas its burning in the air results in Na_2O_2 peroxide:

$$4Na(s) + O_2(g) \rightarrow 2Na_2O(s) + 416 \text{ kJ/mole};$$

$$4Na(l) + O_2(g) \rightarrow 2Na_2O(s) + 436 \text{ kJ/mole};$$

$$2Na(s) + O_2(g) \rightarrow 2Na_2O_2(s) + 499 \text{ kJ/mol}.$$

In the molten sodium, only Na_2O oxide is stable, while Na_2O_2 dissociates as follows:

$$Na_2O_2 + 2Na \rightarrow 2Na_2O.$$

When sodium interacts with water, some reactions occur and, depending on reaction temperature, impurities of different composition would be present in sodium.

Hydroxide is produced by the following reaction at 201–300°C:

$$2Na + 2H_2O \rightarrow 2NaOH + 142 \text{ kJ/mole}.$$

Oxide as well as hydroxide is produced at 350–400°C:

$$2Na + NaOH \rightarrow 2Na_2O + NaH;$$

$$2Na + H_2 \rightarrow 2NaH.$$

At t>420°C, hydride dissociates and reaction goes escaping intermediate stages:

$$2Na + H_2O \rightarrow Na_2O + H_2.$$

Burning reaction is characterized by a zone of small flames at the sodium-air interface, formation of Na_2O on the sodium surface and vigorous emission of high density white oxide fumes.

However, this burning causes relatively low heat release, namely 420 kJ/mole by Na_2O or 500 kJ/mole by Na_2O_2. This is equivalent to about 10 kJ (~2 kcal) per gram of sodium burnt, being approximately equal to that for 1 gram of sulphur, one third of gram of magnesium or aluminium, and less than one quarter of gram of gas/oil. With the same volume of fuel, sodium burning results in the energy release equal to 50% of that for sulphur, 30% of that for gas/oil, 25% of that for magnesium and slightly over 10% of that for aluminium.

Saturation concentration of element in solution (C_s, wt%) follows the Arrhenius equation:

$$lg\ C_s = A - B/T, \quad (3.1)$$

where A and B are experimentally determined constants: A-entropy of solution, kJ/mole and B-heat of evaporation, kJ/mole. Therefore, Eq. 3.1 can be used to estimate solubility of chemical elements in liquid metals as well as material corrosion resistance in the liquid metals. Solubility of different elements in liquid sodium is given in Table 3.9 [3.4].

TABLE 3.9. SOLUBILITY OF DIFFERENT ELEMENTS IN LIQUID SODIUM

Elements	Constants of Eq. 3.1		Temperature range, K
	A	B	
C	7.2	5465	873–1223
Cu	5.45	3055	573 973
Fe	5.16	4310	573–1173
H_2	6.067	2880	273–673
Mo	3.27	3962	1073–1278
Na_2O	1.2	1777	373–873
Ni	2.07	1570	573–1173
O_2	6.257	2444	383–823

3.3. CHEMICAL PROPERTIES OF LEAD

In dry air solid lead is not practically oxidized, whereas in humid air it is coated with oxide film of PbO. This film under air exposure is transformed to basic carbonate $3PbCO_3 \cdot Pb(OH)$. However, oxidation of molten lead by air occurs resulting in its transformation initially into Pb_2O and then into PbO oxide. At the temperature of 450°C the latter is transformed to Pb_2O_3 and then at 450–470°C to Pb_3O_4. Being unstable all these compositions dissociate into PbO and O_2.

Lead interacts with water producing hydroxide $Pb(OH)_2$. In hard water lead is coated with film, preventing water from being polluted with soluble lead compounds. Detectable lead amount dissolves in distilled water resulting in water poisoning.

High lead resistance to diluted sulphuric acid is of practical value. Lead practically does not dissolve in diluted hydrochloric acid, whereas it readily dissolves in nitric acid because of high oxidizability of lead.

Lead dissolves in alkaline medium, although its solubility rate is low. Lead does not interact with either nitrogen or carbon. Lead resistance to chlorine exceeds that of Al, Cu and Fe up to 300°C, because lead chloride exhibits protective properties. Interaction of lead with most electropositive metals (Li, Na, Mg, Ca, Ba, Zr, Hf, etc.) results in formation of intermetallic compounds.

Solubility of different elements or their corrosion resistance in liquid lead and eutectic PbBi alloy is shown in Table 3.10 [3.5] and Table 3.11 [3.1].

TABLE 3.10. SOLUBILITY OF DIFFERENT ELEMENTS IN LIQUID LEAD

Elements	Constants of Eq. 3.1		Temperature range, K
	A	B	
C	1.026	3850	350–1000
Co	2.60	4400	350–1650
Cr	3.74	6750	908–1210
Cu	2.72	2360	327–1000
Fe	0.34	3450	330–910
H_2	–1.946	2360	500–900
Mn	2.02	1825	327–1200
Mo	solubility $<10^{-3}$ wt.% at 1000°C		
N_2	no solubility		
Nb	solubility $<10^{-5}$ wt.% at 1000°C		
Ni	2.78	1000	330–1300
O_2	– 0.106	2176	350–850
Si	3.886	7180	1050–1250
Ti	solubility $\sim 5.6\cdot 10^{-4}$ wt.% at 500°C		
U	3.921	5121	400–800
Zr	solubility $\sim 1.2\cdot 10^{-9}$ wt.% at 500°C		

TABLE 3.11. SOLUBILITY OF DIFFERENT ELEMENTS IN LIQUID EUTECTIC Pb-Bi ALLOY

Elements	Constants of Eq. 3.1		Temperature range, K
	A	B	
C	–1.36	1870	-
Cr	–0.02	2280	400–500
Fe	2.01	4380	-
Ni	1.70	1000	450–550
O_2	0.106	2176	327–1000
Zr	0.15	3172	350–750

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4. PRODUCTION OF SODIUM, LEAD AND BISMUTH

4.1. SODIUM

Sodium is among the most abundant elements. Its content in the earth’s crust is about 2.5 wt.%. The most important sodium compound, produced in the amount of millions of tons, is NaCl, the content of NaCl in seawater being about 3%.

Sodium can be produced by high-temperature reaction from almost any its compound (NaCl, NaOH, Na_2CO_3 and Na_2S). The method of sodium production that has enjoyed the widest application is electrolysis of the molten salts, for example:

$$4NaOH \rightarrow 2Na + 2NaOH + H_2 + O_2.$$

Since water interacts with the one-half amount of sodium produced in this reaction, sodium yield cannot exceed 50% of theoretical value. In other electrolysis reactions, the yield of sodium could be even lower. Metallic sodium production by electrolysis of molten NaCl having melting point about 800°C is the most wide spread method. In order to reduce melting temperature such salts as $CaCl_2$, Na_2CO_3, etc. are used. For instance, mixture consisting of 40% NaCl and 60% $CaCl_2$ has melting temperature of 580°C, while mixture of 35.6% NaCl and 64.4% Na_2CO_3 melts at 600°C.

In electrolytic vat, the anode is usually made of graphite, the cathode being made of metal (Fe). Chlorine being by-product of this process is either discharged into atmosphere or accumulated for further using. Electric energy needed for sodium production is about 15 kW-h/kg Na.

Sodium produced by electrolysis contains 99.7 to 99.8% of basic metal and impurities (<0.1%K, <0.001% Fe, <0.15% Ca and others, such as Ba, Zr and Sn). It should be noted that the use of graphite electrodes causes sodium to be polluted with carbon. The worldwide sodium production data is given in Table 4.1 [4.1, 4.2].

TABLE 4.1. WORLD SODIUM PRODUCTION (thousand tonnes/year)

Years	1930	1952	1970	1990	2000 (prediction)
Quantity	25	140	270	354	340