American Journal of Engineering Research (AJER)
e-ISSN : 2320-0847 p-ISSN : 2320-0936
Volume-03, Issue-02, pp-84-89
www.ajer.org

Research Paper Open Access

A review of qualitative inspection aspects of end fittings in an Indian pressurized heavy water reactor

Urva Pancholi[1], Dhaval Dave[2], Ajay Patel[3]
[1, 2, 3] *MechatronicsDepartment, G. H. Patel College of Engineering & Technology, India*

Abstract:-The paper provides a summarized description of the current state of knowledge and practices used in India, in the qualitative inspection of end fittings – a key component of the fuel channel assembly of a pressurized heavy water reactor (PHWR), generally of a Canadian Deuterium Uranium (CANDU) type. Further it discusses various quality inspection techniques; and the high standards and mechanical precision of the job required, to be accepted as viable nuclear reactor component. The techniques, instruments and specific data for such components mentioned here are synthesized results from primary research and knowledge available in this area, in order to produce coherent argument focused on quality control of end fittings.

Keywords:-*CANDU, end fitting, fuel channel assembly, nuclear reactor component safety, PHWR, quality control.*

I. INTRODUCTION

Pressurized heavy water reactor (PHWR), Canada Deuterium Uranium (CANDU) specifically, is one of the key types of nuclear reactors used in India. The basic working of it includes use of pressurized heavy water as coolant as well as moderator. Natural Uranium-235 is used as fuel pallets to produce electricity via steam turbines and heat exchangers. In India, currently there are 16 such CANDU reactors and 6 more are planned or under construction. The electrical power produced ranges from 100 MW to 700 MW depending upon the model of reactor.

Vast facets of interdisciplinary engineering areas are utilized in the design and construction process of such a PHWR reactor components – Quality inspection methods being one of the most important areas. Such methods play an important role to ensure that parts of nuclear reactor core are manufactured to the strictest and most precise standards. The following section gives an overview of main components of CANDU reactor core.

1.1 CANDU PHWR: Core components and importance of end fittings

The CANDU reactor core has a number of mechanical components, assembled together to form a complex fuel transport system. The key characteristic of this core are its pressure tubes, which contain fuel bundles located in a cylindrical, low pressure moderator tank or 'calandria'. The major components, as shown in Fig. 1, namely pressure tube, liner tube, end fitting, calandria, garter spring spacers, rolled joints, feeder pipe and fuel bundle, along with many other accessories, comprise the fuel channel assembly. Heavy water is used for moderation. In our case, natural Uranium is used as fissile fuel, so such reactors are heavy water cooled. The fuel channel assembly of CANDU nuclear reactor supports the fuel bundles of the reactor core. So they are essentially part of primary heat transport system. Heavy water coolant and moderator flows reversibly through these channels and over fuel bundle, to remove the heat generated by nuclear fission reactions. These activities call for mechanical components, precisely inspected and tested, to meet such pressure, temperature, wear and radiation containment characteristics.

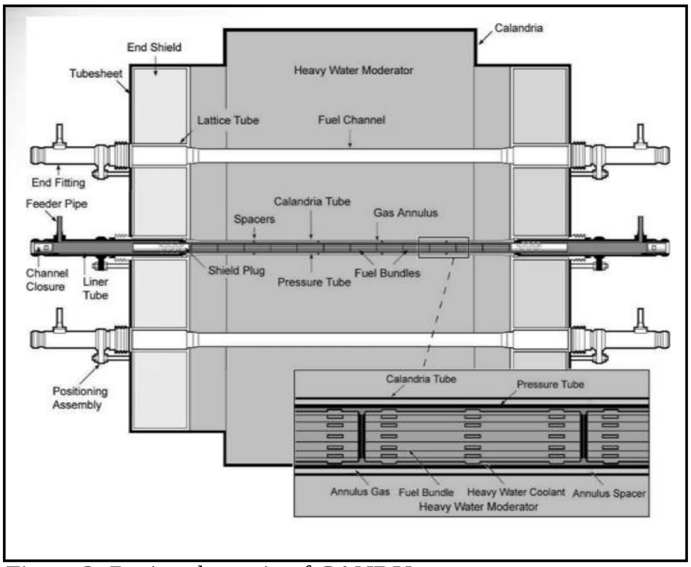

Figure 2: Basic schematic of CANDU reactor core components

The ‘end fitting’ is one of such critical mechanical components (Since it may have direct contact with fuel, it is classified as class-1 component). End fittings are located at each end of the fuel channel and is connected to the pressure tube by means of a highly precise zero clearance rolled joint. Its inner end is connected to the calandria tube. (Detailed schematic can be seen in Fig. 2). They also contain critical sealing surfaces to curb leakage. Generally there are about 380 fuel channels in a reactor core, hence the number of end fittings are 760. These are the parts visible on the outer wall of reactor core. Half of the fitting is inside the concrete shielded wall of the reactor and half of it is kept outside. End fittings are made of balanced material properties. Ideally they are made of Stainless Steel (SS403L) with 12% Chromium and 0.1% Carbon. The raw material (Drop forged cylindrical hollow billets) are then heat treated, quenched and bored to make them stress free. A number of precision manufacturing operations then lead to a finished job with intricate contours, ready for final quality inspection. Several qualitative test are also run intermediately during the manufacturing process.

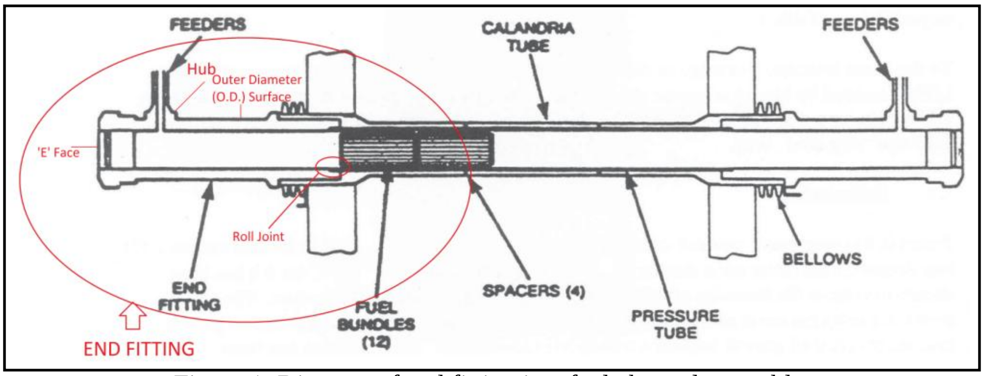

Figure 1: Diagram of end fitting in a fuel channel assembly

Primary coolant flows into and out of the channel though end fitting side ports which are joined to feeder pipes by bolted joints, at high pressure and temperature ranges (~100 kg/cm^2 and ~300°C). The coolant tubes are made of Zirconium alloy with 2.5% of Niobium as a standard material. Another importance of end fitting is that during fuelling operation, outer ends of each fitting act as a primary input/output port. This allows fuelling machine to make a sealed connection and allows removal and insertion of fuel bundles when their nuclear life cycle expire. When not connected to the fuelling machine, end fittings are sealed by channel closure plugs. To ensure that the end fitting is compatible with rest of the assembly with impervious seals; that it effectively shields radiation flux; and withstand high pressure and temperature, a number of properties need to be met with Atomic Energy of Canada Limited (AECL) specifications. Internal faults are checked all along the length by 100% ultrasonic inspection technique. To avoid degrading and ill-safety implications in the reactor, due to manufacturing defects and faults, it is very critical to conduct a proper qualitative inspection of end fittings.

II. QUALITATIVE INSPECTION TECHNIQUES FOR END FITTINGS

A variety of qualitative inspection techniques are available for mechanical components like end fittings and similar jobs. The principal techniques used in India, are explained below with description, procedure, equipment used, specific acceptance criteria, importance and implications on failure of tests.

2.1 Ultrasonic testing

Ultrasonic testing (UT) is a non-destructive material testing technique, which uses ultrasonic oscillations for detecting the presence of inhomogeneity of density, discontinuities, internal defects or elasticity in materials. For instance if the forged raw billet of end fitting has a hole or a crack within it, UT manipulator allows the presence of such flaws to be detected and their position located, even though the flaw lies entirely within the forging and no portion of it extends out to the exterior surface. Pulse-Echo technique is used by contact method with use of straight as well as angular beams. High frequency vibrations are sent into the part to be inspected and time intervals of arrival of the direct and reflected vibrations at outer surface are recorded (Fig. 3-a). By examining peaks produced on the time versus amplitude graph on device, flaws can be detected. Since highest safety requirements are demanded for end fittings, the operator scans the job after ensuring that the scanning surface is free from dust, paint, loose scale and has a moderate surface finish. Then couplant, petroleum jelly or spindle oil is applied and scanning is done of: (1) 'E' face of end fitting by normal beam technique before trepanning operation and (2) On outer diameter (O.D.) by angle beam technique both longitudinally and circumferentially, before trepanning operation and after rough machining (Fig. 3-b). An example of UT equipment used for this purpose is GE USM 35, with a 10-20 mm probe and 2-4 MHz frequency. The angle during angle beam technique is 28° to 45°. The acceptance criteria here is that readings should not exceed the amplitude of the reference standard. For example, if the reference standard is set to 250 mm (diameter of job) and if the waves are reflected at an earlier time; it indicates intermediate flaws, making the sample unacceptable. The results of this test are 'non-reporting', expressed as accepted, satisfactory, further process required or rejected. The importance of UT is, it is the only method by which internal discontinuities, distortions, material porosity and metal fiber discontinuity of micron scale can be detected. Failure of this test and thus a defective component implicates that failure/fracture will occur from the point of inhomogeneity due to high pressure, high temperature moderator flow. Additionally, associated components won't fit in assembly as these defects may cause major changes in the coaxiality and symmetricity of end fitting.

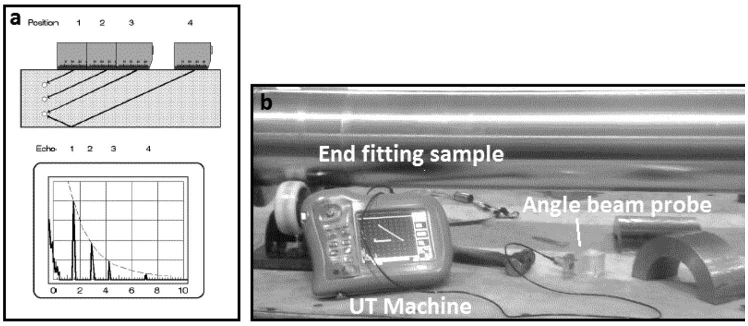

Figure 3: (a) UT Procedure and resultant echo response of flaws, (b) Angle beam UT technique setup for end fitting sample

2.2 Dimensional inspection (including inspection using profile projector)

After assuring UT testing, the end fittings pass through a series of strict dimensional quality control steps. During machining process, care has to be exercised so that numerous dimensions are maintained within close tolerances (ranging 10 µm to a maximum of 50 µm). It can be observed that the metrology instruments used for various dimensional inspections (Table I) are very precise and have lower least counts. Another inspection concerns the final material quality of end fittings (to check if they have good stress concentration balance), after they are heat treated. This test requires the hardness of steel to be between 255 to 350 BHN (Brinell harness), to be considered as acceptable. Some measurements, like the dimensions of rolled joint profile which are inaccessible, need to be measured using a special technique called mould inspection or profile projection. Here a mould replica of this profile is taken using silicon composite putty (with a very low deformation (5 µm) to maintain precision); and measured and compared with reference drawings on a horizontal profile projector (Fig. 4-a/4-b).

Table I: Dimensional inspection and instruments

Mechanical properties /parameters to be tested	Instruments	Comments
Symmetricity, Squareness, Parallelism	2D height gauge, Bearing V-blocks, Dial gauges	Instruments have least count of 0.001 mm (1 µm)
Absolute and relative concentricity		
Burnishing and surface roughness	Contact type surface roughness tester	Tester has a micro-sensitive probe/stylus with least count of 0.01 mm
Distance, Radius, Lengths	Vernier caliper, Ball type digital caliper, Radius gauge, Slip gauge	Least count varies from 1 µm to 10 µm
Chamfer, Angles	Bevel protector, Special gauges	Special templates are made from metal strips by precise laser cutting and calibrated by coordinate measuring machine (CMM)
Coating thickness, Wall thickness	Ultrasonic thickness machine	Special probe is used to measure coating thickness of hard chrome plating (HCP)
Outside diameter (O.D.), Inside diameter (I.D.), Ovality	3 point inside micrometer, Digital micrometer	Additionally snap gauges are used as special gauges to precisely measure ovality on O.D.
I.D. and O.D. grooves	Spline O.D. micrometer, Insider calipers	-

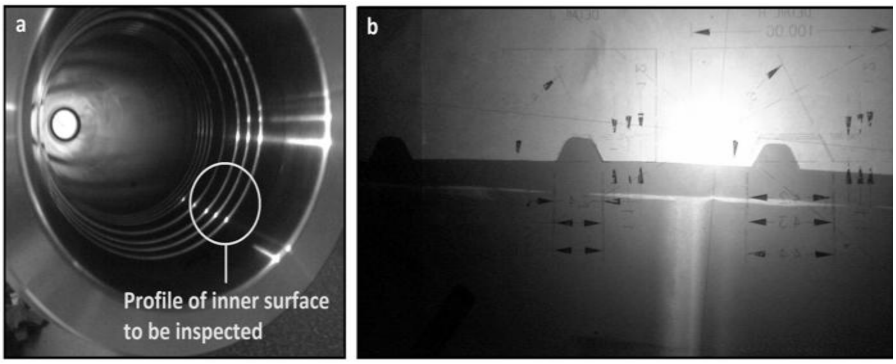

Figure 4: (a) Inner surface profile of rolled joint area to be inspected, (b) Profile projection / mould inspection of indicated groove profile

2.3 Hydrostatic testing

Hydrostatic tests are used for checking the strength and leakage of pressure vessels and pipelines. In our case, end fittings in a reactor are subjected to high pressure and high temperature moderator flow. Hence such a check is required. The finished machined end-fitting is put under a special facility for testing, filled with de-mineralized water (a nearly incompressible liquid) for 10 minutes. (Fig. 5). Initially uniform pressure of around 70 kg/cm^2 is applied and then gradually increased to high pressure (183 kg/cm^2) at controlled temperature between 80°C to 300°C. The test pressure is always kept considerably higher than the operating pressure to give a margin for safety, so as to simulate if a failure/leakage were to occur in reality. An examination for leaks is then done, usually indicated on calibrated pressure gauge connected to the hub or permanent changes in dimensions. Red or fluorescent dyes may be added to the water to make leaks easier to see. The acceptance criteria demands that there is absolutely no pressure drop and leakage from external surface. The importance of this method is that it allows us to simulate results similar to actual setup in a reactor. Implications of a quality failed component it would mean leakage of moderator induced with radioactivity.

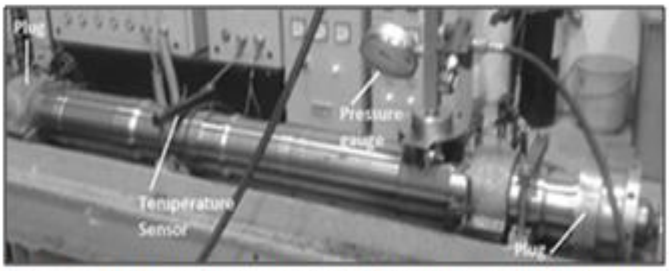

Figure 5: Hydrostatic testing setup for hollow cylindrical parts

2.4 Magnetic particle inspection

Magnetic particle Inspection (MPI) is a non-destructive testing process which detects surface and subsurface discontinuities, cracks in ferromagnetic materials (Stainless steel in our case). The technique involves use of magnetic fields and small magnetic particles (i.e. iron filings) to detect flaws in components. Here, wet magnetic particle inspection method is used, where suspension liquids like well refined light petroleum distillate or water containing additives (Wet fluorescent particles, typically 5 µm and smaller) are sprayed on the job. Petroleum-based liquids are highly recommended carriers because they provide good wetting of the metallic surfaces. Ultra violet (UV) light source is used to highlight these fluorescent particles. The initial procedure involves cleaning of the end fitting of oil and other contaminants; and mounting it on the MPI setup between two current coils by a copper rod (Fig. 6). Then a magnetizing pulse is applied for 0.5 seconds during which the operator washes the part with suspension fluid. Direct magnetization occurs when electric current ranging from 700 to 1500 A passes through the end fitting and a magnetic field is formed in it. When surface or subsurface discontinuity are present in the material, magnetic flux leaks and the particles build up a fluorescent indication at the area of leakage and acquire shape of the irregularity when UV light is applied. Demagnetization of job is crucial before unloading. End fitting is either accepted or rejected based on comparison with pre-defined classified reference standards. The importance of this method is that tight surface discontinuities, distortions, material pit marks and metal fiber discontinuities of micron scale can be detected. Advantages include high sensitivity and visual representation of flaws.

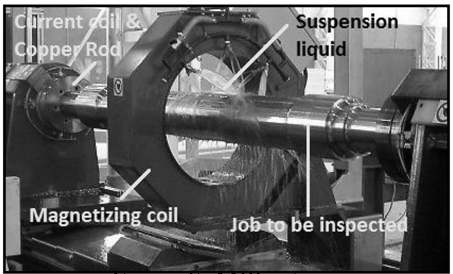

Figure 6: MPI setup

2.5 Borescopic and visual inspection

A borescope is an optical device which consists of a flexible tube with a display on one end, an objective lens and image or video capture device on the other, linked by optical fibers. Borescopes are used for visual inspection where the area to be inspected is inaccessible by other means (e.g. interior properties of end fittings). Such inspection is done with 1 out of every 15 jobs (sampling) and is one of the last qualitative inspections carried out on finished end fittings. Generally a video borescope with 3” LCD display (320x240 pixels or better) is used to inspect critical interior surfaces for imperfections, burrs, circumferential discontinuities, scratch marks, surface finish or through holes. Also, internal burrs at the edges of rolled joint and discontinuity in bore are particularly checked. Assurance of these details ensures smooth flow of coolant, as well as proper interlocking of pressure tube during assembly.

III. CONCLUSION

The paper introduces end fittings in a CANDU PHWR nuclear reactor core and signifies its importance. In conclusion, further it may be said that the design and manufacturing of end fitting of PHWR must meet high standards of qualitative inspection criteria for class-1 components; and thus having met so, can be used safely in the fuel channel assembly of the reactor core. Major qualitative inspection techniques are reviewed with procedures, implications and acceptance or rejection criterions. Strict quality control protocols are implemented at intermediate as well as final stages of manufacturing of end fittings. When such a quality assured component is subjected to reactor conditions, a fail-proof working should be obtained as far as end fitting quality is concerned. Future directions may include automation of measuring, testing and gauging instruments and techniques, when used for quality control and engineering metrology of such customized reactor components in mass quantities.

IV. ACKNOWLEDGEMENTS

We would like to acknowledge the official materials and reports available on the websites of International Atomic Energy Agency (IAEA), Atomic Energy of Canada Limited (AECL), Candu.org, Bhabha Atomic Research Centre (BARC), the open access NDT database and media licensed under creative commons attribution 2.5 (Generic). We would also like to thank Nuclear Power Corporation of India Limited (NPCIL) for valuable inputs for informational and educational purposes.

REFERENCES

[1] Alizadeh A, *Design and construction of Canadian advanced PHWRs*, Atomic Energy of Canada Limited, 2009.
[2] Arumugham P.N.,*Steels for Indian CANDU type nuclear power reactors and sources of supply*. Symposium on nuclear science and engineering, 1973.
[3] Ashby M.F., Smidman M.,*Materials for nuclear power systems*. Granta material inspiration, 2010. version. 1.1.
[4] Bajaj S.S., Gore A.R.,*The Indian PHWR*. Nuclear Engineering and Design 236, 2006. p. 701-722.
[5] Bereznai G.,*Nuclear power plant systems and operation*. 2005. rev. 4.
[6] Brown D., Cassis H., Dicks B.,*Calandria tube replacement in CANDU reactors*. CANDU maintenance conference, 1987. p. 2A-1-10.
[7] Brooks G.L.,*A Short History of the CANDU Nuclear Power System*. 1993.
[8] Chowdhury M.K.,*Quality assurance in design and manufacture of coolant channel components*.
[9] Dimitrov L.,*ACR fuel channel design*. Meeting with the USNRC and CNSC, 2002.
[10] Goldberg S.M., Rosner R.,*Nuclear reactors - Generation to generation*. American academy of arts and sciences, 2011.
[11] Hosbons R.R., MacPherson J.K.,*The development of steels for the end fittings of CANDU pressure tubes*. American society for metals, Ohio, 1983.
[12] International Atomic Energy Agency (IAEA), *Heavy water reactors - Status and projected development*. Technical Reports Series No. 407, Vienna, 2002.
[13] Kapoor H., Dixit K.B., Gupta R.K., Rao V.S.G.,*Quality assurance in design of reactor components of PHWR*. Symposium on quality assurance for safety and reliability of nuclear power plants, 1987.
[14] Porter R.S.,*Design of the CANDU reactor assembly*. A lecture series given at Chulalongkorn University, Bangkok, 1997.
[15] Sahoo A.K.,*Models for assessment of flaws in pressure tubes of CANDU reactors*. University of Waterloo, 2009.
[16] Sinha R.K., Kakodkar A.,*Design and development of the AHWR - the Indian thorium fuelled innovative nuclear reactor*. Nuclear Engineering and Design 236, 2006. p. 683-700.
[17] Srivastava S.P., Lahiri B.N., Manjunatha A., Patankar V.H., Joshi V.M., Kataria S.K.,*Ultrasonic C-scan imaging of end fitting forging for 500 MWe PHWR using automated scanner and Ultimate-100M4 system*. BARC Newsletter, 2003.
[18] Subba Raju J., Duraisamy S., Saha A.K., Tikku A.C., Andhansare M.G.,*Pool site inspection facility (PSIF) at DHRUVA*. BARC Newsletter, 2003.
[19] Suizheng Q., Johnston N.C.,*Description of the Reactor Core of the Third Qinshan Nuclear Power Plant (TQNPP)*. 1999.
[20] Varghese J.P., Verma V.S., Rajput C.D., Ramamurthy K.,*En-masse coolant channel replacement in Indian PHWR*. Asian Nuclear Prospects/Energy Procedia, 2011. p. 374-383.