Induction Heating System for KKNPP Primary Coolant Circuit Welds – A Technological Development

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Abstract

The reactor pressure vessel (RPV) and steam generator (SG) of VVER-1000 type nuclear reactor, being constructed at Kudankulam Nuclear Power Project (KKNPP), are made of low-alloy steels of special grade. The weld joints of these vessels to reactor main coolant pipe (MCP) warrant very stringent pre-heating and post-weld heat treatment (PWHT) operations. The massive size and non-uniform geometry of the nozzles poses challenging requirements with respect to power source and inductor coils. Such power sources and inductors are not readily available in the Indian market. KKNPP has gone ahead with developing its own induction- heating system to meet this challenge. This article describes the cycle of its conceptualisation, design, mock-up tests, validation and field application of the systems developed by KKNPP.

The Material and Heating Requirements:

Material to be heat-treated

Three basic materials are involved in PWHT, viz. RPV, SG and MCP. The chemical compositions of these materials are shown in adjoining table.

The exact physical parameters such as magnetic permeability (μ) and electrical resistivity (σ) are not known. Hence, these values and surface emissivity were assumed while designing the system. A sketch showing various joints to be heat-treated and profile of RPV nozzle is given below as Fig-1.

Heating Requirements

Preheating and interpass heating

A pre-heat temperature of 150-225°C is to be maintained. During the welding, an inter-pass temperature of 200-250°C is to be maintained and is not to exceed 270°C. At no point of time the temperature is allowed to fall below 150°C, till intermediate tempering is completed. This requirement puts additional challenge of very high reliability of the heating system. Once heating is started, till the completion of intermediate tempering, there is to be no interruption in heating. This period is typically 3 weeks.

Post-weld heat treatment (PWHT)

During PWHT of RPV nozzle to MCP joint, the temperature at monitoring point BK5 is not to exceed 230°C, and that at BK3 is to be in the range of 350°C to 500°C. The temperatures at points BK1, BK2, BK4 and BK6 are required to be in the band of 620°C to 660°C.

Conceptualisation and Design

Varying sectional thickness and

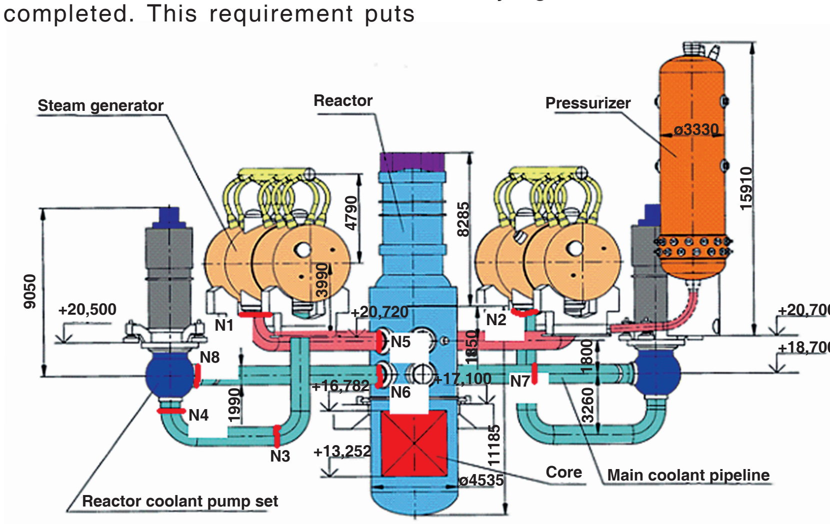


Figure-1: MCP Joints (N5, N6, N1 and N2) are to be Induction-heated

RPV

	C	Mn	P	S	Si	Cr	Mo	V	Ni	Thickness
Minimum	0.13	0.30	.010	.012	0.17	1.80	0.50	0.10	1.0	70 mm
Maximum	0.18	0.60	___	___	0.37	2.30	0.70	0.12	1.5	300 mm

SG and MCP

	C	Mn	P	S	Si	Cr	Mo	V	Cu	Ni
Minimum	0.08	0.80	0.02	0.02	0.17	0.3	0.40	0.03	0.3	1.80
Maximum	0.18	1.10	(max.)	(max.)	0.37	(max.)	0.70	0.07	(max.)	2.30

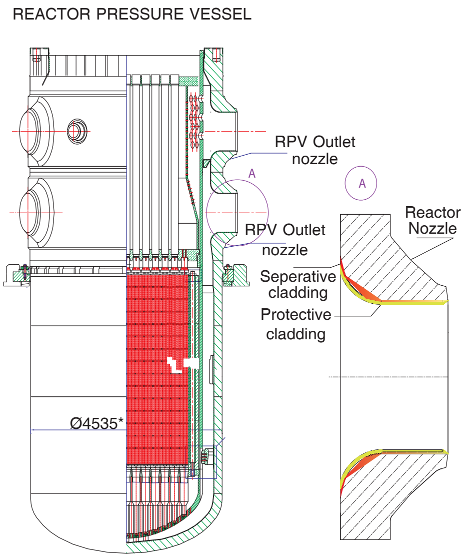


Figure-2: RPV Nozzle

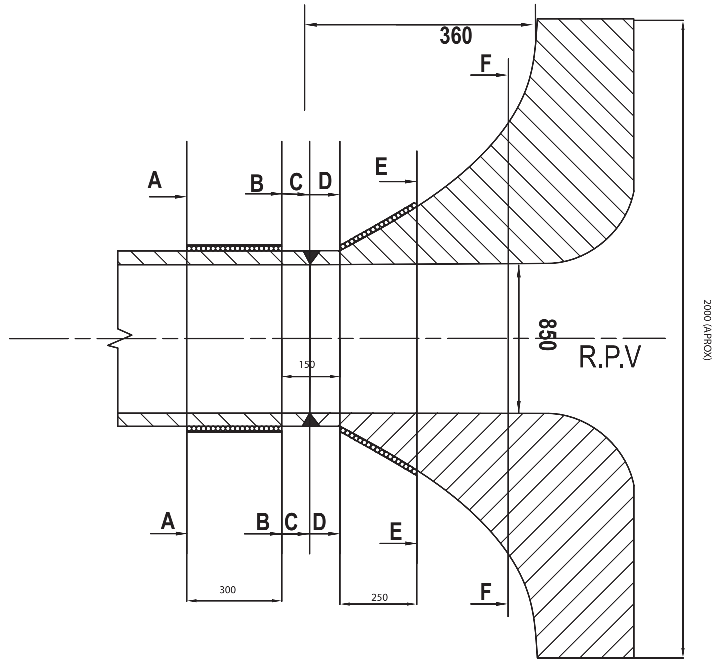
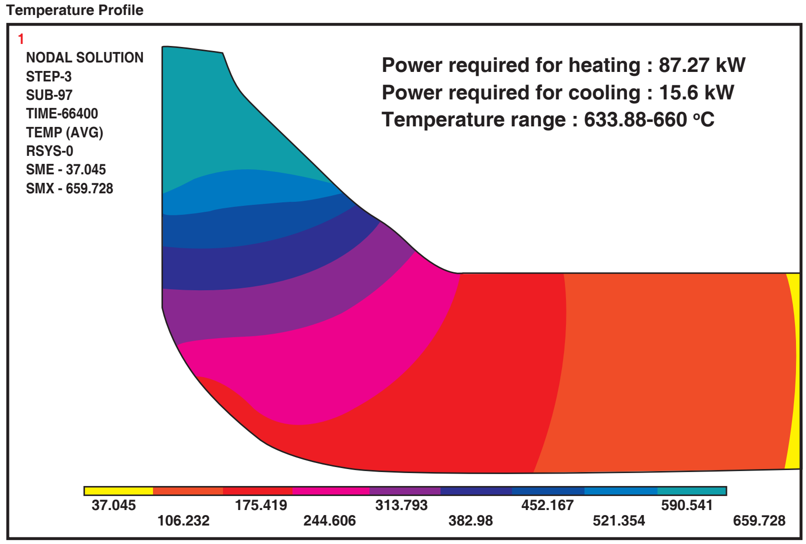


Figure-3: Location of Thermocouples BK1 to BK6 on RPV to MCP Joint

temperature requirements made manual calculations very difficult. Hence, two-dimensional computer models of RPV and MCP were prepared and heat calculations were made using computer software. Analysis of temperature profile across the section, considering more than 1000 nodes were done. The heat input required to achieve the temperature profile was thus calculated. The amount of heat to be removed from the curvature portion to maintain 230°C at point BK5 was also computed using computer software. It was estimated that a total power of 200 kW is required for heating and around 18 kW will have to be removed from the RPV internal diameter (ID) to cool the clad area of RPV.

Due to heavy mass and varying thickness, it is not feasible to input 200 kW heat with fine control of temperature using conventional methods of heating. Hence, it was decided to go for induction heating. In order to achieve a fine control over temperature, the heat-affected zone (HAZ) was divided into two parts, viz. RPV-nozzle-side and MCP-side. Separate inverters and inductor coils were designed and manufactured for heating of these two parts.

Temperature Profile



NODE	TEMP						
101	217.41	115	637.62	369	636.98	391	637.88
102	218.76	116	643.12	370	639.84	392	621.00
105	634.17	117	653.79	371	636.83	403	658.44
106	639.99	119	652.10	372	636.12	405	604.63
107	659.73	120	650.63	383	647.36	406	576.85
108	659.25	121	649.10	384	645.17	488	633.54
109	658.62	363	652.25	385	642.21	489	640.75
110	655.45	364	651.24	386	637.97	542	635.91
111	654.18	365	634.42	387	631.43	546	639.92
112	653.13	366	635.50	388	621.27	547	645.61
113	636.31	367	637.74	389	649.33	614	633.85
114	634.93	368	637.37	390	645.79	615	633.83

MAXIMUM ABSOLUTE VALUES
NODE 107
VALUE 659.73

Figure-4: Result of Modelling RPV Nozzle for Final Tempering

Rigid-type conical-shaped inductors were initially developed considering varying section thickness of RPV and SG nozzles, and the requirement of uniform heating. These inductors posed difficulty in accommodating the radiography film cassette while conducting radiography in hot condition. A flexible-type inductor with carbon-free tubes and round-copper conductors was developed to get the flexibility of accommodating the radiography cassette as well as better accessibility by the welder and grinder.

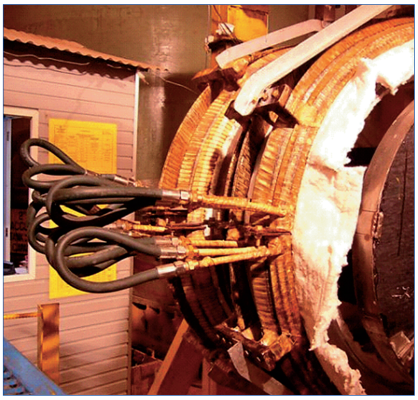


Figure-5: Rigid Inductor Installed on Specimen for Technology Certification

This type of inductor performed well but posed a threat of chilled water leakage in case of tube rupture. Considering this fact, the inductor was further redesigned by a using flexible metal tube to hold the pressure of the chilled water.

Insulation and Cooling

For minimal thermal loss and optimised coupling efficiency, a thermal insulation of 50-mm thickness was selected. This can also prevent minor water leakages from reaching up to the metal surface.

For cooling inner surface of RPV with SS cladding, various cooling methods, viz. mist cooling, thermit cooling, quench ring, etc., were considered for cooling the vessel ID. Based on the results of full-size mock-up, fan cooing was finally selected for its simplicity.

Power Source

Current commutated inverters in series-resonance mode were considered. The frequency range was limited to 3 kHz to reduce concentration of heat on the skin. The lower frequency was set as 1 kHz to reduce interference of induction current on arc of SMAW. RPV-nozzle-side inverter was rated for 200 kW and MCP-side, 50 kW. This is to provide adequate margin to cater to increased power demand, if any, due to slight change in material properties as well as the assumptions of various parameters made in the computer modelling to actual job.

The power source was designed employing a bare minimum of components to maximise reliability. All power electronic components were de-rated with adequate margins as per NPCIL component policy.

Since the heaters are to be accommodated in the reactor building, it was essential to make the inverter as compact as possible. Water-cooled inverters were made for this purpose. The inverter and converters were split into two cabinets, so that the inverters can be kept on small platforms at 15-m El and comparatively bigger-sized converters and chiller units, water tanks and circulating pumps can be located at 31 m El.

Chillers of 12-T capacity were selected for each set of heating system to provide chilled water for cooling the inductor and power electronic devises. Chilled water is required for cooling inductor coils, lead cables, converters and inverters.

Electrical Parameters

Power	Mode	DC Volts	DC Amps	Frequency-kHz	Inductor Turns
200 kW	Pre-heat	500	400	1.0	8
	PWHT	500	400	0.75	9
50 kW	Pre-heat	530	100	3	4
	PWHT	530	100	3	3

Control and Data Acquisition

In order to achieve precise control of temperature, programmable-type PID controller was selected for controls. SS-sheathed mineral-insulated thermocouples of class-1 accuracy, with extension leads of class-I, were selected to minimise the errors and to maximise reliability. A 50-channel data acquisition system with a laptop computer was selected for continuous data acquisition. A UPS with a 2-hour back-up power capacity was selected for uninterrupted data acquisition.

Manufacturing and Testing

The manufacturing and full-scope mock-up testing of the induction heating system was done at M/s. VEL Electronics, Mumbai. A full-size mock-up castings of SG nozzle to MCP and RPV Nozzle to MCP was made to conduct the mock-up trials and tests. The castings were made of steel of similar chemical composition and dimensions of that of the actual job.

Temperatures at 32 locations were monitored on RPV nozzle mock-up joint. Extensive trials and evaluations were carried out to finalise the scheme.

Temperature variations along the surface as well as gradient across the thickness were controlled by proper placement of inductor and tuning of PID controller.

The chiller system, control system, inverters and converters, and data acquisition system were fully integrated and subjected to full-load burn-in test as per the separately developed test procedures. All worst-case conditions

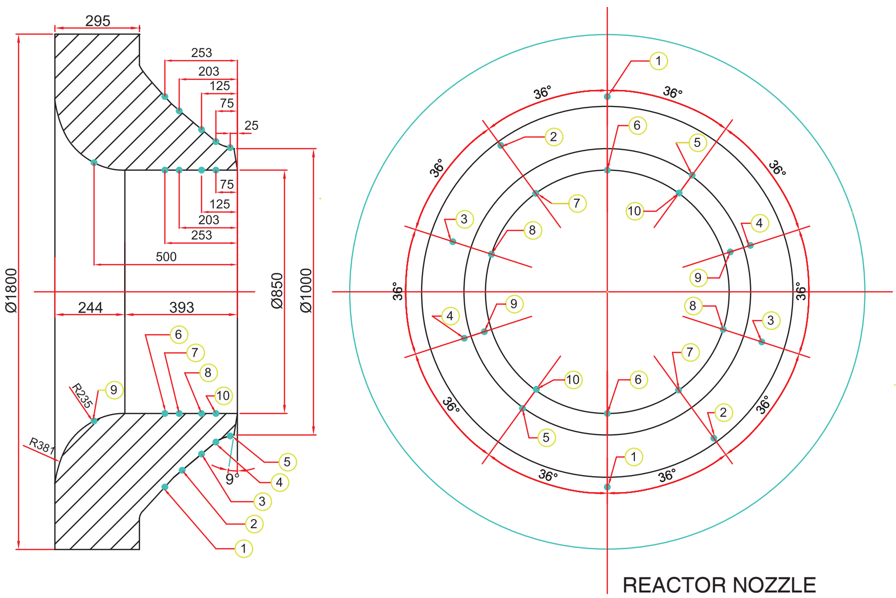


Figure-6: Monitoring Points for Design Validations Tests-RPV Nozzle

like power interruption, chiller failure, etc. were simulated during this test. The temperature rise of various components and chilled water was monitored continuously. The mock-up casting was used as a load for the inverters. The test results showed that enough design margin is available for catering to the requirement of heating the job as per temperature rise and cooling requirements.

On Job Validation

After the successful completion of the mock-up tests, the necessary approvals for the exploitation of the above system were obtained from the designers of the reactor plant welding and heat-treatment, M/s. TsNIITMASH, Moscow. Two N5 joints of loops 1 and 3 were taken up for welding.

One set of 200-kW and 50-kW inverters was employed for each joint. Another set of inverters with dedicated chiller plant, converters and control system was kept ready on hot stand-by. Three sources of AC power supply, viz. 2 sources of 500-kW DG sets and TNEB power were hooked up through motorised changeover switches to prevent the temperature of the job falling below 150°C in the event of a failure of any source or component in the induction heating system.

Pre-heating and inter-pass heating operations were completed simultaneously. Intermediate tempering and final tempering operations were taken up sequentially. After completion of NDTs, the system was shifted to N5 joints of loops-2 and 4. All heating operations of four joints were completed at site, meeting fully the specified requirements.

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KKNPP Site Team

KKNPP Headquarters Team

M/s. TsNIITMASH

M/s. Atomstroyexport

M/s. Larsen & Tubro Ltd.,

ECC Division

After graduation in Mechanical Engineering in 1970, A. K. Pal joined Department of Atomic Energy at Rajasthan Atomic Power Project [RAPP-1 & 2] in the year 1971. He did his M.Tech. from IIT, Kharagpur and specialised in Thermal Engineering during 1979-1981.

After Post-graduation, he joined Narora Atomic Power Project [NAPP] where he succesfully completed Ventilation and Air Conditioning of the main plant systems. $D_2$0 and vapour recovery system were also executed by him.

After completion of Narora Atomic Power Project, he was designated as Project Engineer at Kaiga Atomic Power Project-1&2. He was responsible at Kaiga for various mechanical installation jobs, which included Reactor Core components - End shield, Calandria, their alignment, welding of End shield - Calandria etc. He was also responsible for erection of Fuelling Machine Bridge and Steam and Feed Water pipeline of turbine system, secondary piping of turbine system. He also overhauled and commissioned Chilled water plant at Kaiga Atomic Power Project along with Air Compressor.

On completion of Kaiga Project, his services were required at Tarapur Atomic Power Station where he was assigned the charge of Chief Engineer. At Tarapur, he was responsible for nuclear core components and piping installation etc.

Presently he is Chief Construction Engineer at Kudankulam Nuclear Power Project where civil, electrical and mechanical streams of engineering are being guided by him. The project has made substantial progress under his guidance and civil works for Reactor Building, Turbine Building, Pump-house and other auxiliary buildings are nearing completion. Reactor Building of KKNPP is of specialised civil work having hermetically sealed liner inside the building. Besides above, 220KV GIS installation, Turbine Generator installation, various pumps at Pump House, various nuclear components like Reactor Pressure Vessel, Steam Generator and Coolant circulating pump are being installed with precision accuracy and tolerances under his guidance in a co-ordinated manner with the experts from the Russian Federation.