A study on sodium - the fast breeder reactor coolant

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Abstract. Sodium, the second alkali metal in the first group of periodic table is highly chemically reactive. Sodium is widely used in pharmaceutical industries to manufacture lifesaving medicines. Liquid sodium is an excellent reducing agent and heat transport medium, which makes it an important industrial material. The application of this element in liquid form at high temperature as a coolant in fast breeder nuclear reactors necessitated development of sodium technology. Physical, chemical and nuclear properties of sodium led to the choice of sodium as the universally accepted fast breeder reactor (FBR) coolant. The manufacturing of sodium is by electrolysis process. The design and manufacturing requirements of high temperature liquid sodium system components are successfully addressed. Special type of sensors needed for high temperature liquid sodium system are specifically designed and developed. Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam is involved in the development of sodium technology in India. Sodium technology is matured to an extent and around twenty FBRs with sodium as the coolant were constructed, commissioned and successfully operated all over the world. Five sodium cooled fast reactors are currently in operation including fast breeder test reactor (FBTR) in India. Prototype fast breeder reactor (PFBR) is in the advanced stage of commissioning at Kalpakkam. This review paper explains the choice of sodium as FBR coolant and gives highlights on the research and development took place in sodium technology all over the world especially in India with an aim to give an exposure to this technology to the academic community.

1. Introduction
All must have heard of sodium and studied about its peculiar properties. Every one also might have seen solid sodium pieces stored in bottles under kerosene, in high school laboratories. A student would be considering it as a dangerous element, which will catch fire when exposed to atmosphere. If it is exposed to water severe reaction and explosion would also take place. It is sixth element in the order of abundance and forms 2.8% of earth’s crust. However this element is finding application in nuclear engineering and is used as the coolant in fast breeder type of nuclear reactors. Because of this, a branch of science and technology by name sodium technology has emerged in India and abroad. This paper describes basic properties of sodium metal, why sodium is selected as the fast breeder reactor coolant, the challenges involved while using it as the coolant, highlights of sodium technology developed and the opportunities for scientific community in research and development. This paper intends to give an exposure to academic community about sodium technology.
2. Physical and chemical properties
Sodium is a group 1A element in the periodic table and is an alkali metal. In the periodic table other alkali metals are Lithium, Potassium, Rubidium, Cesium and Francium. These elements have only one electron in the outermost shell. If we remove this electron, the electronic structure will become that of an inert gas. So the natural tendency of alkali metals is to release electron in the outermost shell and attain a state of inert gas electronic structure. Because of this inherent tendency to release electron, alkali metals are chemically very reactive and attack most of the elements and forms compounds. The atomic number of sodium is 11 and atomic weight is 23. Figure 1 shows the atomic structure of sodium atom. Table 1 gives the physical properties of sodium.

![Atomic structure of sodium atom](image)

**Figure 1.** Atomic structure of sodium atom

| Table 1. Physical Properties of Sodium |
|----------------------------------------|
| Density of liquid sodium                | 0.927 g cc$^{-1}$ |
| Melting point                           | 97.8°C |
| Boiling point                           | 883 °C |
| Thermal conductivity                    | 76 W m$^{-1}$ °C$^{-1}$ |
| Specific heat capacity                  | 1.38 kJ kg$^{-1}$ °C$^{-1}$ |
| Viscosity                               | 0.670 cps |
| Electrical conductivity                 | 9.67 x 10$^{-6}$ Ω m |

3. Why sodium as a coolant
This highly reactive metal, which is solid at room temperature is widely used in pharmaceutical applications for the manufacture of life saving medicines. The element sodium is a universally accepted fast breeder reactor (FBR) coolant. Fast breeder reactors [1,2] will produce power and it also converts fertile nuclear materials such as U238 and Th232 to fissile nuclear materials or nuclear fuels such as Pu239 and U233 respectively. By proper configuration of core, with fuel and surrounding blanket with fertile elements, and by maintaining the neutron energy spectrum high (neutrons at high speed) the conversion ratio can be made more than one. When the ratio is more than one the reactor produces more fuel than it consumes and it will breed nuclear fuel. In fast breeder reactors, the abundant amount of fertile elements available in nature can be converted into fissile elements and the shortage of nuclear fuel can be effectively solved. Because of this special advantage, along with other developing countries, India is also developing fast breeder reactor technology in the second stage of our nuclear power programme.

In fast breeder type of nuclear reactors, heat is generated in the core of the reactor where fission chain reaction takes place. Core is made of fuel pins of around 6 mm diameter. This fuel pin contains pellets, made from a mixture Uranium oxides/carbides and Plutonium oxides/carbides. They are concealed in stainless steel tubes with ends closed. The heat generated in the fuel pin due to fission
chain reaction will be enormous and the power density will be very high. The power density is maintained high to achieve desired economic benefit. The temperature of the fuel pin should be limited by transferring and transporting the heat. For transferring and transporting the heat, the coolant is circulated through the fuel pin bundle which is known as fuel sub assembly. Figure 2 shows schematic of fuel subassembly with sodium flow direction. The economic and safe operation of the fast breeder reactor depends on effective transfer of heat and limiting the hot spot temperature of fuel pins within the design limit. The physical and heat transfer property of the coolant plays a major role here. Any circulating fluid will transfer heat from the fuel pin by convection mode.

A metal in contact with fuel pin will transfer the heat by conduction mode. If a liquid metal is used as the coolant and circulated through the fuel subassembly heat transfer will be in convection and conduction mode, which will elevate the overall heat transfer coefficient to a very high value compared to water, steam or any gaseous coolant. As the boiling point of sodium is high, 882.8°C, the liquid need not be pressurized like water to avoid boiling at the operating temperature. So the sodium which is circulated through the fuel subassembly of fast breeder reactor can remain at low pressure and at high temperature. The high temperature is a challenge but low pressure is an added advantage for the mechanical design of the system. Low pressure leads to low thickness of structural material used in the sodium system components. Since we are able to operate the sodium system at high temperature the sodium heated steam generators can deliver super-heated steam at high temperature and high pressure. High temperature and high pressure steam will increase the thermodynamic efficiency of the steam cycle and hence sodium cooled fast breeder reactors have high thermal efficiency. Figure 3 shows the heat transport system of a FBR [1]. In addition the sodium atoms will absorb less number of neutrons in the fast breeder reactor neutron energy spectrum. If at all it absorbs neutrons and forms radioactive isotopes of sodium, they will have lower halflife which enhances radioactive safety of the fast breeder reactor systems.
4. Manufacturing, transportation and storage

Sodium is manufactured using Downs process by electrolysis of sodium chloride [3]. The mixture of sodium chloride and calcium chloride is used as the electrolyte. Graphite is the anode and the Cast iron vessel act as the cathode. Chlorine gas formed at the anode is collected, treated and used for production of bleaching powder. Sodium element deposited at the cast iron vessel float on the surface of electrolyte and collect in a container located at one side of the cell. Cell operates at around 8 V DC and the current will be of the order of thousands of amperes and it depends on cell capacity. Operating temperature of cell is around 600˚C. Addition of Calcium chloride to sodium chloride will reduce the melting point below 600˚C as it become a eutectic alloy. A metallic wire mesh diaphragm is inserted in between the anode and cathode which is normally separated by around 25 mm gap prevents recombination reaction which will lead to better cell efficiency. Pure sodium chloride is added periodically to the cell as production of sodium progresses. The sodium production is energy intensive and the minimum specific energy consumption reported all over the world is around 15 kWh/kg. Figure 4 shows the schematic of a Downs cell.

For pharmaceutical applications purity of sodium is not a limitation. For this purpose oil coated sodium bricks are stored in steel drums and are closed with rubber gaskets. These sodium drums are normally transported in trucks, through road under water tight double tarpaulin cover. For nuclear application filtered sodium is filled in sealed steel tankers, frozen and an inert gas atmosphere is maintained in the gas space[4]. These tankers with frozen sodium are transported by road, rail or ship to the destination. At the reactor site, sodium is melted and transferred to conditioned storage tanks through fine filters by differential pressure [5]. Storage tanks with sodium will be under inert atmosphere and under positive pressure to avoid any ingress of air. Sodium is frozen and stored if filling of reactors system is delayed. Cover gas pressure is monitored during storage to ensure system integrity. The sodium inventory in the fast breeder test reactor (FBTR) under operation at IGCAR Kalpakkam is around 150 tones. For the 500 MW capacity Prototype Fast Breeder Reactor under construction at Kalpakkam the sodium inventory is around 1700 tones.

**Figure 3.** Heat transport system of a FBR.
5. Challenges in sodium technology
Since sodium is a highly reactive metal and is solid at room temperature most of the conventional systems used in high temperature process industry to handle fluids are not adoptable for sodium systems [6]. Selected materials compatible with high temperature liquid sodium only can be used for sodium system construction. Special instrumentation system is required as most of the conventional sensors are not readily usable. Preheating system is needed as sodium is solid at room temperature. Leak detection and fire fighting is an added requirement. Sodium purity has to be maintained at around 99.95% to limit blockage of flow passages and structural material corrosion. Special purification methods and purity monitoring techniques have to be adopted to maintain sodium purity. Inert cover gas system is required to provide inert atmosphere over free space of sodium tanks, vessels and components. Operation and maintenance techniques are unique for liquid sodium systems. Economic and safe realization of all these special requirements are the major challenges in sodium technology.

6. Sodium system design features
Sodium is solid at room temperature but under operating conditions sodium is brought to liquid state. The material used for construction of sodium system is stainless steel. Because of the favorable mechanical properties at high temperature SS 316 LN grade stainless steel is recommended for use. The specifications are based on ASTM standards. The mechanical design, quality assurance and quality control of sodium systems are carried out as per ASME section VIII division I and associated international codes.

6.1 Special features
Sodium system should not have any flanged joints to avoid leakage. Hence all the joints in the piping and joints in the piping to vessels of sodium systems are of welded construction. Nitrogen or argon is used as the cover gas for sodium system and all free space of vessel and tanks is filled with cover gas. Separate cover gas system is a part of the auxiliary systems for any sodium system. Purified cover gas at desired pressure will be admitted to the free space of vessels and tanks. Provision for venting the gas and evacuating the vessels and tanks are also provided as part of the cover gas system. On any emergency condition the sodium in the system has to be drained or dumped into a storage tank. To
ensure draining of sodium in a passive way, gravity dumping is resorted in sodium systems. Hence the storage tank or the dump tank will be positioned at lower most elevation. In order to avoid trapping of sodium in the pipe lines and to accelerate the flow of sodium to the storage tank a slope of around 3% is provided for pipelines. Conventional valves cannot be used in sodium systems as the gland packing will be a source of leak. Bellows sealed valves made up of SS316 LN material is used in sodium systems. Sodium systems are allowed to operate upto a temperature of 600˚C. The piping system should have adequate number of bends to have structural flexibility to accommodate thermal expansion during operation. Vapor traps are required in the cover gas line close to the interface with sodium system to avoid transport of sodium vapor to gas line and solidification. Solidification of gas line will lead to lack of gas communication which will loose the dumpability of the system.

6.2 Sodium instrumentation
Sodium is a very good conductor of electricity and this property is successfully used for developing sensors for sodium systems. Special type of sensors are required for measuring sodium level in tanks and vessels. Resistance type and mutual inductance type level sensors are used or continuous and discontinuous level measurements [7]. Alnico based permanent magnet type electromagnetic flow meters are used for sodium flow measurement [8]. Figure 5 shows the schematic.

![Figure 5. Alnico based permanent magnet flow meters](image)

6.3 Sodium pumps
As liquid sodium is a good electrical conductor, for pumping sodium in the system electromagnetic pumps can be used [9]. Because of its low efficiency and associated design difficulties for large sodium systems centrifugal mechanical sodium pumps are used. Figure 6 shows schematic of DC Electromagnetic pump.
Centrifugal sodium pumps are vertical type with shaft sealing only at one end that too in the cover gas. These pumps have hydrostatic bearing at bottom which is submerged in sodium and tapper roller bearings at the top with oil cooled mechanical seals. Figure 7 shows schematic of a centrifugal sodium pump.

Figure 6. Schematic of DC electromagnetic pump

Figure 7. Schematic of a centrifugal sodium pump.
6.4 Heating System
Since sodium is solid at room temperature solidification of sodium in a system has to be avoided. The system has to be maintained well above the melting point of sodium which is 98.2 °C. This necessitated a preheating system for the sodium system. All pipe lines, tanks and vessels are provided with electrical surface heaters and thermal insulation. The preheating system allows the sodium system to be heated up around 200°C before filling sodium and also helps to maintain at this temperature after filling with sodium. The temperature of the piping and components are measured by means of Chromel-Alumel thermocouples and the heaters are controlled based on temperature readings. Mineral wool thermal insulation of sufficient density and thickness would be provided over the surface to limit heat loss also and maintain the surface skin temperature below 70°C. In order to raise the temperature of sodium in experimental facilities to desired value, immersion type heaters in heater vessels are provided in sodium systems. These heaters can be used for raising sodium temperature in the system at upto 600 °C. In nuclear reactor heat generated in the reactor core will be used to raise the temperature to the rated conditions.

7. Sodium system operation techniques
Safe operation of sodium system is also a challenge. Minor errors in design, construction, quality control, commissioning, operation and maintenance can lead to major incidents of sodium leak, fire and damage to material, equipment, and injury to human beings.

7.1 Safe operation
Major measures to be adopted for safe operation of sodium system are

- Integrity of sodium system shall be maintained throughout the life of the system and periodically tested at desired and specified conditions.
- Sodium in the system shall be purified and purity of sodium in the system should be monitored periodically.
- Temperature of all parts of the system shall be maintained above 200°C during operation. This will avoid freezing of sodium at any part of the system. Freezing of sodium in dump lines should be avoided at any cost as it will lead to loss of system dumpability.
- Availability of normal power supply and standby power supply shall be ensured
- Remote dumping facility which should be operable even after complete power failure, is needed. Dump valve actuation shall be failsafe.
- Purified Argon cover gas shall be used to avoid system contamination
- Automatic temperature controller and stand by controllers are provided to limit system temperature below the design limits
- Sensitive local and global sodium leak detection system is required. Healthiness of leak detection system should be checked periodically
- Dumping time should as per design intent and shall be checked periodically by actual dumping operation.
- Availability of adequate number of quality fire extinguishers and its operability should be checked
- In-service inspection on the structural material of components and piping at high stressed location shall be carried out at specific intervals.

7.2 Sodium purification
Reactor grade sodium is 99.95 % pure[10]. Impurities in sodium are oxygen, Hydrogen, Carbon, Calcium and Magnesium. Oxygen level should be maintained below 10 ppm. Sodium is purified by two stages of filtration and then by cold trapping. Molten sodium is coarse filtered using wire mesh filter at 125 °C. Bulk sodium oxide and hydroxide suspended over liquid sodium is removed by this process. Coarse filtered sodium is aged at 300°C to convert metallic calcium present in sodium to calcium oxide. Fine filtering of sodium using sintered stainless steel filter elements of 14 microns
pores size, will remove calcium oxide and precipitated sodium oxide. Further purification of sodium is carried out by a process called cold trapping. In the cold trap liquid sodium is cooled to a temperature below the saturation value of impurities and the dissolved impurities allowed to precipitate and deposit on the surface of wire mesh present in the cold trap. Figure 8 shows schematic of a cold trap.

![Figure 8. Schematic of cold trap](image)

Figure 8. Schematic of cold trap

Impurities having temperature dependent solubility such as sodium oxide and sodium hydride only are removed by this method. Purity level of sodium in systems are monitored by a device by name plugging indicator which measures the saturation temperature of dissolved impurities indirectly.

### 7.3 Sodium leak detection

Leakage of sodium from the system is avoided by selecting suitable construction materials, adopting all welded construction and stringent quality control measures. The sodium systems are operated in round the clock shift under enforced technical specifications by deploying trained and qualified manpower. Limiting conditions of operating parameters are defined and are not allowed to violate. However minute probability of barrier failure exists and if it fails, liquid sodium may leak to atmosphere. Detection of sodium leak at the incipient stage by local and global leak detection is the first step of defense followed. Sodium leaks from vessels, tanks and pipes are detected at the incipient stage by wire type leak detectors. These detectors have capability detect leakage of 200 grams of sodium leak within 2 hours. The detection capability of sodium leak detecting system were experimentally demonstrated. Nickel or stainless steel wires are positioned over the vessel tanks and pipes at regular intervals and they are electrically insulated from the system components by means of insulating ceramic beads. In case of a sodium leak, leaked sodium being a good electrical conductor, bridge the gap between the nickel/SS wire and electrical circuit is made to close. This signal is sensed
by proper electronic circuits and alarm indication appears in control room and alert the operator[11,12]. Figure 9 shows sodium leak detectors fixed on pipe line. Sodium ionization detector based system is used for global leak detection.

Figure 9: Sodium leak detector on pipe line

7.4 Sodium fire fighting
Mitigation measures envisaged are collection of leaked sodium in specially designed leak collection trays, which has provision to cut off air supply to the collected sodium and provision for sodium fire fighting. Figure 10 shows schematic sodium of leak collection tray.

Sodium can leak and form a spray fire or pool fire depending on the process condition of the leaking system and ambient conditions. Sodium fire fighting is complicated and risky because of the emission of large quantity of smoke containing of sodium oxide aerosol, which will completely block the vision. On inhalation of sodium oxide aerosols, respiratory system of human beings will be badly affected. Blanketing is the principle adopted for sodium fire fighting. Dry chemical powder (DCP) made of sodium bicarbonate is sprayed over the sodium pool under fire and oxygen supply is cut off. The low density moisture free sodium bicarbonate powder will float on the burning sodium surface and prevent the fire. Fire fighting systems with automatic dispersal of DCP were used in large sodium facilities which enables remote operation.
Figure 10. Schematic sodium of leak collection tray

7.5 Sodium disposal
Sodium is not consumed in a nuclear reactor or in an experimental facility. It is only circulated in the primary and secondary circuits of the heat transport system of a reactor. However, relatively small quantity waste solid sodium is formed during modifications and maintenance of sodium system. These waste sodium may have lot of impurities such as oxides and hydroxides and is not worth to purify and recharge into the system. This waste sodium has to be converted into sodium carbonate or chloride. Disposal of solid sodium waste is by allowing it to burn in air by applying finewater spray. The sodium hydroxide formed is collected in tanks and is neutralized by acidic solutions. The pH of discharge to the environment is kept within the allowable limits. In order to avoid release of sodium oxide to ambient, wastesodium is burned in chemical reactors at controlled air atmosphere and the smoke emitted is admitted to water bubblers for conversion to sodium hydroxide solution.

8. Technology spinoff
The possibility of application of liquid sodium as a heat transfer medium and as a reducing agent in other process industries may be of worth consideration[13]. The equipments, components and systems developed for liquid sodium may find application in other process industries with suitable modifications. Similarly many modern smart sensors, devices and technologies developed elsewhere for high temperature process systems may find application in sodium systems with appropriate modifications. IGCAR has not given priority in this area as the centre was focusing to meet the technology requirements of PFBR and future FBRs. Removal of Sulphur content from petroleum is essential for limiting SO$_2$ emission from automobiles. Sodium may be an effective reducing agent for removal of residual sulphur from petroleum products. The technology is yet to be developed. There are many more areas where technology development took place in IGCAR and results are published and are available in open domain.

9. Conclusion
Sodium which is stored in small bottles in laboratories have wide application in fast breeder type of nuclear reactor as coolant. Thousands of tons of liquid sodium is circulated through primary and secondary heat transport system up to an operating temperature of 550 °C. Sodium technology is branch of fast breeder reactor technology and is around 60 years old. Sodium technology is matured enough to meet the requirement of fast breeder reactor and around 20 reactors are commissioned and operated with sodium as coolant all over the world. However there are gap areas in sodium technology which has to be addressed. Performance enhancement, increased safety and economic measures are to be taken, to make energy from fast breeder reactor economically competitive and safe. In addition the
application of this excellent heat transfer medium and reducing agent in other process industry also has to be considered. Extension of technologies developed for sodium to other electrically conductive high temperature fluids in industrial and process application is also possible. Hence, though this hazardous element poses many challenges in handling, it gives immense opportunity for scientific and academic community for application oriented research.

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