SENSORS IN SODIUM COOLED FAST BREEDER REACTORS

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I. INTRODUCTION

The Fast Breeder Reactor (FBR) program in India started with the Fast Breeder Test Reactor (FBTR) which is a 40 Mwt experimental reactor. FBRs utilize the higher energy neutron spectrum to achieve faster conversion of fertile materials to fissile ones. The light and heavy water reactors which account for the maximum number of reactors in the world, due to their low energy neutron spectrum have a low conversion efficiency. Natural uranium contains only 0.7% of U235 (Fissile) and 99.3% of U238 (fertile). Fast reactors help in larger conversion of fertile to fissile materials, referred to as breeding. Hence complete utilization of the natural uranium resources is possible only through FBRs. Next FBR under construction in India, is the Prototype Fast Breeder Reactor (PFBR) and is a 1250 MWt, 500 MWe plant. Sustaining the higher energy spectrum needs absence of moderating materials like water. Hence alternative coolant chosen was sodium and Sodium-Pottassium alloy in the earlier FBRs. Liquid sodium meets almost all the requirements of a fast reactor coolant with its high thermal conductivity, reasonable specific heat, low neutron moderation and absorption, and high boiling point(~ 900 deg. C) giving a large operating temperature range [1]. This results in a low pressure but higher temperature system, which can finally exchange heat with water to produce steam at higher temperatures. Higher steam temperature gives a higher cycle efficiency (40%) as compared to 30% with Light/heavy Water Reactors. Sensors are used in FBRs for measurement of Sodium Temperature, Sodium Level, Sodium Flow, Sodium Leak Detection, Hydrogen and Oxygen detection in Sodium etc. [2]. Since sodium gets ignited when it comes in contact with air and moisture, it is essential to have an all welded construction with minimum intrusions. This has led to the development of non invasive instrumentation. Under sodium viewing sensors are used to capture the images of objects immersed in sodium. This paper gives an overview of the sensors that are used in FBRs.

II. SODIUM LEVEL SENSORS

Sodium level sensors are of two types viz., continuous level sensors and discontinuous level sensors[3]. While the former is used to measure sodium level continuously, the latter is for measuring discrete levels. The sensors have to work in liquid sodium up to a high temperature of 600 $^{\circ}$ C. Hence the material for sensor construction should be compatible with liquid sodium and in addition be able to withstand high levels of temperature and radiation. The level sensors used are of non contact type which works on the principle of change in mutual inductance with sodium level. The primary coil is excited with AC constant current source and the emf will be induced in the secondary coil of the probe. The emf reduce with sodium level around the probe.

The sensor consists of stainless steel former of cross shaped cross section whose edges are cut into serration or grooves. Two mineral insulated cables of 1mm dia are wound in bifilar fashion into these slots which constitute primary and secondary coils. This former is positioned inside a thimble or well mounted on a vessel in which the sodium level has to be measured. The construction of the probe is as shown in Fig. 1. So far in our sodium rigs we had fabricated and used level sensors up to a maximum length of 2.5 m. Maximum active length of level sensors required for PFBR is about 6 m. Due to longer length of probe, it is difficult to maintain the normal 1 mm gap between the winding and pocket ID.

A theoretical analysis was carried out with the help of a 2D software viz., FEMM to find the effect of various parameters such as change in excitation current, gap between coil and S.S. pocket and pocket diameter [4]. It was seen that though sensitivity decreases with gap, it is still measurable and acceptable. In order to have actual data on the impact of increased gap, three numbers of model sensors of different diameter (30 mm, 32 mm, 34 mm) bobbins with active length of 1 meter suitable to the pocket made of 11/4 inch sch. 10 pipe have been fabricated and successfully tested in sodium.

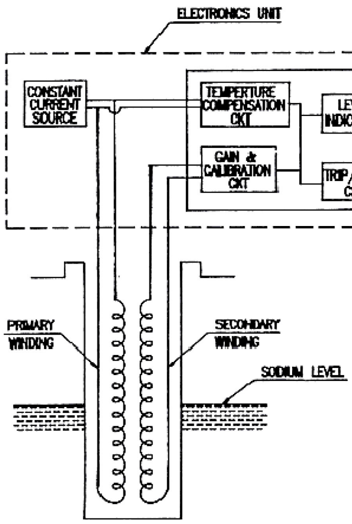


Fig. 1 MI type continuous level probe electronics and the sensor

III. LEAK DETECTORS

Liquid sodium reacts readily with air leading to sodium fire. Sodium burning is accompanied by production of dense sodium oxide fumes though the heat produced is much less compared to conventional hydrocarbon fires. The system is therefore required to be helium leak tight to prevent sodium leaks in the first place. The piping and components are to be equipped with leak detection devices to detect any leakage early in order to limit the effects of fire.

A. Wire Type Leak Detector

These detectors essentially comprise a wire carrying a small current which is wound over the sodium pipes and capacities with adequate insulation in the form of ceramic beads. In case of a sodium leak, sodium will short the wire with the pipe/vessel body giving rise to a short circuit and this is sensed.

B. Spark Plug Leak detector

In case of failure of the wire type leak detector to detect, the sodium would come out of the insulation

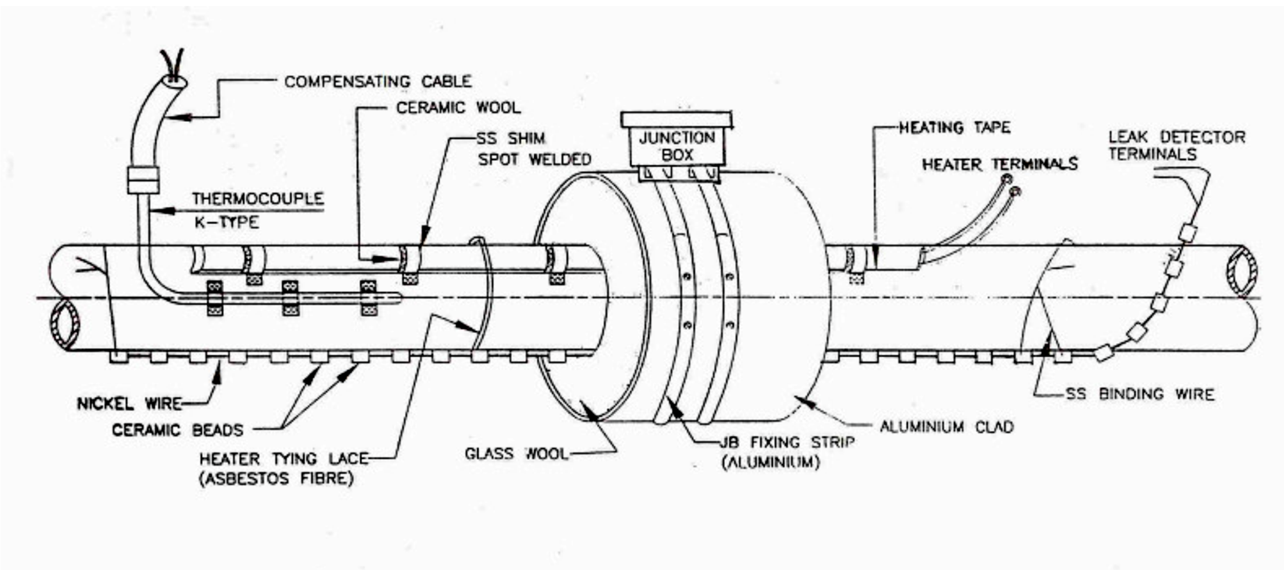


Fig. 2. Wire Type Leak Detector on Sodium Pipe

and drip out. Under all sodium pipes and capacities, leak collection trays are provided and these are provided with spark plug type detectors where the two electrodes will get shorted when sodium fills the gap between them and establish continuity.

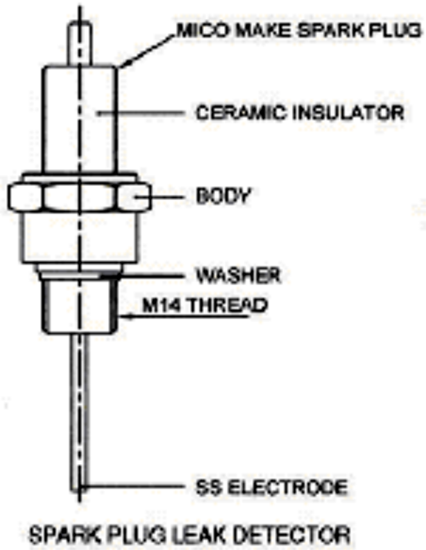


Fig. 3. Spark Plug Type Leak Detector

C. Main-Safety Vessel annulus Leak Detector

There is need for detection of sodium leak from the Main Vessel (MV), which collects in the gap/annulus between Main & Safety vessels (SV). The Leak Detector has to be inserted into and withdrawn through a guide tube on the inner space of the SV in the MV-SV gap [5]. The detector works on the principle of decrease in mutual inductance between two coils when sodium surrounds it. The secondary coil emf will reduce when sodium surrounds the guide tube and is the indication of sodium leak. Fig. 4. shows the photograph of the probe.

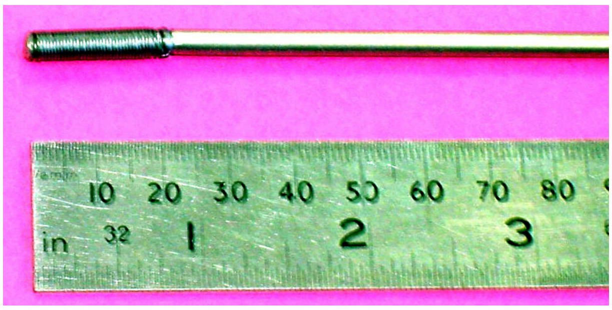


Fig. 4 MILD sensor

D. Sodium Ionization detector (SID)

It works on the principle of preferential ionization of aerosols of sodium and its compounds (oxides and hydroxides) in carrier gases such as argon, nitrogen and air. It is used for area monitoring. Its sensitivity is better than 0.3 nano gram of sodium in a cubic cm of a carrier gas. It works with carrier gases at atmospheric pressure unlike conventional ionization gauges, which work under vacuum [6]. It uses a heated filament to ionize sodium vapour or its aerosols in preference to the constituents of the carrier gas. These positively charged sodium ions are coolected by a collector electrode to provide a measure of ion current, which is an indication of sodium leak.

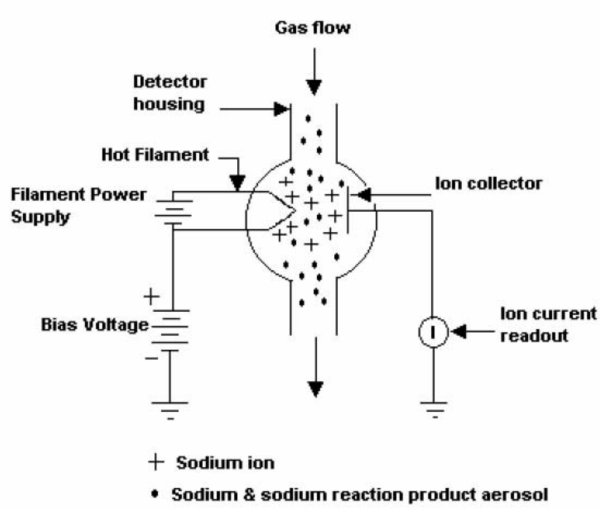


Fig. 5. Schematic of the principle of working of SID

Fig. 6. SID as area monitoring

E. Cross wire type Leak Detector

The main function of the Cross Wire type Leak Detector (CWLD) is to detect the discharge of sodium and its reaction products at the downstream of the rupture disc due to bursting of the rupture disc. This provides the information on sodium water reaction caused due to water/ steam leak in the Steam Generator (SG) and the developed hydrogen gas pressure bursts the rupture disc. While spark plug type detectors were used in FBTR, it was felt that in vertical legs the sodium may not flow fully and could bypass the detector location. Hence the CWLD was developed[7]. It essentially comprises SS foils placed in a crosswise fashion and these S. S. foils are located at the downstream of the rupture disc. When sodium/ sodium reaction products flow past the S. S. foils break them and the loss of electrical continuity of the foils is detected and alarm signal is given. To electrically insulate the foils from the metallic pipeline, a spark plug is installed in pipe with the help of sleeves. The breaking of these SS foils are detected electronically using two by three logic. Fig.7 shows the SS foils before and after breaking.

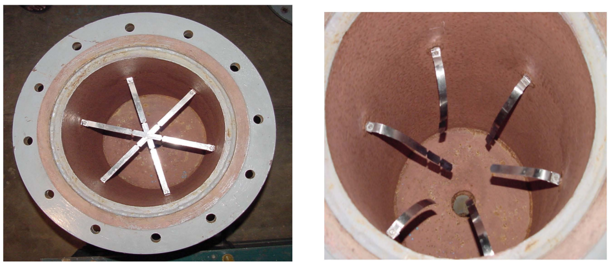
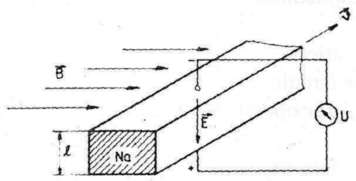


Fig. 7 SS foils before and after breaking

IV. FLOW METERS

Flow meters used in FBRs are of two types i.e. Electromagnetic and eddy Current type. The principle of operation of the electromagnetic flow meters is based on the Faraday's laws of electromagnetic induction, "If a conductor moves in a magnetic field normal to the direction of the field, a potential is developed across the conductor, which is proportional to the velocity of conductor and flux density of the magnetic field" (Fig. 8). The EM Flow meter essentially consists of a pipe made of non magnetic material mounted in a transverse magnetic field between the poles of an electromagnet. Electrodes are mounted on the pipe in diametrically opposite directions at right angles to the field as well as direction of flow to measure the induced emf when sodium flows through the pipe.

Single wall flow meters upto the pipe size of 100 NB had already been designed and constructed (Fig.9) for various sodium experimental facilities [8]. Currently development of flow meters for Double wall pipelines above 100 NB pipe size is being carried out with specially designed magnetic circuit. Experience from flow meter assemblies made with these magnet blocks showed that two parallel magnet circuits each with C type magnet blocks in series would be required to obtain necessary air gap flux density.



Induction law: constant magnetic field.

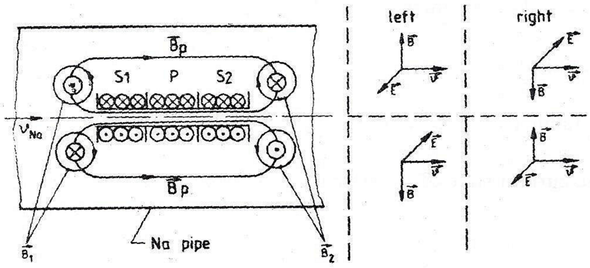


Fig. 8. Principle of EM & Eddy Current Flow meter

If an alternating field is used, which can be processed more easily by electronic circuits, the eddy-current or flux distortion flowmeter can be postulated [9]. The function is explained in Fig 8. Here the central coil is a constant current-excited primary coil *P* flanked symmetrically by secondary coils S_1 and S_2. At a given instant a current flows in the primary coil *P* in the direction shown. This current generates a magnetic flux B_p within the coil and its surroundings as indicated. In the case of stationary sodium, voltages of similar magnitudes will be induced at each of the coils S_1 and S_2, provided geometrically symmetrical design exists. In the case of flowing sodium, circular currents will be generated in the sodium resulting from the interaction of the radial components of the flux

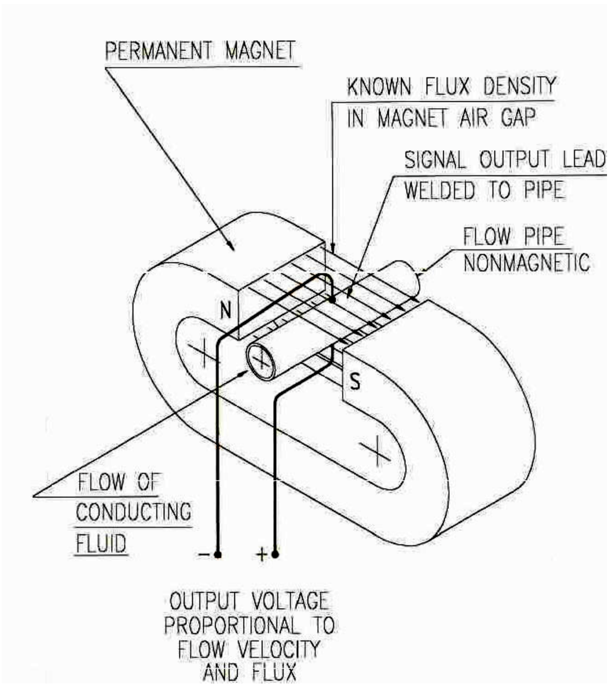


Fig. 9. Permanent Magnet Flowmeter

B_p with the moving sodium. These currents are surrounded by the fluxes B_1 and B_2 which are opposite in radial direction and link the coils S_1 and S_2. Thus the voltage within the coil S_1 is equal and opposite in phase with respect to that within the coil S_2. The resulting voltage difference between S_1 and S_2 is directly proportional to the local flow velocity of the sodium and can be measured in velocity units.

V. EDDY CURRENT POSITION SENSOR

In PFBR, there are three Diverse Safety Rod Drive Mechanisms (DSRDM) in the control plug, which hold the diverse safety rods (DSR). During normal operation, DSR are held outside the active core region by an electromagnet housed in the DSRDM. On receiving trip signal, the electromagnet de-energizes and drops the DSR, which falls under gravity in sodium. DSR gets decelerated due to damping action of sodium in the dash-pot after traveling free-fall distance. For detection of DSR at its bottom most position, an Eddy Current Position Sensor (ECPS) based on eddy current technique was designed, fabricated and tested in air and sodium.

The basic design was arrived at after analyzing different design options taking into consideration the space constraints, high temperature environment and maximizing the response. Finite Element based analysis of various configurations was done and the configuration shown in Fig. was finally selected for air and sodium testing. In this configuration, the primary coil, placed on the mobile assembly of DSRDM is excited with constant current. A pick-up coil is also placed below the primary coil in same axis for getting the output signal. Secondary, signal transfer & sensor coils are placed on the DSR sheath side (static). The induced voltage in secondary drives a circulating current in all the three coils on secondary side. The magnitude and phase of this current depends on the total impedance of coils on secondary side. The impedance of sensor coil (which is surrounding the dashpot region) changes when the DSR is in the deposited condition compared to the non-deposited condition. Thus, the flux linkage with pick-up coil varies, thereby changing the voltage induced in it. This change in pick-up voltage indicates presence of DSR in the dashpot region.

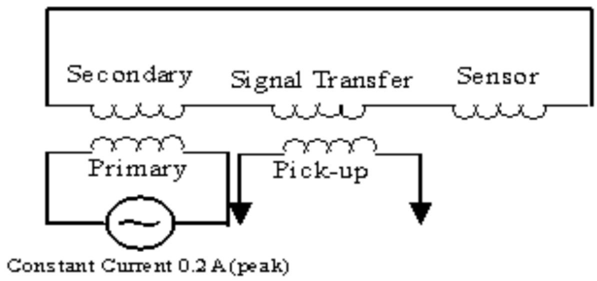


Fig. 10. ECPS Schematic

VII. ULTRASONIC UNDER SODIUM SCANNER (USUSS)

The opacity of sodium has precluded any optical methods for inspection of immersed components. Fortunately sodium is 'transparent' to ultrasound and using the conventional pulse echo technique, scanning under sodium to a temperature of 180°C has already been demonstrated in FBTR [10]. The scanner was deployed to check for any protruding subassembly (SA) in the reactor. A typical scanning region for detecting any protruding SA over a height of 100 mm in the inter space between the above core plenum and the lattice plane has been shown in fig. 11.

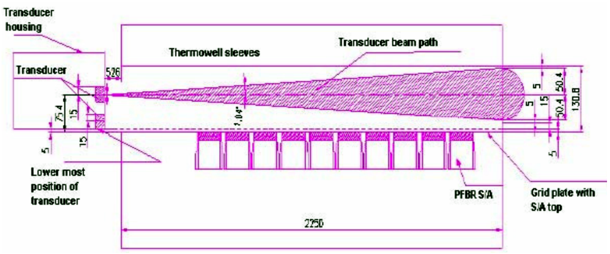


Fig. 11. Scanning region for detecting protruding subassembly

Fig. 12 shows images of two FBTR S/A tops obtaining using an xy scanner under water. From the images the distance between the centres of the S/As were measured. From these images bowing & growth of S/As can be measured. Fig. 13 shows the image of a PFBR type subassembly obtained during water tests.

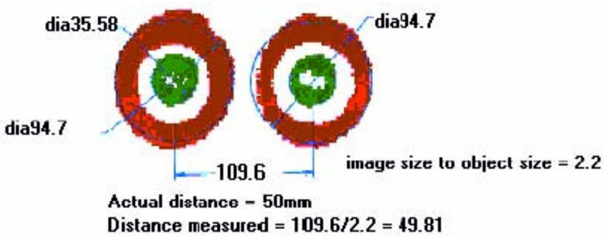


Fig. 12 Distance measured between SA top images-FBTR.

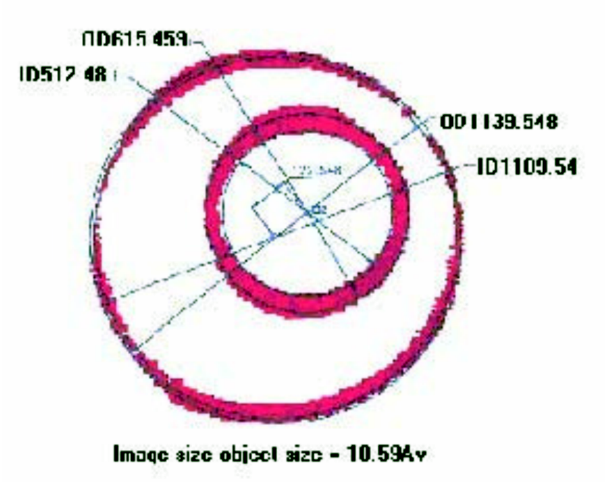


Fig. 13. Image of PFBR Type Subassembly

As transducers capable of being used in sodium at high temperatures viz. 180°C are not commercially available, the same had been developed at IGCAR. The challenging task is to develop ultrasonic transducer capable of withstanding higher temperatures viz. 270°C and sensitive enough to detect protruding SA over long ranges in sodium of the order of 5 m. Two transducers were fabricated successfully with 5 MHz (for imaging purpose) and 1 MHz (for ranging) piezoelectric crystal (PZT plain A) having curie

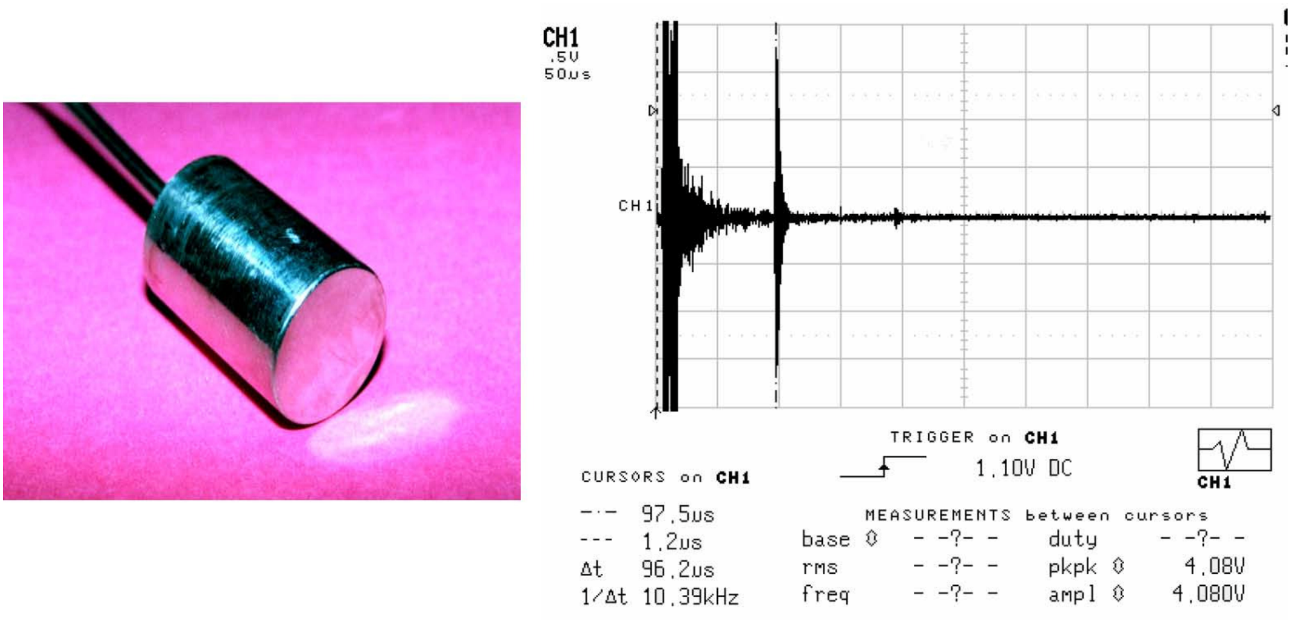


Fig. 14 Ultrasonic transducer & Pulse echo output in sodium

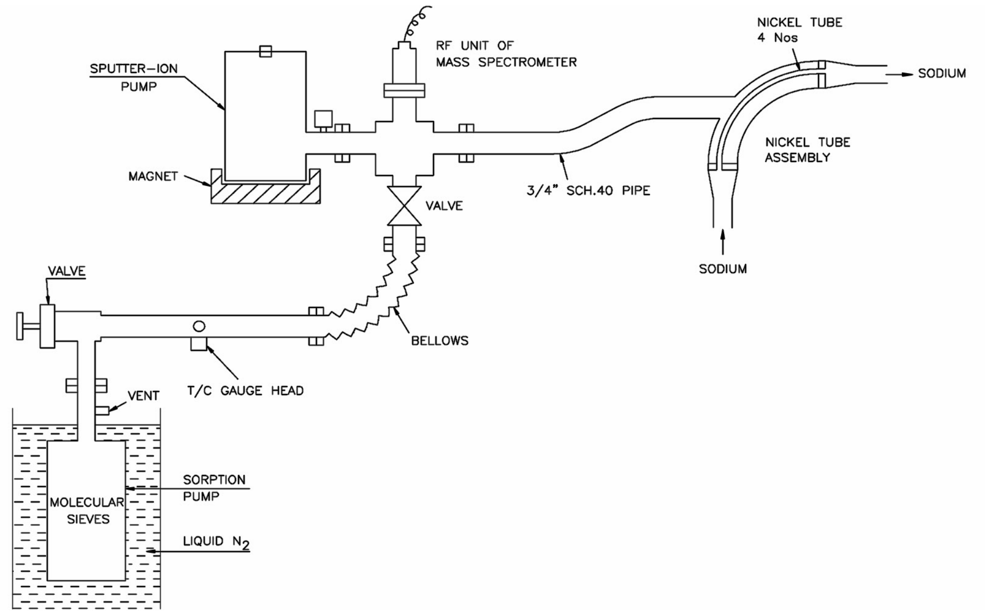


Fig. 15 SIP based Hydrogen Detector

temperature of 380°C. These crystals having a curie temperature 50 deg. C higher than the normal PZT5A type, were obtained specially developed from an indigenous manufacturer of PZT crystals. However, the operating temperature of the transducer is limited by the solder alloy (MP ~ 220°C) used to bind the crystal to the transducer diaphragm. Fig. 14 shows the transducer and the pulse echo output obtained in FBTR in Sodium at 180 deg.C. To operate at higher temperatures (~ 250 – 270 deg.C), suitable solder alloy has been identified (leadsilver alloy MP 300°C) and the efforts made to solder the PZT crystal to the nickel diaphragm.

VII. HYDROGEN DETECTION

Steam Generator in a FBR involves heat transfer from high temperature, low pressure sodium to high pressure water/steam. Generally sodium flows on the shell side and water/steam flow in the tube side. In case of a crack in the tube, the high pressure water/steam will react with sodium producing hydrogen and other reaction products. The early detection of hydrogen will ensure that action can be taken before the leak rate becomes large. The general method of hydrogen detection in sodium utilizes the property of diffusion of hydrogen through nickel (Fig. 15). The detector employs a thin walled nickel tube through which liquid sodium flows. The other side of the nickel

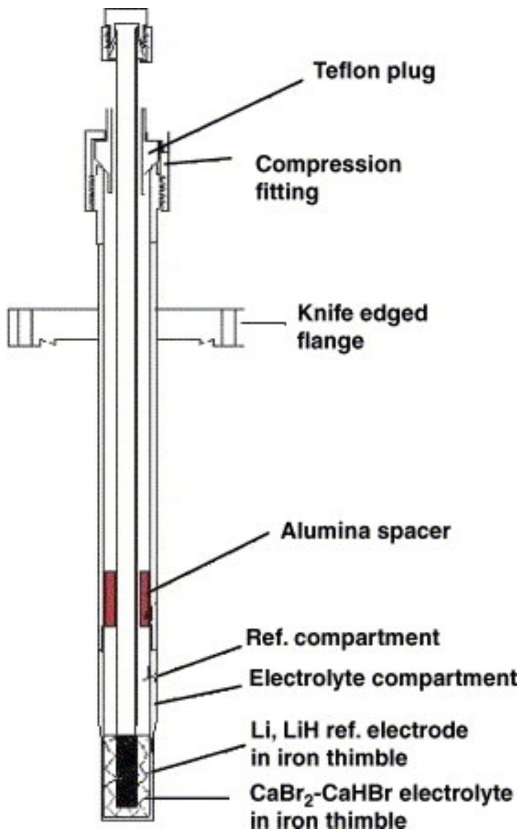


Fig. 16 Electrochemical Hydrogen Meter

tube is maintained under high vacuum by use of a sputter ion pump [11]. The partial pressure of hydrogen in the vacuum side is measured using a mass spectrometer. The detector is operated in a continuous mode.

An Electrochemical Hydrogen meter has been developed at IGCAR [12]. It basically consists of an iron thimble containing the electrolyte (CaBr2-CaHBr) and another thimble containing the reference Electrode(Li-LiH). The annular space between the electrolyte and the electrode compartments (reference and Sample electrodes) are filled with alumina. The meter produces an emf which is related to the hydrogen pressures established at the two electrodes. In this manner the hydrogen concentration in the sodium is established. It can measure hydrogen concentrations from few ppb to ppm level. These have been successfully tested in different sodium facilities and in FBTR and qualified for use in PFBR.

For measurement of hydrogen content in cover gas argon , a Thermal Conductivity Detector (TCD) has been developed at IGCAR(Fig. 17). This meter makes use of the difference in conductivity of the two gases viz. Argon and Hydrogen[13]. Thermal conductivity of hydrogen is many folds higher that of argon. The main constituents are a nickel sensor, Carrier gas manifold, and a TCD block. Fig: 5 gives the details. Nickel sensor with a heater, to maintain an operating temperature 773 K, is inserted into the cover gas space of a sodium vessel .The sensor is a very long nickel tube in the form of a coil. Through its thin wall, hydrogen in the cover gas diffuses into the nickel tube and is swept by a flowing carrier gas into a Thermal Conductivity Detector (TCD) for analyzing the hydrogen concentration in the sample. The conductivity measured in terms of voltage is calibrated against hydrogen concentration.

VIII. OXYGEN PURITY MONITOR

Oxygen is an important impurity in sodium that is responsible for corrosion. In case of precipitation, the

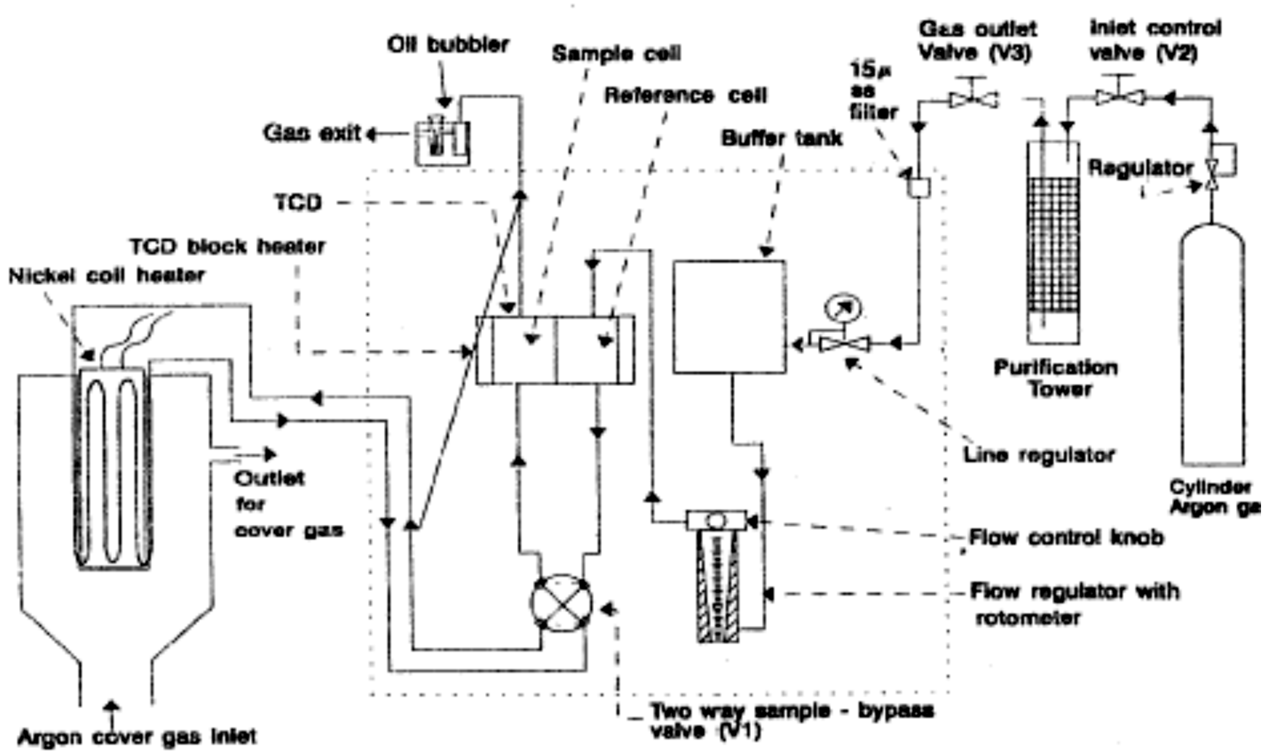


Fig. 17 TCD based HAD

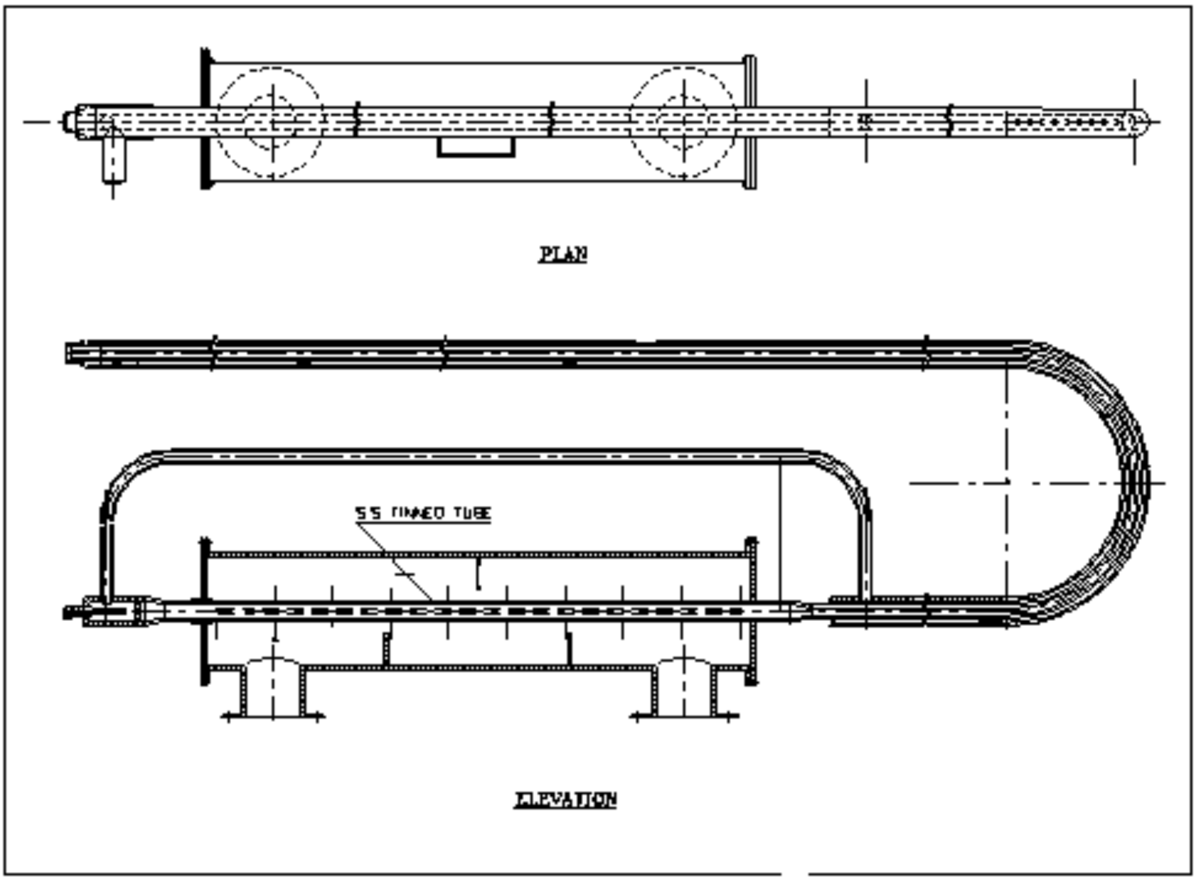


Fig. 18 Plugging Indicator

flow passage would get restricted and this property is used in the design of a simple instrument called plugging indicator. Here a sample of sodium is made to flow through a small orifice. The temperature of the orifice and flowrate are measured. When the sodium temperature is brought down by air cooling to the saturation temperature for that impurity, precipitation gets initiated and flow starts reducing. Further cooling is continued till flow stops, when the orifice is blocked. This is the plugging temperature. Now the cooling is stopped and sodium temperature starts increasing and plug starts melting and at the saturation temperature the plug is totally molten and full flow gets restored. Fig 18 shows a diagram of the plugging indicator.

IX. TEMPERATURE MEASUREMENT

Temperatures in FBRs are in the range from room temperature to 600 Deg. C. For this purpose mineral insulated stainless steel clad thermocouples of conventional design (Chromel-Alumel) are used. The accuracies are of the order of 0.75%. The thermocoples are put in pockets welded to the pipe or sodium capacity. The tip of the thermocouple needs to have good contact with the pocket and for this purpose a special mechanical device is used which keeps the tip pressed against the wall of the pocket. With pocket the response times are of the order of 4+ 2 s. To have faster response thermocouples monitoring the central fuel assembly are immersed directly in sodium. These have a response time of ~ 250 ms.

X. CONCLUSION

Fast Breeder Reactors will form the mainstay of the Nuclear power programme in India in the coming years. Towards this, Fast Breeder Test Reactor of 40 MWt has operated successfully and valuable experience has been gained. These have formed the basis of launching Prototype fast breeder reactor of 1250 MWt, 500 MWe. This paper has brought out the different sensors developed and used in the FBRs. The sensors development and commercialization is a challenging task. In this direction IGCAR has made valuable contributions.

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