# Development of Reactor Vessel Bottom Mount Instrumentation Nozzle Routine Inspection Device

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## 1. Introduction

The safety and reliability of nuclear power plants can be ensured by appropriate inspection and maintenance. The inspection and maintenance of NPP components should be achieved continuously to keep safe and reliable operation of nuclear power plants. Among NPP systems and components, the healthy and soundness of reactor pressure vessel is the most important. To keep reactor pressure vessel in good condition, a regular inspection during refueling outage is preferable.

Bottom mount instrumentation (BMI) nozzles in bottom head of the nuclear reactor pressure vessel are one of the pressure boundaries in re-actor coolant system for inspection of weld cracking, also, the BMI nozzle welds form part of the primary pressure boundary and the weld filler material is of alloy 600 which is known to be susceptible to primary water stress corrosion cracking (PWSCC). In April 2003, two of South Texas Project 1 reactor BMI nozzles were found to be leaking [1-2], furthermore, the surprising discovery of boron from two nozzles were by visual inspection of the outside of reactor vessel bottom-mounted instrument penetrations during a routine refueling outage shown as in Fig. 1 [3]. A small powdery substance about 153 mg was found on the outside of two instrument guide penetration nozzles on the BMI nozzle penetration outer surface. The primary coolant water of pressurized water reactors has created cracks in j-weld of penetrations with Alloy 600 through a process called primary water stress corrosion cracking [3].


Fig. 1. Boric Acid Deposits Adjacent to BMI Nozzles #1, #46 [1].

On October 6, 2013, BMI nozzle number 3 at Palo Verde Unit 3 (PVNGS-3) exhibited small white de-posits around the annulus. Fig. 2 below indicates that the crack and subsequent leakage developed between inspections performed in 2010 (no leakage) and 2013 (with boric acid crystal indications). These were later determined to be boric acid. There are 61 bottom head penetrations (outside diameter of 3 inches and inside diameter of 0.75 inches) in the PVNGS-3 reactor pressure vessel. Nozzle attachment to the RV lower head is by J-groove weld to the inside penetration of the nozzle and the weld material is of Alloy 600 material [4].


Fig. 2 BMI Nozzle No.3 PVNGS Unit 3 [4].

Above two cases clearly show the necessity of routine inspection of RV lower head penetration during refueling outage. Nondestructive inspection is generally performed to detect fine cracks or defects that may develop during operation. Defects usually occur at weld regions, hence most non-destructive inspection is to scan and check any defects or crack in the weld region. BMI nozzles at the bottom head of a nuclear reactor vessel (RV) are one of such area for inspection. But BMI nozzles have not been inspected during regular refuel outage due to the relative small size of BMI nozzle and limited impact of the consequences of BMI leak. However, there is growing concern since there have been leaks at nuclear power plants (NPPs) as well as recent operating experience.

In this study, we propose a system that is conveniently used for nondestructive inspection of BMI nozzles during regular refueling outage without removing all the reactor internals. The system can carry and manipulate a special ultrasonic (UT) probe to insert in the BMI nozzle to scan and detect cracks within the weld region of the inner surface of the BMI nozzle. A 3D model of the inspection system was also developed along with the RV and internals which permits a virtual 3D simulation to check the design concept and usability of the system. Moreover, this approach allows for a virtual walk through to verify the proposed BMI nozzle inspection system. The proposed BMI nozzle inspection system will contribute to finding an early detection of weld defects and lead to prevention of leakage at the BMI nozzle and weld.

## 2. Conceptual design of BMI inspection tool

In this section, the reactor vessel and internals are analyzed for the design of RV lower head BMI inspection tool design. To this end, a 3D reactor vessel and internals 3D model includes a reactor vessel shell, core support barrel (CSB), the core shroud (CS), and lower support structure (LSS) were created. The concepts of BMI Inspection Tool consists of Trolley Body, Carriage, Upper Boom, three Middle Boom, and Lower Boom, and it is also modeled in 3D graphics for the verification of the system feasibility.

### *2.1 Interface of RV and Internal to BMI nozzle*

The reactor vessel is fabricated in accordance with the ASME Boiler and Pressure Vessel Code, Section III. The reactor vessel is a vertically mounted cylindrical vessel with a hemispherical lower head welded to the vessel shell section and a removable hemispherical upper closure head. The construction is welded connection of forged rings, forged hemispherical heads, forged flanges and forged nozzles to form a reactor pressure vessel. The internal surfaces that are in contact with the reactor coolant are cladded with austenitic stainless steel. The bottom head is constructed of a single hemispherical forging. The three shell sections, the bottom head forging, and the vessel flange forging are joined together by welding, along with four inlet nozzle forgings, two outlet nozzle forgings, four direct vessel injection (DVI) nozzle forgings, and sixty-one (61) in-core instrument nozzles (ICI) to form a complete vessel assembly. A cross-section view of APR1400 reactor vessel and internals is shown in Fig. 3. The reactor internals support and orient the fuel assemblies, control element assemblies, and in-core instrumentation, and guide the reactor coolant through the reactor core and to hot-leg pipe [5].

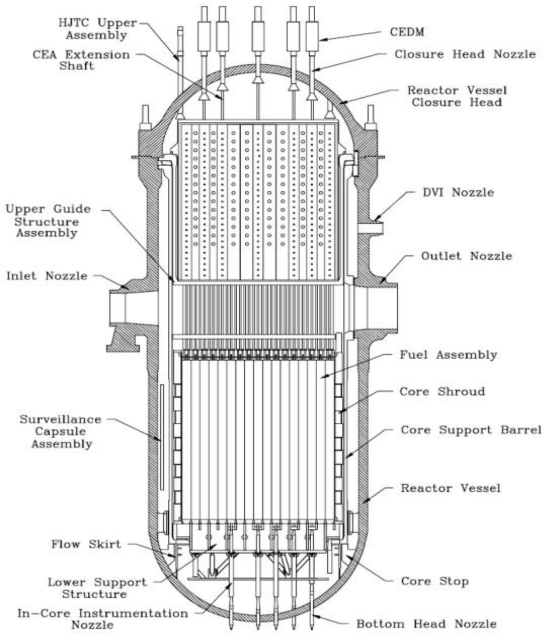


Fig. 3. RV Vertical Arrangement [5].

During refueling, RV closure head and upper guide structure are removed and followed by removal of all fuels in the core. Figure 4 shows access environment of RV BMI inspection device that include RV, CSB, LSS and CS. A 3D model was created for RV, CSB, LSS, and CS to see and understand the interface environment within reactor vessel.

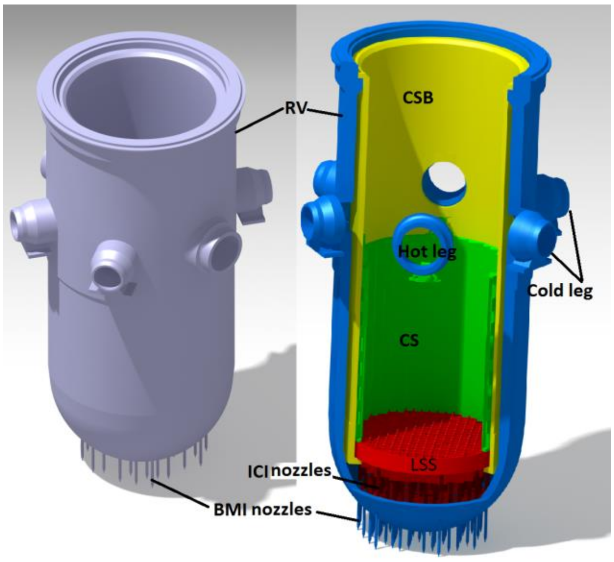


Fig. 4. 3D model of RV, CSB, CS and LSS.

### *2.2 Conceptual Design of BMI Inspection Trolley*

The reactor vessel is inspected for any indication of leak or structural damage from the outside of reactor vessel during a refueling outage, however the vessel welds region inspection is done on a 10 year regular periodic inspection [5]. Because there has been leak through BMI nozzles, it is imperative to inspect in a shorter interval, such as inspection during every refueling outage. In order to make such frequent inspection feasible, a special device is necessary to do the job conveniently. For this objective, BMI Inspection Device was conceptualized.

The function of the BMI Inspection Trolley is to move the inspection module in the desired position and make it possible to do a remote inspection for a reactor BMI nozzle. The concept of BMI Inspection Trolley utilizes the refueling machine bridge for global positioning so that it can move into the desired location of BMI nozzle, and it also provides local fine motion control for lateral movement and tilting control for vertical alignment of the BMI Inspection Trolley.

Since the BMI nozzle is submerged in water, the BMI inspection need to be done in submerged environment. Also the reactor vessel inside environment is highly radioactive, a remote inspection operation concept is adapted to protect operator from radiation. Equipment to protect operator to work under-water would require much more complicated equipment and operation also would require much more complicated procedure to protect operators. Hence, remote operation is more economical option in this case.

The concept of BMI Inspection Trolley was shown in 3D using CATIA v5 as shown in Fig.5 [6].

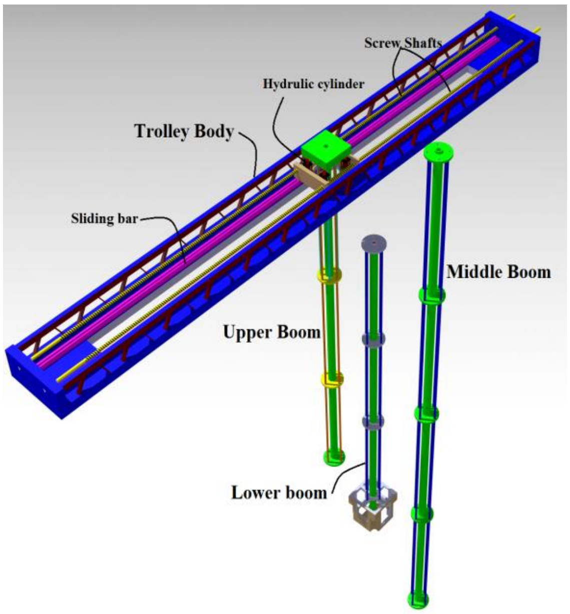


Fig. 5. 3D model development of BMI Inspection Trolley.

The BMI Inspection Trolley consists of Trolley Body, Carriage, Upper Boom, three identical Middle Boom, Lower Boom, and Probe Adapter. The Trolley Body is installed on the Refueling Machine Bridge and the Carriage is installed on top of Trolley Body so that it can provide positioning of the BMI Inspection Probe in a desired BMI nozzle location. The Upper Boom installed on trolley and can travel along in lateral direction by Carriage using the guide screw and provide fine positioning. The Upper Boom can be lifted and lowered by Carriage mechanism that is consisted of four small hydraulic cylinders to control the vertical alignment of the Boom. Fig. 6 shows the concept of motion and component design.

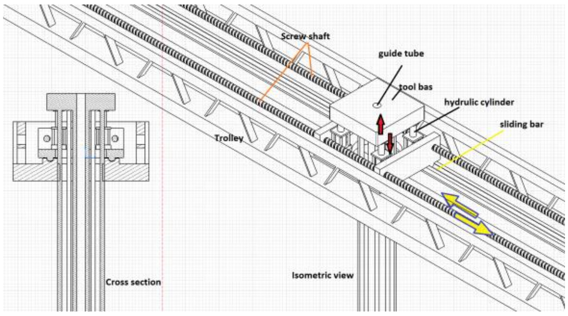


Fig. 6. Isometric view and cross section of BMI Inspection Trolley and Upper Boom

The BMI Inspection Trolley is assembled as follows,

1. Move Trolley Body into the reactor inside area and fix on refueling machine.
2. Connect upper boom, Middle boom, and lower boom with flange and bolts.
3. Using polar crane move the connected parts (upper, middle, and lower boom) into reactor inside area and insert from above of trolley body.

A static linear structural analysis of the Trolley Body using ANSYS was carried out to check the structural integrity of it [7]. Fig. 7 shows equivalent stress and total deformation plot of the Trolley Body.

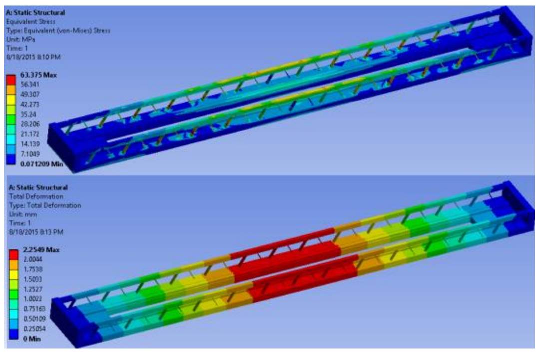

Fig. 7. Equivalent stress and total deformation of Trolley Body

*2.3 Conceptual design of BMI Inspection Module*

The BMI Inspection Module carries Inspection Probe and manipulate the probe into the BMI nozzle inner surface. Fig.8 is a perspective diagram illustrating a refueling machine of APR1400 NPP and a simple sketch of the BMI inspection device installed at the refueling machine bridge reflecting the conceptual design of BMI inspection mechanism.

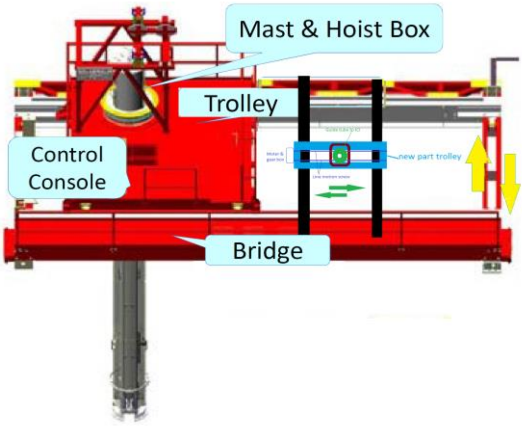


Fig. 8. Sketch of new design on refueling machine.

Fig.9 shows a virtual simulation (3D CAD modeling) of the BMI nozzle inspection illustrating the operation of BMI nozzle inspection. The BMI Inspection Module is designed to fit on the LSS like fuel assembly. The lower support of BMI Inspection Module is the same as fuel assembly lower end-fitting so that it can sit in between 4 corner pin guides of LSS.

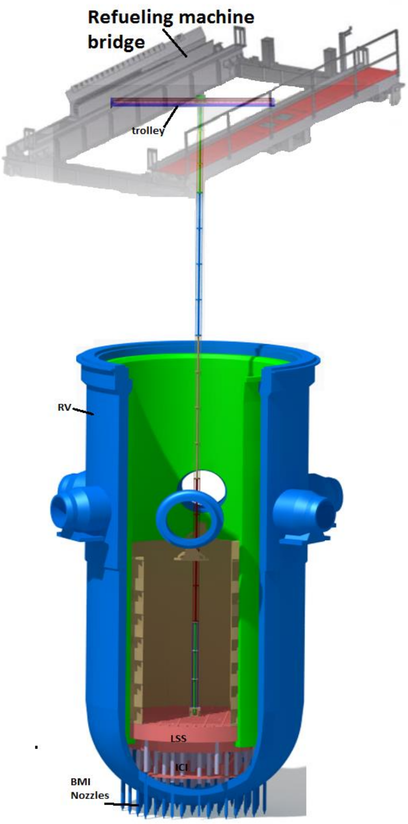


Fig. 9. Virtual simulation of BMI nozzle

Once BMI Inspection Trolley is safely and securely placed in position, the probe is ready to insert into the BMI nozzle from the top using probe delivery system as shown in Fig. 10 [8].

Fig. 10. Integrated inspection systems. (Zetec MIZ-80iD).

The conceptual diagram of BMI inspection is given in Fig. 11. The enlarged view of LSS from above showing ICI nozzles locations, and LSS flow holes is given in Fig. 12. It shows isometric view, top view, and side view of LSS.

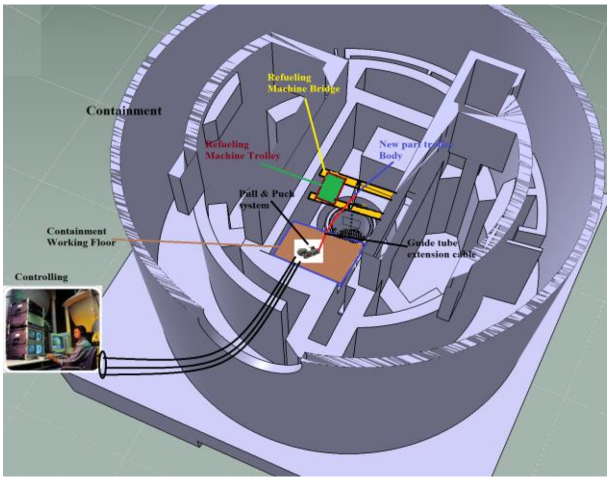


Fig. 11. Remote BMI nozzle inspection system through containment penetration

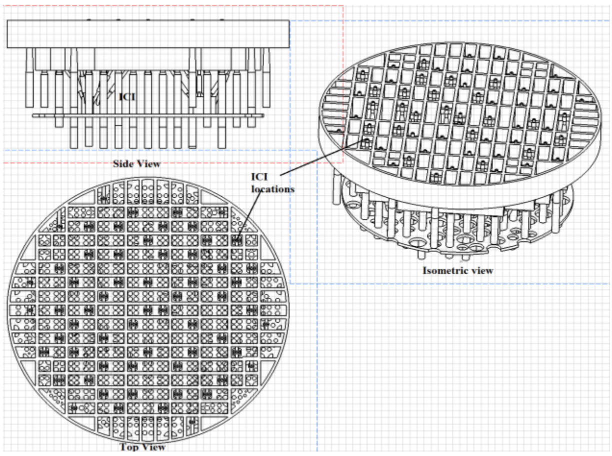


Fig. 12. Lower Support Structure

The distance from LSS top surface to BMI nozzle top position is constant, but the BMI nozzle weld position is different. Figure 13 shows the simulated view of LSS flow holes and BMI nozzles.

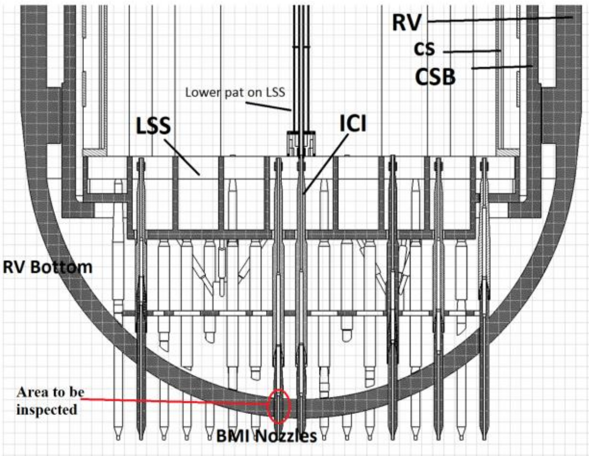


Fig. 13. Lower part of the new design at the RV bottom in 2D using CATIA v5.

### *2.4 BMI inspection probe*

In this section probe technology for UT and ECT inspections are introduced. Current researches and different methodologies currently being used to mitigate cracking is shown in Fig. 14. Also, the safety analysis for the methodology implementation, and inspection probe for BMI nozzle were considered in the concept development of.

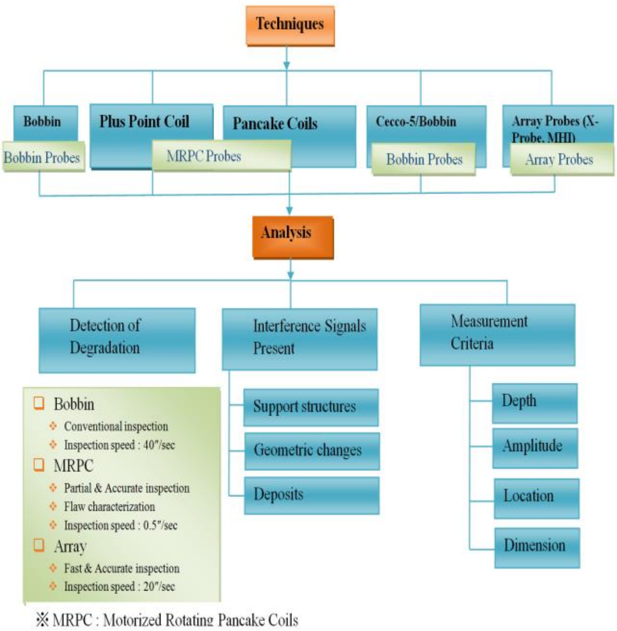


Fig. 14. Inspection technique general

Some information of typical commercial weld inspection probe system that are fit to the inspection of BMI nozzle are collected and presented here.

DEKRA Industrial AB: Mechanized Inspection was inspected RPV Shell Welds, Nozzle Welds and BMI Nozzle Welds as well as visual testing of Radial Support Welds in all three PWRs at Ringhals (units 2, 3, and 4). The BMIs was inspected with a combination of pulse echo, TOFD (time of flight diffraction) UT (ultra-sound test) and ET (eddy current test) probes, manufactured by DEKRA [9].

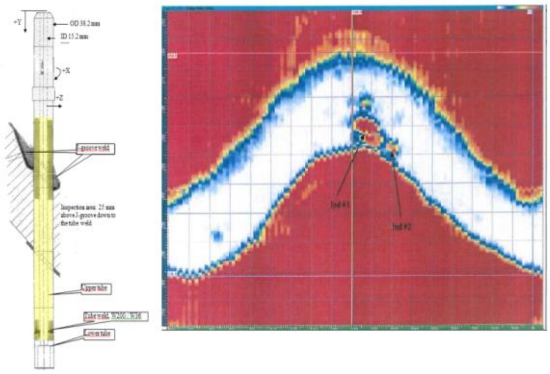

Fig. 15 Fusion face inspection, with reportable defects [9]

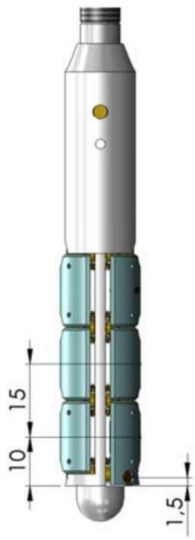


Fig. 16 BMI dimensions and DEKRA BMI probe with, 0° TRL, 2x TOFDT UT and ET [9]

The tubing inspection probe IRIS UT (Internal Rotary Inspection System) shown in Fig. 17 operates in pulse-echo mode to measure wall thickness, material loss, and defect orientation within the range of 0.625 inch to 3 inch depth. The IRIS probe consists of an ultrasonic transducer firing in the tube axial direction. A mirror mounted on a water-propelled turbine deflects the ultrasonic beam in order to obtain a normal incidence wave on the tube internal wall. Because the mirror revolves around the axis, the entire circumference of the tube is examined. A complete IRIS probe includes the cable, a centering unit, a turbine, and a transducer. The IRIS Kit consists of the followings [10]:

- Four centering device (with two kinds of sizes)
  - Two turbines sizes: 12 mm and 17 mm (0.470 inch and 0.670 inch)
- Four types of transducers available
- Two standard cable lengths: 45 ft. and 90 ft.
- Stainless steel flood tube adapter
- Pump, filter, and regulator unit
- Circumferential crack detection turbine.

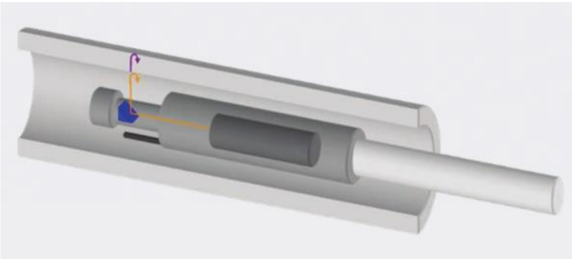

Fig.17 tubing inspection probe [10].

WesDyne Sweden: WesDyne Sweden has a long tradition of designing and manufacturing ultrasonic (UT) and Eddy Current (ET) probes. The BMI probe for inspection of bottom instrumentation nozzles in PWR is made to fit inside nozzles from Ø7.5 mm and up with several different transducers; ET, TOFD and UT 45" 0" as in Fig 18 [11].

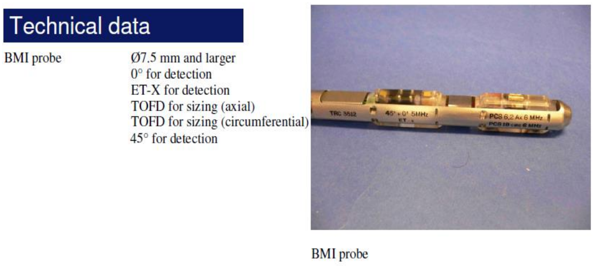


Fig. 18 BMI probe [11].

Olympus tubing inspection probe IRIS UT: The internal rotary inspection system (IRIS) is an ultrasonic technique well suited for petrochemical and balance-of-plant (BOP) tube inspections. This technique uses an ultrasonic beam to scan the internal surface of the tube in helical path, ensuring that the full length of the tube is tested. Olympus tube inspection systems can monitor the front-wall and back-wall echoes in order to measure the tube wall thickness [12]. Fig 19 shows the internal rotary inspection system, in which probe operates in pulse-echo mode to measure wall thickness, material loss, and defect orientation within the range of 0.5 inch to 3 inch ID. The core of IRIS probe is an ultrasonic transducer firing in the axial direction of the tube. A mirror mounted on a water-propelled turbine deflects the ultrasonic beam in order to obtain a normal incidence wave on the internal wall of the tube [12].

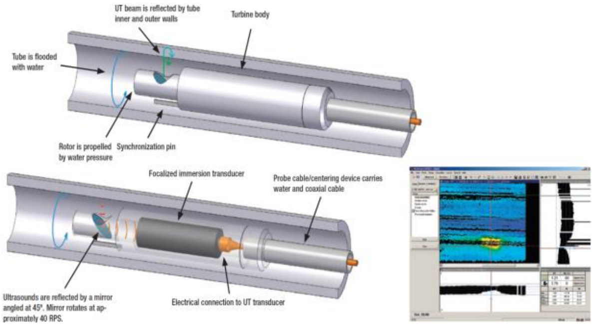


Fig. 19. Olympus tubing inspection probe IRIS UT.

Fig. 20 shown spring-Loaded Arm Centering Devices. These centering devices have two sets of spring-loaded arms linked in both directions to ensure perfect centering with three contact points. The centering device is a self-contained and removable mechanism and can be retracted from the shaft without loss of components or pressure in the arms. This design is available in three sizes: small, medium, large covering tube IDs ranging from 18.0 mm to 76.2 mm (0.70 in to 3.0 in). The large centering device comes with a flexible shaft for bent tube inspection [12].

Fig. 20. Centering device (TUC).

Fig. 21 shows IRIS probe cables have two functions: they supply the water pressure required by the turbine; and, they carry the ultrasound signal via a small coaxial cable. The coaxial cable has a micro-dot connector on the probe end and a BNC connector on the instrument / pump end. The water is supplied by the pump through a quick-connect 1/8 inch brass fitting [12].

Fig. 21. Probe cables.

## 3. Conclusions

The BMI nozzle inspection device for remote inspection of BMI nozzle is investigated and the concept is developed. This mechanism is capable of performing an underwater internal inspection for BMI nozzle welds at PWR plants. The system was developed to operate underwater at depths of up to 20 meters, and operate remotely from the refueling platform via the control console. Using new remote device equipment, it is now possible to inspect reactor vessel lower head BMI nozzles during refueling outages, and reducing inspection interval greatly and ensure safe operation of reactor and maintain the system safety.

A 3D model of the inspection system was also developed along with the RV and internals which permits a virtual 3D simulation to check the design concept and usability of the system.

## ACKNOWLEDGEMENT

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