A Quick Acting Device for Arresting Incidental Gross Leakage of Heavy Water during In-Service Inspection of Coolant Channels

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Abstract

The paper discusses design of an innovative device that can quickly arrest gross leakage of coolant heavy water in the event of accidental ejection/drifting of Special Sealing Plug during in-service inspection of coolant channels in Indian PHWRs (Pressurized Heavy Water Reactors) in reactor shutdown time. Temperatures during in-service inspection in the coolant channel are around 40-50 Celsius (or less). A Special Sealing Plug (installed in the End Fitting of coolant channel) forms pressure boundary in the Primary Heat Transport system (PHT) of reactor for carrying out in-service inspection of coolant channels. It is designed to permit movement of an Inspection Head inside the coolant channel. The accidental ejection of Special Sealing plug can result in gross leakage of heavy water coolant. A special device has been developed and implemented for arresting gross leakage quickly in such a situation. The paper gives detailed design and test results of the device.

1.0 Introduction

In-service inspection of coolant channels is an important activity taken up during shutdown period of the reactor. The inspection of coolant channel is carried out while maintaining the shutdown flow rate of coolant heavy water inside the reactor core. The inspection is done with the help of an inspection Head that houses a variety of NDE sensors. It is driven inside the wet coolant channel from outside dry environment where a drive system BARCIS (Bhabha Atomic Research Centre Inspection System ref [1]) is placed. The pressure boundary of the reactor is penetrated from outside dry environment to drive the inspection Head inside the wet environment of coolant channel. This necessitates use of a Special Sealing plug that has a central sealed opening through which the drive links can be inserted. The Special Sealing Plug remains installed in the End Fitting of the coolant channel while the Inspection Head is driven inside the coolant channel by joining the Inspection Head with drive extension links to the drive system (placed outside in vault). Special Sealing plug is installed in the End Fitting (along with the Inspection Head) by the reactor Fueling Machine. Following this, the drive system (BARCIS) is aligned with the said coolant channel and Inspection Head is driven inside thereafter.

We visualize an event of accidental ejection of Special Sealing Plug that will expose the entire bore (full bore) of the coolant channel resulting in a gross leakage of heavy water. A loss in the capacity to remove the decay heat from the fuel bundles due to loss of coolant may have serious consequences and hence there is a strong requirement of arresting the leakage as soon as possible.

The paper discusses the developed device for arresting gross leakage quickly as emergency preparedness while going for in-service inspection of coolant channels of PHWRs (Pressurized Heavy Water Reactors) in India.

1.1 Coolant Channel in a PHWR

An Indian Pressurized Heavy Water Reactor consists of a large number of coolant channels (also known as fuel channels or pressure tubes) housing natural uranium fuel bundles. In a 220 MWe Indian PHWR reactor core, there are 306 fuel channels. A 540MWe Indian PHWR consists of 392 such channels.

Coolant heavy water extracts heat from the fuel bundles housed in the coolant channels by continuous circulation in a closed loop which is called primary heat transport circuit (PHT). In an Indian PHWR unit, there are 12 fuel bundles in one typical coolant channel and in a 540MWe PHWR unit there are 13 fuel bundles in one typical coolant channel. These coolant channels are horizontal and are typically having a length more than 5 meters (entire coolant channel assembly is around 9 meters long). High temperature, pressure and long periods of operation of reactors results in deterioration of structural health of the coolant channels. Hence it is important to inspect the coolant channels at regular intervals to ascertain their healthiness for continued operation.

A typical coolant channel assembly has an inlet and an outlet connection for coolant heavy water at the north and south ends. A schematic given below shows the general layout of the coolant channel and inspection system while doing in-service inspection. It shows a Special Sealing Plug installed at one end from where the Inspection Head is driven inside the coolant channel.

Scheme and Layout of Inspection

Special Sealing Plug (with a central sealed opening for inserting drive link extensions.

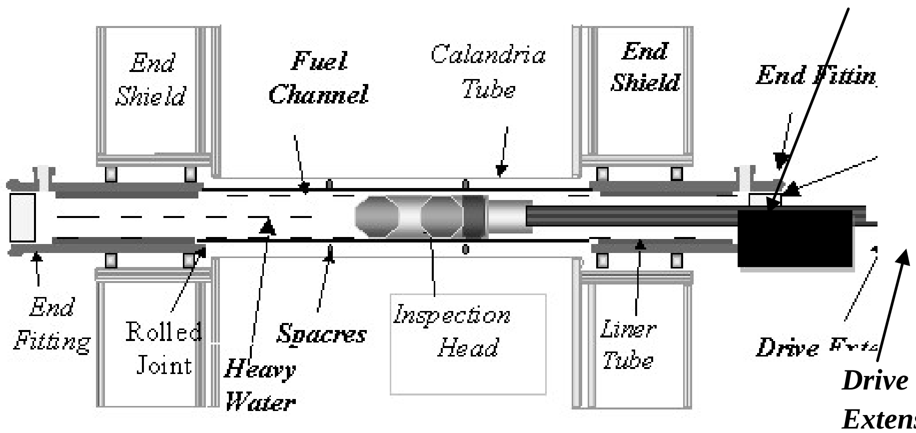

Figure 1 Coolant Channel Schematic for In Service Inspection

This is a typical layout of the coolant channel assembly of an Indian Pressurized Heavy Water Reactor. The Special Sealing plug (shown as black color block on the right end of the assembly) has a central opening through which the drive extension links are inserted penetrating the pressure boundary from dry outside environment. A drive system is kept in the vault dry environment.

1.2 Inspection Head and Special Sealing Plug

All the NDE sensors are mounted on an Inspection Head. This Inspection Head is assembled with Special Sealing Plug for installation into the coolant channel that has to be inspected. This combined assembly is transferred to the Fueling Machine magazine. The Fueling Machine then installs the combined assembly in the End Fitting of the chosen coolant channel for inspection.

After installation of the combined assembly, the Fueling machine moves away and the BARCIS drive system is aligned with the coolant channel in which the in-service inspection is to be carried out.

1.3 Penetration of Pressure Boundary for In-Service Inspection

The Inspection Head rear end is a tube which passes through the central opening in the centre of the Special Sealing Plug. This rear end of the Inspection Head penetrates the pressure boundary and is connected to the BARCIS drive system placed in dry vault area (Drive system is placed on the Fueling Machine bridge).

The in-service inspection system consists of following-

- Inspection Head(ref.[2])

Carries ultrasonic and Eddy current sensors for measuring critical coolant channel parameters.

- Special Sealing Plug

With a central opening (with seals) for pressure boundary penetration, the Special Sealing Plug forms critical part of the whole inspection scheme. It remains installed inside the End Fitting of the coolant channel during the in service inspection work. The grooves inside the End Fitting are used for its installation with the help of Fueling machine RAMs. During in-service inspection work the Inspection Head is moved linearly as well as rotated inside the coolant channel while Special Sealing Plug remains installed in the End Fitting.

- Drive Extension Links-

The drive extension links join Inspection Head's rear end with the BARCIS Drive System. Multiple extension drive links are required as the drive system has a limited linear stroke (~2 meters) while the required travel length to travel is of about 8 meters. It is achieved with the help of 4 drive extensions links.

- Drive System

BARCIS drive system pushes the Inspection Head linearly with extension drive links passing through the seals of Special Sealing plug.. It can also rotate the Inspection Head independently. This is required for 100% volumetric inspection of the coolant channel.

2.0 Emergency Preparedness (Event of Ejection of Special Sealing Plug)

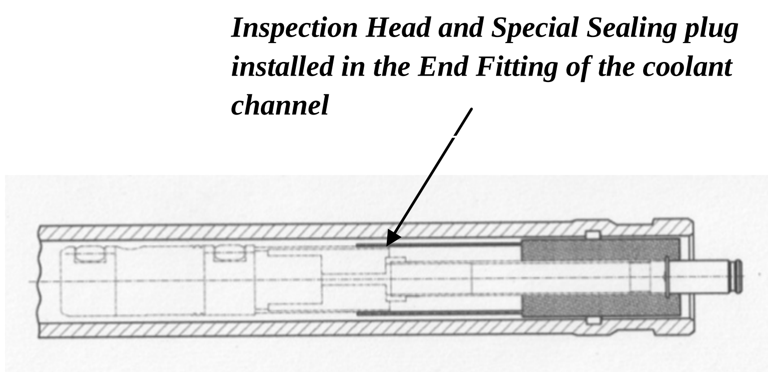

Figure 2 Special Sealing plug and Inspection Head installed

Exposed End Fitting with a jet of leakage coolant

Ejection of Special Sealing Plug as visualized

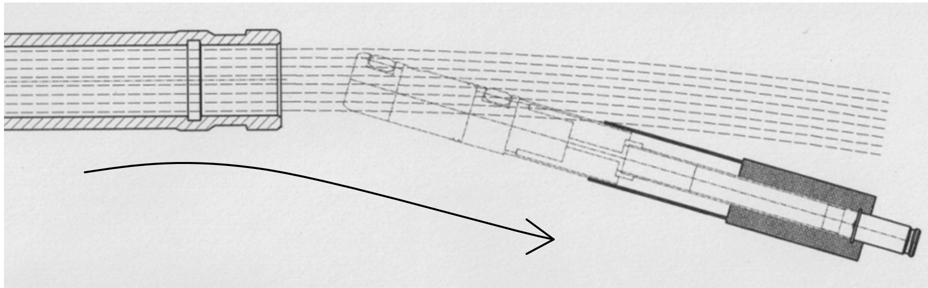

Figure 3 Gross leakage due to incidental ejection of Special Sealing Plug

In the visualized event of ejection of Special Sealing plug gross leakage may occur because the end of the coolant channel will be left exposed with no means to block the flow. There are no fuel bundles in the coolant channel when the in-service inspection is taken up and hence the bore will be fully exposed as shown in Figure 3. If the Fueling machine is able to get back to the channel location and clamp it back, the gross leakage can be handled. However, if the Fueling Machine is unable get back to the channel location and clamp due to any reason then specific separate arrangement must be made available to handle the situation and arrest the leakage as soon as possible. Though the Special Sealing plug design and installation methodology is extremely strong in safe installation and operation, emergency preparedness is necessary from comprehensive safety standpoint.

This quick acting emergency gross leakage arresting device (Also known as Full Bore Leakage Arresting device) has been developed as a contingency measure to handle leakage explained above. It is kept poised during inspection campaign to attend to any gross leakage due to incidental Special Sealing Plug ejection.

2.1 Key Design Features of Quick Acting Leakage Arresting Device

Following are the *key design features* of the Emergency leakage Arresting device

- Semi cylindrical shape / design of the Primary component of leakage arresting device
- Making use of the End Fitting Collar
- Use of special Ball valve attachment with End Fitting ID sealing arrangement

The construction of this device makes use of the collar of the End Fitting.

Semi Cylindrical Shape of the Primary Component of the Device

The innovative use of semi *cylindrical shape* (half cup design) enables simple and quick installation of the device on the coolant channel End Fitting. The design makes it possible for mounting or placing the device from top while standing sideways. This helps in avoiding facing the jet of water head-on. The primary component has a half cup shape on the front side and full cylinder at the rear side which has internal threading. This internal threading is used for assembling it with ball valve attachment (see Fig 7 and Fig.8).

The assembly can be manually installed onto the End Fitting by a single person for arresting the gross leakage.

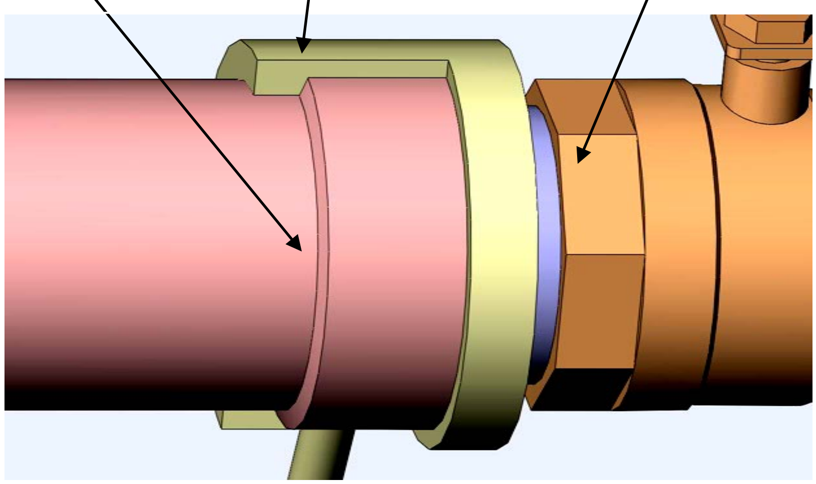

Figure 4 A representation of the design of the Device

In the snap-shot shown below it becomes clear how the device is placed onto the End Fitting collar from top. Also while placing the device from top the person holding the device need not face the leakage water jet stream.

Collar of End Fitting

Suitable step in the device

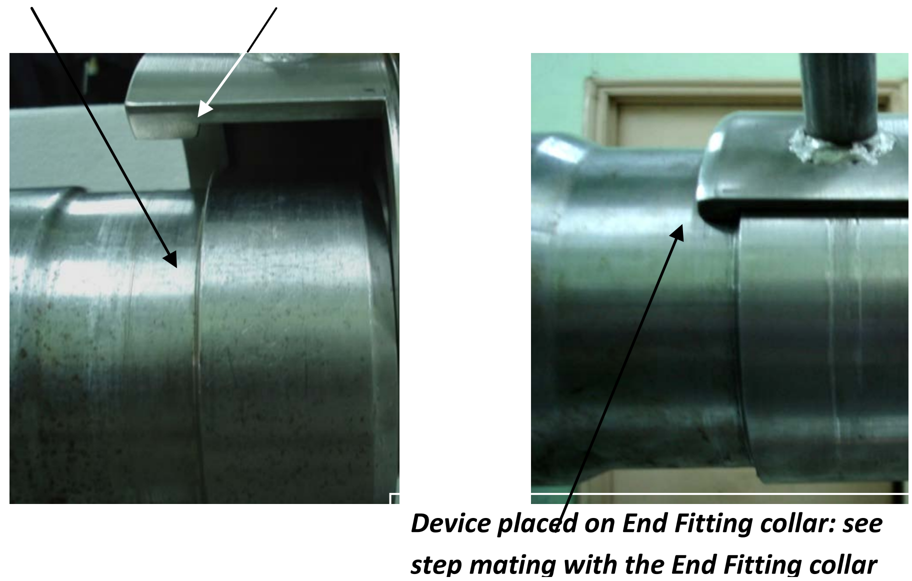

Figure 5. Snapshots of the device getting placed onto the End Fitting

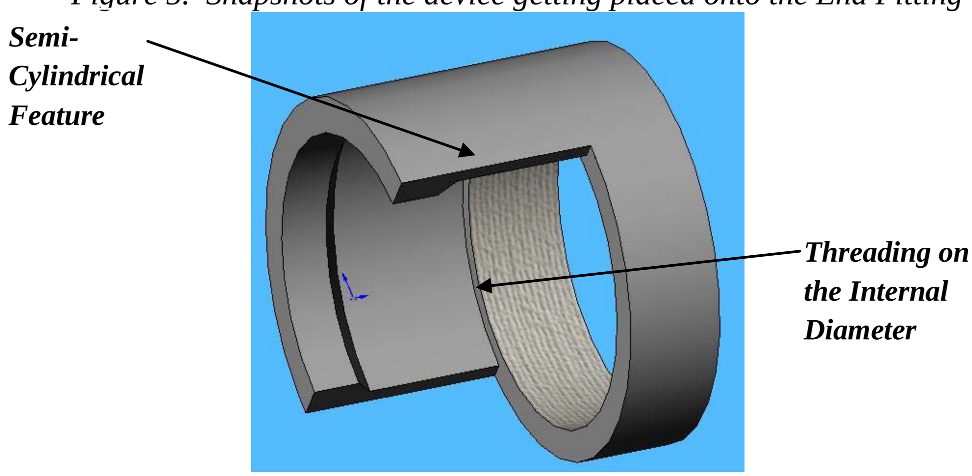

Figure 6. Primary Component showing semi-cylindrical shape feature

2.2 Functioning of the Device

First step is to place the assembly on the End Fitting collar such that the step in the semi cylindrical component matches the step of the End Fitting collar. Once the assembly is placed other operations can follow. In order to arrest the leakage a ball valve is used. Ball valve alone however, is not enough to arrest the leakage fully. The ball valve attachment is equipped with an O’ ring that enters the ID (internal diameter) of the End Fitting when the Ball valve attachment is threaded inside the primary semi-cylindrical component. As the ball valve attachment O’ ring enters the internal diameter of End fitting, the leakage path from that area is sealed. This directs the entire leakage flow towards the ball valve opening. Once it has been made sure that Ball Valve Attachment O' ring has entered the ID of the End Fitting, the ball valve can be closed by operating the lever. Fig.7 and Fig.8 make the operation and functioning of the device clearer.

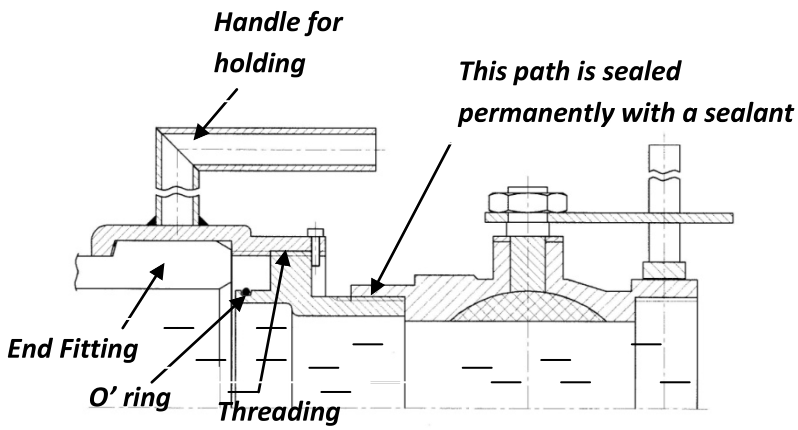

Figure 7. Device placed onto the End Fitting, O' ring is out of the End Fitting

The ball valve attachment is rotated by turning the lever at the ends so that it threads into the primary semi-cylindrical component and advances as per the threading pitch.

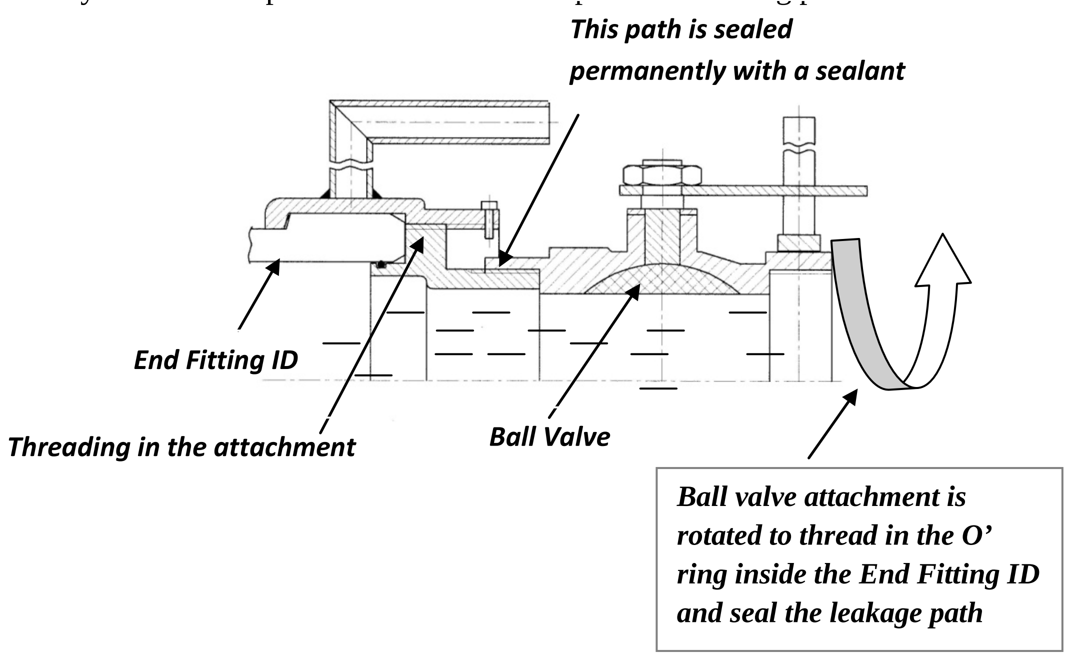

Figure 8. O' ring enters inside the End Fitting ID, component butted with E-face

The ball valve can be closed once it is ensured that O' ring has entered the ID (internal diameter) of the End Fitting (Fig.8).

In the following snap-shot the two components (primary semi-cylindrical component and Ball valve attachment) are shown (the O' ring is visible in picture).

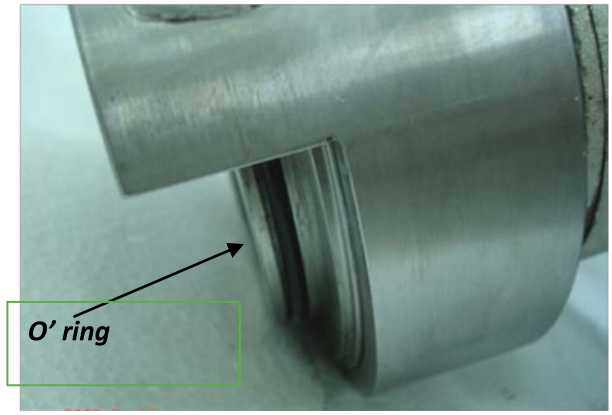

Figure 9. Primary Component & Ball Valve Attachment showing O' ring

A representation of the entire assembly is shown in the following model. The operating lever for rotating the ball valve attachment (that has an O' ring to enter the End Fitting ID) is at the end of the ball valve (lever shown in blue green color). It should be noted that while placing the device onto the End Fitting collar and threading in the ball valve attachment the ball valve <u>must</u> be kept open to vent off the water. Once it is ensured that O' ring has entered the ID of the End Fitting (components butt) the ball valve can be closed. This will completely arrest the leakage. Entire process of performing this operation takes about 30 seconds for a single person to arrest the leakage completely.

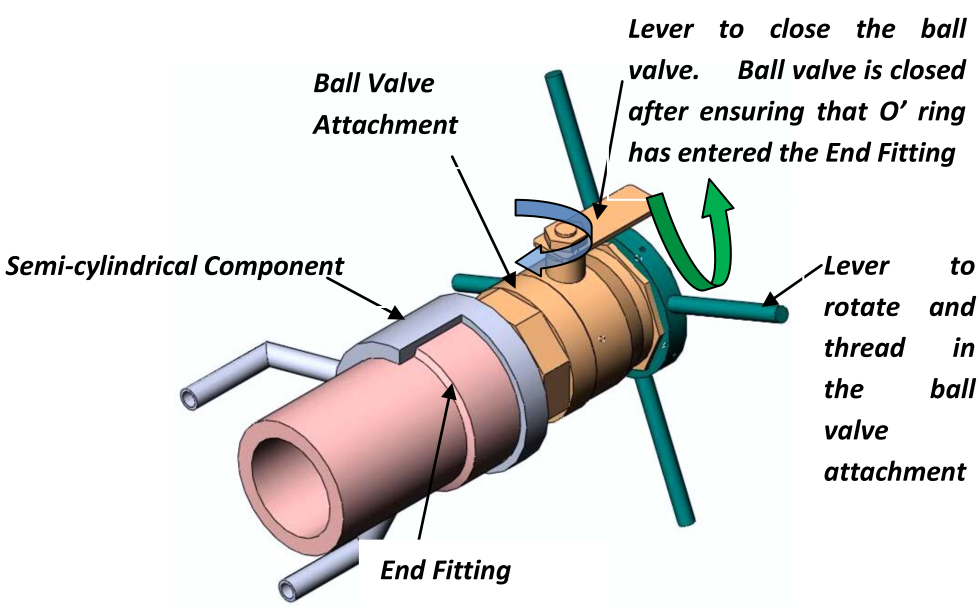

Figure 10. Quick Acting Gross Leakage Arresting Device - Features

3.0 Testing and Qualification

The device was tested extensively for arresting the leakage in the simulated conditions. A shuttle experiment test set up was used to simulate the test conditions. During testing the coolant channel was kept completely empty as is be the case in the in-service inspection of coolant channels.

Following results have been noted-

Sr. No.	Simulated Flow Rate (litres per minute-LPM)	Pressure in Coolant Channel after installation of Device and arresting of the leakage completely	Time taken for installation	Remarks
1	500	13 Kgf/cm2 (~185psi)	25-35 seconds	Device installed & leakage arrested completely- by a single operator
2	1000	13 Kgf/cm2 (~185psi)	25-35 seconds	Device installed & leakage arrested completely- by a single operator
3	1500	13 Kgf/cm2 (~185psi)	25-35 seconds	Device installed & leakage arrested completely- by a single operator
4	2000	13 Kgf/cm2 (~185psi)	25-35 seconds	Device installed & leakage arrested completely- by a single operator
5	2500	Device difficult to install due to heavy outflow	-	Not easy to install due to heavy outflow

Table 1

The estimated leakage rate in the event under discussion is below 400 liters per minute (in 220 MWe as well as 540 MWe PHWRs). The device is suitable for arresting such leakages comfortably.

3.1 Estimated Gross Leakage in Accidental Ejection of Special Sealing plug in 220 MWe and 540 MWe PHWRs During Shutdown

Estimated worst gross leakage in the event of ejection of Special Sealing plug for a 220 MWe PHWR is about 243 liters per minute. For a 540MWe PHWR the estimated worst leakage rate is around 350 liters per minute. Separate devices (similar in design) have been developed for these two units (220 MWe and 540MWe PHWRs). These are now essential contingency devices for the in-service inspection campaign at plant sites. These devices have sufficient capacity to arrest the gross leakages in the visualized event of incidental ejection of Special Sealing plug.

3.2 Future developments to enhance operator safety

The methodology of arresting the device is such that the adaptation to automate the operation of the device can also be implemented conveniently. It is being pursued currently at Bhabha Atomic research Centre-India. The automation may involve keeping the device poised for operation close to the channel (may be supported right on-to the adjacent End Fitting) with convenient measures to arrest the leakage in the envisaged event. This will reduce the human intervention and hence save exposure to the operator, creating increased safety overall.

Operating environment

The in-service inspection is carried out in cold shutdown state of the reactor and the temperature of the coolant heavy water inside the channel is not more than 40-50 Celsius. The ball valves are able to perform their function of closing the flow at this temperature without involving special materials.

3.3 Leakage Arresting Exercise

Fig.11 shows the facility where the leakage was simulated and the exercise to arrest the leakage was taken up. A 9-channel lattice was built to simulate the conditions at the reactor site. The central channel was provided with the leakage flow of the order mentioned in the Table 1. The exercise was carried out by the personnel with proper wearing gear required in the emergency situation inside the reactor in the accidental conditions.

Following are the pictures of the exercise taken up at the leakage simulation facility. These pictures show the operations to arrest the leakage.

Figure 11. Leakage Simulation

Leakage arrested completely

Water jet-stream coming out of coolant channel

Figure 12

Figure 13

Operating the Device and Arresting the Leakage

It may be noted that the operator does not have to face the leakage water straight-on (see Fig.12). Leakage can be arrested standing sideways and placing the device from the top onto the End Fitting collar and rotating the ball valve attachment till components butt - followed by closing the ball valve to arrest the leakage completely. In Fig.13 the component is completely threaded in and then the operator has closed the ball valve that has arrested the leakage completely.

Figure 14. Quick Acting Gross Leakage Arresting Device

Leakage of the order of 2000 liters per minute with a line pressure up to 13Kgf/cm^2 (~185psi) can be arrested comfortably by using this device. Fig.14 shows a photograph of the device.

3.4 Event and Mitigation Action

The probability of such an event occurring is extremely low because of the foolproof methodology adopted in design and operation of the Special Sealing Plug and its operation through reactor Fueling Machine. However, in order to ensure total safety this mitigation plan is strictly put in place during the in-service inspection programme.

In the event envisaged as occurring in the plant, it would require a series of actions described as follows-

- Recognition of the event by visual observation in the BARCIS control room (just outside the air-lock through CCTV camera system). Since the operators in the BARCIS control room are always watching the in-service inspection drive system operating in the vault, the event will be visually observed by them. On identifying the accidental scenario the mitigation action will be taken. It may be noted that in-service inspection activity is under constant observation by operators.

- A convenient ladder remains installed in the vault to reach the top of FM Bridge to access the BARCIS drive system (set on FM Bridge) that carries out the in-service inspection. This is required because BARCIS is a semi-automatic tool and certain manual operations are required and hence operators are sent in the vault for a brief period. Quick acting Leakage Arresting Device is kept ready, close to the End Fitting on the FM Bridge. Additional time will be taken by the operator to enter through airlock, approach and climb the ladder and reach the End-Fitting where the Leakage Arresting Device is kept.

The operators always remain prepared to take care of any eventuality as explained above. Efforts to automate the device are underway at BARC to enhance operator safety.

3.5 Device Can Also Arrest Leakages from Normally Seated Special Sealing Plug in the End Fitting (Not Ejected Out)

The device can also be installed in the same way even when the Special Sealing Plug remains normally seated in place in the End Fitting. In case there is leakage from Special Sealing Plug (due to seal failure while Special Sealing Plug remains normally installed in place) it can be attended to conveniently by using this device. Special Sealing Plug remaining in place in the End Fitting does not interfere with installation of the Quick Acting Leakage Arresting Device.

This makes the device doubly useful as it can be used to arrest gross leakage due to ejecting out of Special Sealing Plug as well as other leakages from Special Sealing Plug while it is in place.

4.0 Conclusion & Acknowledgements

The development of 'Quick Acting Gross Leakage Arresting Device' has critical contribution in providing enhanced safety during in-service inspection campaigns at plant sites. It is an essential part of contingency measures at all PHWR sites in India during In-Service Inspection of coolant channels. Authors are thankful to the authorities of Bhabha Atomic Research Centre and Nuclear Power Corporation of India Ltd. for their support in the development.

References:

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