Development of Helium Leak Testing System and Procedure for testing Welds of Steam Generator

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Abstract

The main function of Steam Generator (SG) in FBR is to extract the reactor heat through secondary sodium system and convert the feed water into superheated steam in the tubes of SG. The Steam Generator is a vertical, once through, shell and tube type heat exchanger with liquid sodium in the shell side and water/steam in the tube side. The highly reactive nature of sodium with water/steam requires that the sodium to water/steam boundaries of the steam generators must possess a high degree of reliability against failure. This paper highlights the experiences in helium leak-testing in vacuum mode to detect a leak rate of the order 6.66 X 10⁻⁹ Pa.m³/s, as specified.

Keywords: FBR; steam generator; ferritic steel; helium leak testing; weld joint

1. Introduction

FBR Steam Generator (SG) is a vertical shell & tube type heat exchanger with sodium on shell side and water/steam on tube side. As sodium and water are highly reactive, the boundary separating these two fluids is designed for the highest integrity. All welds in these SGs are hence very critical and require a very high degree of reliability and integrity, especially the thin joints, viz., tube to tube sheet joints. Failure of these joints will cause a cascading effect. The final integrity of weld joints is required to be ascertained by performing helium leak testing. This paper describes the methodology developed and its implementation for the leak testing.

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Selection and/or peer-review under responsibility of Indra Gandhi Centre of Atomic Research

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2. Leak testing methods

Comparison of various methods available for leak testing with respect to allowed leak rates is as shown in Fig. 1.

![Leak testing methods diagram](image)

To meet the leak rate requirement (1) of $6.66 \times 10^{-9}$ Pa.m$^3$/s, the SG specification also accordingly specifies helium leak testing in vacuum mode. Various parameters which needs to be considered while devising the system and planning for the Helium leak test include,

- Size and internal volume of the equipment
- Internal surface area
- Intricacy of internal design and access to inside
- Rigidity / flexibility of equipment
- Any hidden internal volumes in the equipment or pockets for entrapment
- Cleanliness of the equipment
- Surface finish of sealing surfaces
- The permissible leak rate

3. SG Specification Requirement [1]

To achieve 40 years of trouble free continuous operation of SG and with current trend of life extension, the specification requires, testing of all welds by multiple nondestructive methods viz. boroscopic examination, dye penetrant examination, microfocal radiographic examination, ultrasonic examination and helium leak testing. Helium leak testing is final test to verify integrity and reliability of weld joints. This test is preceded by hydrotesting and chemical cleaning. Leak testing of the steam generators was challenging in view of complex internal construction, material of construction and stringent leak rates specified. The comparison of permissible leak rates for few other nuclear critical equipment known and the permissible leak rates for the steam generators are as shown in Table 1.
Table 1. Permissible leak rates of nuclear equipment

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Description of Equipment</th>
<th>Global Leak Rate</th>
<th>Local Leak Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Argon buffer Tanks</td>
<td>$1 \times 10^{-7}$ Pa.m$^3$/s</td>
<td>$1 \times 10^{-8}$ Pa.m$^3$/s</td>
</tr>
<tr>
<td>2</td>
<td>Secondary Na storage tanks, Na transfer tanks, reserved Na storage tanks</td>
<td>$1 \times 10^{-7}$ Pa.m$^3$/s</td>
<td>$1 \times 10^{-8}$ Pa.m$^3$/s</td>
</tr>
<tr>
<td>3</td>
<td>500 MWe Steam Generators</td>
<td>$1 \times 10^{-7}$ Pa.m$^3$/s</td>
<td>Not specified</td>
</tr>
<tr>
<td>4</td>
<td>Spent Fuel Canister</td>
<td>$1 \times 10^{-8}$ Pa.m$^3$/s</td>
<td>Not specified</td>
</tr>
<tr>
<td>5</td>
<td>Primary Piping</td>
<td>$1 \times 10^{-7}$ Pa.m$^3$/s</td>
<td>$1 \times 10^{-8}$ Pa.m$^3$/s</td>
</tr>
<tr>
<td>6</td>
<td>FBR Steam Generators (SG)</td>
<td>$6.66 \times 10^{-9}$ Pa.m$^3$/s</td>
<td>$2.66 \times 10^{-9}$ Pa.m$^3$/s</td>
</tr>
</tbody>
</table>

4. Constructional features of the steam generators

Construction of tube bundle comprises of 23 meter long tubes with baffles consisting of 29 strip at 19 locations held together using clamping belts, locking clamps, tie rods, etc. In addition thermal shields and flow distribution plate are part of the complex construction.

This type of construction results into larger surface area within small volume. Constructional features of SG are as shown in Table 2.

Table 2. Construction features of SG

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Overall Dimensions</td>
<td>Thk 30/12mm X Dia 1237/855 mm X lg.26168 mm</td>
</tr>
<tr>
<td>2</td>
<td>Material of construction</td>
<td>9Cr 1Mo Modified – Ferritic Steel</td>
</tr>
</tbody>
</table>
| 3      | Volume / Surface area | Shell side : $15 \text{ m}^3 / \sim 900 \text{ m}^2$  
|        |                  | Tube side : $3 \text{ m}^3 / \sim 500 \text{ m}^2$ |
| 4      | Number of tubes | 547                                    |

5. Challenges

Stringent permissible leak rates and complex constructional details posed following challenges for successful helium leak testing of the weld joints of the SG.

5.1. Evacuation of shell side and tube side of the steam generator to the vacuum level of at least $10^{-4}$ mbar.

Past experience indicated that the vessel will have to be evacuated and maintained at a vacuum level of $10^{-4}$ mbar for successful testing of the equipment. Considering the material of construction i.e. Ferritic steel, surface finish, higher surface area, volume and complex internal construction especially on shell side, it was anticipated that for evacuating shell side to the level of $10^{-4}$ mbar will require a robust auxiliary multi stage, multitype pumping system.
5.2. Achieving leak detector sensitivity(1) to the order of $1.0 \times 10^{-10}$ Pa.m$^3$/sec

It is necessary to maintain vacuum level in the range of $10^{-3}$ to $10^{-4}$ mbar for the leak detector to achieve sensitivity / background of $1.0 \times 10^{-10}$ Pa.m$^3$/s or better while the leak detector is exposed to the entire volume. As the SG has complex constructional features with material of construction as ferritic steel, phenomenon of outgassing was envisaged.

5.3. Practical limitations for filling the helium inside the bagging and measurement of helium concentration

The steam generator has large number of welded externals such as insulation rings, deflector cones, thermocouple gauges, leak detectors, acoustic rods and heater support strips. Due to varying sizes of these externals, size of SG viz. 26 meter length and also possibility of increasing helium background in the environment it was not practically feasible to create a hood around the SG.

6. Vacuum system and leak testing procedure

6.1. Design of auxiliary vacuum system

Auxiliary vacuum system comprising of 2 numbers rotary pumps, 2 numbers roots pumps and a diffusion pump coupled with solenoid valves, cold traps and water cooling system was designed to achieve a vacuum level of $10^{-4}$ mbar at the farthest end ~ 23 meter of the SG. Provisions were made to bypass the pumping stages as and when required. The entire system was mounted on a skid assembly for its safe movement on the shop floor. The inlet of the diffusion pump was provided with flexible bellows for ease of alignment with the nozzle connections.

Intermediate Z shape leak tight pipe spool with flexible bellow for fine adjustments in height during connections was fabricated. This also helped in improving the conductance on tube side. The Z shaped pipe spool was provided with 50KF coupling to attach the leak detector.

P&ID of the pumping system and positioning of the steam generator is as shown in Fig.2
6.2. Leak detector sensitivity and system calibration [4]

It was observed in several trials that to achieve leak detector sensitivity of $1 \times 10^{-10}$ Pa·m$^3$/Sec or better, a vacuum level better than $10^{-3}$ mbar was necessary. Refer Fig. 3 showing relation between leak detector sensitivity / background V/S vacuum level [3].

Initially to overcome the problem of outgassing, it was decided to evacuate shell side to a vacuum level of $10^{-6}$ mbar and isolate it from the vacuum system and keep the equipment under vacuum for more than 24 hrs to minimize outgassing effect during subsequent evacuation. After 2 such cycles it was observed that the vacuum level maintained in the equipment with isolated vacuum system was of the order $1.8 \times 10^{-2}$ mbar. With this condition it was now possible to:

- maintain vacuum level to the order of $10^{-3}$ mbar with only one roots pump ON
- observe appreciable change in leak signal on the leak detector with a standard leak of the order $2.3 \times 10^{-9}$ Pa·m$^3$/s.

**Nomenclatures**

- V ----- Pneumatic Valves
- C ----- Connectors
- FC ----- Flexible Couplings
- CT ----- Cold Traps
- M ----- Vacuum Gauges

**Fig. 2. P & I Diagram of the pumping system**

**Fig. 3. P & ID of vacuum pumping system**
To achieve and maintain the vacuum level of $10^{-4}$ mbar and better in SG and to achieve higher leak detector sensitivity / background, the vacuum system was kept ON. However with vacuum system ON the leak detector was not able to sense the helium released through standard leak, as the pumping capacity of the pumping system is much higher than the pumping capacity of leak detector. To get the required sensitivity, few of the stages of the pumping system with higher capacity, were bypassed after the required level of vacuum was achieved. With low capacity vacuum pump ON, the required sensitivity and stable background could be achieved without losing the vacuum inside the equipment.

6.3. Helium bagging

With large number of externals of varying sizes, it was necessary to create a local plastic hood around the weld seams to introduce helium gas. To facilitate the operation, the steam generator welds were divided into 5 sections for bagging. Inlet and outlet ports were specially made up of thermoplastics to avoid helium gas escaping into the atmosphere during filling. Refer Fig. 4 & 5.
7. Leak Testing

For shell side leak testing, SG was placed such that sodium inlet and outlet nozzles were in a horizontal plane. The inlet nozzle was connected to auxiliary pumping system and the sodium outlet nozzle was provided with the standard leak of $2.3 \times 10^{-9}$ Pa.m$^3$/s to establish system sensitivity, response time and vacuum gauges to measure the vacuum level. All applicable welds were bagged with polyethylene for filling up the helium gas. The shell side was evacuated using auxiliary vacuum system. The equipment was maintained under vacuum for required number of hours prior to stabilizing it to a value of $1.8 \times 10^{-2}$ mbar. Subsequently the roots pump was started and the shell side was evacuated and maintained at a vacuum level better than $1.0 \times 10^{-3}$ mbar. Response time and system sensitivity were calculated by opening the standard leak. Helium gas was filled in the polyethylene bagging and the stabilized leak rate reading on the leak detector was recorded after 30 minutes.

Leak testing on tube side was performed by connecting the leak detector and auxiliary pumping system to manway nozzle on top side and standard leak, vacuum gauges assembly to manway nozzle on bottom side. Shell was filled with helium gas to a pressure of 2.0 kg/cm$^2$ gauge pressure.

8. Results

The steam generator with complex construction and ferritic steel as a material of construction was reliably and effectively helium leak-tested in vacuum mode to detect a leak rate of the order $6.66 \times 10^{-9}$ Pa.m$^3$/s, as specified. The leak rate observed was within acceptable limits.

Acknowledgements

All the development program and production experimentation was completed with the support of the management of Larsen & Toubro Limited. The authors wish to thank management of Nuclear Power Corporation of India Limited, Indira Gandhi Centre for Atomic Research (IGCAR) and Bhartiya Nabhikiya Vidyut Nigam Limited (BHAVINI), for their guidance during execution of the Leak Testing of Steam Generator.

References

[4] ASME Sec V