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# NEW KNOWLEDGE AND CONSTRUCTION DIRECTIONS IN THE AREA OF THE LOCOMOTIVE REAR BOILER (STAYBOLTS, FIREBOX, AND BOILER)

Von Dr. Ing. Arnold Tross

*Translated By: Inge von Kehl, Clinical Toxicologist, ret.*
*Edited by: Cynthia Meister, M.S. English Literature*
*Matt Janssen, CEO, Vapor Locomotive Company*
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This publication describes the modern position and knowledge in the area of the rear boiler. After a short description of the experiences of the rear boiler with copper fireboxes. we will describe those with steel fireboxes and staybolts, conditions and causes which will appear and that which will be briefly examined. Thereafter, the conditions of the steel fireboxes in the area of the rear boiler construction and the significance of the staybolts' construction in order to eliminate the copper elements, in particularly the matter of the rear boiler construction, the firebox construction and damages to the firebox as well as the damages to the staybolt bridges, will be explained and clarified. The next part will discuss the staybolt insertion, particularly the welding technique of the staybolts with the proper welding program. Finally, the results of the laboratory pressure system will be presented together with other experiences. With constructive steps, results will be presented with other locomotives where there were no changes of the feedwater treatment, and an extraordinary number of repairs were needed.

In my work I have been supported by various individuals and enterprises:

Lokomotivfabrik Henschel & Sohn GmbH, Kassel, as well as my coworker of many years Dr.-Ing. H. Garrelt who had undertaken a large part of the measurements and experiments, and Deutschen Bundesbahn which supported my work by granting permission to undertake the proposed experimental procedures with a series of locomotive boilers.

## I. REAR BOILER WITH COPPER FIREBOX

From the studies which have been conducted in the last few years, that is, in boilers with a prolonged productivity, many of the experiments and experiences over the last 15 years have already led to improvements of the rear boiler performance equipped with copper fireboxes. These improvements were:

a) The use of staybolts which had been threaded with some play followed by the use of a sealant on the threading at both heads which had been enlarged parabolically

b) Application of the special sealant material for the threading

c) Application of a heat resistant copper amalgamation (Kuprodur) as firebox building material in the fire zone

d) Application of the steel bolt into the Kuprodur firebox position

The copper application with the threaded staybolts has proven to be a substantial improvement. The previously frequently occurring breakage has been reduced to a small number and can possibly be totally eliminated, particularly if one uses a building material that has been amalgamated with sheet and the staybolts have been carefully selected. This material has a temperature quotient that can tolerate a minimum binding (25 kg/mm$^2$) and a much higher stretch (40%) before a break will occur. Furthermore, at the operating temperatures, a much higher flow limitation and therefore a lower light plastic deformation will occur. Also there is a minimum tendency for re-crystallization. That in a larger degree is also a successful procedure when using welding of the copper threaded staybolt in the copper firebox.

For about 20 years it has been recognized that staybolts, which by the water pressure trial in the threading, were completely sealed. However, when these same boilers were exposed to becoming cold, a small tendency of leakage was recognized. These occurred only in the firebox and were limited to the firezone of particularly stressed boilers. This was independent of the construction method and in order to differentiate them from other leakages, which were a consequence of inaccurate threading, have been designated as cold leakage characteristics. For the development of these at the time being I gave the following explanation: "As a result of the particularly high heating of the heads of the staybolts and the fireboxes in the firezone there develops around the staybolts' holes, small pressure holes. The elevation and exceeding of the operating temperature strongly diminishes the elastic limitation of copper which leads to plastic deformation of the boiler and staybolt threading. During the heating process the staybolts stay sealed. However, during the cooling process an intermediary space between boiler and staybolt threading will develop which leads to water leakage. As soon as the boiler once again is heated, the intermediary space is sealed and no further leakage will occur; however, if mineral deposits have occurred between the staybolt and the boiler threads, one will still observe leakage as a result of this. These defects have led to rapid destruction of the staybolt heads and the firebox sheet around these heads. If sealing is attempted of the staybolts while these are cold and there is mineral deposit, accelerated destruction will occur.

In order to prevent this kind of situation a suggestion was made in the 1930's for the firezone, that instead of copper to use a more heat resistant building material for the firebox. During the reheating, tensions will occur around the staybolt holes which must be below the elasticity limits in order to prevent deformation and therefore the cold leakage problem. As useful building material, Kuprodur, had been developed with a particularly high copper amalgam of 98% copper.

The experimentation with copper Kuprodur and various staybolts of various types with attached copper bolts did not yield satisfactory results. This can be clearly understood in terms which when one considers the Kuprodurshoes probably led to an overly elastic deformation of the boiler threading but not to the staybolt threading; also in the case if the staybolt material is not of a high heating elasticity. The leakage of copper staybolts in Kuprodur was less but had not been eliminated. This was in contrast to the monel staybolts when used with Kuprodur which had no leakage. The trial of steel staybolts in Kuprodurshoes had also been tried. One did expect that the pressure on the holes between staybolt and boiler threading, as a consequence of the 25% lowered heat expansion of steel, to be considerably smaller because of the heat elasticity of the steel and the Kuprodur which should be sufficient because of the decreased elastic pressure. This has been verified through experience 15 years ago.

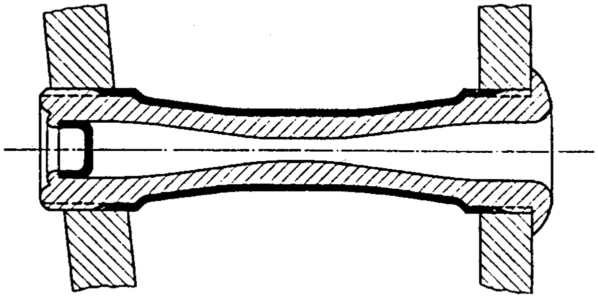


Abb. 1. Aufdornstehbolzen aus Kupferpanzerstahl (KPS-Stehbolzen) mit Gewinde-Abdichtung

However, there is a negative aspect, that is the boiler feedwaters with the steel staybolts which are in the Kuprodurs have a tendency to corrode. In order to prevent this, steel staybolts have been replaced with armored copper staybolts. These are staybolts which are in the water chamber being surrounded by a copper coat of approximately 1.5 to 2 mm. This type of staybolt inserted in the Kuprodur sheet yielded excellent results after having been in use for a long period of time.

The tube sheets made of Kuprodur have not been quite as satisfactory in the flue system, when used at the same strength as the copper tube sheets. As a result of the reduced capacity to conduct heat when Kuprodur is used, a much elevated temperature tension leads to breakage and cracks in the flues. However, if one diminishes the strength of the tubesheet by 15 mm it is estimated that cracks can be avoided. The diminishing of the Kuprodur sidewall strength from 16 to 14 mm was a satisfactory goal. One can expect that a further reduction of the sheet strength from 13 to 12 mm shall also be a satisfactory approach and a reduction in weight and expenses will yield an advantage. Beaded door sheet shoes manufactured from Kuprodur Z, which has a diminished amalgamation and is therefore somewhat softer, have been used with very good success. This is recognized in an elevated heat conductance in comparison to the use of Kuprodur. This experience of many years has produced the best solution of the rear boiler with the copper firebox. In the firezone the sidewalls and doorwalls made of Kuprodur of no more than 14mm of sheet strength have been satisfactory, and that in the face of poor quality feed water. In the case of high quality feed water one can utilize steel KPS-staybolts. In the remaining copper firebox places it is best to utilize copper staybolts. Moreover, the application of threaded staybolts made out of steel or KPS in Kuprodur the sealing method yielded very good results. The application and the knowledge of these problems has been satisfactorily solved in the case of the rear boiler with the copper firebox. However, under the circumstances of inferior feed water, it is best to clean this feed water before water is taken on or a method to clean the boiler must be undertaken responsibly.

## II. REARBOILER WITH STEEL FIREBOX

### A. Present Experiences

The American railroad administrations used with success for several decades steel fireboxes and steel staybolts. However, in Europe during WW I the use of steel fireboxes had not been satisfactory. Therefore, after WWI almost every railroad administration began to utilize copper fireboxes. When however, after the demands on the locomotives with the copper fireboxes increased and Kuprodur had not been available, difficulties were experienced. Moreover, at certain times the supply of copper was unreliable, consequently the return to steel fireboxes took place. In Germany, for the building of the fireboxes, the more resistant Izett-II-Steel was employed. The steel staybolts, like the copper staybolts, had been sealed at the threading only. Nevertheless, the steel fireboxes like the copper fireboxes, underwent during the cooling process, leakages; this was attempted to be overcome with the threaded steel staybolts as well as the firebox threading by welding. In Germany as well as in other countries this kind of work was unsatisfactory.

The reasons were as follows:

1) The number of breaks at the staybolts was much greater than when used in comparison to a copper firebox, this was a particular problem at the upper as well as the farthest distant staybolts. For these reasons flexible staybolts had been applied at the breaking zones whose application was equally unsatisfactory.
2) At the head of the firebox side, frequently small welding cracks appeared which necessitated the repeating of seal welding quite often with strengthening of the seal welding. (Ill. 2)

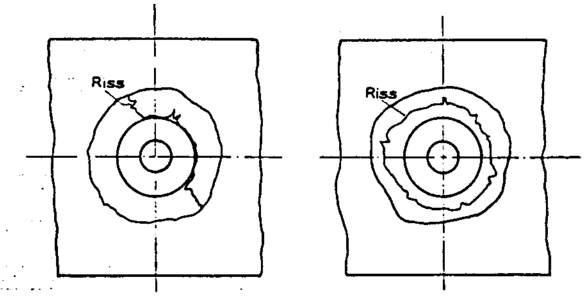


Abb. 2. Typischer Verlauf der Stehbolzen-Schweißnahtrisse, senkrecht zum Kesselblech gesehen

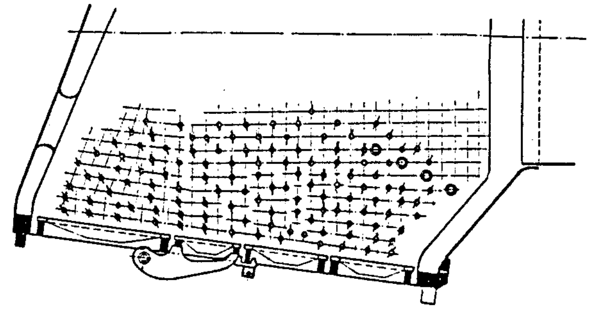


Abb. 3. Typischer Verlauf der Wandlochrisse in der Feuerzone stählerner Feuerbüchsen

3) In the lower row of the staybolts 6 through 9 one could observe at the edges of the holes radial tears at the sheets. One could observe a distinct pattern of regularity. (Ill. 3) Practically all of these showed a star-like formation from the central sheet in all directions. On the part of the staybolts on the firebox side which had not been welded one could note the tears on the fire side. In the case of welded bolts, the tears appeared on the waterside. These tears have also been noted in the USA, particularly in boilers with a steam pressure with 16 atm or more, in a rather high frequency. That meant that often a modification of the lower sidewall parts or, if necessary, an early exchange of the sidewalls had to be undertaken. This occurred quite often after 100,000 km of service.

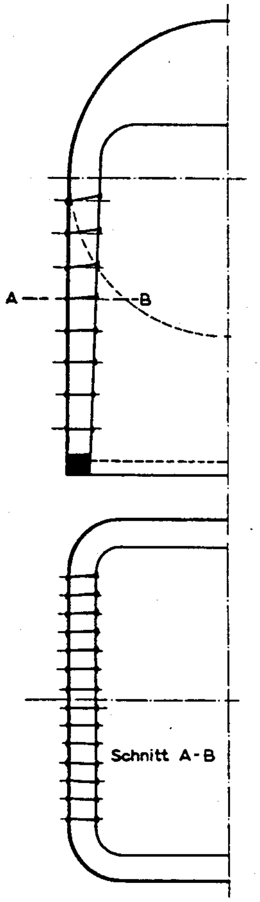


Abb. 4. Ursprünglich angenommene Stehbolzenauslenkung infolge der Mehrerwärmung der Feuerbüchse gegenüber dem Stehkessel ohne Berücksichtigung der Wandverwölbung und -schrumpfung

The reason for the breaks of the staybolts is attributed to the greater expansion of the firebox by elevated temperatures, particularly if one considers the cooler boiler temperature. As an assumption the mudring of the firebox was considered as nonexpanding, a point from which the expansion of the boiler and firebox was determined. Therefore, the bending of the staybolts and of the heads of the firebox side were used as measuring points for above and, depending on the position of the staybolt, whether parallel or not, and of the sheet midline, determined whether they had been bent forward or backwards. (Ill. 4) Such deformation of the staybolt head at the firebox side produced an s-shaped bend of the staybolt. It had been assumed that this was of no consequence, as when the cooling of the boiler had been completed the staybolts would return to their original position. In the case of the tears of the welding seams it became a question of whether this was a result of the welding or not. Regarding the tears at the site of the sheet holes it has been assumed that these tears were a consequence of the bending of the staybolts. Considering the tears at the sheet holes (Ill. 3) one would anticipate staybolts bending (Ill. 4). Moreover, some serious theoretical questions arise while in areas with the most extensive staybolt bending, particularly at the edges where no sheet hole tears appeared. In order to determine the true causes of all these problems to be studied one had to find a starting point, which beginning in 1944, a series of rear boilers while in the process of being rebuilt, provided an opportunity to study all the parts with precision. As a result further clarifications and analysis could be applied.

4) The position of the tears and breaks of the staybolts is not always in agreement with their position in the boiler as had been before assumed and the staybolts bending were unpredictable. The tears of the staybolts began almost exclusively at the site of the boiler or at the firebox side. (Ill. 5) More frequently, tears occurred at the boiler midwall; the same can be said for the firebox side. These findings of the position and length of the tears was exactly opposite from what had been expected. Staybolts which had been removed showed a strong residual bending at the firebox side which were always below the lower end and about in the middle of the sheet.

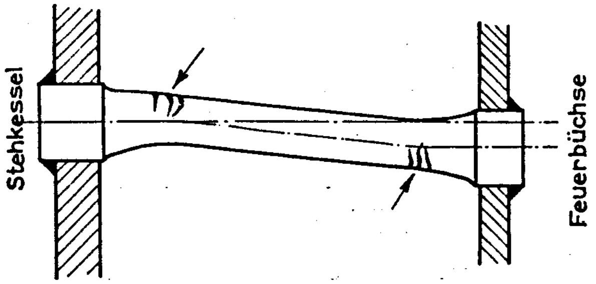


Abb. 5. Tatsächliche Lage der Stehbolzenanrisse

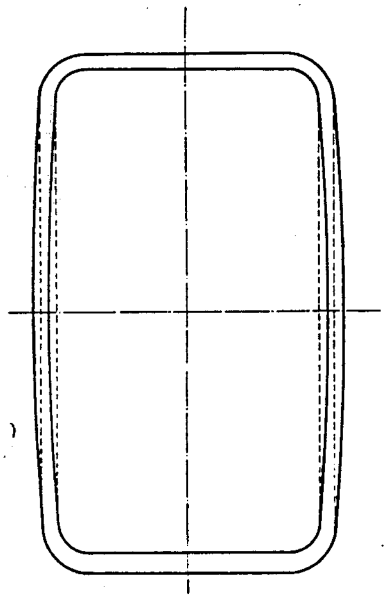


Abb. 6. Bodenringdurchwölbung bei einer Lokomotive der Baureihe 44 nach langer Betriebszeit

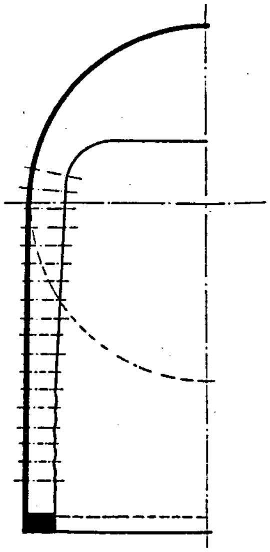


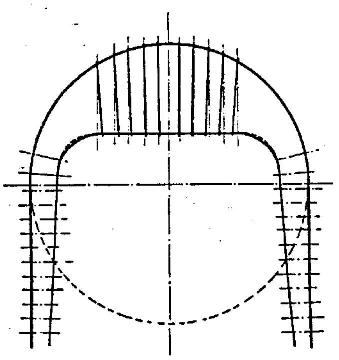
Abb. 7. Wandfeldausbeulung (Matratzenbildung) in der Feuerzone stählerner Feuerbüchsen an ohne Spiel eingebauten Stehbolzen

5) The rear boilers at the long sides had arching throughout the sheet as well as at the mudring. (see Ill. 6) When the hydrostatic test was applied, one would note that some degree of light could be seen through the firebox, particularly at the central part of the sheet. This light disappeared when the pressure was released. This light was only 80 mm in the German locomotives that had a long service period.

6) In those fireboxes, particularly on the sidewalls, one could see bubbles appearing at various locations on the inside of the firebox. This was the case irregardless of bends in the supports which were 10 mm or more dimension. (Ill. 7) This sheet bubbling was mostly limited to the actual fire zone and had already been observed in copper fireboxes. These abnormalities are known as mattress and upholstery formations. In the case of the Kuprodur systems such phenomena could not be observed. Both in the USA and Germany, when steel fireboxes were utilized, the above phenomena were observed.

7) By observation and measurements fireboxes which had seen a long tour of duty, staybolts had been bent into similar s-formation. (Ill. 16) But in addition to that, one would also note simple bending.

8) Measurements on the sheets of many fireboxes at their flat parts noted shrinkage after prolonged duty. This shrinkage was not only limited to the sheets but also in the tubesheets and doorsheets. This shrinkage invariably produced a bending of the staybolts after long services. The observations have been that the bending took place most frequently at the center part of the sheet. In the case of the lateral staybolts, the shrinkage has been at the crown sheet, most often inward. (see Illi. 8) In the case of the presence of bow anchors at the crown sheet, a sagging of the sheet was noted. This can be partially explained by the absence of staybolts normally between the crown and the firebox sheet. (Ill. 9) Here also the shrinkage was a consequence of the firebox sheets.



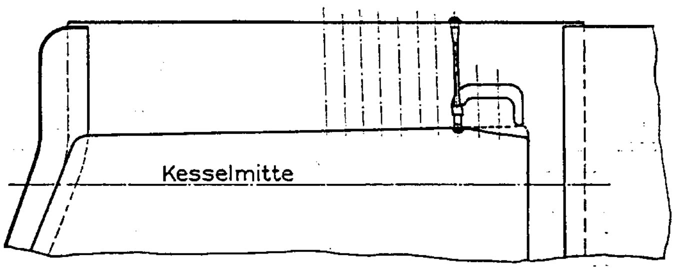


Abb. 9. Absenkung der Feuerbüchsdecke im Bereich der Bügelanker nach längerem Betrieb

Abb. 8 (links). Schrumpfung der Feuerbüchsdecke, Abflachung der Umbüge und Verbiegung der Deckenstehbolzen bei hoch erwärmt gewesenen stählernen Feuerbüchsen

## B. Causes of the Problems

In order to clarify the problems, a thorough mathematical and laboratory investigation was undertaken. One began with precise measurements of the boiler, interior as well as exterior, in order to verify the results of the calculations. Included in these calculations are the deformations as well as the normal shapes, the arching of the rear boiler, the deformation of the firebox areas, the surface shrinkage of the firebox, the bending of the staybolts-with different staybolt construction methods and different installation methods-in locomotives with a long tour of duty in the past.

In the following discussions the term "expansion" always applies to the expansion of the building material as a consequence of the heating, in contrast, the term contraction occurs when cooling. However, when "compression" is applied a new plastic deformation occurs; the part that is involved in the compression becomes smaller as in contrast to when warming occurs. The firebox is unable to be stretched according to the heat index. However, when one considers that the staybolts have been anchored to the boiler while the boiler is much cooler the expansion has been diminished. This diminution becomes much clearer and evident as a result of the uneven heating of the various parts of the firebox. This diminution becomes evident on the waterside of the firebox when compared to the stretching of the fireside of the firebox. As a consequence of the decreased heating around the edges of the firebox, a tension will occur between the warmer and colder sides of the firebox. The largest temperature and elevation in the firebox is in the close vicinity of the mudrings. At this position, the expansion of the firebox has the greatest resistance due to the temperature differences; additionally the mudring has the least ability to expand because of stiffness and the temperature is lower than in the boiler. For these various reasons the greatest temperature tension and deformation occur at these sites.

This inability of the stretching of the firebox will lead to an over elastic buckling, in particular where the firebox parts cannot expand. A thin sheet of steel at 200 degrees C when heated further 100 degrees more but its stretching ability is hindered, one can calculate a tension of about 25kg/mm$^2$. This value is very high and above the line of elasticity which normally would be expected in the case of a thin sheet of metal. The limitations of the elasticity at a particular temperature where the building material is on a differential of heating and cooling will lead to plasticity.

Moreover, shrinking that occurs during the uneven cooling process in parts of the firebox, is augmented in positions where the boiler and the firebox are connected with staybolts and at the edges of the firebox itself. These are not the causes of the problems but rather the inhibition of expansion and contraction which leads to plastic buckling and the inability to contract when cooling occurs. Therefore, the stretching and contraction of the firebox as a whole is not the cause of the problem. In the following section "A" these conditions will be discussed in detail:

1) The enlarging of the light visibility site on the firebox when water pressure is applied can be as much as 5 mm. It is a consequence of the construction method and directly related to the surface of the boiler. (Ill. 10) The vertical distance at the positions where staybolts are utilized is not uniform, for instance, staybolts at the most elevated position and staybolts which are following to 1/3 the elevation are nearly 50 mm larger than when compared to other positions in the firebox. This large difference of the surface of the boiler therefore has an increase of the pressure 21 atm and when calculated will lead to a mass weight of 25 tons. This enlarged pressure

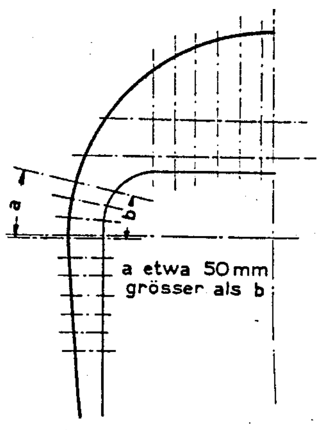


Abb. 10. Größerflächigkeit des Stehkessels gegenüber der Feuerbüchse im Bereich der Seitenstehbolzen

affects the arching of the rear boiler visible from the outside. After release of the water pressure the rear boiler returns to its original shape as has been verified by precision measurements. However, if the staybolts at the points of the arching at the rear boiler have been exposed to a higher stress factor in comparison to the sheet, they will inhibit the return to original conditions of the firebox and the boiler because the staybolts have been bent.

Rear boiler arching formation while the locomotive is in operation have other causes. With an increase in temperature and pressure the large surfaces of the boiler will develop an arching formation. This arching formation is counteracted by the higher temperature at the fireside of the interior is inhibited as a result of the greater stiffness of the boiler firebox wrapper and the higher temperature on the waterside of the boiler which produces a counteraction against arching.  The rear boiler in the condition of heating, will in the beginning, show some arching, which has been ascertained with precision measurements during the application of the steam pressure. The arching is very small and is overridden as a result of the stretching that occurs during the heating which is not uniform on the fireside and waterside. The following pattern can be observed: on the fireside there are zones that will heat differentially. The material of the firebox will exceed the heat elasticity limits and therefore will become plastic from which the arching develops. However, if a stronger pressure tension, as a consequence of the expansion limitation of the total firebox, that is, in a particularly high fire zone, a small difference in the temperature will lead to bulging.

When heating, the temperature differences in the metal affect the differences in limits of the elasticity in such a manner that on the fireside of the material a small tension will occur which will remain by deformation. This is not quite the situation on the waterside. When cooling occurs the conditions are different. When the process of cooling starts, the temperature on the fireside and waterside will ultimately be equal. With further continued cooling the temperature on the fireside will be less than on the waterside. The material used on the fireside will produce a tension that by further cooling will lead to shrinkage. However, reheating it will return it to its original state. The deformation on the cold waterside will be greater than on the fireside, but upon reheating, the fireside and the cold side will be equal. The tendency to form bumps, buckles/arching of the firebox on the exterior will affect the anchoring, which in a way, counteracts the arching process that becomes evident when reheating occurs. These tendencies can translate themselves to the staybolts and the rear boiler and one may find arching in the rear boiler.

The tendency for arch formation towards the exterior is furthermore supported by the modern method of hot water technique when washing the thin firebox metal in a reverse direction.

This is furthermore supported by the observation and the interdependence of this phenomena, when one removes the staybolts from the firebox and additional buckling is then noted while at the same time the buckling at the boiler diminishes. The buckling, as noted on the flues of the locomotive and the corresponding boiler, can also be explained by the same processes. However, in the case of the flues when exposed to the fire, the buckling is more pronounced in the superior part of the flues in contrast to the inferior part.

Based on this knowledge one can derive the following: All parts of the construction which do not belong to a mudring formation crosscut, particularly the sheets where there is a temperature difference between the surfaces while in operation, will have a tendency, when previously exposed to higher temperatures, when exposed to cooling at the sites of the temperature difference, will experience buckling. This rule can also be applied to the construction material of mudring formation crosscuts when a profound temperature difference occurs at the site of installation when connected to other sheets parts. The degree of buckling is dependent on the degree of temperature tension and also on the degree of how frequently the building parts have been heated and cooled. The bending middle point is to be found at the highest temperature of the sheets material. Even flat sheets have a tendency to arch in the direction of the highest temperature with a concave configuration, with a arch formation that is stronger than the contrary arch formation.

This rule can also be applied when welding occurs and explains the deformation of the metal-type building material as well as the deformation of other building material. Also the possibility of utilizing pre-counterbending can be explained by the past observations.

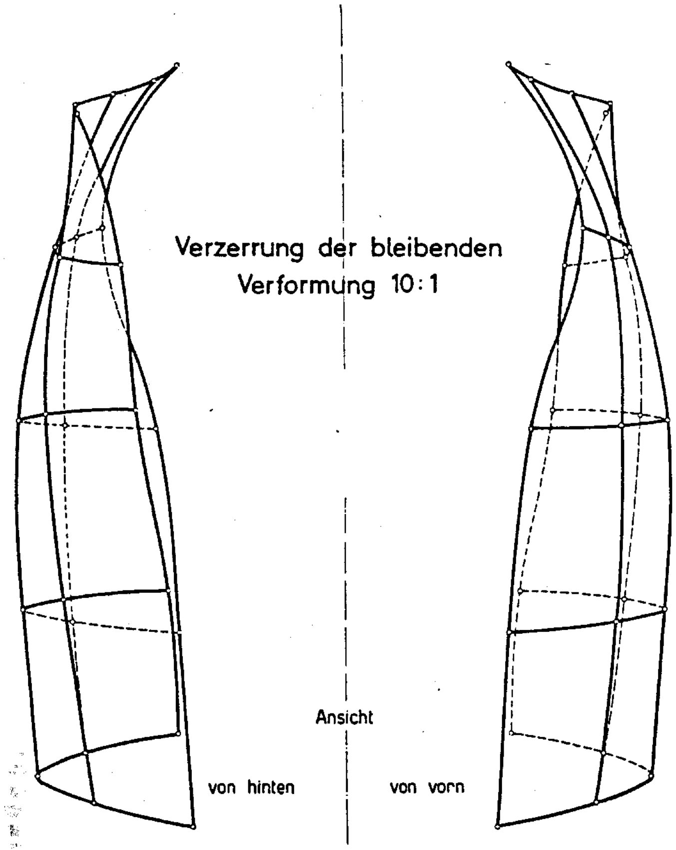


Abb. 11. Bleibende Verformung der Feuerbüchsseitenwände einer Lokomotive der Baureihe 44 nach längerem Betrieb (Vertikal-Projektion)

Therefore, one can surmise that boilers which are equipped with flexible staybolts and with fireboxes which, when undergoing the process of cooling where the flexibility of the staybolt heads leads to an outward buckling, are apparently the most useful and advantageous. That is also the experience of the American locomotives. The reason for this is that the firebox, after repeated heating with increasing boiler pressure, straightens out once again the staybolt heads. However, this deformation involves the plastic area of the firebox and can lead to tears in the firebox.

The remaining buckling or arching of the rear boiler which can be noted from the outside when cooling occurs, creates unfavorable conditions for the boiler sheets because they are counteracting against the buckling stress of the rear boiler when repeated warming occurs. In the manner of how strong the remaining buckling of the rear boiler and the strength of this buckling is shown in Ill. 11 with a vertical projection of the remaining deformation of the firebox sheet of a locomotive of the building series 44 with a unilateral welded threaded staybolt.

The deformation of the boiler in its superior parts can be of great significance as will be discussed below. This is also the case with locomotives where cross anchoring is bending downward. In the United States the boiler pressure produces deformation in the upper part of the rear boiler with fireboxes that have been arched in the front. Measurements taken in the middle and the rear have produced deviations in the upper part of the boiler and the firebox crown with as much as 12 mm on both sides of the upper part, additionally, 9 mm have been noted at the sidewalls. The largest deviations were observed in the middle and the least deviations at the front part of the rear boiler. Measurements of German boilers with cross anchors have been considerably smaller.

The frequently observed tears in the boiler sheets are mostly located in the following places: in the upper flat as well as in the vertical exterior where staybolts have been applied, are also a consequence of the arching of the rear boiler. The phenomena can be observed along the course of the staybolts, that is, at the water site superior to the flat of the boiler and are also more profound in the middle of the sheet than at the end. It is therefore paramount to eliminate these conditions of the rear boiler by design that avoids arching altogether.

## 2) Buckling of the firebox sheets (mattress formation)

The mattress formation is primarily seen in the firezone. It is a consequence of the elevated heating stretch inhibition. In the presence of heavy incrustation, particularly in highly heated fireboxes, mattress formation will take place, and also in other parts of a steel firebox. Under advanced conditions the firebox crown is also involved. This is favored because of the temperature difference between the fire and waterside crown of the firebox while in service and under pressure in the boiler. In a rear boiler which is arched throughout, under high heating of the firebox, mattress formation will take place in the firezone. The buckling may have a different elevation which leads to a nonparallel condition of the staybolts in the firebox. The same can be said regarding the staybolts in the boiler. From these conditions a deviation of the s-shaping bending line of the staybolts will occur. (see point 6 of this section) One can assume that the elevation of the mattress type pattern will be larger while the locomotive is operating than when it is cold. The sheet field buckling becomes evident upon cooling after extensive stretching of the surface. The mattress formation, as many reports from the USA verify, will lead to a dense staybolt forest if non-welded staybolts are used. The staybolt threading on the waterside will become loose. These observations correspond to the experiences in copper fireboxes with copper staybolts.

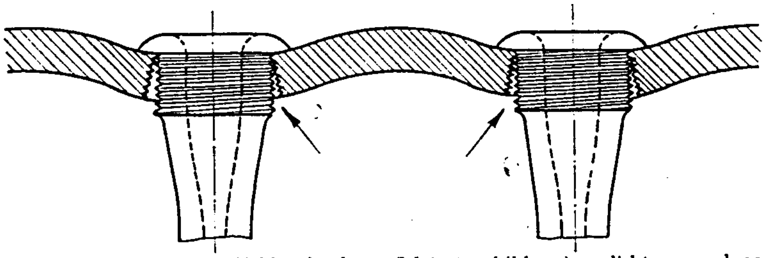


Abb. 12. Infolge Wandfeldausbeulung (Matratzenbildung) undicht gewordene Gewinde-Stehbolzen

### 3) Shrinkage of the firebox

The shrinkage of the flat surfaces of the steel firebox is primarily a consequence of the uneven heating. Only when a surface can be evenly heated and equally evenly cooled is it possible that the heating can yield an uninhibited expansion, or in the case of cooling, an uninhibited contraction. Only then will the original measurements be maintained. However, if great differences between warming and cooling develop, shrinkage will occur; that is also when one only applies uneven heating at the edges of the sheet. Additionally buckling will occur in all directions (see point 1 in this section.) If the expansion inhibition due to the construction is greater than the shrinkage inhibition, the firebox material will be more pronounced. The inhibition caused by the bow anchors prevent the expansion of the firebox fluesheet sheet but not its shrinkage. As a consequence, the particular fluesheet sheet shrinkage mass, as well as the downward sinking of the firebox crown at the locale of the bow anchors, are separating themselves during the shrinkage of the fluesheet. If the inhibition with the consequence of the material being greater than the expansion, therefore when cooling occurs the material will be stretched. In the middle and higher parts of the sheet the shrinkage is less inhibited than in the proximity of the mudrings since the bows have been flattened-out and stretched. The shrinkage is not limited to the side sheets but also in the fluesheet and doorsheet sheets as well as in the firebox crown. If the shrinkage of the firebox crown and the corresponding side sheets achieve a substantial degree, then the horizontal bow would become almost flat. Applying boiler pressure, one will see an outward bending of the bow which has been observed in a few boilers. The shrinkage and shortening of the fireboxes regarding the flat areas is a consequence of the following:

a) the temperature differences between the fireside and the waterside
b) the differential heating of the firezone and the edge zones
c) the inhibition of the expansion because of the multiple site of staybolts from the firebox to the mostly cooler boiler and in addition to the cooler mudrings

The compression occurs when warming and cooling are utilized. The shrinkage which follows during the compression shortens the firebox when cooled. The staybolts reducing the degree of the firebox shrinkage and at the same time the risk of a tear, particularly in the facility of the mudring, may occur. The firebox when undergoing cooling will be limited by the staybolts as is equally the case when warming occurs. The differences on the temperature curve when warming or cooling takes place, can then consequently all be explained by the limits of the elasticity. This already has been explained in the arching of the rear boiler. (see point 1)

In the case of fireboxes which have welded staybolts in place one can already note shrinkage as a result of the welding process. This shrinkage of the firebox at the sheet towards the boiler results in two kinds of measurements: 5 mm when the staybolts were horizontal and 3 mm when the staybolts were vertical. In the inside of the firebox the horizontal staybolts were 5.5 mm and 5 mm in the vertical. The increased shrinkage of the firebox after welding was therefore 0.5 mm on the horizontal and 2 mm on the vertical. The shrinkage was amplified when the weld was greater. In the case of the welding inside the firebox, the shrinkage will be affected by the shrinkage of the boiler and leads to strong bending after completing the welding process.

When applying cold water pressure or steam pressure one can measure bending, particularly with staybolts that have been applied to the sheet, which will become visible in the form of an s-shaped bend which will become permanent, inhibited, and the reformation of the boiler. All this is a consequence of the bending of the firebox. (see Ill. 15)

## 4. Tears in the firebox

The reasons for the tears in the firebox as has been observed in the USA are mostly found on both sides, the fire and waterside. The tears at the firebox sheet and the door sheet mostly have the shape of a star. It is impossible to determine the causes irrespective of investigations and calculations. The results are that the firebox tears are, as a consequence, not related to the bending of the staybolts. The most likely reasons for the tears are the recurring stretching and shrinking inhibitions which are very extreme in the firebox. The flat surface of the firebox will experience strong plastic bulging. When the boiler is being cooled the inhibition of the shrinkage begins at the tangential tension at the edge of the hole. For these reasons, in the area of the vicinity of the firezone, a relatively high and large number of sheet holes of non-uniform shape appear.

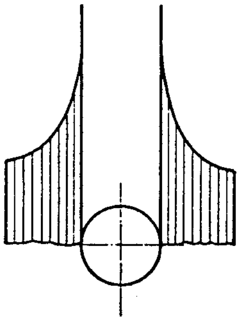


Abb. 13. Spannungsspitze am Lochrand infolge Schrumpfungshemmung des gestauchten Wandwerkstoffs

The tears begin when the cooling of the boiler occurs and as a consequence of the shrinkage inhibition on the side of the firebox where the staybolts had not been welded in and the tension point will develop. (see Illi. 13) In the case of welded staybolts this development takes place only on the fireside. Because of the arching of the firebox this tension on the waterside of the non-welded staybolt will enlarge the hole at the edges. A careful examination of the boiler clearly has shown that the fireboxes with extreme mattress formation will have fewer tears at the firebox side when the staybolts have been welded. The welling up and the danger of tear will be reduced if a large part of the heat expansion is modified by building a field sheet. When mattress formation has already happened in the firezone, it is possible that the single bucklings, because of uneven heating at the fire and waterside, enlargement or diminution may occur. The inhibition will be smaller and therefore pressure and shrink tension will be diminished at the edge of the hole.

In America many are of the opinion that the tears at the fireside in the case of un-welded staybolts are a consequence of the method of sealing staybolts. Apparently this has been observed to be the case in many situations. However, this opinion, after careful studies, is not accepted by some because they do not accept that the tears are a result of corrosion. Moreover, there are cases where firebox tears have occurred where no staybolt sealing was used. Our examinations prove that the staybolts' sealing and the firebox and sheet tears have the same cause. This uneven tearing is caused by inadequate preparation and therefore the tearing is accelerated. The shrinkage tension which occurred during the cooling causes the staybolts to develop a play in the threading. One observes this particularly in staybolts which have not been welded and produces the phenomena of cooling leakage. At the same time one can note a particularly high tangential tension at the edge of the hole (see Illi. 13) which leads to the fireside tears. Also under cold water pressure and furthermore under steam pressure trials, measuring the degree of bending of the fabricated staybolts, this bending produces a permanent s-shaped bend and when all pressure is released the boiler will return to its original form. (see Ill.15)

An accelerated influence of bending will occur with improper sealing which then in turn will produce tears, especially on the superior fireside of the firebox. This is probably the reason why in the USA tears in the sheet will occur particularly with staybolts that have been predominantly welded in the vertical position. The tears in the firebox sheet with holes have the characteristic of permanent breaks.

The cause for these permanent breaks can be noted under pressure when heating and cooling occurs. The tear formation happens when there is a rapid change under high pressure and tension occurs at the edges of the holes in the cold boiler. One can visually measure and observe the plastic deformation. One way to demonstrate that is by wrapping material around to tighten the bent staybolt at the site of the bending or hole. [Zug-(Schrumpf)]

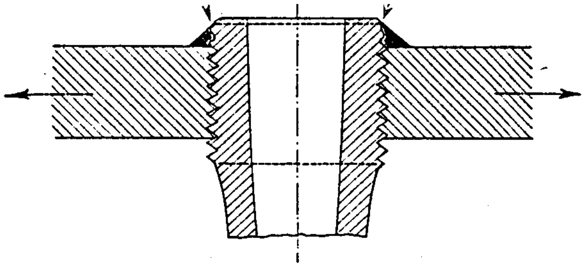


**Abb. 14. Rißverlauf einer Stehbolzen-Schweißnaht im Bolzen-Längsschnitt**

The bending and the tears at the edges in the vicinity of the mudring of the firebox are a consequence of the large temperature differential of the mudring and the adjacent parts of the firebox. One can note this phenomena where strong arching of the firebox occurs. In the area of the superior surface of the firebox the stretching is somewhat inhibited. The firebox in the vicinity of the mudring when heated will undergo plastic stretching and when cooling, also plastic shrinkage. At these sites one will note vertical tears when stretching and shrinkage occurs. These holes are not limited to where staybolts are attached, but also may begin at the holes of the rivets. In the corner one will find the larger tears in comparison to the tears in the firezone. One can observe these at the doorsheet and lateral sheets.

## 5. Bending of the staybolts downward and in the central part of the firebox sheet

The surprise that the steel staybolts at the firebox sheet tilt downward and at the central part of the sheet become permanently bent and the accompanying tears in the firebox sheet was a new discovery. (see Ill. 5) This is a consequence of the shrinkage of the firebox at the mudring and midwall. In the course of welding the staybolts, the bending of the staybolts can already be noted. This is the case for all positions. When applying the hydrostatic test some bending of the staybolts can be observed. (see Ill. 15) The firebox sheet will experience pressure from inside the firebox and from the outside by the boiler pressure. These conditions, however, are capable of subjecting the staybolts to bending and tearing at the side of the weld, as well as a phenomena that as a consequence will effect performance and safety.

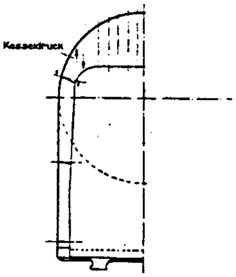


Abb. 15. Verbiegung der Stehbolzen infolge der Feuerbüchs-Schrumpfung und der Wirkung des Kesseldrucks auf die Umbüge

Considering all these possible vectors[1] appearing in the firebox, the boiler, and the staybolts makes it possible to apply mathematical relationships to the boiler, the firebox, and the staybolts. The average number of deviation is 0.4 mm. In consideration the degree of bending of the staybolts can be applied at the cross section. For staybolts of $f_{bzul}$ will already give some bending under hydrostatic test. After terminating the pressure trial the sheets will return to their original shape. The same applies under steam pressure. The shrinkage of the firebox sheet that occurs during the operation will lead to further bending of the staybolts especially of the mudring and the central part of the firebox. The reasons for all these staybolts bending is influenced by the arching of the rear boiler which may be amplified, augmented, or diminished. In Ill. 16 one can note a arched rear boiler where the insertions of the staybolts are exact. The shrinkage of the firebox will produce a bending of the staybolts which is modified by the arching of the rear boiler. The tilting of the staybolts insertion as a consequence of the arching in the rear boiler can be 10 mm towards the edge and will begin as low as 2 mm.

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[1] Footnote for term “Stauchung und Rekung” – un-translated

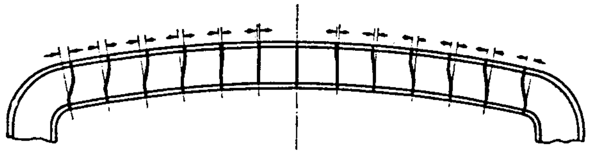

Abb. 16. Infolge Durchwölbung des Hinterkessels erzwungene s-förmige Stehbolzenverbiegung, von der Wandmitte nach den Wandbereichen hin zunehmend

The staybolts bending is at a minimum or non-existent in the center part of the boiler but on the firebox side of the boiler towards the middle of the firebox sheet they are bent outward. The bending direction of the staybolts is as a consequence of the arching of the rear boiler usually to be found lengthwise. On the front end of the firebox on the firebox side bending is towards the front, while the rear part of the firebox side the staybolts are bent towards the rear. In the vertical position in the upper part of the firebox where the arching is the strongest, the staybolts will bend upward, while in the lower part of the firebox they will bend downward. Additional bending is primarily in the lower part which is a result of the shrinkage of the firebox. In the upper part a decreased pressure can be noted.

## 6. Various types of bends of the staybolts

Measurements of bends have been carried out at the research center of Grunweld for over ten years with the German railroad equipment and it became evident that only some of the staybolts will undergo s-shaped bending. Simple bends and twists have been noted. These observations have been verified by our measurements. Twisted bends are the results of different types bending including s-shapes and simple bends.

All of these are a consequence of the larger degree of stretching of the firebox. These changes can be expected during the operation of the firebox. Some of the bending and tilting of the stays can be attributed to the changes of both sidesheets. If both sheets of the rear boiler with respect to the arching and no shrinkage occurs, a uniform s-shaped bending line will be seen. However, if the boiler and/or firebox have local and/or uneven heating in addition to tilting the shape of the staybolts becomes indeterminate. One can note a simple type of bending and twisting and all this becomes possible when:

a) in the zones of the edges of the firebox shrinkage and bends of the sheet have occurred
b) by changes of the radius of the firehole ring
c) changing the bending gradient when the firebox had been formed in pieces (see Ill. 10)
d) when different kinds of buckling occurs at the segments of the sheet that has a variable mattress formation

The progress determining the degree of bending of the staybolts and the type of bending will be further discussed.

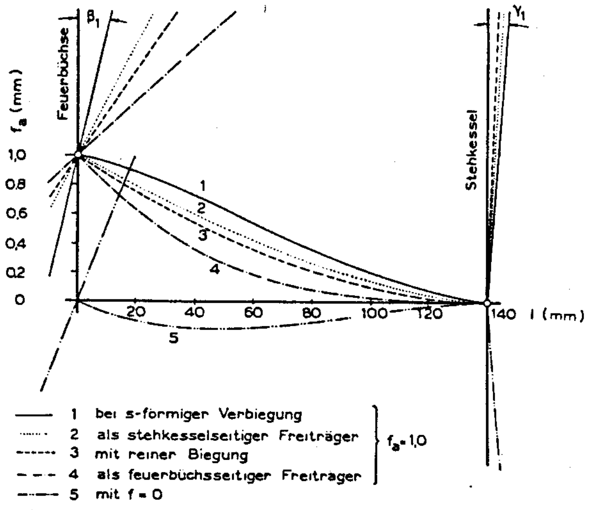

Abb. 17. Verschiedene Biegelinien bei einem Bolzen gleichen Durchmessers (BgD 22/140 mm). Auslenkung und Schrägstellung 50-fach übertrieben

In Ill. 17 one can note different elastic lines regarding the cylinder type of staybolts (BgD 22mm) with the length of the staybolt ($l_s$) not exceeding 140 mm. There is evidence[2] with calculated deviation ($f_a$) of 1 mm that the staybolt will be 50 fold magnified as shown in the illustration. And the same can be applied with the tilt angle of β and the firebox being regarded as a value of γ. In the boiler the elastic lines of the staybolts and their calculations can only be applied to the limits of their elasticity at any point where the staybolts are fastened to the sheet. In other words at the small $f_{bzul}$ these are then the conditions of BgD 22 with an $L_s$ value equal 140 mm and the $f_a$ value 1 mm. The desired values and conditions with values below the above are preferable.

For consideration of the staybolt bending lines a simple picture is sufficient. This is particularly the case with s-shaped bending lines.

(1) The tilting of both sheets leads to a bend in the staybolts at the place of attachment, with no more than 15 degrees at the firebox and no more than 6 degrees at the boiler. The turning point is about 8.7 mm from the firebox sheet. Additional tilting will not occur. The tilting positions in the boiler are illustrated cases 1-4 in Illi. 17.

In the remaining part of Ill.17, additional tilting will only be on the left side of the firebox sheet. With increase in tilting at the firebox attachment, the direction of the bending will be more toward the inner sheet of the firebox. In special cases one can note a dotted line representation of the boiler. (2) The side of the firebox attachment is regarded equal to zero. The tilting angle β in the firebox can be as great as 35 degrees, while at the same time the tilting in the boiler will regress to 3.5 degrees.

If the firebox side is tilted further, so one will obtain 39 degrees, then the case of Pure Bend can be seen. (3) (see Ill. 17) (stippled line), the turning point is infinite and the crosspoint is in the zero. The bending line, in the case of the cylindrically shaped bolt

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[2] Note on Auslenkung, un-translated

forms a circle. The tilting position in the case of the staybolt application in the boiler will further regress to 2.5 degrees.

In the case of the tilting angle β = 1 degree 14 minutes (broken line) the point of the boiler application will be zero. Therefore the tilting will disappear at the boiler side of the application. In this case there will be at the firebox side a "free-carrier" (term invented by author). (4) Number four demonstrates a bending line of a staybolt that has been applied only at the firebox side. With further local and greater tilting the turning point will reoccur at the elastic line. This turning point with an increasing angle β on the boiler side will advance more towards the middle of the staybolt. The angle γ becomes negative, therefore the twist will be in the opposite direction but will only be useful for BgD 22, $L_s$ equals 140 mm. The bending lines and angles in Ill. 17 are of bolts and bolt length where other bending lines apply. Furthermore, the position of special cases will yield a different type of bending error and other tilting angles for β. The smaller the bending error, the smaller the angle β.

(5) At the lower end of Ill. 17 the bending line of another special case can be noted (dot-dash line). In our example, the attachment on the firebox side is tilted 27.5 degrees. In this case the bending line has a turning point of 41.8 mm from the attachment of the boiler sheet. Here one will find a twisting of 2.5 degrees (only the downward part is drawn in the illustration). The turning point is f = 0 independent of the tilting angle β in the firebox, maintaining the crosscut of the staybolt constant. The only factor influencing the differential is the strength of the firebox sheet and the stiffness of the bolt. In the case of uniform strength of the sheet the distance will always be one- third from the boiler. Moreover, in the case of s-forming bends, without additional tilting, the bending error is only depending on the variable strength of the sheet. Additionally, the stiffness of the staybolt may affect the bending error. In the case of uniform sheet strength the bending error will always be in the middle of the bolt.

The curves in Ill. 17 will show the type and kind of demands that are made by the staybolts; one can calculate all these values. The case of f = 0, where the sheets are tilted, leads to greater demands. This is particularly the case if the firebox holes are close and will eventually lead to numerous breaks at the staybolts. Some peculiar breaks previously not understood are often found in the middle or near the attachment and can now be explained, if local additional bending takes place in the firebox. These local conditions lead to unfavorable bending and finally to breaks.

While conducting the Grunwald experiments, with repeated measurements a bending arrow of 5 to 6 mm was obtained. That is when simple bending lines have been applied. This phenomena can best be seen when strong steam discharge occurred and was until now unexplainable. The boilers were equipped with stirrup anchors and therefore underwent less shrinkage while the firebox crown had partially caved inward (compare Ill. 9).

## C. Consequences for the rear boiler

### 1. General viewpoints.

All conditions that affect the copper as well as the steel fireboxes have a common cause, that is, the permanent deformation of the fireboxes and the staybolts as a result of the expansion and shrinkage which results from the heating and the cooling of the fireboxes. These effects are larger when a maximum heating occurs, which will in turn lead to a larger temperature differential, in the individual parts. Mineral deposition in the boiler, general boiler burden, method of water intake, water circulation, water temperature, temperature elasticity limits, elasticity of the firebox building material as well as the building material of the staybolts all will individually or in concert have an effect on the performance.

a) the boiler water intake must be constructed in such a manner that the cold water will never ever come in contact with the firebox sheet
b) the water circulation should be in such a condition that no cold water zones are formed and no small isolated layers of steam are permitted as pockets on the surface of the firebox
c) the heat conductance value of the firebox material should be as large as possible. That means one should use in this case the steel and copper material that has not been amalgated or a composition that does not change heating characteristics. Also the flexible bolts will have a special particular influence. Ferrit (iron) has a 50% higher heat conductance in comparison to Perlitt. Perlitt is the material most favorable for joint articulation.
d) The limits of the heat elasticity of the firebox and the staybolt building material should be as high as possible. The fulfillment of this condition will determine different compositions of amalgam. According to American experiences, the addition of molybdenum produces a desirable condition by the fact that it will not alter the heat conductance, but at the same time will elevate the heat elasticity.
e) The modulus of elasticity should have the lowest possible value. In the case of steel the elasticity modulus value is nearly in all cases the same and can be ignored, only the heat conductance values and the heat elasticity limitations are of importance. The advantages of copper and monel metals as material for staybolts are a result of the higher heat conductance and the corrosion stability. This is particularly the case with low elasticity modules and the decreased tension. Experiments with staybolts using copper- like iron soft material are predetermined to fail. Reasons for failure can be found in the elasticity modules and the heat elasticity modules which is lower.

### 2. Steps in the construction of the boiler

The type and mode of the construction of the boiler will have an effect on the kind of deformation the boiler will undergo. In the case of the building of the boiler the elasticity will exert certain demands. This is a common matter in the building of any type of machine.

In order to achieve these standards for the construction of a locomotive boiler it becomes important to take note of all the temperature dislocations that may occur. In this context all types of deformations are to be minimized. This applies to all parts that are subject to all types of changing temperature conditions.

In detail one arrives at the following guidelines for construction:

a) steps in the prevention of or at least reduction of the expansion and/or shrinkage. In the case of the firebox from copper, as is already explained in segment 1, a diminution of the deformation is best achieved with Kuprodur shoes or steel shoes; the small KPS staybolts have been built into the sheet. Because of the differential heat expansion values between the steel and the Kuprodur, one will find during the heating, a loosening of the staybolts and the small enlargement of the hole in the sheet. The heat expansion of the bolts and the part of stretching of the sheet will follow the pattern of the enlargement of the sheets. In this case the heat expansion will be less. The use of steel or Kuprodur shoes have proven during the operation to be very satisfactory. The formation of mattresses disappeared altogether and also the deformation of the firebox was minimal, if at all, when it was attempted to measure such deformation. In an analogous step with a steel firebox, when selecting a building material of the staybolt with a low expansion value, the conditions cannot be obtained. Staybolts with the desirable characteristics that possess a low expansion value for a steel firebox are at the present time not economical or available.

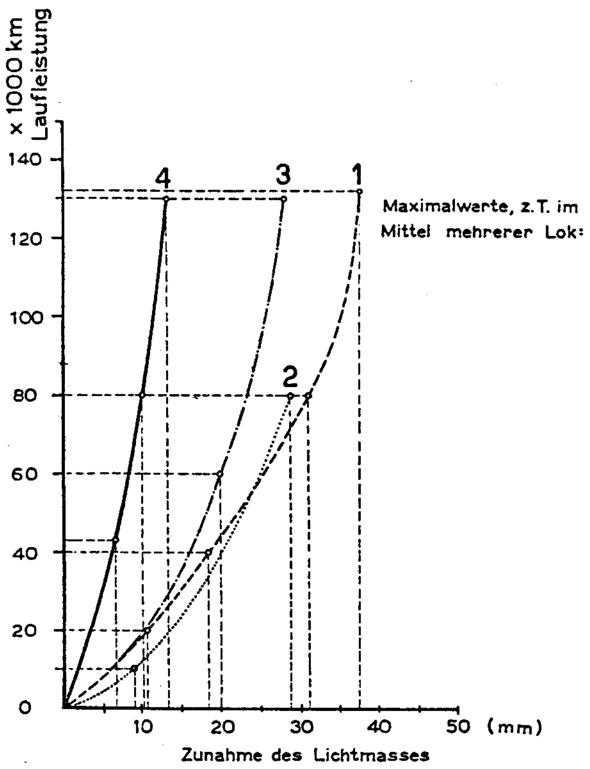
α) The latitude (play) of the staybolt in the hole of the sheet.

A latitude (play) between a staybolt and a hole in the sheet can be modified by the construction mode. Already for a number of years this concept has been applied in many European countries with considerable satisfaction and success. In these cases staybolts without threading have been welded directly into the sheet. One must consider the tolerances involved with staybolts and the sheet. The holes in the sheet should be of such a nature that the staybolts just slide into the holes and still make the entire matter economically possible. One should have more than 0.1 mm of latitude play. In the event of the welding, the changes of the latitude play with regard to the different staybolts had not yet been known and shall be discussed further in segment E, 1b. It is an advantage when the latitude play is at the minimum of 0.5 mm and therefore applying a larger tolerance for staybolts and the hole in the sheet. The heating tension of the staybolts and the sheet will be decreased because of the stretching of the firebox fields and the stretching of the bolts in the direction of the latitude play. Therefore, the heat expansion of the total firebox will not be only upwards or forwards or rearwards but rather in the direction of the hole in the sheet. The expansion of the part of the sheet that experiences the strongest heating must be taken into consideration and naturally are not free from expansion. The local tilting of the staybolts of only 2 degrees is sufficient for the bending arrow in a simple bending line. In the case of several expansions of the sheet, as a consequence of the increased steam extraction and therefore the lifting of the inward caved sheet, a local tilting of the firebox sheet is possible in the area of the stirrup anchors.

In order to find the most favorable conditions laboratory experiments were conducted. Firebox sections and boiler sheet strength with the holes of 18, 22, 26, and 30 mm diameter have been heated 3 times in the area of the holes to a temperature of 500 degrees. Only 1/2 of the experimental parts were equipped with bolts with various degrees of play, and with the remaining holes no bolts were used. The holes without the bolts became smaller approximately in the middle of the firebox (half way down), about 0.25 mm at the boiler and 0.20 mm at the edge. In the case of the experimental parts with bolts, when cooling took place a larger play was noted between the sheet hole and the bolts in the firebox with about 0.22 mm in the middle and about 0.17 mm in the boiler. The total deformation, including the shrinkage in the flat surfaces, was greater if the play was smaller before the heating, while the tolerance of the play affected the entire process.

In all the experiments the deformation was noteworthy, and it was noted that during the second and third heating to 500 degrees no further deformation followed. Of the eight attached staybolts seven showed no change after repeated heating and only one had a deviation of 0.02 mm. The corresponding sheet holes also showed no changes. This observation can be explained in the following manner:

Before the heating the hole is without any tension. When the first heating takes place in the presence of a bolt, radial and tangential stresses will occur. Then when cooling is underway only tangential stresses will occur at the edges of the hole until the limits of stress have occurred. In the process of the second heating, pressure tension and plastic deformation remain small because the tension from the first cooling had not yet reached zero before the pressure tension reoccurs. In addition, one must consider the solidification of the building material because of the deformation from the first heating and the first cooling which yielded and elevated stretch limitations. The plastic deformation is greater when the first heating and cooling takes place in contrast to later heating. It is to be presumed that when heating to only 400 degrees that in the narrowing of the hole with repeated heating no more new elastic tension will be produced. If additional heating occurs and the temperature in the firezone rises, the play will be larger if subsequent cooling takes place.



1) Gewindebolzen dicht geschweisst.
2) Ohne Spiel gewindelos eingeschweisste geformte Stehbolzen.
3) Ohne vorgeschriebenes Mindestspiel eingeschweisste, glatte, zylindrische Bolzen.
4) Mit Spiel gewindelos eingeschweisste geformte Stehbolzen.

Abb. 18. Zunahme des Lichtmaßes zwischen den Feuerbüchs-Seitenwänden von Lokomotiven der Reihe 44 mit verschiedenartigen Stehbolzen

When the staybolts become cold, a play will develop that in the case of the non-welded threaded bolts will yield a manifold cooling leakage. In the case of the welded staybolts the welding seam will reduce the amount of play exactly at the site of the weld as a result of increased heating. The weld seam also inhibits the part of the fireside as well as the expansion of the bolt and the sheet as a result of reheating. The inhibition of the expansion commences at the time when the tension in the weld seam has decreased.

In spite of all these circumstances at the welding seam, the staybolts without any threading that have been welded and have some play in contrast to the staybolts that have been welded with less or no play, but also without any threading, prove to be superior. The play outside the welding seam provides certain advantages by themselves. The welding of the staybolts with some play leads to decreased boiler deformation. This can be shown when deformation measurements are taken with the locomotives of the building series 44 with welded staybolts during continuous running. The results on the average boiler are shown in Ill. 18. These theoretical concepts are shown in the case of the boilers where the threadless staybolts have been welded in with a play, in contrast to boilers where the staybolts have been welded but without sufficient play. The staybolts without the threading that have been welded produced boiler deformation. The line of firebox light measurement magnification for the boiler whose staybolts that have had threading and have been seal welded can be seen in Ill. 18 and is indicated by the number 1. This line is very similar to line 2 where threadless staybolts have been welded in without any play. The boilers where there is a small amount of play (0 to 0.5 mm) with welded cylindrical staybolts with about 18 mm diameter steel (see Illi. 18 BgD 18 line point number 3) had been deformed to a smaller degree. The boiler with the larger play (0.9 - 1.1 mm) with welded staybolts and of the older type of construction but with new-design staybolts (see Illi. 18, BDR extended line 4) gave results that were better than expected. Deformation was less and reduced by half during performance operation. This demonstrated the advantages of the staybolts that had been welded in with sufficient play. Large play can be made smaller during the welding process. (Compare sections II E 1 b)

β) Arching of the firebox and the flooring or mudrings

A second possibility exists, considering the boiler's force of expansion during the heating of the firebox, to produce a arching of the area of the fire in the firebox. These theoretical observations, which do have their detractors, but nevertheless provide a favorable experience with regard to the reparations and the longevity of the boiler with the smaller firebox, in contrast to the larger and wider fireboxes, are well known. This can be explained by the fact that the parts of the sidewall and the lower part in the smaller fireboxes experience less stress when cinder formation is produced. So in the course of heating, the expansion tendency in the specially endangered firezone as a result of the radial diminution, can be counter balanced by the various sheet sections. In the course of heating, the arching will become stronger in these sheet segments and when cooling occurs, a return to the previous state will take place.

Measurements of boiler deformation have shown that types of construction of boilers and staybolts will influence performance. The boiler, while in operation, experiences a minimum of arching in the exterior, while after the welding, the strongest arching will become apparent. One can expect that "breathing" between heating and cooling, in the case of the arched firebox parts, is more preferable to non-arched surfaces.

The arching can be of three types:

### 1. The total firebox

For this purpose it becomes necessary that the lateral parts as well as the mudrings and the overlaying sidewall parts of the firebox and the boiler have been arched towards the interior side. It becomes necessary that the sheet strength of the boiler be reduced to 12-13 mm in order that the additional arching of the firebox does not produce a large degree of resistance during the heating. The arching of the boiler because of the outward flow in the direction of the firebox becomes a consequence.

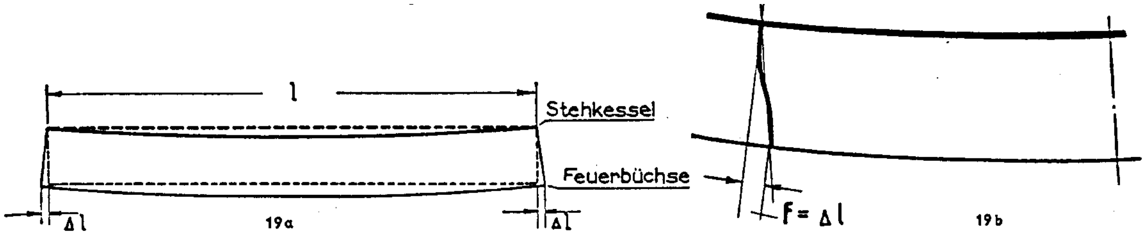


Abb. 19. Mehrausdehnung der Feuerbuchse gegenüber dem Stehkessel auf Grund ihrer höheren Erwärmung.

If the stretching of the firebox during the heating is greater than the boiler, the staybolts will be bent. The same will occur according to Ill. 16a and 19b, if the boiler is arching inward or outward. The accompanying stretching of the firebox at the same time as the inward arching will diminish the bending of the staybolts. With the same train of thought, equal concepts apply during the cooling and shrinkage of the firebox and the outwards arching of the boiler. In Ill. 19a it is presumed that the firebox will be stretched by a 2 Δ 1 value with regard to the stretched boiler. If Δ 1 is a result of the arching in Ill. 19b, one willl note bending arrow f of the staybolt at the edge will become vertical with respect to the firebox and therefore will not bend. In that case Δ 1 = f since f is also a unit for the staybolts and therefore will give an optimal length of the staybolts in the boiler arching which is depending on the expansion or shrinkage of the firebox.

The bending free conditions of the expansion of the firebox would be in the case of the smaller boiler arching following the longer staybolts. Thus it follows that the length of the staybolts, together with the boiler arching, provide conditions where the temperature differences between the boiler and the firebox are larger and permit a larger degree of stretching, all depending on the position of the firebox in relation to the boiler. The stiffer the staybolts are and the softer the sheets are, the more they will be forced to obey the law of least resistance. The work of the deformation of the firebox and the boiler as it takes place by the heating and cooling in the presence of arching will give the least bending of the staybolts.

The arching of the boiler sheet towards the interior of about 2 mm would give the staybolt a length of 150 mm, a stretching value of the firebox of 1.37 mm. This would be the case of middle heating of the firebox about 60 degrees which would be equal to the above values. A arching of the boiler during the heating in the case of the interior arching would yield a value of 2 mm which is a substantial reduction, of the firebox and boiler tension. The difference of the waterside against the heating of the fireside in the firebox is only 4 degrees. The larger part of the expansion of the firebox, because of the arching of the boiler inwards and outwards in the direction of the play, the greater equality can be obtained. As a consequence the plastic aspects during the heating, together with the arching equalization, will develop during the cooling of the firebox.

The arching of the boiler with bilateral welding of the staybolts alone is an advantage in itself. If only seal welding on the fireside takes place, arching will occur at the boiler when seal welding is done at the interior only. Such a boiler will show many tears at the sheet holes. However, if bilateral welding with play is undertaken in a boiler with interior arching, no tears of the sheet holes have been noted.

### 2. Horizontal and vertical undulations

The arching of the horizontal or vertical undulations permit an equalization of the expansion of the entire firebox, or only certain parts of the firebox. The firezone, in relation to the boiler, will be enlarged as a result of the undulations. Regarding the differential heating between the fire and the waterside no particular advantage is obtained. The bending arrow of the undulations becomes larger during the heating of the firebox and becomes smaller during the cooling.

The equalization in the course of heating can be seen in the undulations in either only the horizontal or vertical directions. Since the largest hindrance is in the horizontal direction near the mudring, the vertical undulations become the dominant ones.

### 3. The boiler sheet fields in the section of the firezone

It is desirable to prevent the expansion of all parts. One must keep in mind that the staybolt fields between four staybolts particularly in the firezone, a nap forming undulation is to be constructed. One will obtain a firebox, which will look like a firebox that had seen long term duty. In these fireboxes, mattress formations with undulations had developed. Since everything was equal and the staybolts which otherwise would have to have an elevated tilting, become unnecessary. This came about as a result of mattress formation and that the single and side-by-side undulations depending on height and form that are different in behavior.

This type of mattress formation occurs only when the firebox had been repeatedly heated or particular parts of the firebox had been strongly heated in contrast to the boiler, but not the heat differential between fire and waterside.

The production of a firebox with undulation or with nap form undulations will be of greater expense in contrast to other suggested methods. Since ordinary construction methods have been based on a long line of experiences and have given satisfactory performance, therefore it becomes questionable to utilize more expensive improvements.

### b) Steps for temperature equalization

Another method to minimize temperature differential between the steel fireboxes and steel staybolts is to equalize and minimize temperature.

α) Heating of the mudrings

A lowering of the temperature differences between the firebox and the mudring would diminish the heat tension in the lower part of the firebox considerably. A heating of the mudring can be achieved by lowering the burner grate, possibly by elevating the edges of the grate supports. Additional advantages can be obtained when the bulk of the mudrings are shaped into a U-forming position and by these means the heating of the mudrings from the side of the grate and the water is simplified. Furthermore, it is advantageous to prevent the access of cold air into the proximity of the mudrings. Some of these new ideas have been applied in new construction and experience will show their advantages.

β) Fire Arch

Most of the fire arches have the disadvantage that the majority of the heat is directed toward the firebox sidewalls, or will remain below the arch. All this will lead, in turn, to a higher heating tension. In order to minimize these problems it is best to build a fire arch that is larger and constructed in such a manner that a small amount of heating gases will pass.

γ) Forms of fireboxes

The advantages of the smaller fireboxes with undulation in the arching, in particular in the lower part of the firebox interior, has already been discussed. In the case of the broad fireboxes, that is those with slightly tilted sidewalls (conically shaped), as they are common in America, are preferred for an even heating in comparison to vertical sheets. The radiation shows small differences; however, they require special steps in order to keep the deformation within limits.

### C). Steps for the stiffening of the boiler

In order to prevent the arching of the boiler the following steps may be undertaken.

α) Cross stiffening of the boiler

With the steps for the arching of the boiler to the maximum, particularly in cases of boilers with vertical sheets and with high mudrings, special consideration must be given. Considerable diminution of the arching of the boiler can be achieved when the mudring is stiffened crosswise. A few boilers that had been equipped with a mudring anchor have proven the correctness of this thought. The mudring anchor is a simple and inexpensive means to prevent the arching of the boiler and the breakage of the staybolts. In order to prevent the deformation and arching of the boiler during reheating it is best to stiffen the mudring, which also will prevent arching towards the exterior. This methodology has proven to be rather successful. The arching of the mudring towards the exterior ceased the deformation in the higher parts of the firebox where deformation was reduced to one half. This is in comparison to the grand deformations (light measurements) that can be seen in the three newly built locomotives of the building line 52.(see Ill. 20) They had not been equipped with mudring anchors. After an operation of a 100,000 km the grand deformation was about 5.4 mm. If the mudrings were built in and about 12.6 mm, when no mudring anchors had been used, there would be a difference of more than 2.3 mm. Also the breaks of the staybolts were smaller in number in the mudring anchor equipped locomotives after 100,000 km where only one of the anchors had broken, one staybolt had been broken, and 15 flexible staybolts had been broken. This is in contrast to the locomotives after 100,000 km which did not have bottom cross anchors where 26 of the solid and 28 of the flexible staybolts had been broken. All locomotives had been built with the same staybolts and identical work conditions and were in service over the same distance with equal conditions. In the case of the low burning grate the mudring cross anchor can serve as the best support.

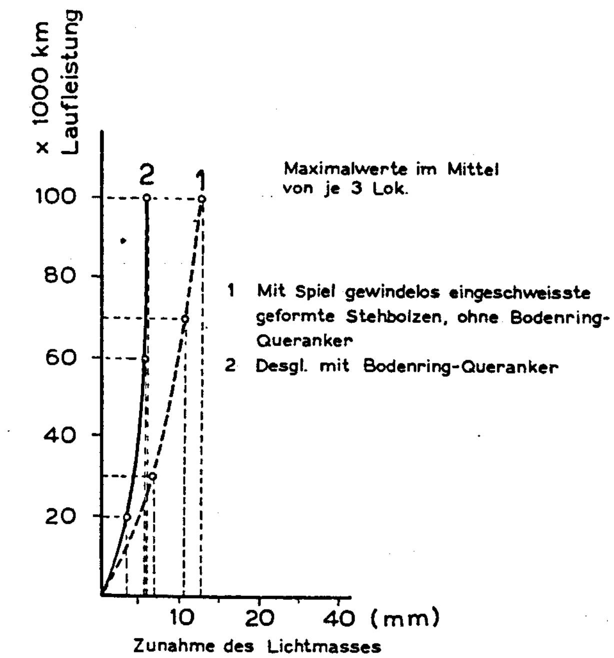


Abb. 20. Zunahme des Lichtmaßes zwischen den Feuerbüchs-Seitenwänden von Lokomotiven der Reihe 52 ohne und mit Bodenring-Queranker.

β) Strengthening of the boiler crown

Because of various reasons, decreasing the load on the staybolts has certain advantages. The boiler sheets will not be strengthened any more than the firebox. However, the strengthening of the boiler crown, particularly in the presence of the arched firebox crown, becomes an absolute necessity. That is the case in order to prevent a deformation in the upper part of the boiler. The crown should be a minimum of 20 to 23 mm stronger if not reinforced by several crossanchors. In the case of boilers with a arched firebox crown it is also good to decrease the distance of the staybolts as the attachments move from the sidewall to the crown.

### 3). Steps during the cooling and washing of the boiler

In order to prevent boiler deformation during the process of cooling and washing the following steps are to be taken:

a) It is best to prolong the washing periods so one will have a lower number of load changes.
b) When cooling, washing, and reheating is to take place in the locomotive boiler, it is best to keep the temperature differences as small as possible in order to prevent deformation which might develop. The cooling and reheating velocity is of little significance in comparison to the temperature curve of reheating and cooling which should be kept to a minimum.

c) The flow of the heat and the cooling in the firebox that has the arching should for both be in the same direction, that is toward the exterior, as it would be in the case when full reheating and operation takes place. When regular cooling takes place, it will involve the fire arch and in the case of oil fired locomotives, the firebricks.

In order to fulfill all these demands it is best that the boiler water is slowly mixed with cold water and the slow cooling will take place in the firebox until the sheets reach a temperature of 30 to 40 degrees. At the beginning of this above process, it is best to prevent access of cold air during the cooling of the water in the boiler. Only after the cooling process has advanced far enough is it permissible to remove most of the fire and the ashes. However, it is best to wait until the overall temperature has fallen to 30 to 40 degrees before emptying the boiler altogether. To prevent the solidification of the boiler sludge one should begin with the washing as soon as the water level is below the firebox crown. The washing water should not be any more than 40 degrees. When refilling the boiler it is best not to use water that is much more than 40 degrees in order to have an equalized reheating of the boiler, so that no local heating will develop. Many of these suggestions, especially those of the mixing of the cold water, have already been used with success and one can expect the following advantages:

a) In the regular procedure, the sludge remains behind during the release of the boiler water. This sludge will adhere to the staybolts, the hot sheets, and in the piping where it will harden promptly and form a heat insulating mass with time. However when cold water is used it will not harden so rapidly and can be removed during the washing.
b) The flow of the heat while in the process of reheating or during the operation will go from the surface of the firebox to the water space, and in the process of cooling it will occur in the same way. The addition of cool air when a small fire is maintained in the firechamber also will inhibit the rapid hardening of the sludge. Now when cooling takes place the arching of the sheets will remain intact. The contraction of the entire boiler shall be a slow process and not alter the arching.
c) The fire arch will hold the heat longer during the cooling process than any other part of the boiler system. This leads in turn that the fire zone of the firebox will hold the heat longer than the surrounding parts of the sheet. This will be the case if the hot water method is used. Therefore, the pressure tension is maintained, even so in the face of the rapid cooling of the parts of the sheet which leads to plastic swelling. With further cooling certain risks may come about. These elevated risks show up as more tears in the holes in the firezone. Cooling cracks, as well as new mattress formations, will develop. When applying the cold water method, the cooling of the firebox, below the fire arch, will develop in the same manner as the rest of the parts of the sheet.

The advantages are considerable, so that the cold water process, in combination with some heat in the fire chamber, should be investigated further. The strong cooling of the boiler facilitates the work in the firebox after the washing.

## D. Special Consideration for the Staybolts

1. Improvements for the shape of the solid staybolts

Staybolts that are easily bent inhibit the return of the firebox and the boiler to their original conditions. For the optimal staybolt, one must have a high and reliable yielding value $f_{zul}$ that can be expected for the average staybolt. $f_{zul}$ corresponds to the yielding of the position of the staybolt towards its' neighbors in which no part of the bolt, including the exterior fiber, is affected by the limitations of the heat expansion.

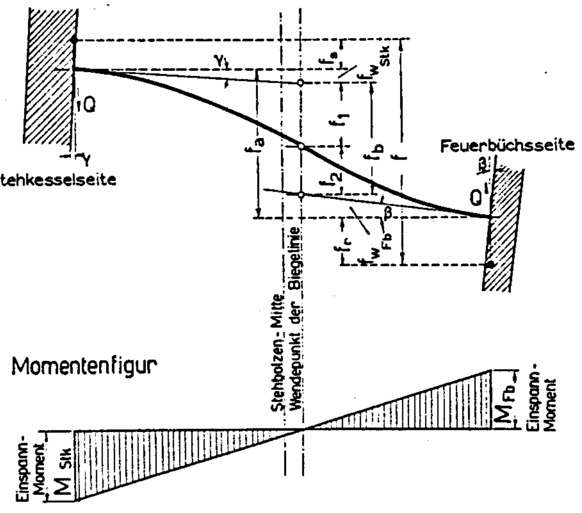


Abb. 21. Zusammensetzung der theoretischen Gesamtverschiebung für die Einspannenden eines festen Stehbolzens bei s-förmiger Biegelinie.

The real shifting of a staybolt f is a result of various influences that come together. In Ill. 21, the total shift f and all the other factors can be seen in the s-shaped bending. Only the value $f_b$, which consists of lateral boiler portion $f_1$, and a smaller lateral firebox portion $f_2$, together will have an effect on the bending of the staybolts. The parallel conditions of the staybolt tension $f_a$ comes about with $f_b$, the apparent bending arrows $f_{wFb}$ and $f_{wStk}$ become additive, see Illi. 21, in the representing tilting of the staybolt installation in the firebox and the boiler. If one or both of the installation positions undergo a change for any one of the reasons mentioned, that, in turn, will yield an additional change of tilting.

In the case of the total shift of f, compression can be seen in the firebox and the boiler. This deserves further consideration. When the bending of the bolts occurs, cross forces are produced that are the cause of compression. These conditions prevent the disengagements of the staybolts. The real parallel engagement of the bolts $f_a$, with regard to both sides of the installations of the staybolts, is dependent on the larger of the staybolt cross forces, regardless of which end compression originates, from either the firebox or the boiler. But theoretically, the smaller total shift f, is a result of the installation of each across from the other in new values. One will obtain f when the installation $f_a$, the compression $f_s$, and the stretching $f_r$ all are added, which will be the case in the cross forces of all staybolts. In order to differentiate clearly between $f_b$, $f_a$, and f, the following three terms are being employed in the process of bending, installation, and shifting. In the case of the bending and installation on the application points of the bolts, the tensions are equal. In the case of the shifting, the parallel distance, as a result of the compression and stretching are not the same but larger. The larger the tilting position of the staybolt installation, $f_{wFb}$ and $f_{wStk}$ with the same position $f_a$, the smaller the bending of the bolts $f_b$.

All these values become part of the index $_{zul}$ in the case of the installation momentum and also the cross forces that are produced when the bolts are bent. Then tension maximum is reached in most of the exterior fibers of the staybolts when the heating stretch limits are reached. For the firebox and the boiler, permissible tensions are expressed by $f_{zul}$, whose maximum has not yet been reached and can, in the case of over charging, not affect $f_b$; not affecting the bolts in the staybolt installation tension momentum and the cross-forces, after passing the staybolt elastic limitation, but only adding in an incremental way.

The mentioned subdivision of the total shifting f, with different factors, is not new and has been considered in previous theoretical publications. All this is applicable for the demands, in which case the staybolts are bent on the side of the firebox upwards or forwards and also backwards. Applying the newer knowledges, the staybolts will be bent when the cooling of the firebox happens, with the bending downwards and also in the middle of the sheet. Even then cross forces will occur during the bending of the staybolts which will lead to swelling and expansion, and shrinkage of the boiler and firebox. In some of these cases the firebox will be swelling and the boiler will shrink. Using the older theories, the situation is reversed. Other deformations of the s-form, increase the mathematical calculations for the swelling and stretching. Nevertheless, in all situations the bolts decreasing load will give a larger cross power.

The new view, that in comparing the calculations, in all types of staybolts, the s-forming line is permissible and applicable for the value $f_{zul}$. This yields the foundation for all types of demands.

With the value of $f_{azul}$ for the staybolts and the lateral attachments produced a total work environment that is permissible for $A_{zul}$. These values should be as high as possible for staybolt attachment and therefore the deformation of the boiler will remain a minimum.

In the course of the mathematical examinations, all the questions in the new method of computations and graphic notation, have been developed in order to understand the demands of the staybolts. This will give the opportunity that for all staybolt construction methods, including the flexible staybolts, the different demands can be determined. With the assistance of these computations, it becomes possible to develop a new and better staybolt for BTH[3]. This will permit a higher shift of $f_{zul}$, coupled with the shape altering conditions that will for all demands ($A_{zul}$), provide the least tension. The reasons for the new developments of the new construction methods BTH are a consequence of the

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[3] Not translated (types of staybolt designs)

experience with BDR, where on both sides the length of the head was 25 mm larger for the length of the bolt. In spite of the new-design staybolts, tears in the cylindrical part of the shaft occur at the beginning of the cones. In contrast, the BTH, by complete use of the free length of the total staybolt, with different heads and in a new design shaft, a total usage can be developed. In addition, the course of the crosscut can be calculated so that the exterior fiber of a new design bolt over the whole of the total length, with various bending lines, that is, different demand situations, can be calculated, and from which an equal stress factor can be applied. Theoretically, best results were obtained with a new design bolt that is not symmetrically shaped. However, the differences were so small, regarding the tension, that it did not justify the additional expenses in the production of these staybolts.

### a) Comparison of the bending lines of cylindrical staybolts with those of the new design staybolts

First it was investigated whether cylindrical staybolts were stronger or were weaker in their favorable values provided. Without consideration of the pulling tension, the value $f_{bzul}$ decreases in the case of the cylindrical bolts with increasing bolt diameter. If one calculated $f_{bzul}$, with consideration of the pull tension, for the heating stretch limitation, $\sigma_s = 14\ kg/mm^2$. One will obtain, in the case of s-formation, that with a strong curve, Ill. 22, which for $D_{ü}$[4] = 19 mm with a maximum of $f_{bzul}$l. ($\sigma_s = 14\ kg/mm^2$) The picture will change if the tilting of both application sites are inhibited in the case of the application momentum. These tiltings enlarge the bending arrow $f_{wFb}$ and $f_{w'Stk'}$ and even more so when application's momentum is $f_{bzul}$.

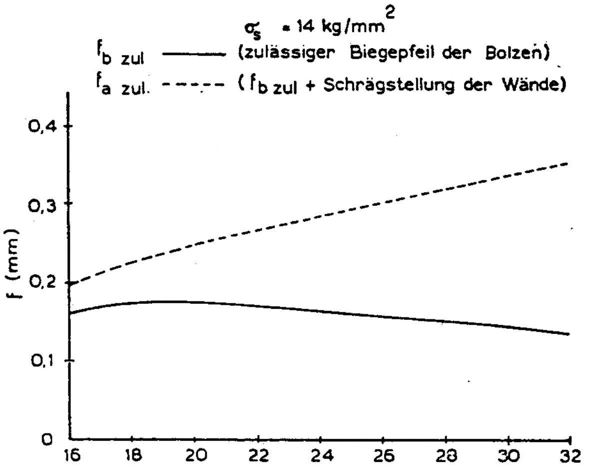

Abb. 22. Zulässige Verbiegung $f_{bzul}$ und $f_{azul}$ bei zylindrischen Stehbolzen (BgD) in Abhängigkeit vom Bolzendurchmesser für $L_s = 140$ mm.

The curve $f_{azul} = f_{bzul} + f_{wFbzul} + f_{wStkzul}$ as the Ill. 22 indicated by stipulations. It will rise for the heating stretch limitation to the sigma value of above increasing diameter. $D_ü$ even

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[4] Note on the variable $D_{ü,}$, un-translated.

shall be stronger on the front part when stretching and swelling of the firebox and boiler is considered.

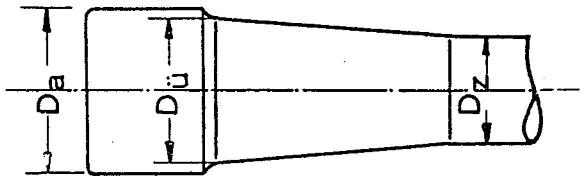


Abb. 23. Kennzeichnung der Stehbolzendurchmesser an Kop und Schaft.

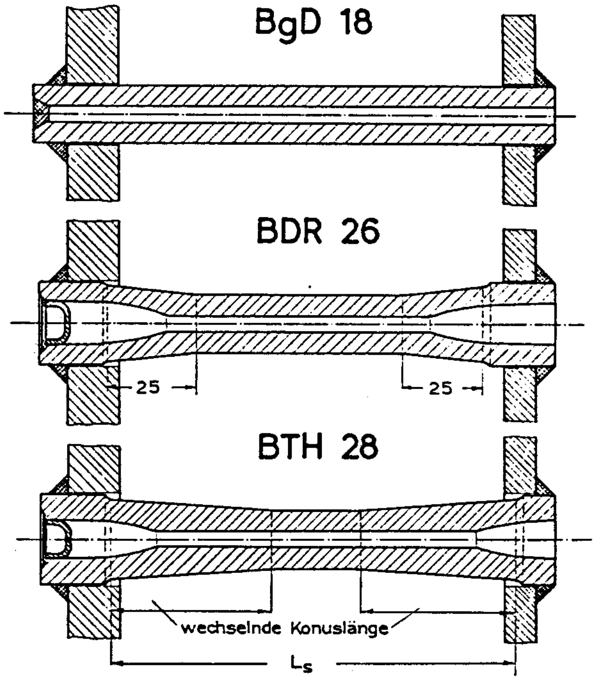


Abb. 24. Vergleichsstehbolzen.

Moreover, it was mathematically examined, if the cylindrically formed BgD or the new design staybolt yields a higher $f_{zul}$ value. For comparison, with new design shaft, as is commonly used in Germany , BTH 28 was selected. The bolts are shown for comparison in Illi. 24 for the heating stretch limitations; $\sigma$ was used and the $f_{zul}$ values were employed for the bolts BgD 22, cylindrical bolts with 22 mm diameter have been used. The lower fields of the columns correspond to the bending arrows $f_{bzul}$ of the staybolts (central field) and on the boiler side the bending arrow $f_{wStkzul}$ and on the firebox side $f_{wFbzul}$ (higher column). The upper limitations therefore depend on the value $f_{azul}$. If one considers the stretching of the firebox and boiler, with the crossforces in consideration, the advantage will be with BDR and especially with BTH. Particularly glaring is the fact that the permissible bending arrow $f_{bzul}$ in comparison to the much stiffer BTH is larger than with the cylindrical staybolt BgD 18. The BTH can be bent to a greater degree than BgD 18 before heating stretch limits are reached. This may be in any of the bolts and at the exterior fiber. The difference of BgD 22 is even stronger. The explanation for these phenomena are as follows:

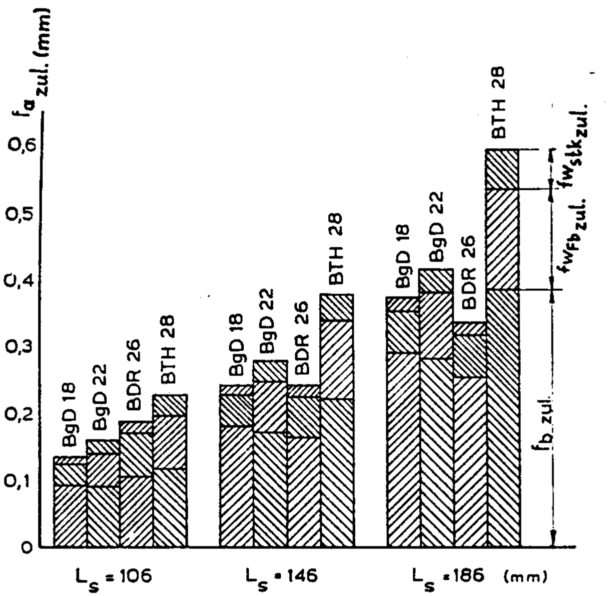


Abb. 25. Zulässige Auslenkung $f_{a_{zul}}$ der Vergleichsbolzen und ihre Zusammensetzung aus Bolzenverbiegung $f_{b_{zul}}$ und Wandwellung $f_{w_{Fb}} + f_{w_{Stk}}$ ohne Berücksichtigung von Stauchung und Reckung bei einer Warmstreckgrenze $\sigma_s$ = 14 kg/qmm und für verschiedene Bolzenlängen $L_s$.

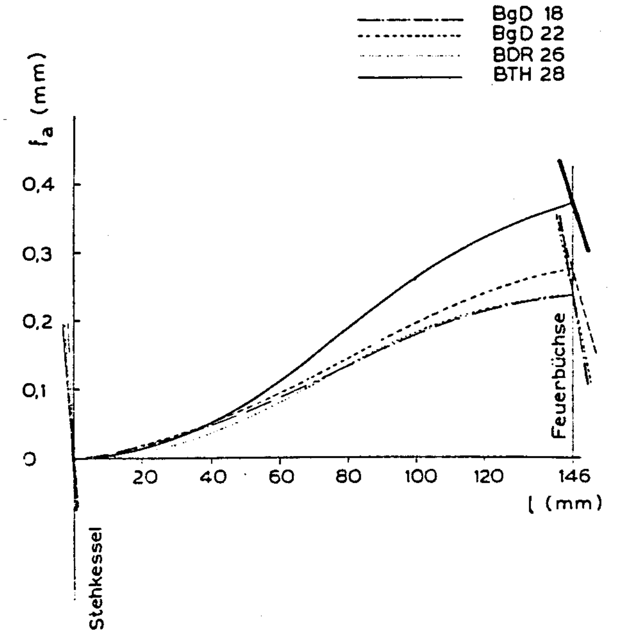


Abb. 26. Biegelinien der Vergleichsbolzen bei höchstzulässiger Verbiegung ($L_s$ = 146 mm, $\sigma_s$ = 14 kg/qmm).

In all BgDs only the diameter (tension point at the application crosscut) until the limitation of the permissible point is used, will changes become apparent. The rest of the diameters experience less tension and therefore less tendency to bend. In the case of the BTH, the exterior fibers at all diameters which are in the conical part of the shaft, will undergo a uniform maximal demand depending on the length. For the expanded exterior fibers, until their limits in the conical part of the shaft have been reached, but in the case of the new design bolt, which are in the central part of the shaft, the distance becomes even shorter from the zero fiber.

The more permissible the crosscut shifts towards the center, the weaker the shaft diameter will become in the conus and therefore a more powerful bending line will develop. Consequently, the total bending arrow will be larger. The BTH over the total length of the conus undergoes a nearly uniform tension in the exterior fiber. (that is, bending momentum/resistence momentum ≈ $\sigma_{zul}$) The best BTH 28 can be bent more than the BGD 18; all this is achieved without elasticity limitations, and therefore, in any crosscut no violation occurred. These advantages, the tilting position of both sheets and the compression and the expansion, are taken into account.

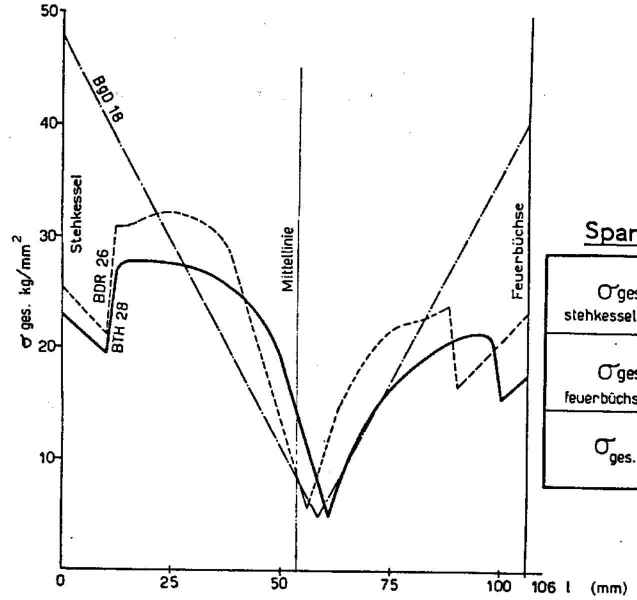
With the complete equal tension in the exterior fibers an s-forming bend will develop. That is the case with equal application momentum but without consideration of the tension that comes about at the transition point. The staybolt can be put into a mathematical formula of a cubic parabola and therefore the bending ability can be previously determined. Such a staybolt with equal tension distribution had been invented by the author several years ago. The turning point of the elastic line also with s-forming bends, as a result of unequal application momentum (uneven sheet strengths, uneven temperature) will shift within the firebox. The staybolts of the best construction, with s-forming characteristics, should be of the type that is not symmetrical. Precise comparing formulations showed that when one relinquishes the non-symmetrical characteristics, in the case of a non s-forming bolt, parabolic crossover yielded no advantages when comparing the conical conditions.

In contrast, in the case of the new design bolts and with elongation when compared to BgS, on the average with various demands, produced the better values and better results.

How the course of bending lines for the s-forming bends are appearing are shown in Ill. 26. For a segment of the installation point $L_s = 146$ mm. There are no differences of any importance for the total permissible bending between BgD 18, BgD 22, and BDR 26, while for the BTH the clear picture emerges. The Ill. 26 shows that the bending line of the permissible bend of BgD 18 is bent stronger in the line point drawing where the boiler effect has been considered. The bending will become smaller in spite of equal tension, but also of equal diameter. In contrast, in the case of BDR 26, and especially BTH 28, the bending near the installation crosscut is of a minimum because of the stronger diameter near the head, which corresponds to a mid situation of the load as a result of the welding. However, in the conical part of the load the tension will become larger. The bending line of the BTH 28 cuts across BgD 18 beginning at the site of the boiler in the conical segment. The demands of the firebox at the installation momentum is below the demands of the staybolts, since the limits of strength and stretch of the bolt occurs much earlier than the installation tension at the sheets. With further plastic bending of the staybolt, the installation momentum rises only slowly at the sheets. (compare point d in this section) Plastic deformation at the sheet installation points, under ordinary conditions of the bolt measurements, because of the installation momentum are not possible. When those phenomena develop there are other reasons, which have been examined in earlier parts of this publication.

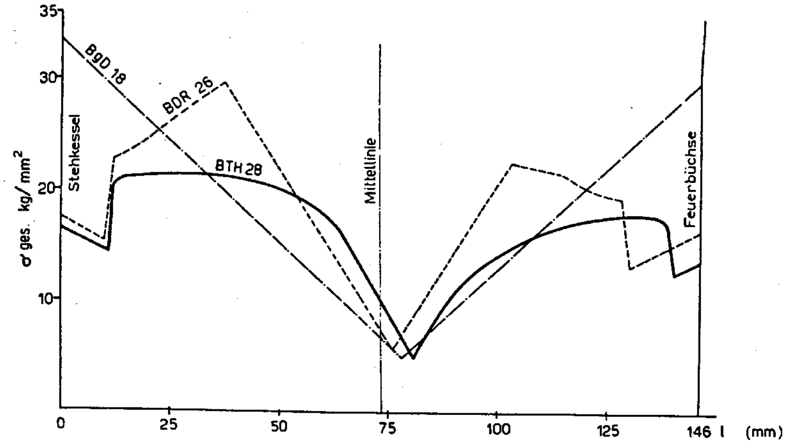
### b) Comparison of the course with cylindrical bolts and new design staybolt shafts

The course of the tension has been studied with the BgD 18, BDR 26, and BTH 28 over the total length of the bolts, including the heads, applicable to 120, 160, and 200 mm length. The excess length of the staybolts on the firebox side was on the average 6 mm and on the boiler side 8mm. This led to all distances of $L_{aW}$ 106, 146, and 186 mm. The sheet strength of the boiler was 16 mm and that in the firebox 10 mm, regarding the measurements of the sheet distance, $L_{iW}$ of 80, 120, and 160 mm.



**Spannungsverhältniszahlen.**

| | L | BgD | BDR | BTH |
|---|---|---|---|---|
| $\sigma_{ges.}$ stehkesselseitig | 120 | 100 | : 53,2 | : 48,0 |
| | 160 | 100 | : 52,4 | : 49,1 |
| | 200 | 100 | : 51,7 | : 49,8 |
| $\sigma_{ges.}$ feuerbüchsseitig | 120 | 100 | : 58,0 | : 44,1 |
| | 160 | 100 | : 54,9 | : 45,8 |
| | 200 | 100 | : 51,0 | : 46,0 |
| $\sigma_{ges.}$ max. | 120 | 100 | : 67,5 | : 58,2 |
| | 160 | 100 | : 88,7 | : 64,0 |
| | 200 | 100 | : 100,3 | : 67,6 |



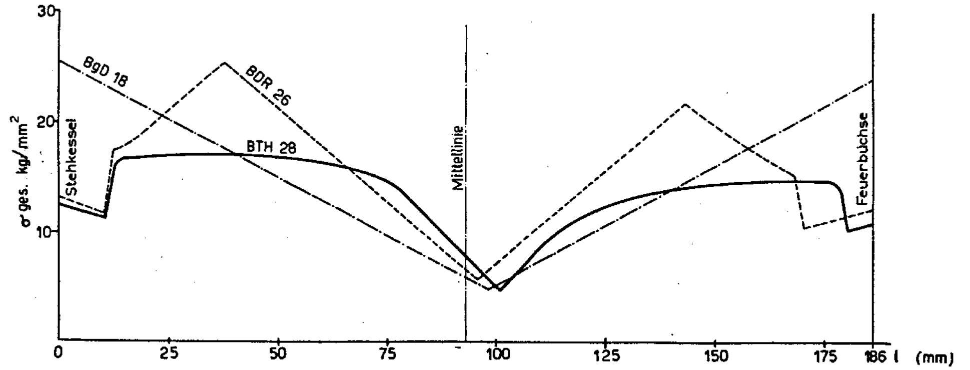
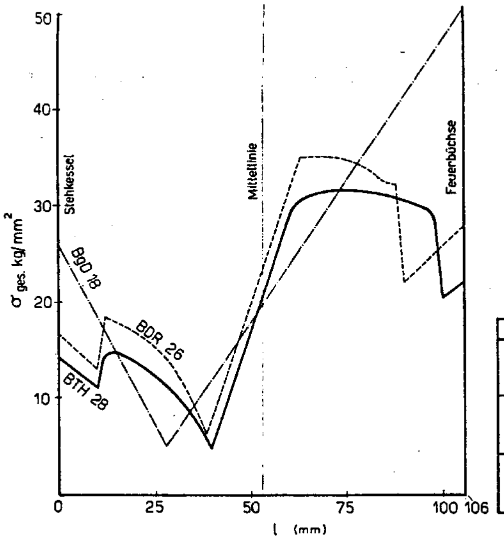
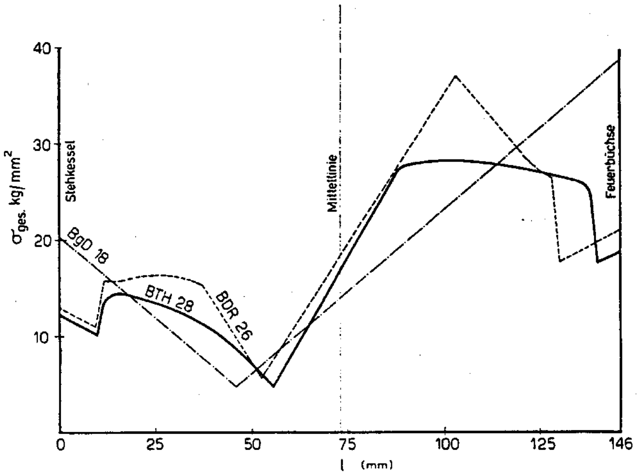


Abb. 27. Spannungsverlauf $\sigma_{ges}$ über die Bolzenlänge für mit Spiel eingeschweißte Stehbolzen BgD 18, BDR 26, BTH 28 von 120, 160, 200 mm Länge bei s-förmiger Verbiegung unter Berücksichtigung von Stauchung und Reckung. ($f = 1$ mm, $\delta = 0$)



**Spannungsverhältniszahlen.**

| | L | BgD : BDR : BTH |
|---|---|---|
| σ ges. feuerbüchsseitig | 120 | 100 : 55,2 : 44,0 |
| | 160 | 100 : 54,2 : 48,5 |
| | 200 | 100 : 51,1 : 49,1 |
| σ ges. stehkesselseitig | 120 | 100 : 64,9 : 56,2 |
| | 160 | 100 : 63,3 : 60,1 |
| | 200 | 100 : 60,2 : 59,0 |
| $\sigma_{ges.}$ max. | 120 | 100 : 69,1 : 62,5 |
| | 160 | 100 : 95,3 : 72,7 |
| | 200 | 100 : 102,3 : 76,7 |



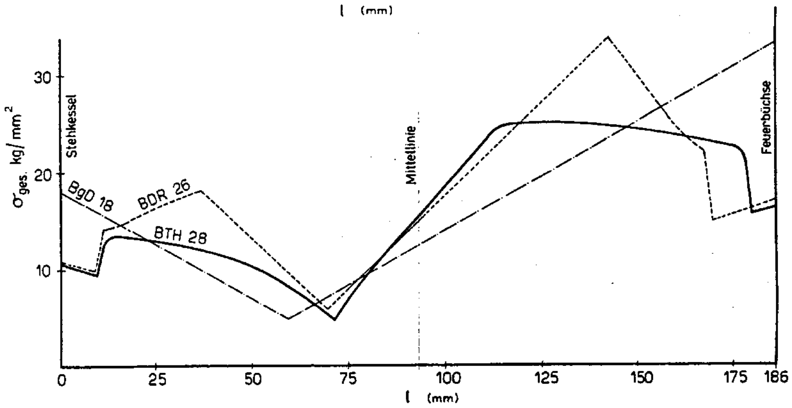


Abb. 28. Spannungsverlauf $\sigma_{ges}$ über die Bolzenlänge für mit Spiel eingeschweiße Stehbolzen BgD 18, BDR 26, BTH 28 von 120, 160, 200 mm Länge bei s-förmiger Verbiegung ohne Berücksichtigung von Stauchung und Reckung. ($f$ = 0 mm, $\delta$ = 0,01)

The heights of the weld seam for all bolts was 6 mm. In Ill. 27 the length of the staybolts and the course of the tension regarding the three types of construction of the staybolts for three kinds of length are drawn for BgD 18 (stippled), BDR 26 (short lines), and for BTH (solid lines). The tension lines of Ill. 27 are in accord with s-forming bends without additional tilting ($\delta = 0$) where the shift equals 1 mm ($f = 1$mm). The effect of tilting of both sheets, as a consequence of the installation momentum, as well as the compression and the expansion of the firebox and the boiler, are affected by the staybolt crossforces that have been taken into consideration. The tension lines are crossing the limits of elasticity $f = 1$ mm depending on the construction material of the staybolts. In the elastic area the crossforce tension and bending arrows shall all undergo shifts in parallel and the values shall be $f_{bzul}$. All that is necessary is to use the tension that has been read and multiply by f in order to obtain the desired tension.

The tension point of the BgD 18 is in all three cases at the side of boiler installation. However, in the case of two other types of bolt construction, on the side of the boiler, in the conical new design part of the shaft or in the transposition to the cylindrical part, tension is found. The tension in the BDR 26, in the crosscut section, are always less in the BgD18. With BTH 28 the tension is less than in BDR 26. But with staybolts that had been welded, in exchange for the looseness to the firmness, the installation crosscuts are of significant importance.

The difference in the tension for BDR and BTH is 10-20 mm. The distance in the cases, as is the situation in bilateral tension, is about 3-4 mm as a result of $D_ü$ because of the increased strength of the staybolt heads. The minimum of tension corresponds in all types of bolts at the turning point of the elastic line, which depends on the position and different stiffness of the bolt. At the turning point, only the pulling tension of the boiler pressure remains. The BDR 26 previously had a shaft diameter of 17 mm and therefore the turning point gives a somewhat higher pull tension. The tension at the firebox side is less than in the boiler as a consequence of the shifting at the turning point. Also in the event of the same sheet strength, there will be a smaller shift of the turning point as a result of the uneven heating and sheet temperature and therefore, in various elastic modules of the firebox and the boiler.

In Ill. 27 Table, the tension of BDR and BTH in v.H. and the tension for BgD are shown. The upper group contains the tension on the side of the boiler installation. In the case of BDR they are slightly over the BTH and about 50% below the BDG 18. The approximate relationship can be found on the firebox side which can be noted in the second part of the table.

In the third level section, one can see the maximum tension. With shortened bolts, one comes near the 25 mm conus of the BDR which is for all staybolts the optimal length of the conus. From these circumstances, one will obtain, in comparison to the BDG 18, a considerable advantage. However, if the bolts become longer, the advantages become less and less and finally cease to be of importance at the length of 200 mm. In contrast to the case of the BTH, the length is independent of the maximal tension and the yields are much better and d.h. lower values.

So the values for $f_{zul}$, with consideration of the compression and the expansion, can be found in Ill. 27. One has only to divide the permissible tension $\sigma_{zul}$ by the readable tension with $\sigma_{max}$ to obtain $f_{zul}$ for the desired staybolt construction method and length, as a consequence of taking into account the expansion and the compression, which then will give a higher $f_{zul}$ value, than the ordinary $f_{azul}$ values, see Ill. 25.

Moreover, without considering compression and expansion, the course of the tension for other demanding circumstances ($f = 0$), like additional tilting angles at the firebox, $\delta = 0.01$, can be seen in Ill. 28. In these cases, the two bolt installations are not shifted against each other, $f = 0$, and in the firebox sheet, $\delta = 0.01$, yields an angle of 34 degrees, that is, with additional tilting in the proximity of the fire hole rings. The difference between the firebox side and the boiler side gives a much larger tension.

### c) Comparison of the permissible shape changing work $A_{zul}$

The degree of largeness of the work involved in the bending of the staybolts, shape-changing work, is of important significance. The higher this work force is, the more arching of the boiler when heating and stretching occurs. If stretching of the firebox occurs towards the interior, the less arching of the boiler towards the exterior when cooling. In both cases, the staybolt will no longer be loaded. A good measurement, in comparison, offers the permissible form change work $A_{zul}$, that is, the work that brings the value of $f_{azul}$ from the staybolt and the sheet together. In Ill. 29 one can find at the exterior sheet distance $L_{aW}$, the permissible form change work $A_{zul}$ to the comparable bolts with the heating stretch limit of $\sigma_s = 14$ kg/mm$^2$. For the BDG and the BTH straight lines will be obtained. The differences of $A_{zul}$ are extraordinary large. In the case of BTH 28, the $A_{zul}$ value is on the average diameter 5.4 times larger than by BgD 18. In the case of the BDR 26, a decrease is noted, because of the permissible and independent bolt lengths; additionally, the non-changing conus lengths, with the decreasing distance of the exterior sheet position, will contribute. The BTH is superior in contrast to the other bolts, even against the BgD 22, with respect to the form altering work. The comparison demonstrates that the stiffening of the boiler and therefore the decreasing load on the staybolts, can influence the selection.

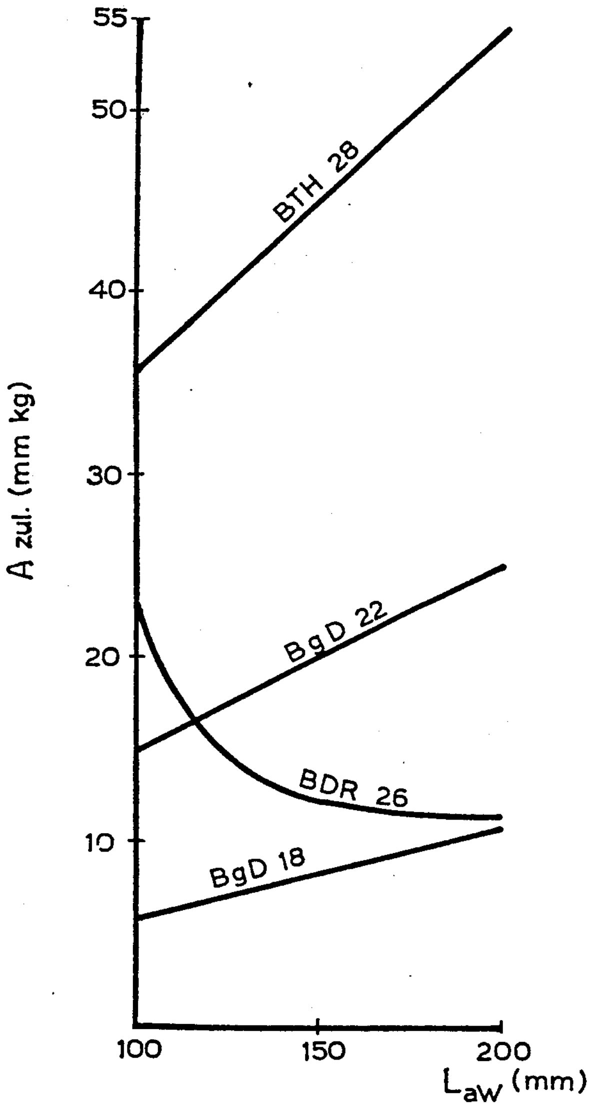


Abb. 29. Zulässige Formänderungsarbeit $A_{zul}$ für die Vergleichsbolzen in Abhängigkeit vom äußeren Wandabstand $L_{aW}$ bei einer Warmstreckgrenze $\sigma_s = 14$ kg/qmm.

## d) The bending of the staybolts in the plastic area

In a large amount of boilers, where measurements of the staybolt bending had been examined, it was clearly shown that a large part of the staybolts, when welded, go far over the limits of the elasticity and therefore, have been bent plastically, as a result of the greater demand. As soon as the plastic deformation begins in the crosscut, at the same time, the rising installation momentum will become a slow process. The additional bending will lead overwhelmingly to further plastic lengthening of a crosscut that has already exceeded the limitations of the elasticity. The more the interior fiber of this endangered crosscut are over the limits of elasticity, so much higher will be the role of the bending, the bolt $f_b$ and the total shifting f, and so much less will be the parts of $f_{wFb}$, $f_{wStk}$, and $f_s$ as well as the prime $f_r$ will play.

The steeper the tension point will fall and the shorter the part of the exterior fiber will be deformed plastically, then so much greater is the lengthening process. This is essentially applicable to the BDG but also to the longer BDR. This is the case in the first installation of the tension crosscut and for the ultimate exchange from the conical to the cylindrical part of the shaft. The more even the tension is distributed, in the conical part of the shaft, so much longer is the part over which the elastic stretching is distributed and so much less is the maximal percentile lengthening. This explains also the tear formation in the case of the BDG soon after a brief operation of the locomotive. But mostly a deep tear is noted in the installation crosscut if within limits. The bolts with the new design shafts, only after prolonged use, will have a smaller tear in the conical part of the shaft.

The bending lines in Ill. 26 are applicable to the elastic part. In order also to determine the bending lines in the plastic part and to be able to compare, G. Sonntag[5], used the bending lines with exclusive plastic demands, ignoring the consideration of the tilting of both ends of the staybolts, see Ill. 30. He arrived at the following conclusions and the results in his report, according to known graphic methods with experiments in conjunction, the bending arrow $f_b = 1.2$ mm and it was determined that the bending lines cross the power lines. The approximate cross powers are:

| | |
|---|---|
| The BgD 18 | 220 Kg. |
| The BDR 26 | 320 Kg. |
| The BTH 28 | 600 Kg. |

Larger bending arrows will yield only small increases in the cross power by way of hardening. It is therefore of importance that the already in high demand field staybolts will undergo a high risk of breakage, when subjected to stronger bending. These dangerous parts or situations in the bending in the case of the BgD are beginning with the installation tension. In the case of the BDR, at the site of the conus, the above process will begin. The conditions will worsen by the neglect of the pull power. BTH showed no particular place or tendency, while the great bending is relatively soft in the conus near the largest diameter. Therefore, enlarging the pulling power to the advantage in favor of the length with the plastic area (demands are more favorable by avoiding sharpness of the demands). However, the acceptance of a large workload, high cross power, will lower the tension and will give favorable conditions for the staybolt.

These results are in agreement with the experiences concerning the use of the BgD, when removed after use the bolts are perfectly straight between the two installation points. The small degree of bending are directly at the point of installation, and when removed is often overlooked. In contrast, bolts with new design shafts have a clearly distinguishing line of bending.

In the case of shaping work, in the plastic area one can note a difference in favor of the new design shaft with a large plastic area.

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[5] Footnote on Dr.-Ing. G. Sonntag, un-translated.

## 2) Improvements of the construction of the building forms of the flexible-type of staybolt

The many questions with regard to the flexible staybolts are too extensive to be discussed in this publication. The author has for the past many years examined these questions many times and reported on the findings. Only the most important conclusions will be mentioned regarding the above findings:

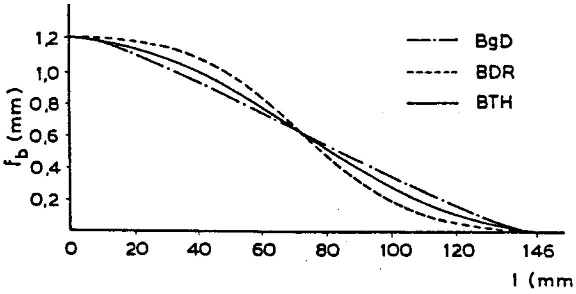


Abb. 30. Charakteristik der Biegelinien für die Vergleichsbolzen bei Beanspruchung im plastischen Bereich ohne Berücksichtigung der Wandwellung.

The theoretical superiority of the flexible bolt in contrast to the solid one piece bolt, with the $f_{zul}$ value on the average, are only half the height of the flexible staybolts, but at some distance from the sheet, has not proven to be the case in actual operations. While the behavior of the flexible bolts have proven to be better in the edge zones, when looking at the solid bolts, the differences are not as large as one would anticipate. This can, in part, be explained to a large degree by the arching of the boiler increasing directly with the number of flexible bolts, since their resistance to deformation is smaller. With the large number of flexible bolts, the American experience was very poor and inadequate. Flexible staybolts should be restricted to positions in the boiler where otherwise solid staybolts, after a short operation time, will have a tendency to break. As a rule, these positions are to be found in the upper and exterior edges, where the use of flexible bolts had already been used customarily. One can therefore expect that the zones where breaks occur in the locomotive boiler are minimized if the suggested measurements to reduce the boiler deformations are followed. The number of flexible staybolts may then be further reduced.

### a) Type of joint

It has been commonly the case that in Europe and in America exclusively staybolts with ball joints had been used on the side of the boiler. However, these possess the disadvantage that a shift on the boiler side of the ball head can take place and therefore no bending of the shaft will be permissible. The ball heads at first will be lifted from their seating when cooling and second when reheating takes place because of the stronger stretching of the crownsheet and then will be more lifted from their seating. Only after a rise in the pressure after reheating, will they return to their beds. But in the meantime firebox and boiler have undergone differential stretching. The bolts when returning to the bedding are often bending or will come to rest outside the bedding. In a questionnaire to the American railroad administrations, wherein had been asked, what in their opinion are causes for the flexible staybolt breakage, more than half responded that the freezing of the joint was the cause for the breakage.

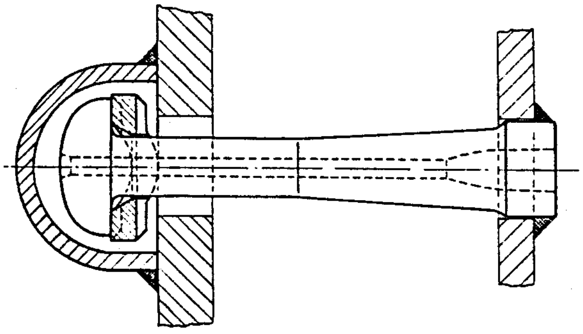


Abb. 31. Gelenkstehbolzen mit Ausgleichring und Verschluß-kappe und mit feuerbuchsseitig großer Konuslänge, gewindelos mit Spiel eingeschweißt (Kreuzgelenkstehbolzen BTH).

This disadvantage is not found in the cross joint [flexible] bolts Ill. 31., but has been experienced in the newly constructed locomotives of the Deutsche Bundesbahn. These cross joint bolts permit a lateral shifting of the joint application on the side of the boiler without bending the staybolt. The bending of the staybolt begins only when a reapplication takes place after cooling and reheating. Moreover, the equalization rings show less resistance than the ball joint heads.

### b) Configuration of the solid staybolt parts

The knowledge gained with the experience from the solid staybolts can also be applied to the construction and configuration of the flexible staybolts to improve their performance and duty. It is of great advantage to consider the lengths of the shaft in the conical part of the bolt and keep in mind the length of the staybolt itself as well as the diameter of the head. However, in the case of the flexible staybolt the resistance in the joint comes closer to the type of staybolt that is regarded as a "free carrier", in which case only the fireside part of the conus is needed and that is much longer than the solid staybolt. The $f_{zul}$ values will rise in the case of the so called preformed staybolts at about 75% and in contrast to the other configuration at the same time the value for $A_{zul}$ will become larger. Therefore the major disadvantage of the flexible staybolt is, in comparison to the solid staybolt which needs less work, the increased workload. In order to have the drillings independent, with respect to the equalization rings of the firebox side, head diameter must be made so that it will accommodate the larger bedding. It is best therefore to place a ring before the compression of the second head on the locale of the shaft.

### c) Double jointed [flexible] staybolts

From the point of view of the demands made on the staybolt, a double-jointed staybolt would have the least demand on the staybolt tension. However, there is a great concern that the deformation of the firebox when cooling and reheating, will exact a greater toll and cost in the long run. All that because the double-jointed staybolt needs only a small deformation at the bedding and the bending will, in most cases be less, but the friction at the bedding will have more influence than can possibly be anticipated. Only after cooling, will both heads seat well when pressure demands appear. One can therefore expect, that in the course of installation, using a large number of double staybolts, the staybolts' positions therefore will be less. But the positions of the normally used installation points in the firebox become larger and with time the firebox itself will be enlarged. Considering all this together these are the most likely reasons that the proposed double-jointed staybolts will not be enjoying a great popularity.

## E) Special consequences for the installation of staybolts

The thoughts and the experiments in Part D. for the best form of construction, are independent of the installation experiences regarding whether these are staybolts with threading, with and without sealing, welding seam, or for the staybolts without threading that have been welded. Also in copper fireboxes with Kuprodurshoes the new building formation will be of significance. The installation of staybolts with threading has already been discussed under the section when dealing with the copper firebox. But the case of staybolts whether only welded or seal welded was used needs some further clarification. These questions will be further studied. This work produced a number of valuable facts where consideration is given to the welding of the staybolts.

### 1) The questions that are related to staybolts that have been welded

a) Arching of the boiler when staybolts had simply been welded and those that had been seal welded will be discussed. When welding of the staybolts takes place the boiler sheets will move and buckle due to the local heat generation from the welding, first on the side where the welder works (buckling midpoint on the waterside of the sheet) for the same reasons. While under operating conditions, arching of the firebox sheet will develop towards the interior. The sheets on the side of the welding have been heated and the surrounding parts of the welding locale, particularly those unheated parts, will prevent the heated parts from expansion. This is the case of the side where the welding had taken place since the stretching is inhibited and therefore a plastic compression will occur. The sheet will shrink, particularly on the welding side, when cooling comes about and will buckle from the side of the welder (buckling mid portion on the welded side). This process will be repeated at each staybolt with a total summation of the events described. This has been examined under laboratory conditions with freely moving and boiler installed strips of sheet.

For this purpose we used strips of 1750 mm length (approximate firebox length) 85 mm wide strips (part of a staybolt) and 10-16 mm sheet strength and 20 threadless staybolt ends from 85 mm to 85 mm which then had been welded two times. In the case of the freely movable 10 mm firebox sheets, the bending arrow had a value of 158 mm after welding and cooling of all ends of the staybolts. This gives a constant sheet arching. This produced a shrinkage in the central fibers 3.8 mm on a sheet length of 1700 mm. The following numbers were obtained: 11 mm firebox sheet, 143 mm bending arrow, 3 mm middle shrinkage, 16 mm boiler sheet, 87 mm bending arrow, and 1.8 middle shrinkage. Bending arrow and shrinkage of the strips will become larger in their central fibers the weaker is the sheet. The deformation follows in the pattern that after cooling, the normally parallel shafts of the bolts will change to the appearance of a porcupine distribution. The Ill. 32 shows three bent sheet strips after welding, all staybolts in the upper firebox sheet 11 mm, in the middle boiler sheet 16 mm, in the lower end boiler sheet where a welded cap for flexible staybolt was used 17.2 mm. From the shadow effect a strong bending of the firebox sheet is visible. The bending of the boiler sheet with the welded cap gave a value of 120 mm. The local bending, as can be expected, is in the near neighborhood of the welding point, and was most pronounced in the middle part and the least is in between two staybolts.

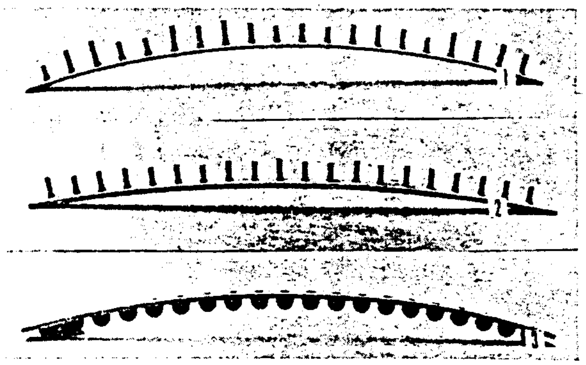


Abb. 32. Durchwölbung von Kesselblech - Streifen infolge des Einschweißens fester Stehbolzen bzw. der Gelenkstehbolzen-Kappen

If the sheets are mounted in their total length in such a manner that during the welding and cooling no bending occurs, but removal of the mounting as a consequence of the retained shrinkage tension capacity, a form of arching will develop. The bending arrow of the strips from the firebox each 10 or 11 mm showed in the sheet only 25 mm, that is, only one sixth of the bending arrow of the non-mounted sheets. In the case of the mounted sheet of 16 mm of boiler sheet the bending arrow was 29 mm, that means one third of the bending arrow in the non-mounted sheet. The diminuation of the bending arrow as a result of the mounting was less in the case of the boiler sheet than in the firebox sheet. The bending arrow of the boiler sheets that had been mounted in the past, however, was larger than those of the corresponding firebox sheet. The existing tension that results from the welding while in the mounted condition will have a residual tension that is larger in the boiler sheet than in the firebox sheet. The shrinkage of the central fiber was larger in the mounted sheets in comparison to the un-mounted sheets.

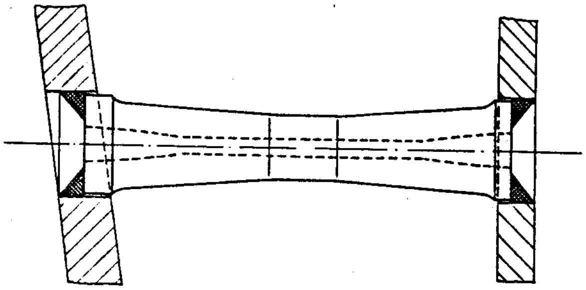


Abb. 33. Fester Stehbolzen (BTH) mit beiderseitiger Innenschweißung

Both results agree with the experience in the boiler. Only when welding takes place on the side of the firebox will strong arching develop in the boiler. When bilateral welding is done, the arching will be stronger in the boiler, that means that the boiler will be arched towards the interior including the mud rings. In order to decrease this arching, experiments had been conducted, see Ill. 33, with a 3.25 mm electrode in the interior. To seal weld the bolts in the sheet holes electric current must be used. The total arching with the freely movable 10 mm experimental strip lowered the bending arrow from 158 to 24 mm, that means only one seventh of the normal arching. Also the shrinkage went from 40 v.H. to 2.3 mm. To assure the wellness of these interior welded bolts, 40 bolts had been installed in the above manner and thereafter were torn apart in which 20 of the bolts had been welded in 10 mm or 16 mm sheets. 38 of the bolts broke at the shaft when loading of 10.1 to 11.1 tons was applied. The two remaining bolts broke at the welding seam when a load of 9.5 to 10.4 tons was applied. The welding seam is stronger in the preformed bolts than the shaft when welding had been employed in the interior. That is, in comparison, (Ill. 24) to those exterior welded BgD 18 where only one shaft broke but 4 of the remaining 5 broke at the welding seam when loaded with 8.2 to 10.3 tons. An interior welding with a BgD 18 is not practical and cannot be executed since the exterior diameter for the interior welding process is insufficient and the control drillings would seal themselves off. It can be expected that according to Ill. 33, that the interior welded bolts will give a better service than those with a gular suture and exterior welding. The following advantages can be noted:

1) 30 v.H. welding seam and therefore less heating and less shrinkage of the sheets. A single welding process, considerable savings on the electrode, over 70 %, in contrast to the need of two exterior weldings.
2) Welding seam near the center part of the sheet, therefore diminuation of a throughout arching during the welding of only one broken part.
3) Staybolts that are 30 mm shorter with equal sheet distance, therefore less weight of the boiler.
4) Less heating of the staybolt heads during the operation, therefore less expansion and less heating tension at the head and at the site of the hole.
5) Expansion possibility while in operation, mostly at the heated fireside crownsheet of the firebox in a radial fashion from the staybolt holes, without demand at the welding seam, therefore a minimum of expansion and shrinkage limitation and less deformation of the boiler while in operation
6) No sharp edges at the staybolt heads and at the welding seam.

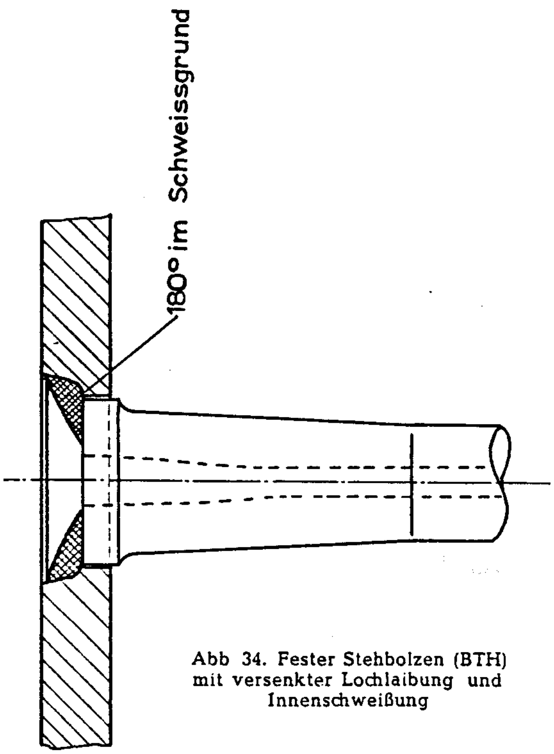


Abb 34. Fester Stehbolzen (BTH) mit versenkter Lochlaibung und Innenschweißung

The concerns are that the exterior welding seam is more difficult to inspect. Poor quality welding seams or tears in the weld which will begin to leak can be discovered with the hydrostatic test alone or during operation. The danger lies in the fact that the welding seams breaks remain unknown, which can be similar like the breaks of the installation crosscuts as is the case with the BgD. The welding in the conical extended hole would eliminate the risk of staybolts being pulled through.

Particular advantages occur when the welding around the sheet hole covers the tears around the shrinkage of the firebox side of the welded seam. In Ill. 37 such tears in a solid welded staybolt with threading has been noted in reports from the USA. These tears will develop the longer the operation time is and the same thing has been noted in some European railroads. These tears have been a consequence of repeated expansion and compression, especially when high heating of the material on the firebox side occurs. The expansion and shrinkage inhibition, especially in the horizontal lines and the tears, are predominately vertical and rarely will encircle the staybolt. They have to be in the approximate parallel of the sheet hole tears, Ill. 35. That is, because they have to be located by the backward lead. During practical experiments in a locomotive boiler with the sheet hole welded, staybolts have not yet been made. In consideration of the selected advantages one would think that there are opportunities at the firebox side.

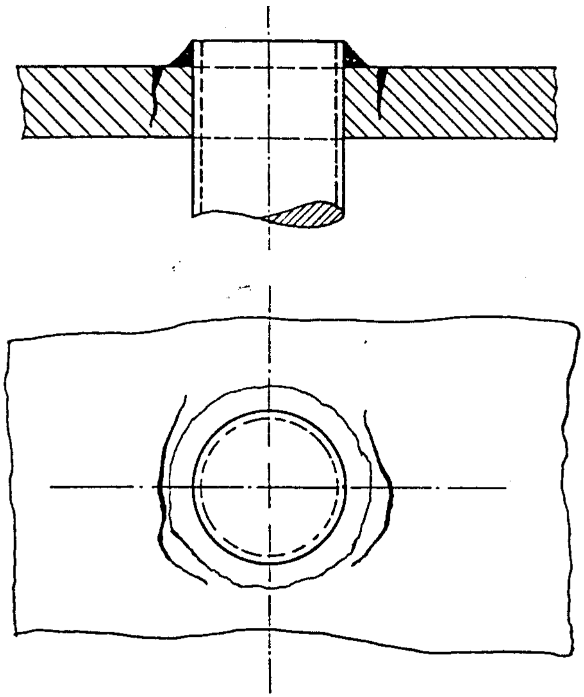


Abb. 35. In USA nach längerer Betriebsdauer beobachtete Wandrisse bei dichtgeschweißten Gewindestehbolzen

## b) The interplay between the staybolts and the hole in the sheet when welding of the staybolts takes place when heating.

Regarding the question of the staybolt and the hole in the sheet, before the welding process begins there are divided opinions. In the case of the BgD 18 one finds a large number of boiler side welds where bolt installation occurs complicated at times with tears. While welding is in progress, the bolts will loosen in their attachment zone. In order to decrease the load in these zones it appears best to weld the bolts in such a manner that no play will develop. For clarification of these intertwined matters the question of the role of the diameter has by this author theoretically in detail been examined and verified by experiments in the laboratory. One has to differentiate three types of interplay:

1) The tolerance play that the difference in diameter of the bolt versus the hole in the sheet makes before the installation and the welding process.
2) The installation play, which the firebox on the boiler side will show after the welding process, this remaining play or absence thereof must be taken into account.
3) The cold play that only on the firebox side, especially in the firebox zone, develops and occurs after each operation. During the cooling, then in addition, the installation play will happen to staybolts with threading. This play will become smaller or will disappear altogether when reheating begins in the boiler.

The original cause for leakage occurs during cooling with staybolts that had not been welded.

The temperature will change at the sheet and the point of installation from the last operational condition. The installation play and the cold play can be united under the concept of operational play. During the process of welding, an installation of the bolts, as well as the surrounding parts of the sheet, when producing the welding seam, will be heated beyond the melting point. The bolt will expand to such a degree as is permissible in the relationship between the hole in the sheet and the bolt itself. The expansion of the bolt in such a case will clearly be without any tension. If there is no tolerance play the bolt will press at the beginning of the heating process against the hole in the sheet. Depending on the position, the strong temperature flow limitations of the sheet and the building material of the bolt will be pressed together and the enlargement of the hole in the sheet will develop.

The real diameter value of the hole in the sheet and the bolt are changing during the welding process. They no longer relate to the original measurements because of heat expansion. When cooling takes place, the bolt becomes smaller or the hole in the sheet becomes larger when compared to the original measurements. The sheet parts that are surrounding the place of welding have a tendency to heat up in a radial manner and expand in the same pattern. However, this is moderated by the fact that they are surrounded by cold parts of the sheet and inhibit this process. As far as the play of the tolerance permits, they will expand towards the central part of the hole in the sheet but this expansion is not tension free. If there is no play of any tolerance, the heated sheet parts and the hole in the sheet, as well as the hole of the bolt, depending on the limitations of the flow, shall plastically be compressed, or will exert more pressure on the bolt at the point of installation. The compression pressure at the sheet and from the bolt will be additive and will lead to considerable plastic deformation. All this together when cooling takes place will yield a play between the bolt and the hole in the sheet, and even so, when there was no tolerance play under the original conditions.

When cooling develops after the welding of the bolt, there shall be a tendency to return to the original measurements, meaning that it will contract beyond the plastic compression unless the welding seam is unilateral and prevents such compression. Concerning the hole in the sheet, no such expectations exist or can be anticipated. But with the expansion of the sheets in the direction of the hole in the sheet, tension will develop. This is with certainty the result of the high temperatures involved, which then will yield high plastic deformation. A return in the hole in the sheet during cooling to the original measurements are expected in such a case. The welding seam inhibits the shrinkage of the bolt and the hole in the sheet the closer the crosscut is to the welding seam. The installation play, that is the one in the nearest proximity of the welding seam, becomes smaller in comparison where the distances are much farther away.

With these thoughts in mind of the hole in sheet shrinkage measurements are in full agreement both practically and mathematically. Also in the case of pressure seating, a degree of installation play at times will develop. The deformation and the shrinkage of the flat surfaces in these cases of pressure seating produce some degree of tolerances which were as a rule larger than the ordinary expected tolerance play.

The measurements yielded the following:

1) Welding heat applications without bolts and with a hole of about 18 to 30 mm diameter were smaller by 0.23 to 0.38 mm on the side of the welding after cooling.
2) On the waterside the holes had been reduced by 0.16 to 0.20 mm in the boiler.
3) In the firebox sheet the reduction was 0.26 to 0.36 mm, therefore it can be assumed that the hole without a bolt during the heating will suffer a reduction of 0.2 to 0.4 mm when the process of cooling commences.
4) Regarding oversize boltheads, when they underwent cooling, a 0.18 mm correspondingly smaller hole was observed. But nevertheless, 0.18 mm larger than the original measurements.
5) Since the hole where no head is situated has been smaller by 0.23 mm which then gives a difference of 0.50 mm, because of a plastic deformation of the hole in the sheet.

This is related directly to the difference of measurements of the diameter of the hole in the sheet without a bolt and no pressure seating bolt in the hole in the sheet. In addition to all these matters one must regard the bolt deformation of 0.18 mm so that total deformation is the sum of bolt deformation and deformation of hole in the sheet and their difference when there is no bolt to be considered. The total difference between with bolt and without bolt comes to 0.68 mm. The total plastic deformation of all parts calculated on the same basis, gave for the firebox sheet 0.55 to 0.68 mm and in the boiler 0.30 to 0.50 mm. If the total deformations are added, that is the and/or negative, one will find in the experiments conducted 18, 22, 26, and 30 mm of diameters as the sum of the tolerance play and the plastic deformation of the bolt. The sheet diameter of the firebox shall be between 0.36 to 0.71 mm and in the boiler 0.41 to 0.52 mm. These results remain independent of the bolt diameter and the tolerance play. Practically all of these values are within the narrow limitations. One has to keep in mind that during the welding process, there could not be kept a constant temperature in all parts. The larger the tolerance play that had been selected, the smaller the total deformation as a result of the heating during the welding. The remaining installation play (diameter difference calculated) was for the firebox 0.3 to 0.4 mm and for the boiler 0.16 to 0.22 mm.

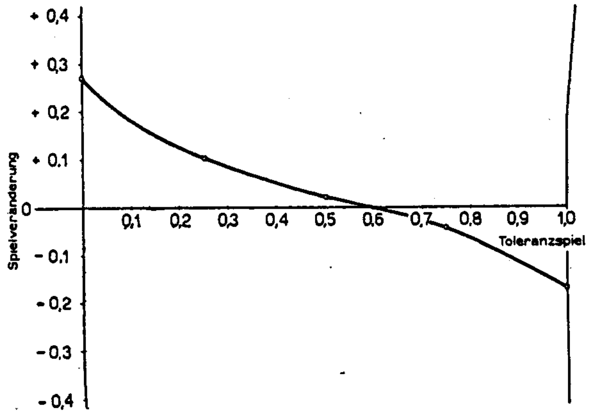


Abb. 36. Spielveränderung infolge des Einschweißens der Stehbolzen in Abhängigkeit vom Toleranzspiel.

Ill. 36 shows that during the installation welding of the staybolt on the average the play tolerance will not change. The Ill. 36 points out that up to a tolerance play of 0.6 mm, the play for the installation may become larger than the accepted tolerance play. The change in play will become larger if the tolerance play becomes smaller. However, if the tolerance play surpasses the value of 0.6 mm the installation play will become smaller. Beginning with the tolerance play of 0.75 mm the deformation of the bolt will be limited to the proximity of the welding seam. At the point of tolerance play of 1.0 mm the deformation of the hole in the sheet begins with the bolt approximating the same amount of deformation as it would be with the hole in the sheet without a bolt.

The results of the investigations leads to the following conclusions:

1) The goal to have a solid installation with a pressure seated bolt in the neighborhood of the welding seam before the welding cannot be obtained. Installation play will always develop on the side of the welding. This also applies for the seal welded staybolts with threading where the solid seating shall be lost.
2) The remaining sheet and bolt, which have suffered compression, will therefore, when cooling takes place, experience shrinkage at the welding seam, sheet and staybolt. The following developments will take place, bolts that have no tolerance play and bolts that have tolerance play at the beginning of the above processes. The larger the tolerance play so much less deformation will remain.
3) The loads after the welding at the welding seam is larger in the case of bolts without tolerance play. This load is also larger for the corresponding sheet when compared to bolts that do not have a tolerance play.
4) The power connected installation of the bolt at the head end can possess positive or negative values. The elimination of the non-preventable installation play before locomotive operation begins is undesirable, but in the boiler, probably of advantage, but not so and not desirable in the firebox. The advantage in the boiler can only be gained by enlarging the head.

**c) The loosening of the staybolts**

The welding of a staybolt has a distinct disadvantage that the material of the bolt in the vicinity of the welding seam may loosen the bolt. The loosening can be of substantial value or problem. It is a result of the over heating during the ongoing welding process. In order to counter balance this loosening, a strengthening of the staybolt head is necessary and especially of importance while in operation and an effective installation in the proximity of the welding seam. Those by the author initiated bending endurance tests, of which the results are reported in $F_1$ have been ascertained to be useful when such steps as above are undertaken.

**d) The installation of staybolt heads**

The possibility of creating and the maintenance of an operational play constitutes on the firebox side a large advantage. Comparing the welded staybolts in contrast to the staybolts with threading the welded bolt has an advantage. If the play is large enough and heating takes place, then the hole will seal itself without plastic deformation. As has been shown by the experiences and experimental results in the case of a large tolerance and equally large installation play, that the cold play will be smaller when the firebox installation play will be large. The closing of the firebox side during operation while reheating, leads to a minimizing of the load on the welding seam. The welding seam comes under pressure during the stretching of the sheet and the bolts as it occurs during the operation. The remaining tension which is residual from either heating or cooling will be reduced. The fact that the operational play will seal itself in the presence of welded bolts on the firebox side has been observed at the ring forming pressure points in many cases with bolts that had been removed after operation.

Due to the different circumstances these pressure points are absent in the side of the boiler. The installation play in the boiler cannot seal itself. The demands of the bending has to be carried by the welding seam on the side of the boiler. Also the boiler pressure and the bolt cross forces expand the boiler while in operation on all sides and produce further tension. When cooling occurs the arching of the boiler will be towards the exterior and an enlargement of the tension on the boiler side welding seam. For these reasons it becomes clear why staybolts which lack threading on both ends that had been welded, fail. The welding seam will show tears in the loosened staybolt zone, and almost always will appear at the boiler side. For the same reasons it is best to have pressure tension in the welding seam.

As previously mentioned, with a simple approach dealing with the bolts, all this an be circumvented by welding enlarged heads at the bolts. By this procedure are not only the bolts installed in a hard manner, but also the welding seam, as well as the hard bolt zone will have a decrease in load. In addition, the tensions in the welding seam and the desired pressure tensions are achieved. Experiments in the laboratory that the arching as a result of the installation welding, will diminish when accompanied with spinular formation. That is the case with the experimental parts where the arrow will change from 29 mm to 18 mm after application of the enlarged heads. In the case of the staybolts without threading which have enlarged heads, never has a leak or any other disadvantage been noted. Therefore there is no reason that at the boiler side post, enlarged heads application should yield any disadvantages while the locomotive is in operation. In order to verify the laboratory work it was thought best to check the enlarged head application in a few newly built boilers.

### e) The fact of the affordable, permissible length of the staybolt and the strength of the welding seam

In the course of the installation welding one frequently has the experience, that the push is entered only on the unilateral fastened bolt. It appears to be that they are too short during the welding. All of this is in stark contrast to the assumption that boiler and firebox will be arching in a concave way towards the welder. From this thought comes the idea that the distance on the interior sheet shall be smaller as a result of the arching and the staybolt is excessively larger. To clarify the incremental steps, the installation of the staybolt and it's measurements of the distance in these zones at the time, no welding had been accomplished. It was discovered that both sheets welded installation had been done to produce a concave arching, but that such changes also involved the neighboring parts where no staybolts had been welded. The sheets are bent backwards in the proximity of the fastening with other parts of the boiler of already installed bolts through welding. Therefore the distance of both sheets will be larger in spite of the fact that the staybolts had not yet been welded on both sides. Under these conditions longer staybolts are needed (this can be corrected by using a series of half staybolts) in order to inhibit a larger sheet distance.

The bolts originally used in Germany were 4 mm longer but it soon became apparent that they were obsolete in their function. For these reasons it became necessary to lengthen the bolt by 6 mm and to equalize them in the firebox. In the boiler the values were a minimum of 6 mm but could have variations so that they were able to meet the conditions of equalization. In the USA where the welding installation were predominately of the type called seal welding at the firebox, it was found that the staybolts were best in excess regarding the firebox if the staybolts had threading, the type of threading used was ¼" = 6.3 mm.

### f) The bending of the staybolts, when in the welding process, are reasons to develop a correct dependable program for welding

Local arching, while welding installation from the many adjacent staybolts, will lead to shrinkage of the sheets that will cause a constant changing of the staybolt bending. A series of measurements in a number of boilers demonstrated that under unfavorable welding conditions, a large number of staybolts will bend and under extreme situations, break. This is particularly the case with those bolts that are the first ones to be welded, and including those bolts that only had been attached, did bend as much as 5 mm when the welding of the remaining bolts was undertaken. When the conditions for welding are less favorable, the staybolts are able to have the ability to change directions of the bending, back and forth. This will happen before the staybolts will be stabilized in one certain bending position. Consequently, as a result of this behavior, the first installed welded bolt showed tears at the site of the welding. This oscillation of the staybolt will come to rest after the welding of the remaining staybolts has been completed. It is possible that under these conditions a breakage may occur. The test for steam was done under ordinary operation conditions.

This fact demonstrates the importance to reduce to a minimum the bending, and select the most favorable and economical situations, the best longevity for the staybolt will then simply have been selected. Many experiments and measurements have clarified and illuminated the questions posed above. In this publication only essential and basic results can be reported.

The optimal steps for the welding were that part of the firebox that had already been used contained welded staybolts. During this process of welding the other parts no further shrinkage was shown. Moreover with continuous welding of the staybolts, the increasing arching of the boiler is kept to a minimum. In order to achieve this goal it would be best to weld the staybolts at the outside and the inside simultaneously. Also when one is switching, while welding, between the firebox side and the boiler side, there remains the chance of erroneous welding at a very small limit. The same can be said if the unilateral field of welding can be maintained at a minimum area. For practical reasons it has become clear that tagging of the staybolts is best not employed. The two times heating, once in  the tagging and second during the welding, will lead to a larger surface area shrinkage and arching.

The tagged staybolts are bent to and fro before they are hard welded. The elimination of the tag is not desirable from the viewpoint of completion since during simultaneous bilateral welding no greater amount of time is needed but greater care is in order. When one wants to pre-anchor in the boiler and the firebox during the welding it becomes necessary to use a half bolt 5 v.H. That is needed to replace during the welding the normal staybolt in order to exchange them with a half bolt. For the welding the following steps are important and recommended, meaning that the direction of the sheets without resistance, at best in the direction in which the welding of the staybolts take place. The best results are obtained, when simultaneous welding takes place, beginning with a staybolt head at the lower bottom ring, and one horizontal row after a flexible staybolt had been placed at all four sheets to complete the welding. The completed welded staybolt rows will be exposed to very little significant deformation. The bending of the staybolt will regress to about one eighth. Between these best technical positions and the others with their high cost of previously, commonly used methods, the different combinations will be studied in depth. This is to find the welding step that is not inferior to the technically best but economically more demanding, a comparison will have to be made. This goal has been partially obtained with the welding step when one begins at the bottom rings and not with a very large number of horizontal staybolts. At the same time, the weld at the firebox and at the boiler side should be done simultaneously. After this step, turn the boiler on the opposite side to begin welding in that manner. In this position more horizontal staybolts can be attached in longer rows and then welded before the boiler is returned to its previous position and the welding can be continued by the same method. It is also a good opportunity to weld additional horizontal rows at the fluesheet and doorsheet in order to hold the shrinkage of the boiler quite uniform. A welding of the crownsheet staybolts should only proceed after completion of the welding regarding all the lateral staybolts.

## 2. Advantages and disadvantages of the non-threaded staybolts with staybolts that have been threaded

The past experiences permit the discussion of the advantages and the disadvantages of the different methods of staybolt installation. One can make useful comparison of these different entities. The correct measured and built in threadless staybolts have the following advantages:

a) Permanent sealing at the firebox
b) Decreased play at the firebox side and lower expansion-inhibition with smaller arching of the boiler and possibly also less shrinkage at the level of the firebox while in operation
c) Diminuation of the radial hole in the sheet tears in the firebox by avoidance of play
d) Elimination of special repair steps
e) Less long steps by d) and in e) a lowering of the width of the threaded bolts to one tenth
f) Simpler and less expensive production of staybolts
g) Elimination of the very expensive thread cutting tools

The non-welded threaded staybolts have the following disadvantages:

a) Deformation of the firebox, the boiler, and the staybolts when welding, therefore the increase of arching of the boiler towards the interior which may be regarded as an advantage.
b) There will be no free tension when shrinkage of the flat surfaces occurs and also in the firebox and the boiler when welding, even when following the best welding methods.
c) During the installation welding, the staybolts will be pre-bending beyond the flow limitations that should be in the same direction as will be later during operation.
d) Installation in the boiler will require a strong demand from the operational play and the boiler's welding seam, if the heads are not equipped with enlarged heads.
e) In the welding zone, the loosening of the bolt can be noticed, with therefore the highest degree of danger of breakage of the staybolt head that had not been fortified, and with tension especially in the side of the boiler. Knowledge of the tears at the installation point, even after removal of the staybolt, is evident. The reason for the tears are a result of drilling in some cases.

The points of b and c demand the strictest adherence of the welding plan which requires particular care and attention when preparing for improvements at the locomotive boiler. Only on the fireside of the welded staybolt with threading will one encounter leakage with a staybolt. But also in the firebox there are additional disadvantages:

a) Only at the welding on the firebox side will one note arching at the beginning of the welding process in the boiler towards the exterior. This is magnified during the operation of the locomotive. These are the explanations for the poor performance of the boiler where on the firebox side threaded staybolts had been used. The nearly vertical sheets of the boilers' sidewalls have a record of undesirable consequences. In contrast, when bilateral welding took place, only light arching of the boiler in the rear part towards the interior one could notice some remaining arching.

b) If unilateral welding is done then only the firebox will shrink. As a result of the unilateral welding a unilateral bending of the bending arrows of the staybolt shall be greater than in the case of bilateral staybolts. The bending is a result of only the difference of the shrinkage of the boiler and the firebox.

Based on the experience from the operation which serves as a guide one can look at the staybolt without threading in comparison to staybolts in the welding process with and without seal welding in spite of the mentioned disadvantages. Under certain circumstances, this disadvantage can, without any doubt, at sometimes be considered to be superior. This is particularly the case when applied to the steps as suggested for the welding process of the staybolts, and if everything is taken in full consideration, to diminish the disadvantages as much as technically possible.

## F) The results of the staybolts oscillating experiments plus the obtained experiences from this operation

### 1) Oscillating experiments in the laboratory

In order to verify the calculations and the thoughts and also to check the knowledge gained, several experiments were conducted in the laboratory of the company "Henschl & Son GMBH", Kassel, Germany. Numerous staybolt oscillations had been undertaken. These experiments have not yet been concluded totally. A special built tool was utilized as a piece of equipment for the staybolt, that also can check for corrosion while the experiment is still in progress. Already it can be stated that the experiments with the oscillation have proven theoretically correct. At this point in time all of the same type of construction have been bent backwards and forwards, utilizing a unilateral plate like a "free carrier". Under warm and cold conditions the breakage experiment continued until breakage took place. Every series of experiments had staybolts that were of the same type which then had been used for bending purposes with a strong force. The bending arrow was between 3 to 8 mm , that is, in other words, very deep in the plastic area. These preliminary results can be summarized:

a) Condidering the staybolts with three different types of construction, that is BTH, BDR, and BgD 18, have in all methods of installation shown that the laboratory experiments are in agreement with the results obtained. The BTH showed the largest and the BgD 18 the least of the loading values. The strong superiority of the shaped bolts has been the best without any doubt. The difference in the loading values between BTH bolt and the BgD 18 bolt are in the order of the magnitude of 1:10.

b) The highest oscillation number always was a result of the installation at the welding scene and always with a enlarged head bolt. In the case of the non-welded bolts with the threading, there were breaks almost always exclusively to be found at the shaft. In the case of the weld installed BTH that had enlarged, breakage rarely took place at the shaft. Concerning the rest of the bolts, breakage occurred with the cold experiments in the welding seam or at the installation crosscut in extreme close proximity of the welding seam. This proves that the welding seam and the welding zone can create a loosening of the bolt during the welding but are not suitable for these reasons from above for continued bending demands.

c) In these experiments the identical same amount of play of about 4 to 6 mm was used with the bolts that had been welded with some excess length, some with and some without, a counter seated and a non counter seated welding were studied. The best choice was with a counter seated welding seam with 6 mm and thereafter the 4 mm. Therefore, those with the sunken welding seam of 4 mm were the worst ones. Only cold experiments had been used. The welding seam was not subject to tension as is the case during the operation when loading at the firebox side takes place. In experiments while warming is underway, the difference between counter seated and non counter seated welding seams should be small.

d) As has been mentioned, the oscillation experiments were conducted with different kinds of staybolts and had cold and warm temperatures (320 degree C). In the final ones the plate was surrounded by tension in order to study the expansion inhibition. The results of the experiments with the heat always proved to be superior to those conducted in the cold. This is particularly the case with the bolts that had a play of 0.8 mm. During experiments in the cold the break always took place in close proximity to the welding seam or in the welding seam itself. In the experiments under warm conditions, the breaks always occurred at the shaft. The difference between the welded installed bolts with a play and the welded bolts whereby with the use of enlarged head, play had been removed and was much smaller in the case of warming than in the case of cold. The advantage in the case of the bolts that had been enlarged does not apply to the firebox side when the locomotive is in operation. The arching and the bending of the staybolts as well as the firebox tears, shall become larger during operation with bolts that had been enlarged. The laboratory experiments varify the correctness of these, that is, the play will be closing itself during the warming and the welding seam and therefore a lowering of the load.

e) In order to obtain clarification of the tension momentum produced by the swelling of the boiler sheet, the tilting in some of the bent bolts at the sheet and in the evaluation of accurate and precise measurements were taken at the hole in the sheet. The value for the tilting, which at first was only determined by mathematical calculations, has been found to be basically accurate. The determined tilting, when put in relationship to the bending arrow of the bolt, were small, when calculated for the plastic area. This can be understood since the tension momentum in the area of the plastic part, where the measurements had been taken, no longer will follow the matter in a linear pattern, for the bending arrows.

f) Especially favorable and pleasing were the results of the warming experiments for the BTH with a short 10 mm head in comparison to the more frequently used 20 mm head. All these theoretical advantages had been verified, meaning that the short head in the firebox was better, where a larger bending length and also on the water-side, a larger play can possibly develop.

The precise results of al these laboratory experiments shall be published after completion of these studies.

## 2. Operational experiences

Some parts of the obtained experiences of locomotive operation have been discussed previously. At this point additional matters concerning the operations, shall be considered. The expectations that the tears from the hole in the sheet will cease if the staybolt will have sufficient play and had been welded into the firebox, have been fulfilled. Also the shrinkage of the surfaces in the firebox, when on operational duty, has been found to be smaller. The measurements between two granulated points yielded no improvements with the firebox where staybolts and mud ring anchors had been welded with some play. That is, the instruments of measurement could not detect any change. Accurate results could only be obtained with the instrument capable of curved measurements. A specially constructed instrument called by the author the "bending meter" determined the heights of the bend with a long yarn of 100 mm. With increasing operational time of the locomotive and small heights of the bend could be determined with precision. This corresponds to an increase in the gradient of a double back, that means the flattening of this double back will occur while in operation. The largest measurement regarding the diminuation of the heights of the bend, when double backing by the firebox with threaded staybolts, could be observed. With an accumulated 108,000 km only 1.3 mm at the site of the firebox and no threaded staybolt BDR which had been welded had been recorded. A run of 125,000 km produced 1.0 mm at the firebox with the threadless welded BTH and bottom ring anchor. A run of 114,000 km produced only 0.3 mm of diminuation, that means one quarter less with the threaded staybolt height's contribution. All three boilers have been built by the same construction method and using the bending meter diminuation of the bedding height is equal to 1 mm depending on the bending radius. If a possibility of shrinkage between two of the possible values then it can only be from 1 to 7 mm. With a radius of the vertical turn around the bends between the two sidewalls of about the distance of 100 mm, according to the author's calculation, will yield only 1 mm decrease of the bend height and a likelihood of shrinkage of both sheets of 2 mm will be produced. With a radius of the horizontal bend between two sidewalls of 200 mm, the contribution is either elevated to 8 mm or a diminution of the bend height may develop. The missing material, while shrinkage of the sheets occurs, can be found in turn around the bends while flattening. In the proximity of mudring no flattening is possible. The great inhibition of the shrinkage will for these very reasons lead to tears in the firebox, which necessitates the installation of corner patches.

The number of breaks that occur with the welded cylindrical staybolts of the BgD 18 and 19 is increasing both inside Germany and outside Germany and is not limited to the edge zones of the sidewalls. Most of the breaks are found on the side of the boiler and particularly near the welding seam, that is, in the loosened material of the staybolt and may also be partially found at the level of the waterside surface of the sheet and on occasion on both sides. The locale of the breakage near the welding seam does not show any compression, while the breaks near the waterside surface near the sheet exhibits a strong compression. That proves that in the course of welding the remaining play is too small to permit water to effectively produce the corrosion point. However, concerning breaks in the loosened area of the bolt are a result of pure tension stress breaks. A small controlled drilling in the case of the BgD is filled rapidly with boiler scum and seals itself, therefore the broken staybolts will only then show leakage in a short time. This in itself might indicate a break. In the edge zone tears were shown in a large number of locomotives already after an operation of only 30,000 to 40,000 km. Bolts had been torn and showed the beginning of much more larger and dangerous tears. In the remaining zones the breakage took place depending on the circumstances of operation, which could be sooner.

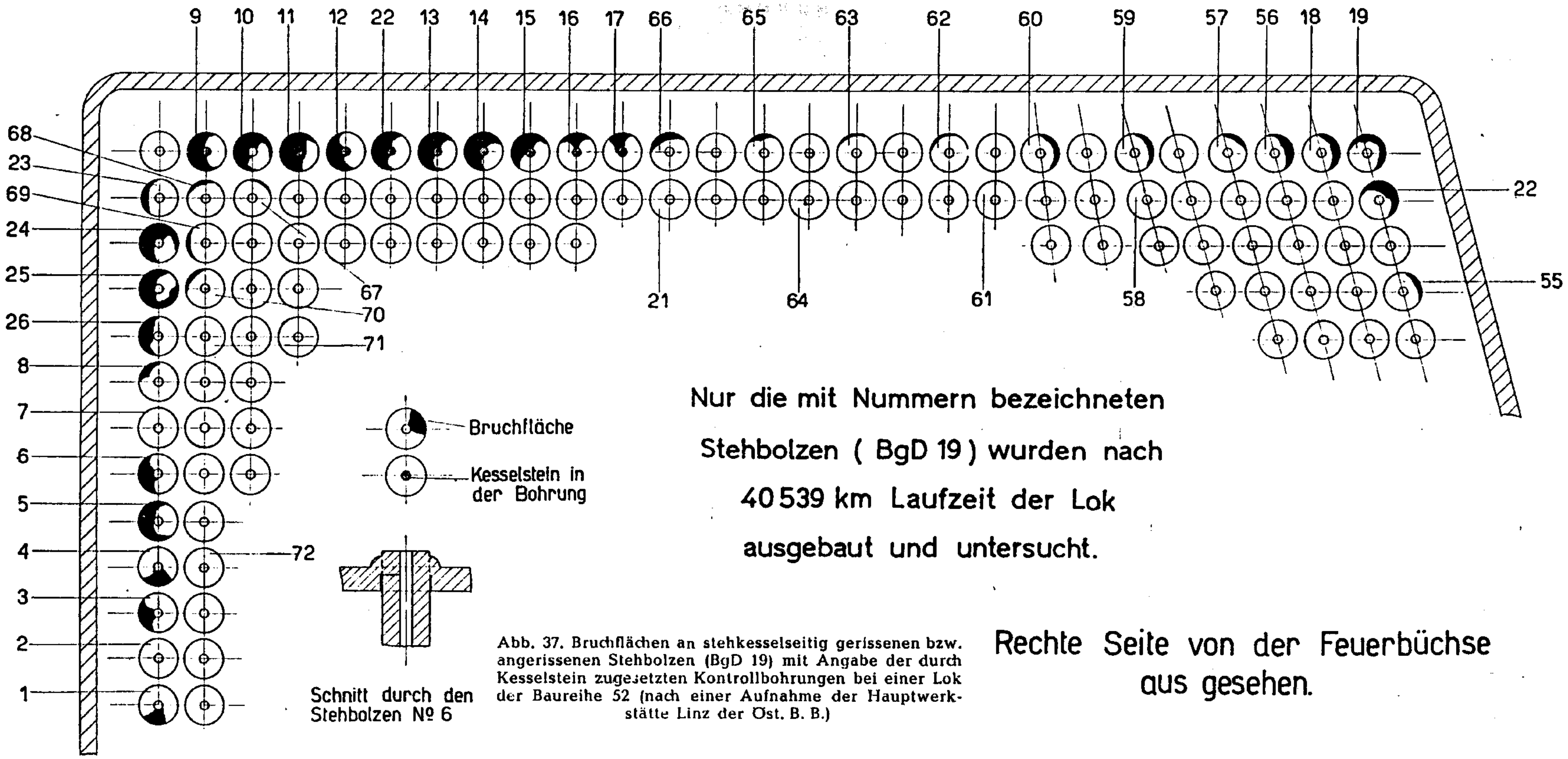
A very interesting observation has been made with respect to the staybolts breaking surfaces in the case of cylindrical staybolts as used in BgD 19. In the head repair and maintenance department at Linz of the Austrian Railroad with the locomotives of the building series 52 during maintenance and improvement work, repeatedly they found breaks with the BgD 19 which were not discovered during routine boiler inspection. The presumption is that these staybolts had small tears that only became evident when pressure was applied which often led to complete tears that could be seen. When by drilling these staybolts in order to remove them, no breaks were noted. It is therefore to be presumed that the breaks are a result of the welding and when drilling was used at the removal time of the bolts, the breakage was noticed.

There is an interesting case of the locomotive 52 4775 when the pressure test was applied, 32 staybolts, which previously had not been suspected, in actuality had breaks. After this discovery, 72 staybolts were removed in such a manner that at the site of the break the bolts could easily have broken off totally. It has been observed that all damaged bolts had their defect on the boiler side, at the site where welding had taken place. The exact situation and the degree of kind of break can be seen in Ill. 37. Only those staybolts identified with numbers had been removed and studied in further detail. Of the 34 staybolts that were examined all but two were located in the most exterior row of the right-sided sheet. Regarding the 10 bolts of the second row only four showed some defects. The bolts had been in operation for 40,539 km before removal. They had been replaced previously for flexible staybolts. The case of the second locomotive of the same building type had 43 staybolts exchanged after only 30,301 km because of breaks, see Ill. 37. At the same time a large amount of boiler scale during the test drilling was noted. With only one exception, all of the control drillings in the upper part had boiler scum together with bolts that showed tears.

A careful examination of the surfaces of the breaks showed clearly that all the tears of the staybolts had been in the upper part of the boiler. In the case of the firebox, beginning at the rear end in a position that is contrary to earlier assumptions, the conditions were no different than from the boiler. The other strong formation of tears was in the vicinity of the fluesheet. The corner bolt without a number appears to have been exchanged earlier before the pressure test was applied. Also those locomotives with welded staybolts of the type BDR had broken staybolts.

The dominating number of the breaks were in the interior of the boiler and particularly at the point where the transition from the conical part to the cylindrical section of the shaft.

Furthermore, breaks occurred at the installation crosscut at the boiler. These observations are of significant importance because the bolts have been without and also with minimum of tolerance welded into the system. According to earlier thinking and pseudo experimental results, there never was any tolerance. However, the operational conditions during the running of the locomotive produced breaks at the site of the boiler. The breaks in the conical part of the shaft was always associated with corrosion. This is understandable for obvious reasons since water has free access.



Nur die mit Nummern bezeichneten Stehbolzen ( BgD 19 ) wurden nach 40539 km Laufzeit der Lok ausgebaut und untersucht.

Rechte Seite von der Feuerbüchse aus gesehen.

Abb. 37. Bruchflächen an stehkesselseitig gerissenen bzw. angerissenen Stehbolzen (BgD 19) mit Angabe der durch Kesselstein zugesetzten Kontrollbohrungen bei einer Lok der Baureihe 52 (nach einer Aufnahme der Hauptwerkstätte Linz der Öst. B. B.)

In order to have a clear means for comparison of the old BDR with the newer BTH staybolts and also to study a few other bolts, with the permission of the Deutsche Bundesbahn the boilers of a large number of locomotives of the series 52 have been examined. This type of locomotive had been of a different design and equipped with different bolts and had been put in service immediately, all under the same identical conditions. The locomotives had been for study purposes subdivided into four groups, in which the first two groups had been equipped with mudring cross anchors and the last two without the mudring equipment. All locomotives had staybolts welded in that had a tolerance of 0.6 to 1.2 mm. The following pattern evolved:

| | |
|---|---|
| Group 1- BDR with ball joint length staybolts | (7 Locomotives) |
| Group 2- BTH with ball joint staybolts | (10 Locomotives) |
| Group 3- With ball joint staybolts and also with mudring anchors | (4 Locomotives) |
| Group 4- BTH with cross-lengthened staybolts and also anchors | (19 Locomotives) |

Every locomotive had 1130 solid and 350 movable staybolts. In each boiler where the welding was a difficult chore 20 bolts were equipped with enlarged heads. These then had a higher tendency to break.

The number of breaks is inclusive of those staybolts that had been welded in a solid manner. In the door and pipe sheet of every locomotive of the four groups, one will find that for reasons of construction ball length bolts had been used. The breaks of the fourth group are especially noteworthy. The rest of the 321 flexible bolts in the boilers of group four are cross-lengthened bolts of the BTH type according to Ill. 31. Moreover, the group four had in their boilers staybolts with deviant features at the shaft and at the head. Some had on the side of the boiler heads those that had been enlarged. Defects have not occurred on any of these other locomotives, even when the operational distance was more than 100,000 km.

In Table 1 the number of damaged staybolts, mud rings, and crown sheets had to be exchanged as a consequence. When the amount of operation time was about 100,000 km on the calculation of the four groups, on the average the breakage and exchange was of small consequence for all four groups. Since group three and four are only different in the type and method of construction of the flexible staybolts, the number two group had been taken into account and had no differences of importance altogether. The locomotives that had been compared shared the operating conditions in almost identical service so that the demands showed no differences. In Table 1 the only locomotives used for comparison had at least covered 100,000 km by October 1, 1951. That means all seven locomotives of group one and all ten of group three and only one locomotive of group four had served 100,000 km by October 1, 1951. The results of all this data is very informative.

The number of broken and damaged solid staybolts after a use of 100,000 km, in the boiler of group two, equipped with BTH was only 1.9%. The number of exchanged bolts was 9.5% in the group one equipped with BDR. The relationship therefore is 1:10. The number of breaks in groups three and four is even lower. This comes to a relationship to group one of about 1:100. It cannot be assumed that these relationships will remain constant as the operational distance will begin to exceed 100,000 km. The definite advantage of group two, three, and four in comparison to group one is a larger and longer operational time. Also the number of the broken ball joint staybolts was a consequence of the very small amount of the arching in the boiler and only 6% of the BTH in group two. Comparing this information to group one with BDR one can draw their own conclusions. Regarding the cross length staybolts BTH in the group four not a single one had been torn but sixteen of these ball joint bolts that had been built in the fluesheet were damaged. Also concerning the fourteen boilers, however with less than 100,000 km, not a single of the three ball joint staybolts, or the cross length staybolts, had shown any indication or signs of breakage.

**Anzahl der Stehbolzen- und Bodenringschäden sowie der erforderlichen Auswechslungen an Neubaulok der Reihe 52, auf je 100 000 Betriebs-km umgerechnet**

Tabelle 1 (Stand vom 1. 10. 1951)

| Gruppe | | | BDR Kugelgel. Stb. Gö 1 | BTH Kugelgel. Stb. Gö 2 | BTH Kugelgel. Stb. Gö Bodenringqueranker 3 | BTH Kreuzgel. Stb. BTH Bodenringqueranker 4 |
|---|---|---|---|---|---|---|
| Zahl der Vergleichslok mit Leistungen über 100 000 km | | | 7 | 10 | 3 | 6 |
| durchschnittliche km-Leistung je Lok | | | 161.700 | 134.687 | 126.091 | 120.414 |
| Gelenk-Stehbolzen | gebrochen zugeschlagen | auf je 100 000 Betriebs-km umgerechnet | 20,1 | 13,2 | 10 | 0 (1,9)[1] |
| | ausgewechselt | | 21,3 | 11,4 | 3,4 | 0 (1,7)[1] |
| feste Stehbolzen | gebrochen zugeschlagen | | 57,0 | 6,2 | 0,18 | |
| | ausgewechselt | | 188,2 | 17,8 | 1,6 | |
| gewechselte Hohlstehbolzen | | | 2,7 | 0,37 | 0,18 | |
| Bodenring | Feuerbüchsflicken an den Ecken eingeschw. | | 2,5 | 1,8 | 0,36 | |
| | Nieten gewechselt | | 40,0 | 23,4 | 4,2 | |

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[1] in Klammern die Zahlen, die sich auf die Brüche der insgesamt 29 Kugelgelenkstehbolzen Gö in Rohr- und Türwand beziehen

**Anzahl der Stehbolzen- und Bodenringschäden sowie der erforderlichen Auswechslungen an Neubaulok der Reihe 52, bis zur Zwischenausbesserung L2 einschließlich**

Tabelle 2 (Stand vom 1. 10. 1951)

| Gruppe | | | BDR Kugelgel. Stb. Gö 1 | BTH Kugelgel. Stb. Gö 2 | BTH Kugelgel. Stb. Gö Bodenringqueranker 3 | BTH Kreuzgel. Stb. BTH Bodenringqueranker 4 |
|---|---|---|---|---|---|---|
| Zahl der Vergleichslok mit Zwischenausbesserung L2 | | | 7 | 10 | 2 (4)[1] | 4 (7)[1] |
| durchschnittliche km-Leistung | | | 87.148 | 91.286 | 97.143 (115.584)[1] | 111.284 (116.427)[1] |
| Gelenk-Stehbolzen | gebrochen zugeschlagen | bis einschließlich Zwischenausb. L2 | 18,0 | 9,2 | 8,0 | 0 (1,9)[2] |
| | ausgewechselt | | 18,0 | 11,4 | 8,0 | 0 (1,7)[2] |
| feste Stehbolzen | gebrochen zugeschlagen | | 68,3 | 4,9 | 0,33 (0,18)[1] | |
| | ausgewechselt | | 204,0 | 22,8 | 3,0 (1,6)[1] | |
| gewechselte Hohlstehbolzen | | | 3,7 | 0,40 | 0,33 (0,18)[1] | |
| Bodenring | Feuerbüchsflicken an den Ecken eingeschw. | | 3,4 | 2,4 | 0,67 (0,36)[1] | |
| | Nieten gewechselt | | 51,6 | 31,6 | 7,7 (4,2)[1] | |

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[1] in Klammern die Werte, die sich einschließlich der Lok mit über 100 000 Betriebs-km, jedoch hisher ohne L2, errechnen

[2] in Klammern die Zahlen, die sich auf die Brüche der insgesamt 29 Kugelgelenkstehbolzen Gö in Rohr- und Türwand beziehen

The favorable influences of the minimum arching , as well as the shrinkage, have in the cases of hollow staybolts and the mudring preparation a positive effect. Of the eight staybolts, which are used to accept the staybolts with threading, for the carrier of the fire arch in group one, who had 100,000 km , the need to replace 2.7 bolts was necessary. Regarding replacement, in group two only 0.37 bolts were needed and in group three and four only 0.16 bolt had to be replaced. That means, in other words, the numbers were 13.7% or 6.7%. Because of the greater stiffness of the boiler of the BTH, these numbers remain small.

In all locomotives in group one, and 60% of the locomotives in group two, with always more than 100,000 km operation time, it became necessary to install patches in the corners and the replacement of the rivets on the mud rings were necessary. The replacement of rivets were specifically mud ring rivets was the case with only one locomotive with mud ring anchors. A further diminuation of the damages can be achieved by lowering the fire grate.

The locomotives of group two through four had been built later and therefore have about 17 to 26% of the operational km of those in group one equipped with BDR. Utilizing Table 1, it can be calculated by mathematical methods the difference of values as has been discussed above and project the circumstances as they would be after 100,000 km. Since the damages increase proportionally with the increase of operation, up to and beyond 100,000 km, it can be computed. Utilizing Table 2 the maintenance improvements and repair of damages (L2) can be seen as it is the case with L2 overhauling exchange.
In all locomotives of group one and two (17 locomotives) there were at least two that needed some form of attention. Regarding the three in the third group, these had according to Table 1, 123,000 and 145,000 km by October 1, 1951 and no maintenance repairs. L2 from group four of three locomotives had each 118,000 and 129,000 km. In Table 2 and in the third and fourth group, the number of clamps and repairs can be mathematically determined when the locomotive has reached 100,000 km operation distance and no L2 had taken place. Therefore, one will be able to determine the numbers for each locomotive under consideration when time and number of kilometers will be reached for L2 repairs. In both groups it is at least always one locomotive that has less than 100,000 km operation, but somewhere between 86,000 to 96,000 km, that will have at least one L2 service. In both locomotive groups no service for ball joint flexible staybolts, rigid staybolts, or mudrings was needed.

The average kilometer work, until repairs are done, L2, group two, is somewhat smaller, but somewhat larger in group three and four. The values of the damages and the rate of exchange are of approximately of the same order as shown in Table 1. In group one the kilometer work in Table 2 is only about 54% of that listed in Table 1. The kilometer work in the rest of the groups is larger. The current results indicate without doubt that the hard BTHs are superior in contrast to the BDR, which are ball joint flexible staybolts. Moreover, the efficiency and favorable actions of the mud ring cross anchor are clearly evident. The comparable numbers of Table 1 and 2 are particularly valuable because the locomotive is from the same type and produced in the same factory.

They have been used in nearly the same operating conditions and district. The advantages arise because of the improvements, and the identical building material, and without change of the water conditions, and by using common construction methods for the installation and in general.

Comparison for the same circumstances are not available for BgD. However, one can go on the assumption and previous experiences that those BgD which have been welded are superior than the earlier BDR with threading but unilateral welding. However, threadless BDR that have been welded unilaterally are inferior in group one of Table 1 and Table 2.

This judgment relies on many years of experience of the Austrian Railroad, which had been among the first railroad administration after1945 that exclusively for the installation used threadless welded BgDs. The tears which have been found at the edge zone of the boiler, using BgD 19 have already been discussed (compare Ill. 30). At the same time in the rest of the zone, tears have been observed. The relationship of the broken staybolts between the edge zone and the rest of the sheet are 4:1. Because of the poor experience and the broken staybolts, the Austrian Railroad abandoned the BgD and returned to a type of a staybolt with a much stronger head which has on one side a conus like the BDR. The danger of unmarked breaks with the BgD was also the reason for abandonment. The bolts that have a strong head are welded as threadbare and with some play.

According to a recently released piece of information from the General Directorate of the Austrian Railway dated October 27,1951, in the case of BgD 19 after 13 operation months, 100 and more bolts had been broken, while the staybolts with stronger heads only 34 had been broken, beginning with the 13th until the 22nd month of operation. In one Austrian locomotive building series 42, the following suggestion had been made by the author to install cross anchors to stiffen the boiler after 14 subsequent months showed no operational breaks at all. That is, for the building series 42, which has a great tendency towards breakage of the staybolts, a remarkable result.

## G.) Summary

The investigations undertaken during the last few years, both theoretical and practical, and have led to a clarification and deepening of the understanding of the pressures in the boilers and also in the steel firebox with steel staybolts, and it is important to summarize all this newly acquired knowledge together. Therefore it is expedient to publish this new gained comprehension at this time:

1) The problems and difficulties as noted in the steel fireboxes with steel staybolts have the same basis as the copper fireboxes with Kuprodurshoes and steel staybolts. That is, the plastic deformation, because of the hindrance of expansion of the firebox when heating, and the inhibition of shrinkage when cooling the locomotive boiler. These inhibitions developed by steel fireboxes because of their lower heat conductance capacity, and therefore a greater temperature difference in every aspect.

2) In the case of the steel fireboxes, the heating process is much higher for the building material and as in the expansion of the flat surface areas a stronger plastic compression will develop at the waterside. When cooling towards the ambient temperature occurs a multifold shrinkage at the fireside will develop and therefore a pressure of bending the firebox sheet towards the exterior. This will lead, during the operation of the locomotive, increasingly towards a permanent arching of the boiler towards the exterior and therefore a strong bending of the staybolts, particularly at the rows of the edges. This tendency for arching towards the exterior becomes stronger when the process of cooling and washing out the heat through the firebox sheet will then all be reversed while in operation.

3) With the pressure effect at the boiler and the pressure of the fire and waterside, differential expansion and arching between four adjacent staybolts in the sheet field in the

direction of the firebox interior, will develop. This so-called mattress formation becomes permanent in the area of the firezone. Especially when high firebox temperatures are noted, then the total boiler will be arched toward the exterior.

4) The firebox shrinks in the areas of the flat expansion when welding takes place to install a staybolt and also during the course of the operation. The boiler shrinks only when the staybolts are welded in but not while in operation. The shrinkage during the welding of the boiler depends on the strength of the sheet and is as a rule somewhat less than the corresponding sheet strength of a smaller firebox. The shrinkages are a consequence of the compression of the sheets during the high heating temperatures while welding and also while in operation. The compression and the inhibition of expansion when heating are the cause of the above phenomena. Less inhibited strong shrinkage leads in the process of cooling to large mostly staybolt bending. Strong bending in the boiler with buckle anchors in the front higher row of the sidewall will lead to shrinkage. Inhibited shrinkage leads to firebox tears, especially in the proximity in the corners of the mud rings.

5) Although the star shaped hole in the sheet tears are the result of inhibition of shrinkage, when cooling occurs in the firezone, especially after very high temperatures had developed and strong compression of the sheet parts, the developing tangential shrinking tension at the edges of the hole are in the direction of the largest degree of inhibition of expansion. That explains the typical tear position. In the case of non-welded bolts the tears begin at the fireside and in the case of the welded bolts at the waterside.

6) After removal of the bolts, the permanent bending will remain at the firebox side towards the lower and the middle of the sheet. These are the results of several shrinkages of the firebox when seal or ordinary welding has taken place. In the course of the operation, the arching of the boiler, as a result of several shrinkages, will occur. These phenomena of bending, as well as the arching of the boiler, become additive and in other cases nullify each other.

7) The staybolt bending in the plastic area is overlaid by size and direction because of changing bends as a consequence of the variable temperature while in operation, and between operation and cold positioning of the locomotive. These are the basic causes of staybolt tears and breaks.

8) It is obligatory to minimize the deformation of sheet and bolts at the same time. The expansion should be permitted and not hindered in such a way that adequate space be given to decrease these demands. For example, this can be done by creating a play on the side of the firebox between bolts and the hole in the sheet and arching of the firebox towards the direction of the fire.

9) The diminuation of the high temperature differences between the area of the firezone and the adjacent mud rings as well as the zone over the fire arch is of urgent necessity.

10) The staybolts have to permit the most possible highest degree of bending, so when they are cooling they are not inhibiting the boiler to return to it's original position.

Furthermore, the staybolts must permit a very high position of bending and be subjected to form changing work. Therefore the arching of the boiler will be more difficult to obtain. The values of the staybolt lie with the ability to shift the installation point without permanent deformation and $A_{zul}$.

11) The expression of a strong local tension elevation (like BDR) or the redirection of the tension maximum at the installation point cylindrical staybolt (BgD) has to be avoided. In the first case, the bridging of the shaft, and in the latter part the bolt installation tension, will have a greater demand and in the last, to prevent and inhibit the risk of break.

12) When welding begins at the staybolt, there will develop near the welding seam, a tension crosscut in those fastened in the hard zone of the building material. The tension maximum in the installation crosscut has a higher risk of breakage. By applying correct formation of the staybolt, the installation crosscut will be strengthened and therefore the load removed. Staybolts with strong head ends for the equalization of the building material fastening, because of the welding heat and being pure cylindrical, have several advantages.

13) A correctly removed staybolt shaft needs an equal demanding position like any other new design staybolt. By avoiding the tension point, in spite of a large form changing work, the maximum demand can be reduced and eventually the elastic limitation can be avoided. In the case of the cylindrical bolt, the tension rises and herewith the stretching of the exterior fiber up to the welding seam.

14) In the plastic area using a cylindrical bolt only, a short fastened part must be lengthened. In the case of the bolt with the very strong head and the truly new design shaft, some plastic lengthening in the work material must follow and reach all the way to the conus.

15) The number of flexible staybolts should be kept to a minimum, otherwise it will lead to an enlargement of the sheet of the boiler. Cross length heads are superior to the ball jointed heads because of the lateral ability to shift and the minimum of friction. Also by flexible staybolts, a truly new design shaft will bring great advantages on the firebox side.

16) The stiffening of the boiler with the aid of the mud rings cross anchors reduces the maximal arching of the boiler by more than half. Also a strong diminuation of the bolt bending and therefore the bolt breaks are smaller in number and timing.

17) After the welding of the staybolts there always develops an installation play between bolt and hole in the sheet and usually towards the interior even if one uses before the welding, a patching seat to be applied between bolt and the hole in the sheet. The plastic deformation of the sheets during the welding of the staybolts is usually a true tolerance play, smaller in comparison to one without.

18) The operational play (installation play and cold play) will become smaller and closes itself on the firebox side during reheating. It is desirable that only on the firebox side a

minimizing of the inhibition of expansion will occur. On the side of the boiler it is best to eliminate the installation play by enlarging the head appropriately.

19) The smallest staybolt bending during the welding can be achieved by a welding plan, beginning at the mud ring and the horizontal staybolts row, when one forgets about the tagging before the welding process.

20) For each method of staybolt construction there is a demand limitation when surpassed, the staybolt seating will begin: the correctness of the largeness and the form of the boiler, the boiler pressure, the boiler demands, and the boiler water, also the boiler scum, the method of staybolt installation as well as the type of building material used for the staybolt construction and the firebox construction. When all are taken together, a certain amount of boiler deformation will occur. The most favorable operating conditions having been gained by experience cannot under any circumstances be translated or transposed to unfavorable operating conditions, even if the same type of locomotive is involved.

The advances that have been made by utilizing improved construction forms, the hard flexible staybolts, the welding with play, and at the mud ring cross anchors, while a steel firebox is used with steel staybolts have been of great value. Further advances that can be expected are in the following boiler as part of experimental work; the applied steps that can be anticipated are a) lowering the grate, b) strengthening the boiler ceiling, c) decreased strength of the sheets of the boilers, d) u-shaped crosscuts of the mud rings, e) replacement of the buckle anchors with special staybolts, f) application of the best means of welding, g) heads on the boiler side to be enlarged before the welding, h) improvement of the water purification.

Furthermore, suggestions which have not yet been applied should prolong the life of staybolts and firebox are a) improved process for working with heating of the warm water and used in the same direction as if it were in operation, b) firebox side welding of the staybolts in sheet holes, c) application and use of fire arch with openings on the side.

There is no doubt that under today's standards and the developing work, that it is possible to lengthen the life of the steel staybolts and that it will be possible to perform under normal conditions with superior water purification techniques to operate several hundred thousand kilometers more. In other words the prescribed recommended inspections of the boiler without any reparations while in operation can be achieved.

Nearly all these suggested improvements will not require a large outlay, in fact savings can be achieved by lower maintenance cost. After completion of these improvements one can expect that the maintenance of the boiler will give no troublesome conditions, and steam pressure and loading can be increased. These are the measurements which according to American experiences have increased utility considerations. As a matter of fact, some of the economy is accomplished by removing the unnecessary work, and therefore have increased the value of the steam locomotive.