Leak Tests at Real Bolted Flange Joints – Verification of Gasket Characteristics determined with Standardized Test Procedures

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ABSTRACT

A prerequisite for the strength and tightness proof of bolted flange joints is the knowledge of gasket behaviour represented by several gasket factors. For floating type flanges joints, different calculation methods are used (e.g. ASME code in USA, the new European code EN 1591, or the KTA code 3211.2). Specific sets of gasket factors are defined which can be related to each other. For the choice of a gasket for given boundary conditions (construction, loading, temperature, medium,..) as well as for the calculation of bolted flanged joints (strength and tightness proof) gasket characteristics are required which reflect the deformation behaviour and sealing capability of the gasket. These gasket characteristics have to be determined with standardized test procedures in order to obtain comparable, reproducible and transferable results. For technical and economical reasons, the testing conditions of the standardized test procedures have to be idealised and simplified. But it is obvious that these testing conditions are not fully capable to consider the real conditions at bolted flange joints e.g. bending of flange blades, finite bolt distance, scatter of bolt load, or surface quality of flange face which might influence the actual leak rate significantly. Especially for existing flange joints at running power plants, there an exchange of flanges should be avoided, the fully knowledge about the actual leak behaviour during service is required to maximize tightness and to minimize material stress.

INTRODUCTION

As mentioned before standardized test procedures are developed to achieve gasket characteristics required by the tightness proof [1]. Comprehensive and systematic gasket testing programmes have been carried out during the last few years in North America on behalf of and supervised by PVRC, and in Europe, sponsored by the Europian Commission [2]. Up to now a various of gaskets have been tested and their leakage behaviour has been determined. Additionally many manufacturers of gaskets meanwhile undertake effort to test their products entirely (e.g. compression test, leakage test, relaxation test) because theirs clients request more and more detailed gasket characteristics. It seems that there is no need to do further research work in this field. But this is only the first view of this issue. It is required to focus on technical consequences of leak requirements for existing flange joints from view of the tightness and strength proof. In the following the situation for floating-type flanges will be discussed.

Concept of tightness proof

Tightness (limited leak rate) of flanged joints can be achieved only by assuring specific loads in the assembly stage and during service. Since the configuration of the gasket in floating-type and metal-to-metal contact type flange joints is very different, these two types clearly have to be treated differently. In floating-type flange joints the bolt load and additional external loads (e.g. bending moments) are transmitted to the gasket. In metal-to metal contact type flange joints the gasket load remains constant as soon as metal-to-metal contact (flange face contact) is reached. The tightness of floating-type flange joints is subject of this paper only.

The concept for tightness proof according [3] for floating type of flange joints is the following: in the assembly stage as well as during service, the actual gasket load must be within certain limits: on one hand the gasket load must be higher than the minimum required gasket load ($\sigma_{VU/L}$, $\sigma_{BU/L}$) in the view of tightness, on the other hand the actual gasket load must not exceed the maximum allowed gasket load (σ_{VO}, σ_{BO}) in order to avoid the destruction or excessive creep of the gasket. These gasket load limit values represent the four most important gasket characteristics. In the following the gasket characteristics $\sigma_{VU/L}$, $\sigma_{BU/L}$ are discussed only.

Gasket characteristics $\sigma_{VU/L}$, $\sigma_{BU/L}$ and their determination with standardized test procedures

During assembly the gasket load has to be increased up to the minimum gasket load $\sigma_{VU/L}$. This loading is necessary to close inner leakage channels in the gasket and to bridge existing gaps between the gasket and the flange face. During service the inner pressure and external loads (if any) unload the gasket. Here it is required to ensure at least the minimum gasket load $\sigma_{BU/L}$ in all service conditions. In [1] a test procedure is described which enables the determination of $\sigma_{VU/L}$ and $\sigma_{BU/L}$. The test apparatus is idealised and simplified as shown in Table 1. The gasket is assembled between two rig plates. Then the

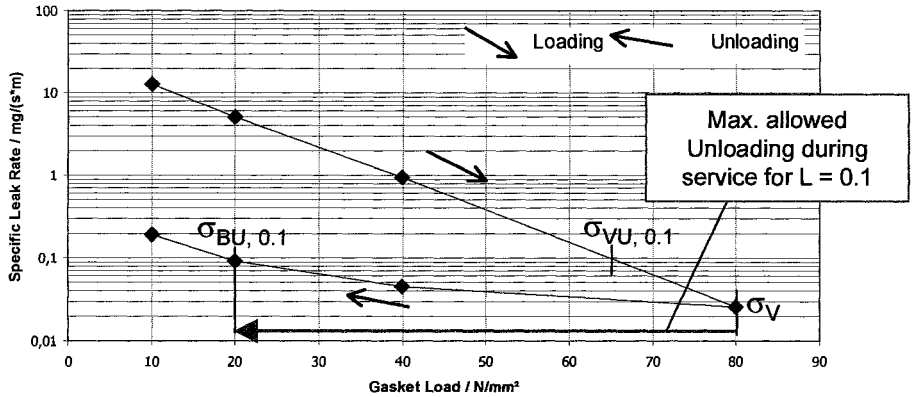

Fig. 1 Leak Test conducted on Sheet Gasket based on Fibres determined with Standardized Test Procedure according DIN 28090-1 (Gasket: inner diameter 50 mm; outer diameter 90 mm; test pressure 40 bar; test fluid N_2)

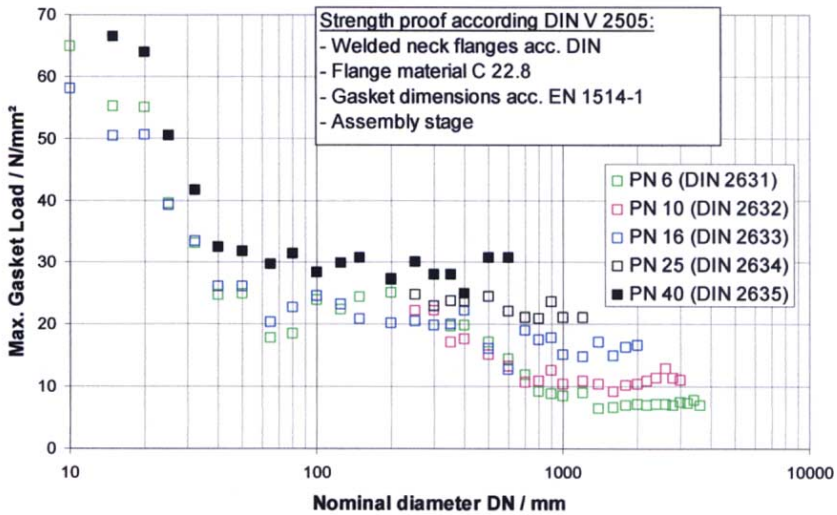

Fig. 2 Maximum gasket loads for Welded neck flanges PN 6, PN 10, PN 16, PN 25, PN 40 according code DIN in the assembly stage

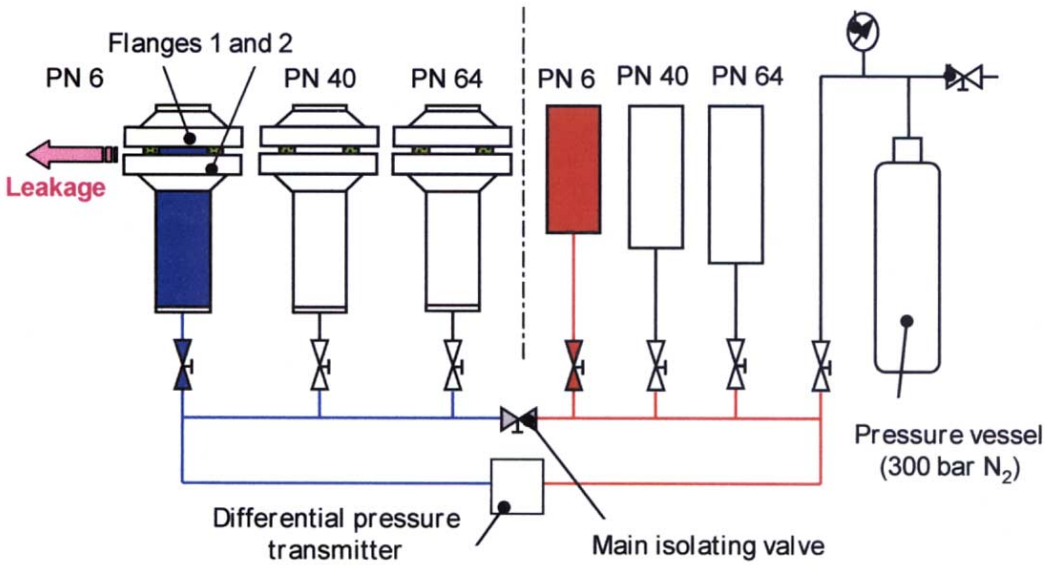

Fig. 3: Test facility to measure the leak rate at real bolted flanges with the pressure drop method

effective gasket load is increased step-by-step (Loading: here the assembling shall be simulated). At each step the actual leak rate is determined. After reaching the maximum gasket load the gasket load is decreased also step-by-step (Unloading: here the service conditions shall be simulated) and the related leak rate is determined. Figure 1 shows a typical leak behaviour of a gasket at floating-type boundary conditions in a standardized leak test [1]: the leak rate decreases significantly during loading and increases slowly during the following unloading (gasket sticks on the flange face so that the leak channels between gasket and flange face do not grow significantly during unloading). For example if a tightness class L = 0,1 is required (i.e. the maximum allowed leak rate is 0,1 mg/(s·m)) the gasket has to be loaded with a minimum load of approximately 65 N/mm² (= $\sigma_{VU/0,1}$) in the assembly stage. If there is a certain unloading of the gasket during service (Unloading > 0 N/mm²), it is required to load the gasket in the assembly stage up to σ_V ($\sigma_V > \sigma_{VU/0,1}$) in order to ensure the tightness class L = 0,1 after unloading during service (see Figure 1 "Unloading example").

Table 1. Comparison of Standard Test Condition with Real Flange Joint Situation [4]

Influencing Parameter	**Standard Test**	**Real Flanged Joint**
Gasket Dimensions	small	small ... large
Load	defined	Variable
Gasket Stress	uniform	- radial distribution (bending of flange blades) - circumferential distribution (finite bolt distance, scatter of bolt load, flexible flange blades, bending moments,...)
Temperature	defined; constant	variable (within limits)
Time Span	short term	long term
Medium	a few reference media (N_2, He)	a lot of very different media

Results of Standardized Tests in the view of the Strength Proof

Now it has to be clarified which gasket loads are critical in view of the strength proof. Figure 2 shows the maximum gasket load which can be reached by German standard flanges according DIN of nominal pressure PN 6 [5] and PN 40 [6] in dependence of the nominal diameter DN. As material was chosen the usual C 22.8 with a yield stress of 210 N/mm² at RT according [7]. The gasket dimensions are given by [8]. It is obvious that:

(1) the bigger the nominal diameter the less the maximum allowed gasket load due to the strength of the related flange
(2) Example PN40: for flange diameters DN > 100 mm the maximum allowed gasket load due to the strength of the related flange ($\sigma_{V,F,max}$) is smaller than 40 N/mm². Referring to Figure 1 this means that the minimum leak rate which can be reached in the assembly stage is 1.0 mg/(s·m) only.

Tightness Requirements according new KTA code 3211.2 (2001) and Consequences for the Strength proof

In [3] a detailed tightness proof is mentioned first time. Based on the gasket characteristics $\sigma_{VU/L}$ and $\sigma_{BU/L}$, and the tightness requirements mentioned in Table 2 it has to be proofed if the flange joint fulfils the strength proof in the assembly stage and in all service conditions.

Table 2. Recommended tightness requirements according [3] to be applied for nuclear power stations

Tightness class L	**Allowed Leak Rate (N_2) mg/(m·s)**	**Medium**
$L_{1,0}$	1	Water without activity
$L_{0,1}$	10^{-1}	a) Water with activity b) Water steam without activity c) Pressurized air
$L_{0,01}$	10^{-2}	Water steam with activity

Let us focus on consequences of the tightness requirements mentioned in Table 2 for the strength proof with the following example: Flange joint: welded neck flange; medium: water with activity; material: C 22.8 (1.0460) according [7]; nominal pressure: PN 40; nominal diameter: DN 100; tightness requirements: L = 0.1 mg/(s·m); Gasket: Sheet gasket with fibres). The leak test with standard test method according [1] with an inner pressure of 40 bar and gasket dimensions 90 x 50 x 2 mm requires a minimum gasket load in the assembly stage of 65 N/mm² (= $\sigma_{VU/0,1}$) approximately. According Figure 2 the strength calculation allows only a maximum gasket load up of 30 N/mm² (based on the maximum allowed flange

stress according [9]). This example shows clearly that at existing flange joints a conflict can occur between tightness proof and strength proof. This situation becomes additional critical when deviations during assembly (e.g. scratches, foreign matters on flange face, damages of gasket due to handling, insufficient lubrication of bolts, inexact setting of torque wrench,...) have to be considered as an additional gasket load (e.g. $\sigma_{VU/L} = f \cdot \sigma_{VU/L,\ Leak\ test}$; f = safety factor). In order to minimize this uncertainty the research work was started in August 2000 [10].

LEAK TESTS AT REAL BOLTED FLANGE JOINTS, RESULTS, AND COMPARISON WITH STANDARDIZED TEST RESULTS

Testing facility

Figure 3 shows the test facility which was erected to measure the leak rate at real bolted flanges [10]. In compliance with [1] the pressure drop method is used. The test fluid is nitrogen (N_2). The pressure drop in the test volume (volume with flange joint) is measured against a reference volume of same size. Thus the accuracy of measurement (differential pressure transmitter) could be maximized. The test facility enables leak tests at welded neck flanges of nominal pressure PN 6, PN 40, and PN 64. Table 3 obtains the design parameters of the test facility.

Table 3. Design parameters of the test facility

Flanges				Bolts	
PN	**DN**	**Type**	**Material**	**DN**	**Material**
PN 6	DN 150	Welded neck acc. DIN 2631	C 22.8	M 16	21 CrMoV 5 7
PN 40	DN 150	Welded neck acc. DIN 2635	15 Mo 3	M 24	21 CrMoV 5 7
PN 64	DN 150	Welded neck acc. DIN 2636	15 Mo 3	M 30	21 CrMoV 5 7

Results

Leakage tests were conducted on sheet gaskets with fibres (in the following shortly "Fibre gasket") and sheet gaskets based on expanded graphite with stainless steel foils (in the following shortly "graphite gasket") at the flange joints PN 6 and PN 40 each (in the following shortly "Flange leak test"). The inner pressure was 6 bar at PN 6 and 40 bar at PN 40. To evaluate the real effects at bolted flange joints the following additional leak tests were conducted with a standardized test facility:

- leak test with same gasket types of same effective gasket width ("Reference leak tests") as in the Flange leak tests
- leak test with same gasket types but of different effective gasket width as in the Flange leak tests (dimensions according [1]; "Standard leak tests").

Figure 4 and Figure 5 compare the results of the Flange leak test PN 40, related Reference leak test PN 40, and Standard leak test PN 40 conducted on the Fibre gasket (Fig. 8) and Graphite gasket (Fig. 9). The figures show that:

- at same gasket load the tightness of the Graphite gasket is higher than the tightness of the Fibre gasket
- the gradients of the loading curves are different between the three leak test types
- the gradient of the unloading curves do not distinguish significantly from each other
- the influence of "Real flange" conditions on the tightness of Graphite gaskets is lower than on the tightness of Fibre gaskets.

In the following only the loading curves will be discussed. First we focus on possible effects which are responsible for the leak rate differences between the Flange leak tests, the related Reference leak tests, and the related Standard leak tests. It is obvious that at same gasket load the tightness determined with the Flange leak test is higher than the tightness with the Reference leak test, and the tightness determined with the Reference leak test is higher than the tightness with the Standard leak test. The difference in $\sigma_{VU/L}$ between Reference leak test and related Standard leak test can be explained by the different effective gasket width (Reference leak test: 28 mm; Standard leak test: 20 mm). It can be assumed that the difference in $\sigma_{VU/L}$ between Flange leak test and related Reference leak test is caused by the radial distribution of the gasket stress (bending of flange blades) and the circumferential groove track of flange faces. In Table 4 the leak test results are summarized as resulting values $\sigma_{VU/L}$.

The bending of the flange blades was calculated according [9]. The calculation results are given in Figure 6. The slope of flange blades due to bending in the assembly stage is in the range of 0.05 grad to 0.23 grad. Figure 7 demonstrates the influence of the flange blade bending on the radial distribution of the gasket stress. The effective gasket load in the outer area of the gasket is obviously higher than in the inner area of the gasket. This high effective gasket load exits circumferential that means it is relevant for the actual tightness. Figure 7 also shows the circumferential groove track of flange face PN 40 in the gasket face after conducted leak test. This special surface influences the leak rate as well because due to the grooves the gasket will be loaded like (e.g. graphite) layers on grooved metal gaskets.

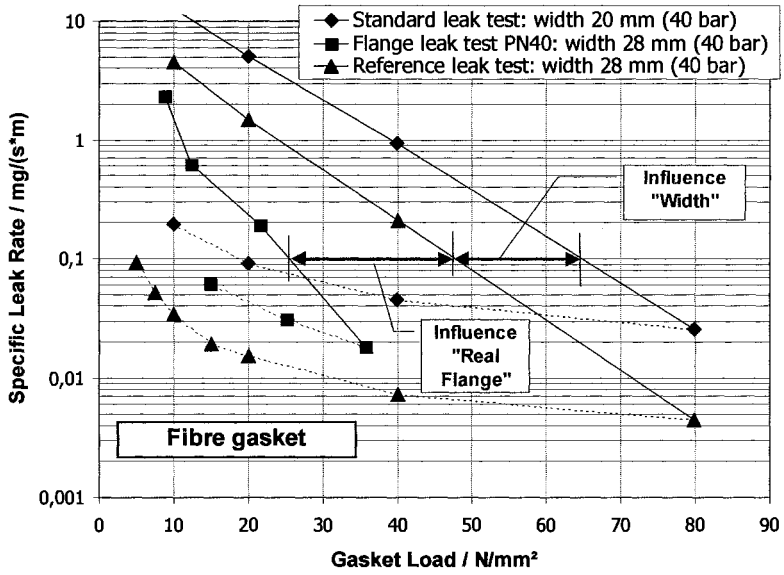

Fig. 4 Results of the Flange leak test PN 40, related Reference leak test PN 40, and Standard leak test PN 40 conducted on the Fibre gasket

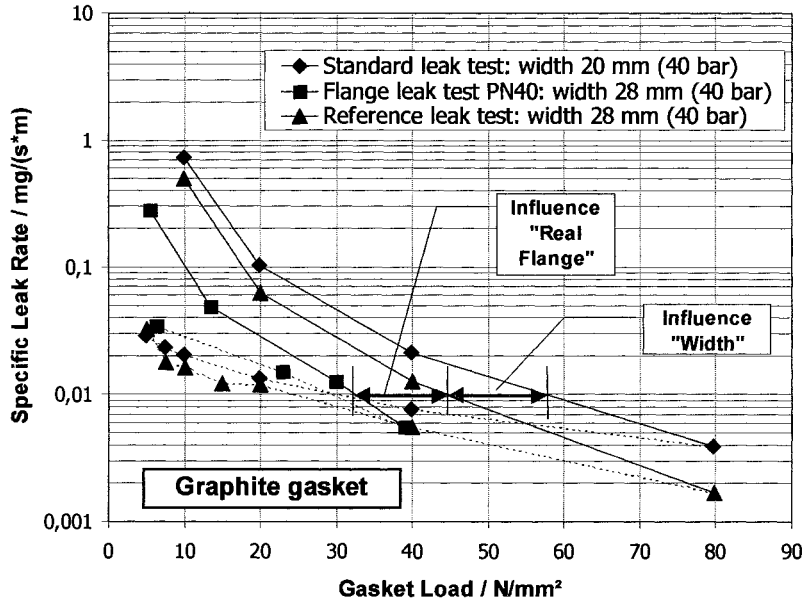

Fig. 5 Results of the Flange leak test PN 40, related Reference leak test PN 40, and Standard leak test PN 40 conducted on the Graphite gasket

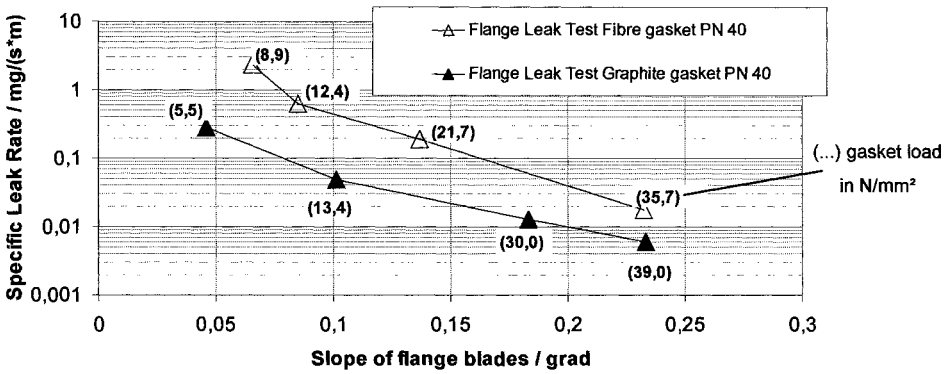

Fig. 6 Calculated slope of flange blades due to bending in the assembly stage (Flange leak tests).

Table 4. Minimum required gasket load in the assembly stage $\sigma_{VU/L}$ determined with Flange leak tests, Reference leak tests, and Standard leak tests PN 40. Additionally σ_{VU} as specified by the manufacturer is given.

Tightness class L	Fibre gasket Required $\sigma_{VU/L}$ for Tightness class L			Graphite gasket Required $\sigma_{VU/L}$ for Tightness class L		
	Standard leak test (40 bar)	Reference leak test (40 bar)	Flange leak test (40 bar)	Standard leak test (40 bar)	Reference leak test (40 bar)	Flange leak test (40 bar)
mg/(m·s)	N/mm²	N/mm²	N/mm²	N/mm²	N/mm²	N/mm²
1.0	39	24 ≅ 62 %	11 ≅ 28 %	<10	<10	< 10
0.1	65	48 ≅ 74 %	26 ≅ 40 %	20	18 ≅ 90 %	10 ≅ 50%
0.01	(90)	72 ≅ 80 %	(40) ≅ 45 %	57	45 ≅ 79 %	33 ≅ 58%
0.001	-	-	-	(110)	(90) ≅ 82 %	(56) ≅ 51 %
σ_{VU} as specified: Fibre gasket: 30 N/mm²; Graphite gasket: 20 N/mm² (...): extrapolated values; ≅...% = percent of related Standard leak test						

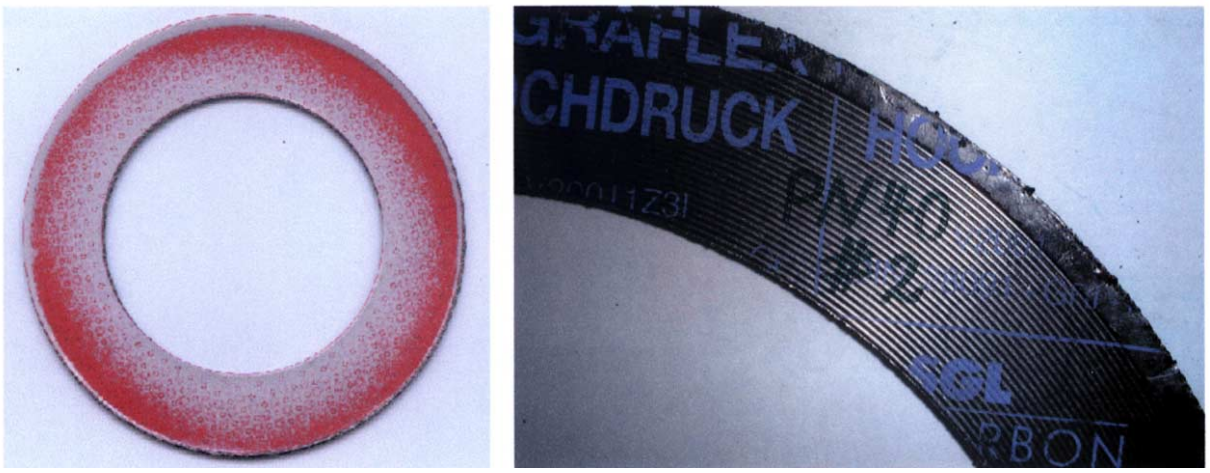

Fig. 7 Example for radial distribution of the gasket stress due to bending of the flange blades in the assembly stage (left) and circmferential groove track of flange face PN 40 in a gasket surface (right)

CONCLUSIONS

The research shows clearly that due to real boundary conditions at bolted flange joints the tightness is higher than determined with standardized test procedures. That means for the design of bolted flange joints that gasket characteristics determined with standardized test procedures are fully sufficient to ensure the required tightness. They are conservative. From view of practise deviations during assembly sometimes occur (e.g. scratches, foreign matters on flange face, damages of gasket due to handling, insufficient lubrication of bolts, inexact setting of torque wrench,...) so that the tightness might be affected. This research shows that these "negative" affects should normally be covered by "positive" effects at bolted flange joints on the tightness. Thus there is no need to foresee additional safety factors. This is very important for the tightness and strength proof of existing flange joints at nuclear power stations. Furthermore the safety potential of real bolted flange joints regarding their actual tightness is also a safety potential for the safe and reliable operation of nuclear power plants.

SUMMARY AND OUTLOOK

This research should focus on leak behaviour of gaskets at real bolted flange joints in order to verify gasket characteristics determined with standardized test procedures. Therefore a test facility was developed which enables leak tests at three floating type flanges joints (PN 6, PN 40, and PN 64). The leak tests were conducted on graphite gaskets and sheet gaskets with fibres at room temperature. The test fluid was nitrogen (N_2). The test results show that in order to ensure a certain tightness at real bolted flange joints the minimum required gasket load in the assembly stage is due to

- the radial distribution of the gasket stress (bending of flange blades) and
- the circumferential groove track of flange face

lower than the test results determined with standardized test procedures prescribe. Or wise versa at the same gasket load in the assembly stage the leak rate at real bolted flange joints is much smaller than at standardized test facilities.

This research only focus on two types of sheet gaskets. The leak tests were carried out at room temperature, the maximum tests duration was less than 24 hours (one gasket load step). No external loads (e.g. bending moments) were considered. Only the combined influence of the radial the radial distribution of the gasket stress (bending of flange blades) and the circumferential groove track of flange faces was determined. Consequently the measurements should be extended by leak tests at service temperature (e.g. 100 ° C), under consideration of long time effects (creep effects), and under consideration of external loads. Additionally investigations should be done to determine the influence of the radial distribution of the gasket stress (bending of flange blades) separately from the circumferential groove track of flange faces. Different types of sheet gaskets and gaskets of different manufacturers should be tested in order to choose the best gaskets types and manufactures as objectively as possible.

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