In nuclear power plants, continuous efforts are made to ensure that plants are operated in safe, reliable and economical manner. While utmost care is taken during design, construction and commissioning of the structures, systems & components (SSCs), continued healthiness has to be ensured during operation phase in accordance with the design intent. This is primarily achieved through the establishment of a comprehensive life management programme of surveillance, condition monitoring, periodic In-service inspections (ISI) and maintenance, the purpose of which is to ensure that required safety margins are maintained for all important SSCs throughout plant service life.

In any industry, the important mechanisms which lead to SSCs degradation are general corrosion, Flow accelerated corrosion, erosion, thermal effects, fatigue and mechanical wear & fretting. In a Nuclear Power Plant, in addition to these, degradation also occurs due to irradiation and creep. Therefore SSCs need to be designed with due consideration of all such degradation mechanisms.

During operation phase, the limiting conditions for operation and requirements of surveillance & condition monitoring for all components important to safety are documented in Technical Specification. A plant specific ISI manual defines and elaborates the ISI internal inspection methods and acceptance criteria. The ISI requirements are decided taking into account best industry practices and operational experience and meet the requirements of existing codes and standards. Both these documents are approved by AERB.

In pressurized heavy water reactors, major components covered in ISI programme are coolant channels, feeder pipes, steam generators, heavy water heat exchangers, pressure boundary components, relief valves etc. The inspection methods adopted include use of UT, ECT, DPT and visual inspection. In addition to functional checks for some of the components, ferrography, vibration monitoring and thermography etc are also utilized for rotating equipment. The SSCs where unacceptable indications are revealed by ISI are repaired, replaced or isolated. The base line data generated during Pre-Service inspection is used for comparing and trending of observations. The observations made during ISI are subjected to thorough review and analysis by qualified experts to obtain assurance that unacceptable degradation in component quality is not occurring and it remains fit for service.
The containment system of a NPP plays a crucial role in minimizing dose to the public in case of an accident situation. The integrity of Primary and Secondary Containment is assessed by conducting integrated leak rate tests in every Biannual Shut Down. The concrete structure is also subjected to NDT checks on a specified frequency to ensure continued healthiness. Indian nuclear power plants have accumulated an operating experience of more than 380 reactor years of operation. Over the years, the programmes for surveillance, condition monitoring and in-service inspections have been improved significantly and match with best in the industry. As a result, there has been no major age related failure in any of the important SSCs and thus continued safe and reliable operation of NPPs is assured.

This paper brings out the ISI & health monitoring methodology adopted at Indian NPPs, to ensure safe and reliable operation.

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Introduction

The Indian Nuclear Programme is committed to generate electricity in Safe, Reliable, Economical and Environment Friendly manner. The Paramount Importance in Nuclear Power Plants is Safety. While utmost care is taken during design, construction and commissioning of the structures, systems & components (SSCs), continued healthiness has to be ensured during operation phase. To ensure that the plants are operated in accordance with the Design Intent, within the Operational Limits and Conditions and to to ensure that required safety margins are maintained for all important SSCs throughout plant service life , a comprehensive programme of surveillance, maintenance and In-Service Inspection (ISI) is established.

The Maintenance programme covers all preventive and remedial measures which are necessary to detect and mitigate degradation of systems, structures & components. The Maintenance programme also enhances the reliability of the equipment. The surveillance programme is to maintain and improve equipment availability and to confirm the compliance with the operational limits and conditions, which are mandatory. The ISI programme is to examine systems, structures and components to identify any possible deterioration and to determine whether SSC are acceptable for continued safe operation.

In Service Inspection (ISI)

Normally it is ensured that the components are in healthy condition at the commencement of plant operation. Experience has shown that some components have failed even before design life whereas some components could be used beyond their design life. Certain operational experiences have shown that degradation during their design life are Coolant channels, PHT system Feeders, D2O heat exchangers, Steam generator and piping systems.

In service inspection is carried out on these and some more components such as Pressure vessels, pumps, valves etc. to verify that no unexpected mechanism is degrading the systems, components and structure of the plant, and verify that known degradation mechanisms do not cause damage or deterioration which is significant from safety point of view . The purpose of ISI is to ensure that required safety margins are maintained for all important SSCs throughout plant service life. The inspection of structures, systems and components is carried out at stipulated intervals during the service of a plant as per ISI programme. Inspection performed prior to or during commissioning of plant is called Pre-service inspection (PSI) and provides data on initial conditions of SSC. Manufacturing and construction data supplement the PSI data and form a basis for comparison with subsequent examinations during service.
The important mechanisms which lead to SSC degradation are corrosion, flow accelerated corrosion, erosion, thermal effects, fatigue, mechanical wear and fretting. In nuclear power plants, in addition to above degradation, there is degradation due to irradiation and creep. Therefore SSC’s are designed with due consideration to all such degradation mechanisms and ISI is implemented to measure the effect of these and assess the service life and ensures safe operation of the plant equipment. The ISI requirements are decided after taking in to account the best industry practices and operational experiences. The requirements of existing codes and standards like AERB Safety guide, IAEA Safety Guide, ASME Boiler and pressure vessel code are duly considered. On the basis of these documents, a plant specific ISI manual defines the list of equipment on which ISI is to be carried and the manual covers the ISI interval, inspection methods and acceptance criteria. The limiting conditions for operation and requirements of surveillance and condition monitoring for all the components important to safety are documented in station specific technical specification. The ISI manual and technical specifications of the plant are approved by AERB.

The ISI of structures, systems and components is carried out at stipulated intervals during the service life of the plant and is conducted in a realistic and logical manner to provide, within the capabilities of current techniques, an assurance for the improbability of failure. To achieve the stated object, a plant specific ISI programme is adopted which involves identification and categorization of components and Systems which are to be subjected to inspections. It also involves Selection of inspection methods and procedures along with location and extent of inspection, Inspection intervals, establishing the acceptance criteria and review of results.

Various Inspection Methods of ISI

The different inspection methods employed during ISI are brought out below

Visual examination- visual examination is used to provide information on the general condition of the plant and components which are examined for wear cracks, scratches, corrosion or erosion. Various visual aids like inspection with naked eye, Boroscope, Fibroscope etc. are used. For visual inspection of internal parts and components, the equipment needs to be opened.

Surface examination: surface examination is undertaken to determine discontinuities at surface and sub surface levels by methods such as Dye Penetration/Liquid Penetration test (DPT/LPT) and Magnetic Particle Test (MPT).

Volumetric Examination: volumetric examination is undertaken to determine depth in size of sub surface flaws or discontinuities and usually involves Radiographic examination, ultrasonic Examination (UT) and eddy current testing (ECT).

Scope of ISI

System subjected to ISI are the Reactor coolant pressure boundary, Systems essential for the safe shutdown of the reactor or the safe cooling of nuclear fuel or both in the event of process system failure and other system & components whose failure may jeopardize the safety.

Some of the Major Components Which Are Covered in ISI

Coolant Channels

Coolant channel assembly of pressurized heavy water Reactors (PHWRs) forms the reactor core and mainly consists of Pressure Tube (PT), Calandria Tube (CT). The PT is located concentrically inside CT and supported by Garter Springs (GS) which are placed along the length of PT and rolled to end fittings at both the ends.
The coolant is passed through PT to remove the heat generated by natural uranium fuel which is located in PT. The moderator which is low temperature water surrounds the CT. In view of functional reasons and safety requirements the contact of PT with CT is undesirable.

![Figure 1 Arrangement of coolant channel](image)

The in reactor degradation mechanisms associated with coolant channels are mainly irradiation induced creep, sag, irradiation growth and hardening, in service flaw generation & propagation, CT - PT contact and hydride blister formation, delayed hydride cracking.

The first generation Indian PHWR’s used Zircaloy-2 material for PT and Zircaloy-2 material for CT with loose fit Garter Springs of Zirconium alloy. Based on PSI / ISI data of the operating stations and International experience, better material like Zr-2.5%Nb for PT and tight fit GS are used.

![Figure 2 Loose and tight fit Garter spring](image)

All channels are subjected to PSI after hot conditioning (Light water hot run commissioning of D2O systems) prior to criticality. Based on PSI data, history dockets are prepared for individual channels. The major data captured in PSI are dimensional details like thickness of PT, Garter spring location. After few years of Power
operation, the first ISI is carried out on selected channels. The criteria for the selection of the channels is high neutron flux channels and low neutron flux channels and channels close to Reactivity mechanisms, Moderator entry nozzles etc. The inspection of all selected channels is completed in stipulated time by distributing total number over a specified time through planned schedule.

As a part of ISI, all the inspections that are done as part of PSI are repeated for comparison. The data regarding the extent of Deuterium ingress into the coolant channel is evaluated by in situ scrape sampling (Sliver sampling). This is supplemented by examination of pressure tube removed from reactor. The fatigue toughness, critical crack length at different temperatures, Ultimate tensile strength (UTS), Yield strength (YS) and ductility of removed Pressure Tube are measured.

Figure 3 Front view of coolant channels with Fueling machine engaged with one channel

The tooling developed by BARC called BARCIS (BARC Channel Inspection System) is used for channel ISI and hydrogen content measurement by sliver sampling of channels. BARCIS and sliver sampling is done with the help of fuelling machine. Channels for ISI and sliver sampling are selected based on creep data, channel location, G.S. location, failed fuel history and previous ISI data etc.

Figure 4 General arrangement Of BARCIS
Feeder Pipes and Headers

The feeder pipes and Headers are part of Primary Heat transport (PHT) system to extract the heat from reactor core. The PT is rolled on End fittings which are supported in end shield and the feeder pipes are connected to the end fittings at one end and header at other end and part of pressure boundary of PHT system. Hence integrity of feeder pipes and headers is to be ensured and any breach in PHT pressure boundary will lead to loss of heat removal path.

Feeder pipes have complex three dimensional shapes and are connected to highly radioactive region of the reactor and are small in diameter. All these features make the feeders pipes inaccessible and make the inspection difficult and time consuming. The thickness measurement of feeder elbows is done through UT. The dissimilar metal weld joints are inspected through visual, surface and volumetric examination. Readily accessible portion of feeders and their supports are visually inspected. ISI is carried on sample basis and sample size is arrived on a criteria. On selected feeders the first ISI is carried after 5 years and subsequent ISI in every 10 years.

In old units like RAPS-2, MAPS and NAPS, the feeder pipes material was carbon steel confirming to ASME SA 106 Gr.B. Based on ISI data of operating stations, from KAPS onwards and during en-mass coolant channel replacement activity in old stations, lot of improvements are done in feeders like changing the material to SA 333Gr.6 with minimum Cr 0.2% and higher thickness elbows for better flow assisted corrosion resistance and better operating life.
Steam Generators

Steam Generator (SG) is one of the most critical components in Nuclear Power station. SG tubes provide the required heat transfer surface for heat flow from radioactive primary side to non-radioactive secondary side water. The tube constitutes the physical barrier and any tube rupture leads to failure of pressure boundary which may result in leakage of activity.

In RAPS-2 and MAPS 1&2, the SGs are of Hair pin type and not amenable to ISI and the tube material is Monel-400. From NAPP onwards, the SGs are mushroom type SGs which are amenable for ISI and the tube material is incoloy -800. No generic degradation in SG tubes has been observed so far in Indian PHWRs.

![Figure 6 Cut view of mushroom type SG](image)

However, few SG tubes in mushroom type SGs are found leaky due to hitting of foreign material from shell side of the tubes which might have entered through secondary side as construction debris or during maintenance activities. Some of the major methods and techniques commonly used to identify leaky tubes and estimate the leak rate are helium leak testing, water leak test, Air hold test etc.
Under PSI and ISI, minimum 25% of tubes of each SG are selected for inspection which includes the tubes with most significant indications detected previously. ECT is used to record the thinning of tubes and a fitness-for-service assessment is used to access the capability of tube to perform the required safety function, with in the specified margins of safety, during the entire operating interval until the next schedule inspection. As a part of reduction in man-rem consumption and time of inspection in carrying out ISI on SGs, a semi-automatic eddy current testing robot which is capable of moving probe head remotely parallel to the tube sheet to the next selected tube and pushing the eddy current probe remotely into the full length of tube, is deployed. The leaky tubes and tubes which have wall thickness less than the acceptable value are closed by plugging.

**D₂O Heat Exchangers**

In D₂O Heat Exchangers like Moderator Hx, Shut down Hx, Bleed cooler, the heavy water is in tube side and light water is in shell side. Hence rupture of tubes will result in breach of boundary. ECT of the D₂O heat exchanger tubes is carried out in the BSD of the plant as per ISI programme. The tubes with thickness below the acceptable range are plugged. Based on operating experience, a number of D₂O Heat exchangers have been replaced with new ones, especially in old generation units like RAPS-2 and MAPS.

**Pipe and Equipment Weld Joint Inspection**

Pipe welds, shell welds and equipment welds of PHT, Moderator, Feed water, steam and process water system etc. is carried out by UT and DPT/MPT as per ISI programme.
Supports & Support Structures

DPT/MPT and visual examination of supports and support structures of the identified systems is carried out as per ISI programme. For the entire stroke length, the Snubbers are checked for free operability and also checked for their sensitivity which measures the acceleration at which snubber gets locked.

Fuel Handling System Components

FM supply system is a high pressure heavy water system. Fuelling Machine, Transfer Magazine, and shuttle transport station are subjected to periodic pressure test as per surveillance schedule. Sealing plugs are selected for ISI. Selection is based on the performance history of the plug. All components of sealing plug are subjected to DPT. Spent Fuel transport duct is pressure tested and inspected periodically in BSD.

Surveillance Checks on Equipment

Healthiness of all safety systems is ensured by a surveillance programme. Surveillance checks which are included in the Station Technical Specification are carried out periodically on the specified components and systems. The checks include monitoring, calibration, functional tests and their frequencies. All relief valves are re-calibrated and installed as per schedule. Primary shutdown system drop timings are monitored after every trip/drop. Any degradation noticed during the checks is analyzed and corrective actions on the equipment are taken.

Surveillance Checks on Civil Structures

Reactor containment integrity is very important to contain radioactive substances. Hence primary and secondary containment integrity test and air flow from high enthalpy to low enthalpy zone (V1/ V2 test) are carried out once in two years to ensure containment integrity. As part of ageing management, all the important civil structures including containment were subjected to a number of NDT checks. These include Visual Examination, Impact hammer test (Rebound hammer), Ultrasonic Pulse Velocity test, cover meter test, carbonation test, core extraction etc.

Condition Monitoring

The ISI programme ensures that the required safety margins are available with SSC and avoid likely hood of SSC failure before the next ISI. The condition monitoring is a predictive maintenance technique which evaluates the equipment condition at the time of monitoring. There are on line condition monitoring techniques like vibration monitoring and motor operating current monitoring of important equipment etc. There are off line condition monitoring techniques like Ferrography, Thermography etc. all these techniques are in use in Indian NPP’s.

Flow Accelerated Corrosion (FAC)

FAC is a degradation phenomenon in which normally protective oxide layer on carbon steel and low alloy steel dissolves in to stream of flowing water or water –steam mixture leading to thinning of wall. FAC related degradation has been experienced in Indian NPPs. In order to address the issue effectively, a comprehensive UT thickness measurement programme has been introduced in all plants operated by NPCIL. This involves thickness measurement on typically more than 1500 vulnerable locations in every Bi-annual shutdown. The data collected is trended and appropriate remedial measures as necessary (repair/replacement) are implemented. Replacement material used is having better resistance to FAC.

Post Irradiation Examination (PIE)

PIE of pressure tubes, SG tubes and other core components which were removed from reactor as part of ISI is an important Aging management tool and helps in understanding the behavior of material in the reactor service. A large number of components including coolant channels, feeder pipes, Hx. Tubes etc. have been subjected to PIE to understand failure mechanism and mechanical properties.
Turbo-Generator (TG)

The inspection schedule of Turbo-Generator is not part of ISI quantum. However, TG has strong safety and operation linkages with reactor operation. In view of this, TG inspection and maintenance is carried in every two years. The major inspections carried on the Turbine are Wet Fluorescent Magnetic Particle Testing (WFMPT) of both HP and LP turbine blades and UT of HP blade roots, DPT of turbine diaphragms (stationary blades), DPT and UT on Bearing surfaces and WFMPT on both HP and LP casing bolts. In addition to above other major activities include maintenance on major equipment of Turbine auxiliaries and electrical checks on generator like Insulation Resistance (IR) check and Polarization Index (PI) check of stator winding and Capacitance Tan Delta check of stator winding etc.

Conclusion

The ISI programme of operating station has generated large data to assess the life and performance of various important reactor components like coolant channels, feeder pipes, SG, D2O HX etc.. The ISI programme has helped in improving the materials of construction, design and operational procedures. ISI is a valuable tool for improving the availability and safe operation of a nuclear power plant. As a result of establishment of a comprehensive ISI and condition monitoring programme at NPP, NPCIL has adequately addressed the issue of in-service degradations in various systems, structures& components. The same has been reflected in excellent performance of NPPs, consistently achieving more than 85% of availability factor over the years.