Development of Indigenous Instrument for Visual Inspection of Reactor Internals

R.V. Sakrikar[1], A.M. Kadu[1], R.L. Suthar[3], R.K. Modi[1], M.G. Radke[1], D.V. Udupa[2] and S. Kumar[2]

[1]Division of Remote Handling and Robotics, BARC, Mumbai-400 085
[2]Spectroscopy Division, BARC, Mumbai-400 085
[3]Centre for Design and Manufacturing, BARC, Mumbai-400 085

Abstract

Pre-commissioning and periodic in-service visual inspection of reactor vessel internals, of Prototype Fast Breeder Reactor (PFBR), is a mandatory regulatory requirement. An Indigenous Instrument (Periscope) is designed for this purpose.

The instrument is accommodated within a tube of 400 mm outer diameter and has a length of 10 meters. The single tube contains viewing, illumination and the associated auxiliary systems. The Periscope is a sealed system and operates in Argon environment saturated with sodium aerosol at temperature of 150 Celsius and radiation field of 1.3R/hr.

The Periscope has facility for focusing of image, scanning in vertical plane, image rotation and zooming to the area of interest. The Periscope can also be rotated around its axis through 360 degree for complete coverage of the reactor internals.

Optical Relay lens based system is used to transfer the image from the objective prism to the eye piece. All the motions are motorized using high temperature stepping motors and position sensors. An additional viewing port is also provided for photography and video recording.

The illumination level of 2500 Lux at 4 meter distance from Periscope, required for inspection is provided by combination of two lamps. Compact, short arc Ceramic Xenon lamps with integral reflector are used for the illuminator. Both the lamps are provided with motorized beam deflecting arrangement. The lamps are force cooled by Argon. An elaborate cooling arrangement is designed for this purpose.

The Periscope is provided with PLC based controls. The control systems provide interface for operation of the periscope systems, display of status information and monitoring of the operation interlocks.

The Periscope is designed for its designated handling and maintenance requirements that may arise during its life time. The Periscope is designed for operating life of 40 years, during which it is to be used for 20 planned inspections. Another 15 unplanned and exceptional operations are also envisaged. The paper presented here highlights the design aspects of the various sub-systems of the Periscope.

Keywords: *Periscope, Visual inspection, Reactor vessel, Cover gas*

1. Introduction

The Periscope is an in-service inspection instrument used for visual inspection of Prototype Fast Breeder Reactor's (PFBR) main vessel internals and various other components and equipments installed inside the main vessel.

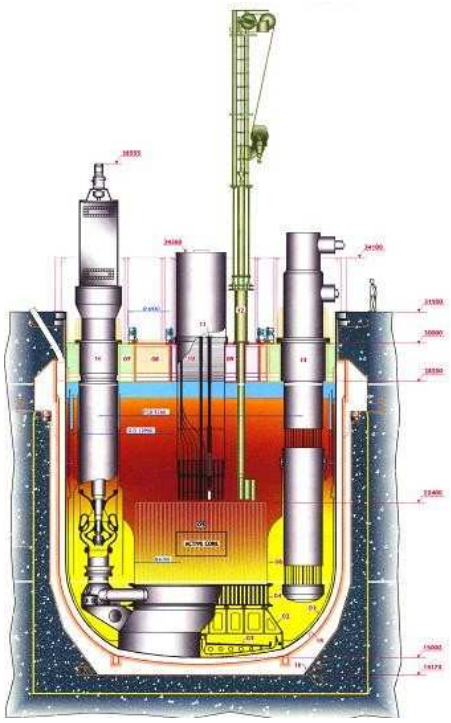

Fig. 1:

The Fig. 1 shows the various components and their arrangements for PFBR. The PFBR has a Main Vessel of 12.9 meters diameter and 13.2 meters height, with a Roof Slab and Large Rotatable Plug at the top. The Roof Slab has six openings, four openings for intermediate heat exchanger and two for primary sodium pump. The Large Rotatable Plug (LRP) has openings for invessel fuel transfer machine and control and safety rod drive mechanisms. The equipments are installed inside the reactor through their respective openings and are partially submerged in liquid sodium. The gap between the top of the sodium and bottom of Roof slab is filled with Argon cover gas. There are also some components like Purified sodium inlet pipe, Argon inlet pipe, Siphon break pipe that are fixed from the top of roof slab. The Periscope is required for visual inspection of these components also. The inspection is carried out with the reactor in shutdown condition.

The Periscope is designed to operate at ambient temperature of the cover gas which is 150º C and radiation field of 1.3 R/hr. The complete inspection campaign is to be carried out in a leak tight manner. An elaborate periscope handling and installation procedure has been evolved to meet this requirement. This requires the use of associated accessories such as Leak Tight Chamber, Preheating Chamber and Gate Valves. The Periscope is also sealed, purged with Argon and maintained at slightly higher pressure compared to the reactor cover gas, so that there is no leakage of reactor Argon in case of the failure of the seal.

The Periscope is a 10 meters long instrument with an outer diameter of 400mm. The assembly houses both the viewing and the illuminator system. The viewing system of the periscope has provision for scanning the area of interest, zooming arrangement, image relay, image focusing, image rotation, image deflecting mirrors and eyepiece for viewing. The Periscope has a number of relay lenses in the straight line for transmission of the observed image and a set of stationary and movable prism mounted in front of the objective lens provides the object scanning in vertical plane. By moving these prisms, rotating the periscope about its own axis and adjusting the height of the Periscope the operator can survey the complete area of interest. The final image obtained at the eyepiece must be erect and non-laterally reversed for proper operator perception. The Illuminator system provides the requisite illumination over the area of interest.

2. Design of Periscope

2.1 Optical Design

Figure 2 shows a schematic optical layout of the periscope designed using the concept of paraxial ray trace [3]. The periscope has three main parts as objective sub-assembly, relay lens sub-assembly and eyepiece module. Relay lens sub-assembly contains an image canal to transfer the image of the target area under inspection, to the eyepiece for viewing by the operator. All the optical components have been designed and fabricated using radiation resistant glass [4] such as BK7G25 and F2G20.

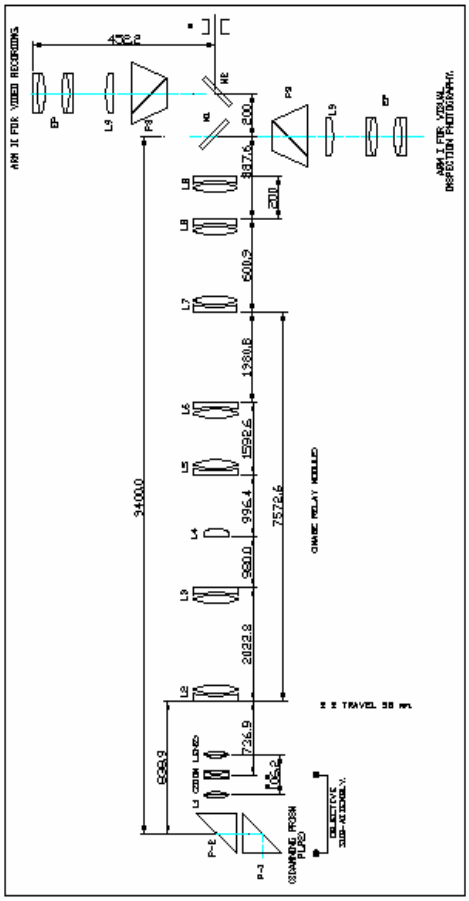

Fig. 2

2.1.1 Scanning Prisms and Objective

Two prisms (P_1, P_2) of 45^0-90^0-45^0 type are used for scanning the object space in vertical direction. The prism P_2 is fixed and the prism P_1 can be rotated on the horizontal axis. The rotation of prism P_1 scans the object space in vertical plane. The scanning in the horizontal plane is achieved by rotation of the entire periscope.

The objective lens L_1 of the Periscope is a zoom lens system for obtaining a continuously varying magnification from 3X to 9X. This covers a field angle of 5^0 for 300 mm focal length and 15^0 for 100 mm focal length of the objective system. The zoom lens system is an "*optically compensated*" type and consists of three doublet lenses. The first and the third lens are movable and they are mechanically coupled so that they can be moved together by an equal amount. The central lens is a fixed lens. Moving the coupled lenses along the optical axis changes the magnification. The zoom lens design has been optimized for an object distance of 4 meter from the periscope end.

2.1.2 Relay Lens System and Eyepiece

The relay lens system is for the purpose of relaying the primary image formed by the lens L_1 to the object plane of the Eyepiece (EP) for viewing/recording. The EP is at the distance of about 9400 mm from the scanning prism for the 10 meter Periscope. The relay lens system consists of two field lenses L_4, L_9 and six relay achromatic doublets L_2, L_3, L_5-L_8 as shown in Fig. 1. The Pechan prism P_3 is used for correcting the image rotation of the image which gets rotated due to the motion of the scanning prism P_1. This feature is desirable for reading any marking on fuel assembly. The eyepiece EP has two achromatic doublet lenses arranged to give a focal length of 65 mm

2.2 Mechanical Design

The Periscope is housed in a single main tube to facilitate ease of handling during deployment and removal of the unit. The

overall design of periscope is governed by the optical layout of the periscope. The main design requirement is the optical alignment of optical elements and maintaining optical alignment during movement of optical elements for zooming, scanning and focusing. The design is based on modular construction of optical mounts for ease of assembly and disassembly of optical elements.

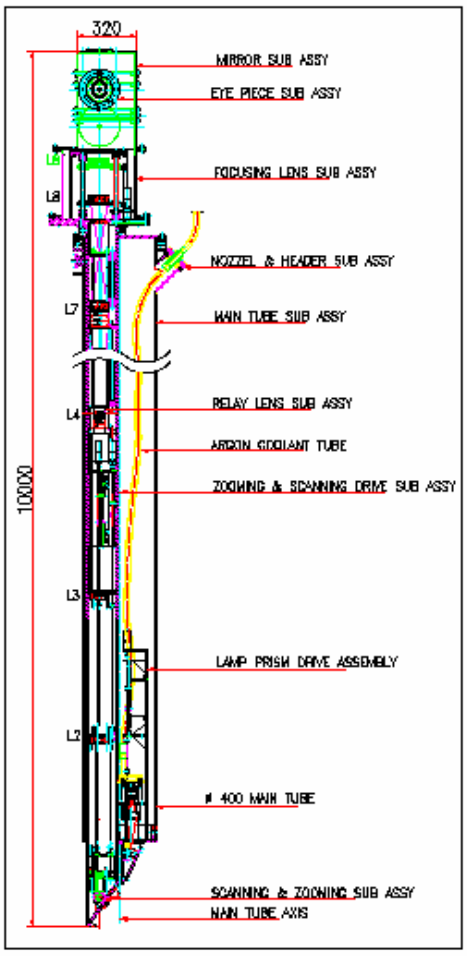

Fig. 3

The Periscope consists mainly of four sub-systems,

- Main tube assembly
- Viewing assembly
- Illuminator
- Controls

The resulting Periscope assembly is as shown in Fig. 3.

2.2.1 Main Tube Assembly

Main tube is a 400mm OD and 380mm ID, SS304 pipe and is hard chrome plated and ground from outside to have scratch proof surface, as per the sealing requirements. The bottom plate fixed to the main tube provides support for lamp modules and associated systems. The main tube assembly provides the required support and rigidity to the Viewing assembly. The top portion of the main tube is provided with lifting lugs and openings for services such as cooling argon, electrical cables, motors and switches etc. The main tube also supports the control panels and the operator cabins mounted.

The main tube is installed on the rotating table to facilitate axial rotation and the linear axial movement of the Periscope.

2.2.2 Viewing Assembly

Viewing sub assembly consists of about 25 optical elements as described in optical design, which are assembled with high mechanical accuracy.

Scanning prism assembly consists of two prisms P_1 and P_2. The prism P_2 is a fixed prism, transmitting image to zoom lens sub assembly. Prism P_1 rotates with respect to prism P_2 to facilitate scanning by 105 degrees in vertical plane. A bush bearing is provided between P_1 & P_2.

Zoom lens assembly consists of a set of 3 lenses L_{1A}, L_{1B} and L_{1C}. The lens L_{1B} is a fixed lens and L_{1A} and L_{1C} forms a single unit and moves across L_{1B}, this is achieved by guide rods and bushes. These are high precision machined components maintaining a concentricity of lenses in the range of 0.05mm.

The image is then transmitted to image relay assembly. This assembly consists of accurately machined lens mounts, connected to each other by tie rods. Tie rods ends are accurately machined and are fixed into reamed holes of corresponding lens mounts. The design of the lens mounts is such that the concentricity of 0.05mm is maintained through out the relay lens system.

Lens mounts have provision of spacers for axial distance adjustment and Viton 'O' rings for cushioning.

The periscope has focusing lens assembly, after the relay lens system. The focusing arrangement is required since variations in image quality can occur due to change in magnification or during observation through second eye piece.

The focused image is then transmitted to eyepiece by deflecting the image by 90º using mirror mounts. The periscope has two eyepiece assemblies, one for direct viewing and other for photography or video recording.

There are two mirror mounts that gets optically aligned with respective eyepiece. Each mirror mount is designed for achieving very fine adjustment in two directions. This is achieved by pivoting the mirror with a ball joint at one corner and two spring loaded adjustment screws at other corners.

The eyepiece assembly consists of Pechan prism, Field Lens and Eyepiece. This system is designed for getting a very high accuracy of concentricity of all these optical elements since they get located in ball bearings and has to rotate about its central axis.

2.3 Illuminator

The visual inspection of the reactor internals requires high light intensity over the complete area of interest. For carrying out the inspection of an area for defects such as cracks, it is recommended to have an illumination levels of the order of 700 to 1000 lux over the area. The Periscope is an optical instrument having about 25 optical components in the visual canal. These include lenses, prisms, mirrors etc. There will be some loss of light due to reflection and absorption (about 2-3%) in each of these components. On the basis of our previous experiences of such systems the efficiency of the complete visual system will be in the range of 35 - 40%.

Taking in considerations all the losses it was decided that the light intensity of 2500 lux will be required on the target, which is at a distance of 4 meter from the Periscope. Due to the limitations of space, a compact lamp is essential. The short arc type Xenon lamps with integral reflectors are used for the illuminator. Two such lamps, one with ellipsoidal reflector and the other with parabolic reflector are used.

The 500 watt lamp with ellipsoidal reflector provides a diverging beam of light. The optics associated with this lamp controls the angle of divergence of the beam to 18 degree. This arrangement provides 1.2 meter diameter spot at a distance of 4 meter having the requisite light intensity.

It is expected that inspection of an area of interest with higher magnification will require higher light intensity. An additional 300 W lamp, with parabolic reflector provides an almost parallel beam of spot diameter 0.6 meter. This lamp provides the additional high intensity light required for the inspections with higher magnification.

The operator can selectively switch on the lamps as per his requirements. An additional provision is available for reducing the lamp power, in steps, if desired.

The Ceramic type of Xenon Lamps, used for the illuminator, has heat-sinks mounted on copper rings, which also act as power

terminals. The heat sinks require forced cooling during the operation of the lamps. The gap between the heat-sink terminals is dielectrically designed to operate the lamps in air. However the Periscope is a sealed device and has Argon as operating environment. The dielectric strength of Argon is almost one sixth, as compared to that of air. The Xenon Lamps are arc lamps, in which high voltage pulse of about 25 kV is applied across the terminals of the lamp for striking the arc. This would result in the breakdown of the Argon gap between the heat-sink terminals. This phenomenon is avoided by designing a ceramic enclosure around the lamp. The enclosure effectively elongates the Argon gap, to ensure that the arc strikes inside the lamp. The ceramic material used for the enclosure, has high thermal conductivity, comparable to that of Aluminum, in addition to its good dielectric strength, hence it effectively provides heat removal from the lamp ceramic body. The enclosure also has provisions for the supply of adequate quantity of cooling argon over the lamp heat sinks. The lamp enclosure for one of the lamps is as shown in the Fig. 4.

The two lamp modules are provided with optics to deflect the light beam in vertical plane through angle of 105 degree. The design is identical to image scanning mechanism.

The heat-sinks on the lamps are provided with Resistance type Temperature Detection Probes. The operation of the lamps is interlocked with temperature to ensure that the lamps are operated within their safe operating zone.

The requirements of cooling Argon are decided on the basis of detailed thermal analysis. The requisite Argon supply is derived from the Argon Header available in the Reactor Containment Building. The supply is routed to the lamp modules through SS flexible hoses. The hoses are provided with arrangements for quick disconnection from the illuminator modules to facilitate maintenance of lamp modules.

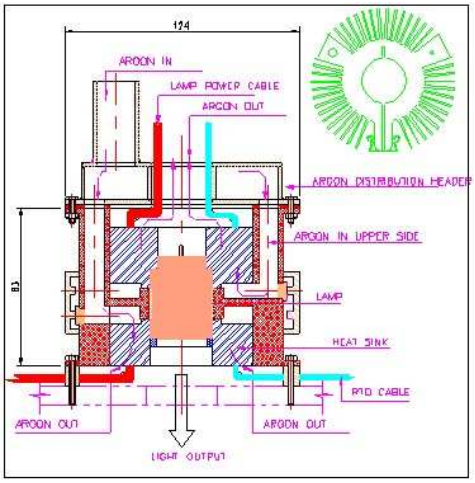

Fig. 4

2.4 Periscope Controls

The periscope optical components are provided with motorized motions for view scanning in vertical plane, continuous zoom, focusing and light beam deflection. All these actuators inside the periscope are working in Argon environment and face ambient temperature in the range of 100 to 130 Celsius. Hence all the actuators are based on high temperature stepper motors. The stepper motors have the advantage of simple open loop control. The position of the actuators can be estimated on the basis of number of steps supplied to the motors. The motors are controlled by individual controllers. The speeds of the each motor can be adjusted online by the operator. The actuators are also provided with non-contact type of magnetic position sensors, suitable for operation up to ambient temperature of 200 Celsius. These sensors provide the end of travel information and are used for calibration of the actuator position counters.

The Periscope Main tube has motorized arrangement for rotating around its axis through 360 degrees and its height is discreetly adjusted using the overhead crane and adjustable spacers.

The overall control is provided through a PLC based system. The control panel is split into three parts.

2.4.1 Main Panel

The Main Panel houses the main control PLC and its associated local I/O interfaces and the stepper motor controllers. This panel is situated at a convenient location about 15 to 20 meters away from the Periscope.

2.4.2 Remote I/O Panel

The Remote I/O Panel is mounted on the periscope main tube but is away from the operator. It is connected to main panel through a suitable serial link. All the sensors and actuators mounted inside the periscope are interfaced to this control panel. This data is then communicated to the main controller over the serial link. This arrangement considerably reduces the number of cables running between the Main Panel and the Periscope.

2.4.3 Operator Panel

The operator panel is designed ergonomically and is mounted below the Eye Piece assembly. It consists of a joystick interface, for operation of various motions and a touch screen for setting of various parameters and for information display. The operator controls are also duplicated on the main panel for complete remote operation of the periscope. This is especially useful during the photography and video recording of the area of interest.

3. Conclusion

The Periscope is a vital instrument for the PFBR. A similar Periscope, of smaller size, was developed for inspection of Fast Breeder Test Reactor (FBTR) internals. The experiences during the development of FBTR Periscope have been utilized for the current design. The PFBR Periscope would possibly be the longest such optical instrument developed in the country and enable us to undertake much bigger challenges.

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