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Roll-expanded plugs for steam generator heating tubes verification of leak tightness over the component lifetime

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HIGHLIGHTS

- Design description of roll-expanded plugs.
- Experimental simulation of 40 years lifetime of plugged steam generator tubes.
- Destructive testing for off-design loads.
- Evaluation of release pressure and tightness before and after the tests.

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ABSTRACT

Steam generator heating tubes are the boundary between the irradiated primary cycle and the conventional secondary cycle in a pressurized water reactor. Despite their operational task to transfer the heat from the primary to the secondary cycle, these tubes have a crucial safety function: the retention of irradiated primary coolant inside the circuit in all operating, emergency and off-design conditions. The heating tubes are subject to various degradation mechanisms during operation. To verify the integrity of each single tube, nuclear power plants carry out frequent in-service inspections. In case of a tube wall degradation beyond the permissible limit, the tube needs to be taken out of service in order to maintain the overall component integrity. The most common method to do so is to plug a damaged tube by a roll-expanded plug. After plugging, the roll-expanded plug acts as pressure boundary between the primary and the secondary cycle instead of the damaged heating tube. The plug must be able to maintain this function, previously provided by the heating tube, in all operational, emergency and off-design conditions.

This article describes the approach to this verification by launching several comprehensive process qualification programmes consisting of mechanical analyses as well as static and dynamic testing programmes. The result was a qualified roll-expanded plug which remains leak-tight even during off-design conditions.

1. Introduction

The steam generators (SGs) of pressurized water reactors (PWRs) join the nuclear island with the secondary cycle. The SGs are key components which have a large impact on the plant performance in terms of operation and safety. Since the SGs are the main heat sink and the pressure boundary of the primary cycle, these components are highly safety-related.

During operation, SGs are subject to degradation mechanisms which have an impact on the component lifetime. Most effected parts are the heating tubes. These transfer the heat and constitute the barrier of the contaminated primary cycle towards the secondary side. Various corrosive attacks caused by deposited impurities on the secondary side as well as low susceptibility of some tube material towards corrosive chemical environments may cause tube wall thinning. Whenever the remaining tube wall has reached the permissible limit, repair measures must be applied.

Although various attempts have been made in the past to develop repair mechanisms to keep heating tubes in service, the most common is to remove a tube with a critical wall thinning from service by sealing the inlet and the outlet of the tube with a plug. Different approaches have been made for tube plugging, whereas the preferred solution consists of mechanically expanded plugs inside the tube. Mechanically expanded plugs are differentiated in mandrel-types, using a bolt connected to a mandrel for

Abbreviations: FWLB, feed water line break; LOCA, loss-of-coolant accident; R&D, Research and Development; SG, steam generator.

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Nomenclature

Symbols

H	expansion ratio
P	load
p	pressure
S	permissible load
S	safety factor
T	temperature
α	thermal expansion coefficient
ε	strain

Indices

G	German
L	limit
m	membrane
p	primary
s	secondary
T	tube
TS	tube sheet
US	US-American

expansion and mechanical roll-expanded plugs using a rolling tool which is afterwards removed from the SG.

Tube repair by mechanical plugs is covered by the ASME Boiler and Pressure Vessel Code Section XI (ASME, 2007). This guideline is very comprehensive and generally applied by most national regulatory bodies. However, national regulations might imply additional obligations on the plug performance and the required qualification of the repair concept.

A range of R&D projects in recent years was launched to investigate the different parameters which influence plug tightness and tube repair concepts. The projects aimed at adjusting the plug design to serve most demands of national regulations that sometimes exceed the requirements imposed by ASME. The following paragraphs describe the boundary conditions of a plug used for SG heating tube plugging and explain the design approach taken for the development of a roll-expanded plug. The analyses and the test set-up are described in the following. They resulted in a roll-expanded plug designed to maintain its leak tightness until end-of-life even in beyond-design conditions.

2. Regulatory demands and operating conditions

SGs are designed according to the highest nuclear quality standards. Despite the fact that all these standards have the common aim to ensure the highest safety in terms of manufacture and operation, the detailed requirements may differ. An international service provider needs to comply with several of different standards. To minimize the product range a covering approach may be more beneficial, even though the most stringent design requirements need to be applied. Such an approach was taken for the design of the roll-expanded plug.

2.1. Regulatory demands

To cover the regulatory requirements of the ASME Boiler and Pressure Vessel Code and the German KTA (Sicherheitstechnische Regel des KTA, KTA 3201.2; Sicherheitstechnische Regel des KTA, KTA 3201.3) as far as applicable, both were considered for the basic design of the mechanical roll plug. This approach combines the comprehensive definition of the plug requirements and the more stringent, although not clearly defined implications of the German legislation. The combination of both regulations proved to cover all regulatory demands to date.

2.1.1. ASME Boiler and Pressure Vessel Code

Since the year 2000, section XI of the ASME Boiler and Pressure Vessel Code contains a very comprehensive definition of the required compliance of a roll plug in terms of analysis, testing and qualification issues. The ASME Boiler and Pressure Vessel Code is generally accepted by most utilities and national regulatory bodies and – lacking a similar comprehensive definition – ASME is also applicable if similar definite national regulations are missing. Therefore, the ASME requirements were generally followed as an overall guideline for plug design.

2.1.2. German regulatory implications

The German regulation does not differentiate in manufacturing and repair activities. Usually, the same standards apply to repair as well as to component manufacture. This implies the verification of leak tightness during all transients specified during component design for the whole lifetime which had to be considered in the testing programme.

2.2. Operational conditions

During operation the plug is exposed to varying thermal and mechanical loads resulting from load transients. The plug has to compensate the tube sheet bending during normal operation as well as during emergency conditions. The loading and unloading of the SGs during operation and testing reduces the elasticity of the tube sheet over the life time and has a significant effect on the retention force and the tightness of the plug. In addition to thermal and mechanical fatigue chemical attack needs to be considered:

- Potential corrosion attack by primary and secondary side medium.
- In addition, no flow at the secondary side with potential impurity concentration and formation of hard deposits.
- Surface tension on the roll transition zone on the primary and on secondary side.

These factors require a high insusceptibility of the plug material against intergranular attack (IGA) and stress corrosion cracking (SCC). In order to be able to verify the actual condition of a plug in operation these should be inspectable. Space needs to be provided for common eddy-current test (ECT) probes to enter. Besides inspection, removability of the plug is profitable, if repair on the plug or the tube-to-tube sheet connection of the plugged tube is necessary.

3. Design determination

The combination of the boundary conditions described above restricts the design of a roll plug to a hollow, thimble-like shape, common to all roll-expanded plugs (see Fig. 1). The plug has a neck on the bottom to facilitate the positioning. The thread in the tip is used for removal. The interface to the heating tube consists of a specific profile with a coating to ensure leak tightness of the expanded plug without any additional measures.

3.1. Determination of the expansion parameters

The most sensitive parameter of the plug design is the expansion ratio. This geometrical variable considers the geometry of the tube and of the plug in the expansion region before and after the expansion and defines the degree of plastic deformation.