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Repair of Steam Generator Heating Tubes by Roll Expanded Plugs

Approach to Cover Multiple National Regulations

J. Beck[1], R. Ziegler[1] and N. Schönheit[1]

[1]AREVA NP GmbH
Paul-Gossen-Straße 100
91058 Erlangen, Germany

ABSTRACT

During operation, steam generators in nuclear power plants are subject to degradation mechanisms which have an impact on the component life-time. Most affected are the heating tubes which constitute the barrier of the contaminated primary cycle to the secondary side. Various corrosive attacks may cause wall thinning which requires tube repair. A common repair method is to plug the tubes by roll expanded plugs. This is a fast method, easily applicable and requires less equipment or personnel qualification as needed for weld plugs. After insertion, the plugs act as a pressure boundary from primary to secondary side.

Although the function of the roll plug is simple, the different national regulations define the requirements which need to be fulfilled by a roll plug differently. In order to reduce the tooling as well as the plug types to a minimum, an approach according to one common design for different regulations and steam generator types is profitable. It was found, that the regulations according to the ASME Boiler and Pressure Vessel code in combination with the German Safety Standards of the German Nuclear Safety Standards Commission covers the regulations of the majority of utilities-

To develop a roll plug which suits the different regulatory demands, efforts were made to consider all technical and regulatory boundary conditions implied on roll expanded plugs. This covering approach had an impact on the plug design, which was required to be Helium tight after installation and suitable for a 40 year component lifetime also in accident and emergency conditions. To prove the suitability of the plug design a comprehensive testing programme of the mechanical and chemical properties of the designed roll-expaned plug was launched. A summary of the plug design and testing as well as the main test results are described.

1. INTRODUCTION

The steam generators (SG) of pressurized water reactors (PWR's) join the nuclear island with the secondary cycle. As such, the SG's are key components which have a large impact on the plant performance. Since the steam generators also provide the main heat sink so that these components are also safety related.

During operation, SG's are subject to mechanisms which have an impact on the component life-time. Most affected are the heating tubes which constitute the barrier of the contaminated primary cycle to the secondary side. Various corrosive attacks caused by impurities deposited on the secondary side or low susceptibility of the tube material to certain chemical environments can cause tube wall thinning. If the remaining tube wall reached a certain limit tube repair measured must be applied.

Although various attempts have been made in the past to develop repair mechanisms to keep heating tubes in service (i.e. sleeving) the most common repair is to remove a tube with a critical wall thinning from service by plugging. Currently the preferred solutions are either mandrel-type plugs which are mechanically expanded inside the tube using a bolt connected to a mandrel or mechanical roll-expanded plugs, which are expanded by a mechanical rolling tool which is removed after plugging. Owing to the simple design with only one part, the roll-expaned plug design was pursuit in this case.

Tube repair by roll expanded plugs is covered by the ASME Boiler and Pressure Vessel Code Section XI [1]. This guideline is very comprehensive and is usually accepted by other national regulatory bodies. However, national regulations such as the *Safety Standards of the German Nuclear Safety Standards Commission* (KTA) [2] do not differentiate between erection and repair. As a consequence, a repair method needs to be consistent with the design of a new plant. This implies additional obligations on the plug performance and the required qualification of the repair concept.

Based on extensive qualification tests AREVA NP has started a series of R & D projects during the last years to investigate the different parameters which influence plug tightness and tube repair concepts in order to be able to adjust the plug design to serve most demands of national regulations that extend beyond ASME. The following paragraphs describe the general specifications of a roll plug used for steam generator heating tube plugging. On this basis, the design approach of AREVA NP GmbH for the roll plug is derived and the attempts which where made to comply with the most stringent regulations to date.

2. REGULATORY CONSIDERATIONS AND OPERATING CONDITIONS

Steam Generators are integral parts of the primary cycle of a Pressurized Water Reactor (PWR) and are as such safety relevant components. For that reason, highest quality standards are applicable. Depending on the type of regulation applied by the national regulatory body, similar standards may be applied to any parts used to restore the primary – to secondary side pressure boundary.

2.1 Regulatory Demands

To cover the regulatory requirements of the majority of AREVA NP GmbH’s customers the ASME B & V code and the KTA were considered by the basic design of the mechanical roll-expanded plug. This approach combines the comprehensive definition of the plug requirements and the more stringent, although not clearly defined implications of the German regulation. The combination of both proved to cover all regulatory demands to date.

2.1.1 ASME Boiler and Pressure Vessel Code

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

2.1.2 Safety Standards of the German Nuclear Safety Standards Commission (KTA)

For some aspects, ASME is not applicable. According to German regulation no leak from primary to secondary side is permissible. In consequence, the leakage criterion of the He-leak rate test from SG-manufacture shall be applicable which is in the range of $1 \cdot 10^{-6}$ cm³/s/bar. In addition, ASME requires the cyclic testing of heat-up and cool-down and test loads only. The KTA, not giving detailed acceptance criteria for stream generator repair, is to be interpreted in such a way that a 40 year lifetime of the component shall be proved. This implies testing of all relevant design transients of a steam generator within this time including corrosion tests to simulate a 40 year lifetime of a roll expanded plug at pressure and temperature in primary and secondary side media.

2.2 Type of Tube-to-Tube Sheet connection

There is no specific requirement in any major regulation that covers the type of tube-to-tube sheet connection, i.e. if mechanically or hydraulically expanded. However, the details of the tube-to-tube sheet connection are important to consider guarantee life-long tightness. Some SG manufacturers apply tube expansions in several steps, usually at some varying elevation from the primary side. This might create a circumferential discontinuity which may be within the roll expansion area of the roll expanded plug, for instance when for the dimensions X and Y in Figure 1 X > Y is true. The roll-expansion process and the plug design need to consider this effect to allow the use of one type for all applications.

2.3 Operational Issues

The most important operational issue is the inspectability of the plug by commonly used methods; roll plugs usually do not require specific provisions since the inside of the plug requires accessibility by the mandrels for the roll expansion which provides enough space 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 might be required at some point.

2.4 Material Selection

After having the heating tube plugged, the plug constitutes the pressure boundary from primary to secondary side. As such, the material needs to be of at least the same quality as the tubing material since the plug as similar features:

- 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 primary and on secondary side

These factors require a high insusceptibility of the plug material against IGA, PWSCC, ODSCC and other common heating tube corrosion mechanisms.

3. DESIGN DETERMINATION

The combination of the requirements restricts the design of a roll plug to a hollow, thimble like shape (Figure 1) common to all roll expanded plugs.

This plug design has a neck on the bottom to facilitate the positioning. A thread in the tip is used for removal. As plug material Alloy 690 was chosen. 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.

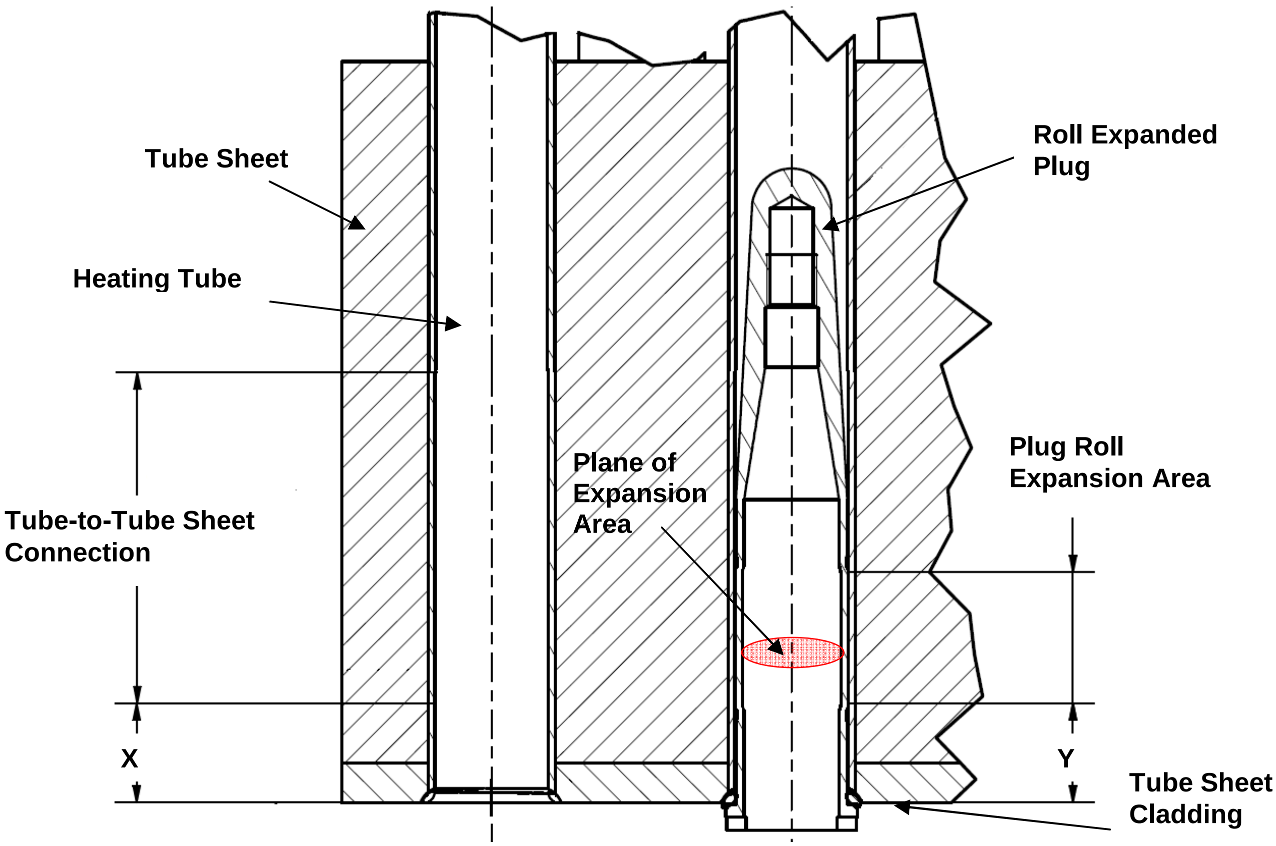

Figure 1: Scheme of a tube plugged by a roll expanded plug

3.1 Determination of the Expansion Parameters

The most sensitive parameter of the plug design is the expansion ratio. This is a geometrical variable which considers the diameter of the tube in the expansion region before plugging, the outer and the inner diameter of the plug as well as the clearance between plug and tube and the plug wall thickness.

For the definition of the expansion ratio it is important to define whether it is based on the radius in the plane of the expansion area (US), on the diameter in that plane (Germany) or on the area (Germany), see *Plane of Expansion Area* in Figure 1.

The expansion ratio defines the degree of the remaining plasticization after the expansion process while any plastic deformation of the tube wall usually is neglected. This however, is a permissible assumption since usually the tube wall is thin with a negligible degree of plasticization. The appropriate expansion ratio needs to be determined for any possible combination of material geometry. Ideally, the plug and tube are plasticized up to the tensile strength of the of the tube sheet material to achieve the highest retention force. Due to the complex interaction of different parameters it is practicable to determine the required expansion ratio in test series. This approach is usually also recommended by mandrel manufacturers of the roll expansion tools.

For steam generator tube plugging it is not possible to determine the geometry parameters once a steam generator was in operation due to radiation constraints. Therefore, the motor torque of the roll expansion tool is recorded instead. This parameter is depending on the expansion ratio as long no other parameter is changed.

3.2 Stress Analysis

The requirements of stress and fatigue analysis according to the ASME B&V Sec. III are precisely defined and were followed for the mechanical analysis of the plug design.

A stress analysis was carried out for primary- and secondary stresses for Level A, B, C and D loads. The stresses were defined in a covering manner and a utility with the highest stresses in the tube sheet was taken for reference in order to allow a justification of the design for other applications.

Primary stresses result from the pressure load of the plug. Secondary stresses caused by tube sheet deflection are necessary to consider as these influence the elasticity of the expansion joint. The analysis gave the highest utilization for design loads for limit $P_m < S_m$ and $P_L < 1.5\ S_m$, which showed a utilization of 77.7 %. All other utilization factors were almost significantly below that value.

3.3 Testing

The mechanical roll expansion process is extremely difficult to model and the results of a FE Analysis therefore might become subject of detailed discussions.

The ASME B&V Code [1] gives a well defined guideline of how to test roll-expanded plugs for the use in steam generators. For cyclic testing only thermal cycling needs to be tested and the tube sheet deflection does not need to be verified. The KTA does not distinguish between erection and repair, therefore implicitly the same standards for repair by plugging as for the manufacture of new SG's apply. This does include the verification of applicable loads for the whole lifetime including the tightness similar as for new components.

Accordingly, the mechanical parameters of the plugs were examined in two stages. In static tests the overall the basic design parameters and the different plug and heating tube conditions were verified. During the subsequent dynamic testing the load cycles of a 40 years lifetime were simulated for all relevant Level A, B C and D loads.

3.3.1 Static Testing

In static testing the load bearing capability of the plug in static conditions without temperature or tube sheet deflection was tested. It was found that for the retention of the plug the condition of the heating tube had a significant impact. Plugs were tested in different tube conditions:

- clean/as delivered,

- corroded/oxidized
- corroded/oxidized with debris.

It was found that the release pressure for the tested plug design was lowest for clean/as delivered tubes. Since the condition of a tube which already was in service is difficult to determine – it may range from clean to highly oxidized – it was decided in a covering approach not to follow ASME, which requires testing of tubes in oxidized condition. For the current plug design clean/as-delivered tubes cover all other conditions.

On this basis, the achieved release pressure for a reference plug was determined for the coated plugs in clean tubes by hydrostatic testing. Prior to hydrostatic testing, the leak rate was determined by He-leak testing. On this basis, the minimum release pressure was 560 bars. The static release pressure is significantly above the ASME criterion which is $S > 3.0$ for normal operation and $S > 1.43$ for accident conditions. The minimum He-Leak rate of $1.8 \cdot 10^{-7}$ cm³/s/bar is significantly below of the permissible leak rate of a steam generator of $1 \cdot 10^{-6}$ cm³/s/bar. However, these margins are necessary since these relate to newly set plugs. The aim of the plug design was to achieve the required values after the component lifetime, which was determined by dynamic tests.

3.3.2 Dynamic Testing

Due to bending and deflection of the tube sheet during different load transients the elasticity of the tube-to-tube sheet connection as well as the plug to tube connection decrease, since both rely on the resilience of the tube sheet which provides the force for their retention. In order to determine the influence of operation and load transients on the remaining elastic behaviour of the tube sheet a dynamic test was carried out. For the set up, the relevant covering load transients were determined and the mean ligament surface strain on the primary and on the secondary of the tube sheet was calculated. This strain was converted to a tube sheet mock up of the same qualified material but only 150 mm in thickness. Furthermore, an addition in strain was applied to consider the different temperature expansion coefficients of the materials and geometrical deviations owed to the test set-up [3].

The strain was applied by a stress-strain measuring, see Figure 2. The tube sheet mock up with an outer diameter of 1400 mm was slotted in order to realize the desired strain. On the outer diameter it was fixed with clamps and on the circumference of the test field with the specimen a loading ring was fixed by screws.

Altogether four different plug geometries and material combinations were tested. Per set eight specimens were tested. Each specimen was connected to a pressure line on both sides of the plug in order to superimpose the tube sheet deflection with the corresponding primary and secondary side pressure of the tested transients. The pressure of each line was recorded simultaneously in order to detect any pressure drop which may indicate a leakage during the tests. The test set up is shown in detail in Figure 3.

After completion of the test set-up the He-leak tightness was determined. The following dynamic testing consisted of two parts. First, the relevant transients were tested by cyclic testing to simulate 40 years lifetime. The test sequence consisted of different periods for Level A and B and for level C and D load cases. Each period corresponds to 10 years lifetime, whereas for level C and D loads only one period was tested. After the cyclic testing, a He-leak test was performed.

The He-leak tightness was not changed significantly still above the acceptance limit of $1 \cdot 10^{-6}$ cm³/s/bar, see Table 1.

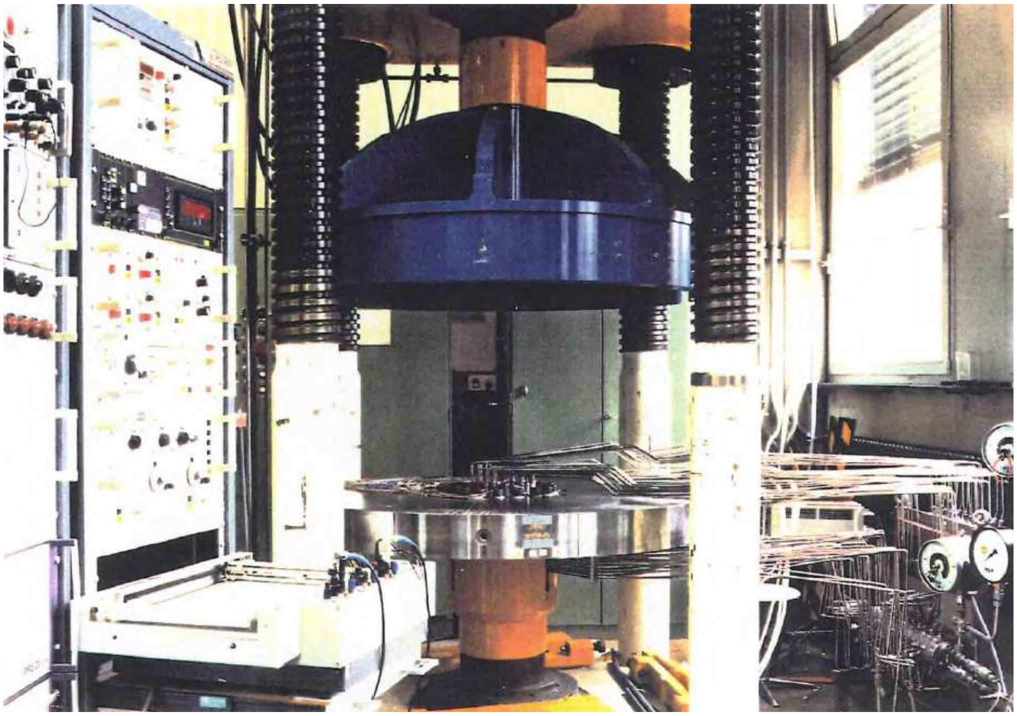

Figure 2: Tube Sheet mock-up for dynamic testing in the stress-strain measurements machine in the laboratories of AREVA NP Erlangen

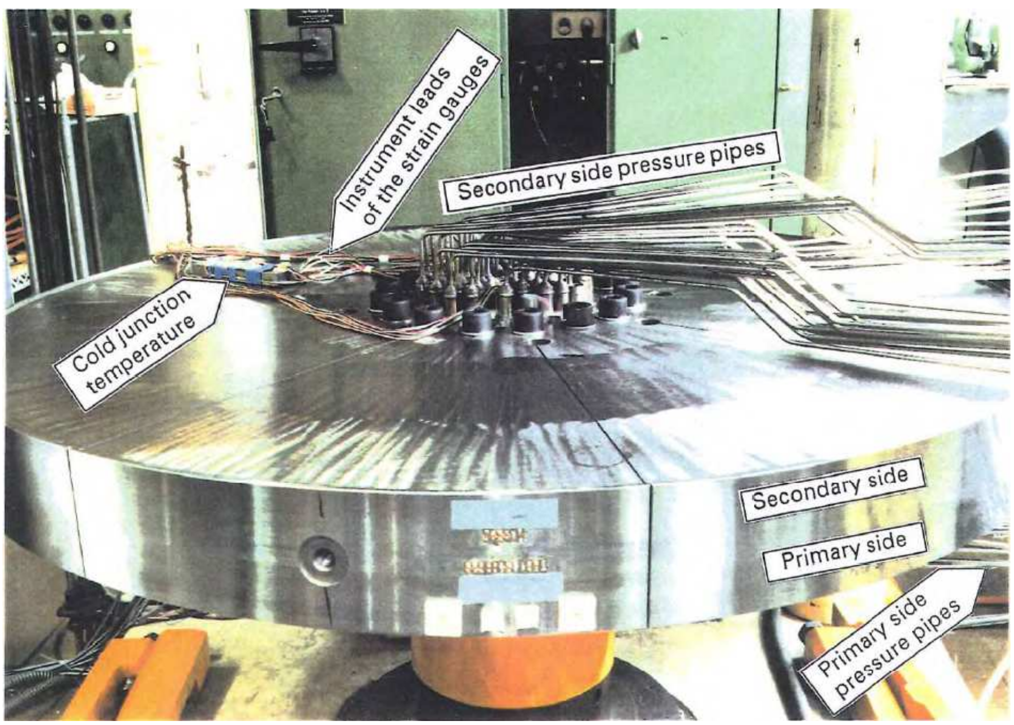

Figure 3: Detail of the test set-up with test specimen and pressure lines

Following the cyclic testing with He- leak test, a destructive test sequence was added where the tube sheet mock up was loaded with beyond design loads as to create leakage. Then, the specimens were tested for water tightness and subsequently the remaining release pressure of the test specimens were tested by applying hydrostatic pressure. It was found that after the dynamic tests the hydrostatic release pressure was reduced. But even the lowest pressure of 45.5 MPa still fulfills the ASME criterion: S = 4.33 > 3.0 for normal operation and S = 2.68 > 1.43 for accident conditions, see Table 1.

Specimen	Before Cyclic Testing		After Cyclic Testing		After Destructive Testing	
	Release pressure MPa	He leak rate cm³/s/bar	Release pressure MPa	He leak rate cm³/s/bar	Release pressure MPa	He leak rate cm³/s/bar
1	56.0 *)	$1.8 \cdot 10^{-7}$ *)	not tested	$0.5 \cdot 10^{-8}$	52.0	not tested
2			not tested	$0.5 \cdot 10^{-8}$	52.0	not tested
3			not tested	$0.4 \cdot 10^{-8}$	52.0	not tested
4			not tested	$1.0 \cdot 10^{-7}$	52.0	not tested
5			not tested	$0.3 \cdot 10^{-8}$	51.5	not tested
6			not tested	$1.0 \cdot 10^{-7}$	49.0	not tested
7			not tested	$1.0 \cdot 10^{-8}$	45.5	not tested
8			not tested	$1.0 \cdot 10^{-8}$	47.0	not tested

*) lowest value tested

Table 1: Test results of static and dynamic testing

4. CONCLUSION

To suit the different legislative and regulatory boundary conditions of utilities in different nations AREVA NP GmbH developed a roll plug for the repair of steam generator heating tubes which covers the majority of obligations imposed by current standards. Due to the covering approach taken it was not always possible to follow a single regulation since none covered all relevant aspects. Where necessary, adaptations where made to limit testing and cover more stringent regulations. The result was a comprehensive testing programme which simulated real life conditions of steam generator operation with special attention of the operational implications on the plug performance. With the plug design and the plugging parameters even beyond design cases were tested and the acceptance criterion in terms of tightness and release pressure could still be fulfilled.

REFERENCES

[1] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Edition 2007 without Addendum Section XI: Rules for In-service Inspection of Nuclear Power Plant Components: Sub-Section IWA 4713 Heat Exchanger Tube Plugging by Expansion, 2007

[2] Safety Standards of the German Nuclear Safety Standards Commission (KTA), KTA 3201.1-4 Components of the Reactor Coolant Pressure Boundary of Light Water Reactors Parts 1 to 4

[3] Schweigerer, S.: Festigkeitsberechnung im Dampfkessel-, Behälter- und Rohrleitungsbau, 3. Auflage, Springer Verlag 1978