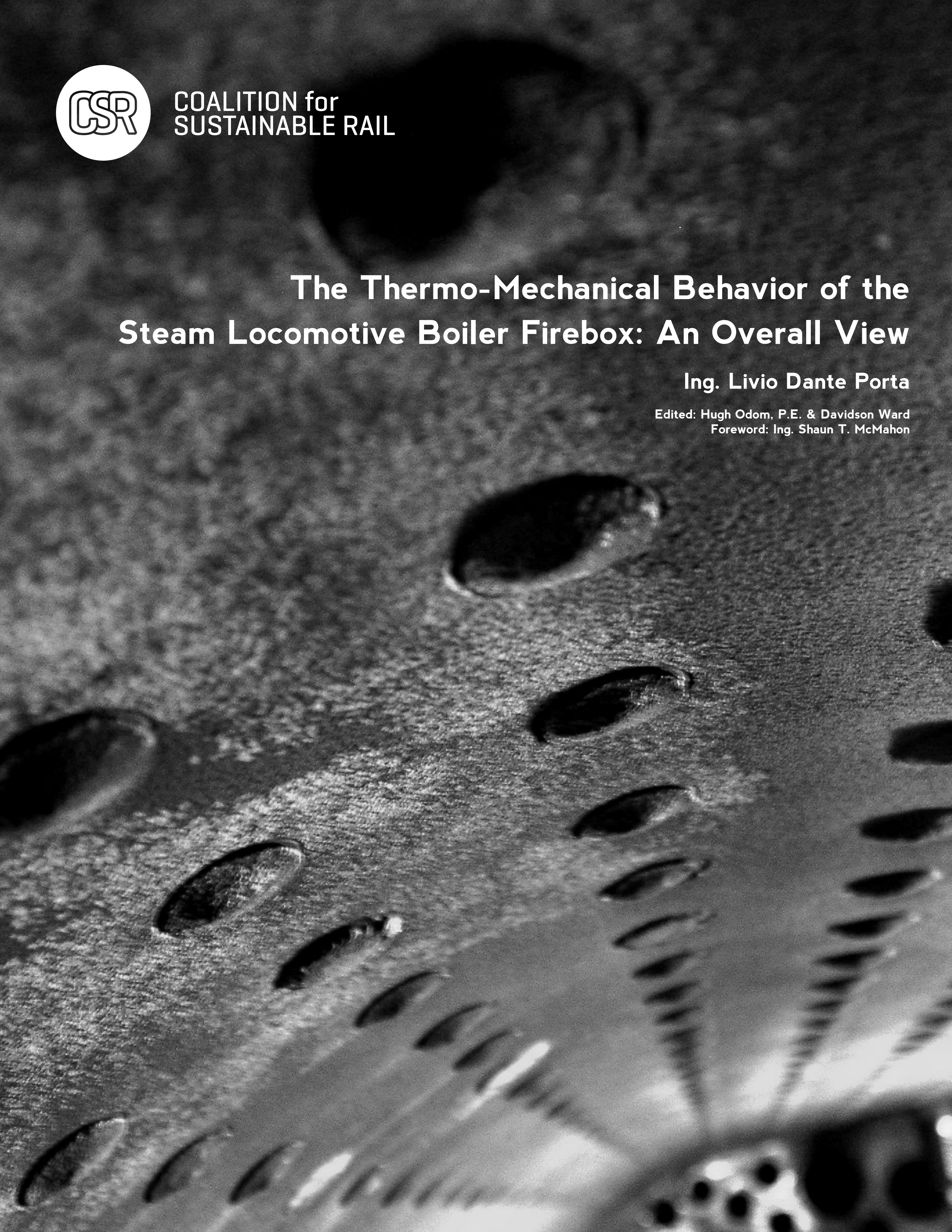

COALITION for SUSTAINABLE RAIL

The Thermo-Mechanical Behavior of the Steam Locomotive Boiler Firebox: An Overall View

Ing. Livio Dante Porta

Edited: Hugh Odom, P.E. & Davidson Ward
Foreword: Ing. Shaun T. McMahon

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Working in conjunction with the University of Minnesota (U of M), the Porta Family Foundation, and other not-for-profit rail and biomass research organizations, CSR's White Paper Program brings works pertinent to biofuel, modern steam locomotive and transportation research into the public discourse.

Cover Image - *An image of the crown sheet of a mainline, U.S. steam locomotive taken during routine maintenance.*

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Foreword

Dear Reader:

This never-before-published report on the fundamental principles of steam locomotive fireboxes is a unique glimpse into the mind of modern steam engineer Livio Dante Porta. The source paper has been emailed around among a few modern steam proponents for years, but it was a grainy, hand-written, and hand-illustrated version of the digitized text presented here in this CSR White Paper.

The piece is an interesting look into the design process and, at times, struggles encountered in the pursuit of advanced steam locomotion. Porta wrote the paper at the time of preparing and testing former Chesapeake & Ohio Railway 4-8-4 number 614 as part of the ACE 3000 project. The document was written in 1984 and revised in 1985 following the completion of the testing of 614T. Porta left ACE shortly thereafter and worked for Foster Wheeler in the US for two months, after which he returned to live and work in Argentina in January 1986.

The original paper does not have a revision date written on the cover underneath the "Issue Date" nor does it have a reference address or company name written. The only time that this lack of information occurred during Porta's working life was during the time period that he was under ACE contract, and this was done so as to ensure that he was not breaching the ACE IP agreement that he had signed. The issue date is April 1984, just over one year after Porta had moved to the US to live and work. In effect, by only writing "L.D. PORTA" and "Issued April 1984" on the cover, he could not be accused of breaching the contract and the paper could be read and used by others in the future, including in this capacity as a CSR White Paper.

The paper was written to get the ideas across to David Wardale who was, at that point in time, on standby in Germany waiting for ACE to give him the "all clear" to live and work in the US on the project. The revisions made in 1985 were for the benefit of David Wardale's test report on 614T. Of note: Phil Girdlestone was on standby to head to the U.S. to live and work on the ACE project as chief draftsman and assistant to David Wardale, but his full time involvement never came to pass. Wardale was contracted by the Chinese in early 1986 so as to carry out the QJ modification scheme whilst Girdlestone left the Ffestiniog Railway in September 1985 to work on the Sudan steam locomotive modification program.

The way in which Porta organizes this paper provides a systematic, point-by-point analysis of firebox sheets, staybolts, tubes and water treatment, is of interest, in that it dispels a variety of the commonly-quoted shortcomings of steam locomotives with compelling facts. A point in case is information pertaining to the U.S.-built 141R locomotives operating in France after WWII. These 2-8-2's operated with an advanced internal boiler water treatment that allowed them to operate more than 1,250,000 miles with only 200 man hours of maintenance on the boiler (an equivalent of $0.004 boiler maintenance cost per mile of operation at $25/hour labor rate)!

This paper has been transcribed from the original, hand written text and has been edited only slightly to allow greater clarity in reading. The diagrams have been redrawn digitally to also further aid in clarity of understanding.

This paper is but one of many provided to the general public by CSR free of charge. We welcome you to share this paper with your friends, read our other papers, and promote the work CSR undertakes to keep the dream of steam alive.

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Sincerely,

Shaun T. McMahon
Director of Engineering

Summary:

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1. Introduction

The design of the steam locomotive boiler firebox was a matter of empirical, crude, cut and try. By the turn of the 20th Century, long after many commercially successful locomotives had been built, boiler code rules appeared. They prescribed minimum plate thicknesses and minimum stay cross sections by means of a couple of formulas which are still the rule today. Heavy firebox maintenance was taken as a necessary evil, and development proceeded, changing little the dimensions here and there. In Europe, copper fireboxes were the rule, and steel in the USA. Substitution of steel for copper in Germany in 1914-1918 was an utter failure, and copper came back after the shortage. In the USA, circa 1910, it became apparent that stay breakages occurred in spite of the very low design stresses included in the above mentioned formulas. That was found to be due to the flexions resulting from the relative displacement of the inner and outer firebox: the flexible stay was invented and quickly adopted.

Cracks in the firebox plates, stay breakage, and stay leakage were the three plagues of firebox maintenance. Water treatments gradually improved between 1910 and 1940, and they had a direct impact on firebox maintenance in spite of not achieving the state of satisfaction realized after WWII. Firebox size became enormous in the USA, and its development continued along empirical, cut and try methods aided by intelligent, educated guess. Eminent engineers, like Chapelon, himself, accepted that state of affairs [See CSR White Paper on Chapelon - www.csrail.org/chapelon]. Two breakthrough approaches started before WWII: in France, the search for the solution was sought on the water treatment side, and in Germany, through improved design. The study and experimental work carried out by Tross in Germany from 1937 onwards (2) disclosed, in a breakthrough manner, the nature of the phenomena leading to firebox failures and maintenance. His findings opened the door to an unprecedented panorama. The resulting better understanding of said phenomena led to progress essentially based on the "steps-in-the-right-direction" method. His aim of minimizing maintenance work between general repairs was attained, and the German Railways, after a large scale experimentation (both in the laboratory and in service) adopted Tross' proposals as standard.

The parallel development carried out in France in 1944 resulted in an unqualified success. The application of the TIA water treatment to boilers designed by said empirical methods, and then even abused by scale and corrosion, reduced boiler maintenance to 1/10th of what was prevalent before, and this to the scale of thousands of locomotives. American engineers designed by similar rules showed still better results: boiler maintenance required only 200 man hours in 2,000,000 km of operation in spite of digesting 60 tons of scaling materials!

Advanced steam locomotive engineering faces two areas requiring a thorough, quantitative understanding of the phenomena associated with firebox engineering:

i) The design of new, advanced, locomotives and
ii) The application of advanced principles to existing locomotive rebuilding

In the first case, designing from scratch affords the maximum freedom; in the second case, the existing elements are to be respected. In both cases, **prediction of hardware behavior based on principles is required**. The existing knowledge leaves much to be desired: in spite of the progress achieved concerning

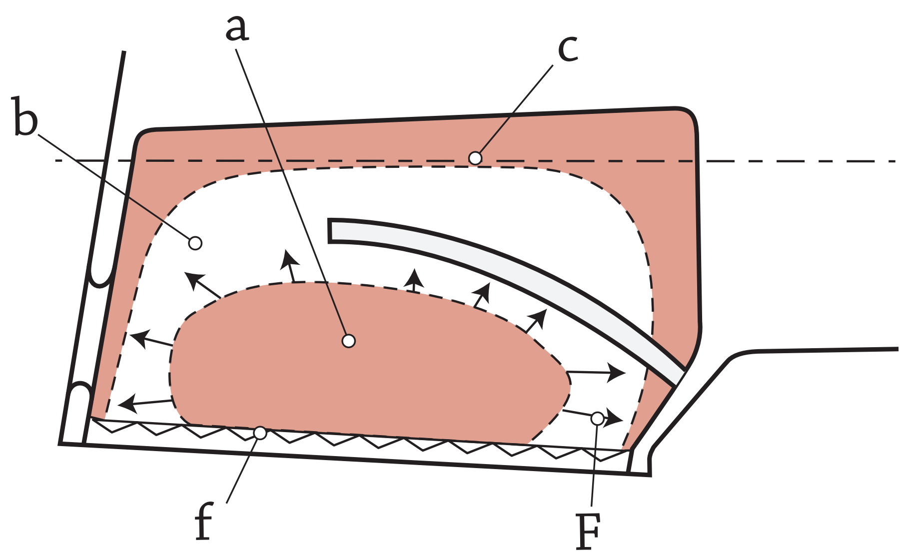


Figure 1: This cross section through a locomotive firebox shows: (a) areas of greatest heat flux; (b) area of lower heat flux; (c) breakage zone; (f) foundation mud ring; and (F) expansive force due to area of greatest heat flux. The areas shaded red correspond to the areas subjected to the greatest heat transfer in a locomotive firebox.

water treatment and design, it is in not as yet possible to design on the basis of (low cycle) fatigue stresses because the actual strains are not more than vaguely (if not wrongly!) known. Tross' work showed that many past opinions and assumptions were false, and that a vast amount of phenomena were not suspected.

The present exercise is an effort to summarize and learn Tross' description of the concerned phenomena as a **first** out of three steps leading to rational design: the **second** will be to cast them in figures of increasing accuracy, related to heat transfer and materials' sciences, the **third** should be a better engineering. For the sake of giving a totalizing picture, only fundamentals are addressed here. For the same reason, neither proofs are offered for the assertions, nor details (available at large) are included.

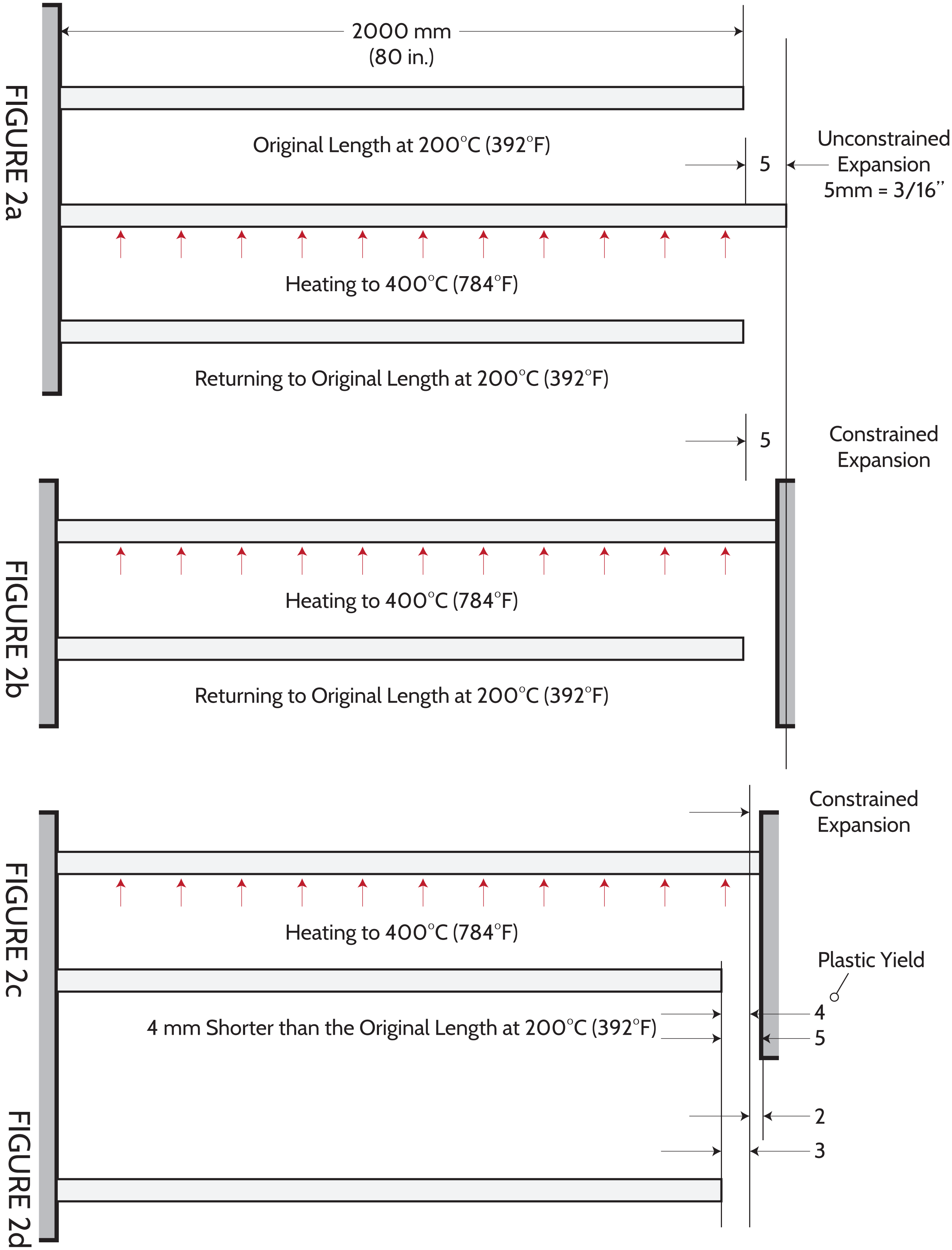
Locomotive rebuilding requires, perhaps with great urgency, much better knowledge and understanding of firebox thermomechanics. The example of No. 614 showing alarmingly premature stay leakage and firebox cracks, besides its political significance, requires urgent correction action **based on fundamental knowledge and not only on boiler makers' opinions**. Rebuilt engines will be more powerful and responsive to a "heavier" hand because combustion rates can be coincidentally higher. Firebox heat flux will therefore be increased, and steam-heated air will contribute to it. Therefore, mastering firebox phenomena is a must if surprises are to be avoided.

2. Firebox Phenomena

The lower part of the firebox is heavily taxed due to the heavy heat transfer. This is so because the flame temperature and emissivity are higher, and also because of the proximity of the firebed.[1] The heat transfer is more intense by the middle of the plates (Fig. 1 "a") as compared to that occurring at the corners, while the foundation ring is comparatively cool because it receives no heat (Fig. 1 "f"). Measurements have shown that the local heat flux can be as high as four times the average. The heat flux leads to phenomena like:

1. The temperature of the metal in the fireside is higher than that of the water side: it can read 400°C (750°F) at the hottest spots, this for a clean, not scaled boiler;
2. At that temperature, the yield point of a current firebox steel becomes quite low: about 13 kgf mm^{-2} (18,000 psi), which approaches one half of that at room temperature. Thus, plastic deformations can comparatively easily occur;
3. Said high temperatures lead to expansions; if the latter are constrained, heavy stresses arise;
4. Scale, even if its thickness is as small as 1/16 in, acts as a heat insulation on the water side, thus leading to an aggravation of the previously spoken phenomena;
5. Temperature effects increase with the heat flux, which on its turn increases with the evaporation and power demand to the locomotive. Because of the very nature of the railroading service, the steam load is extremely variable and intermittent; thus all the concerned phenomena are cyclic by nature. The

1 - Not to mention arch radiation



Figures 2a-2d *Expansions, strains and stresses occurring in a steel rod upon heating.*

resulting thermal strains and stresses are therefore cyclic, leading to **fatigue** in the metal;

6. Fatigue cycles, even if not counted by the millions as for crankpins, are numerous. A commuter engine typically numbers them at 10,000 per year, 100,000 in ten years; this fatigue proceed on the metal (i) at relatively high temperature (which steeply increases with scale); and (ii) is a corrosive medium – on the water side – if the water treatment does not fully control the corrosion;
7. While the combustion-originated heat flux works from the fireside towards the water side, the abuse of the blower with little or no fire on the grate reverses it, thus leading to contractions which extend the range of the temperature oscillations;[2]
8. The outer firebox is always at saturation temperature, therefore expansions, strains, and stresses resulting in the inner firebox because of the heat flux also affect the members connecting both [sheets] because of their relative displacements: i.e. the stays bend, and their clampings on the plates incline;
9. All the above-mentioned phenomena cause stresses which, besides the frequency and amplitude of heat flux cycles, is coincidentally higher than that of pressure up and down;
10. The combination of very high draft (700 mm H_2O = 25 in H_2O) and the Gas Producer Combustion System (GPCS), renders possible very high heat fluctuations in the furnace, thus leading to combustion intensities much higher than in the past. This leads to increased heat fluxes;[3]
11. Expansions are leger the larger the plates are: this is the case of American sized fireboxes, etc.

With reference to Fig 2, let a 2 m (80 in) steel rod to be uniformly heated from 200°C (392°F) to 400 °C (750°F): it will expand 5mm (3/16 in) if unconstrained (Fig 2a). If the temperature returns to 200°C (392°F), the rod will resume its original length of 2 m (80 in).[4] If (Fig 2b) the rod is not allowed to expand freely by an obstacle (say limited to 4 mm = 0.016”): compressive stresses result. In this case:

$$\frac{(5-4)mm}{2{,}000} \times 21{,}000\, {}^{kgf}/_{mm} = 10.5\, {}^{kgf}/_{mm} = 15{,}000\ psi$$

2 - *Same happens in the case of improper washout practices.*

3 - *On occasions at Rio Turbo, the whole brick arch was sucked into the combustion chamber.*

4 - *The temperatures have been chosen to correspond to saturation and hot-under-heat-flux conditions for the inner firebox.*

Since this is just about the yield point at 400°C (750°F), upon cooling, the heated rod will return to its original length at 200°C (375°F). No plastic yield will result, hence no permanent deformation.

If the expansion is severely constrained, say to only 1 mm, the rod will accommodate itself by plastically yielding the remaining (5-1) = 4 mm. When returning to the starting temperature of 200°C (375°F), it will be 4 mm shorter in length (Fig 2c). Thus, it will show a “squeezed-in,” “shrunk,” compression (Fig 2c). If the heating-cooling cycle is repeated, the rod will play 5mm to and fro, just touching the construction.

If in the cooling half-cycle, the rod is impeded to feely contact more than 2mm (Fig 2D), the remaining 3mm will be absorbed by a plastic stretching, but this time the corresponding yield stress will be that of the 200°C (392°F) temperature, namely:

$$18\, {}^{kgf}/_{mm} > 12\, {}^{kgf}/_{mm}$$

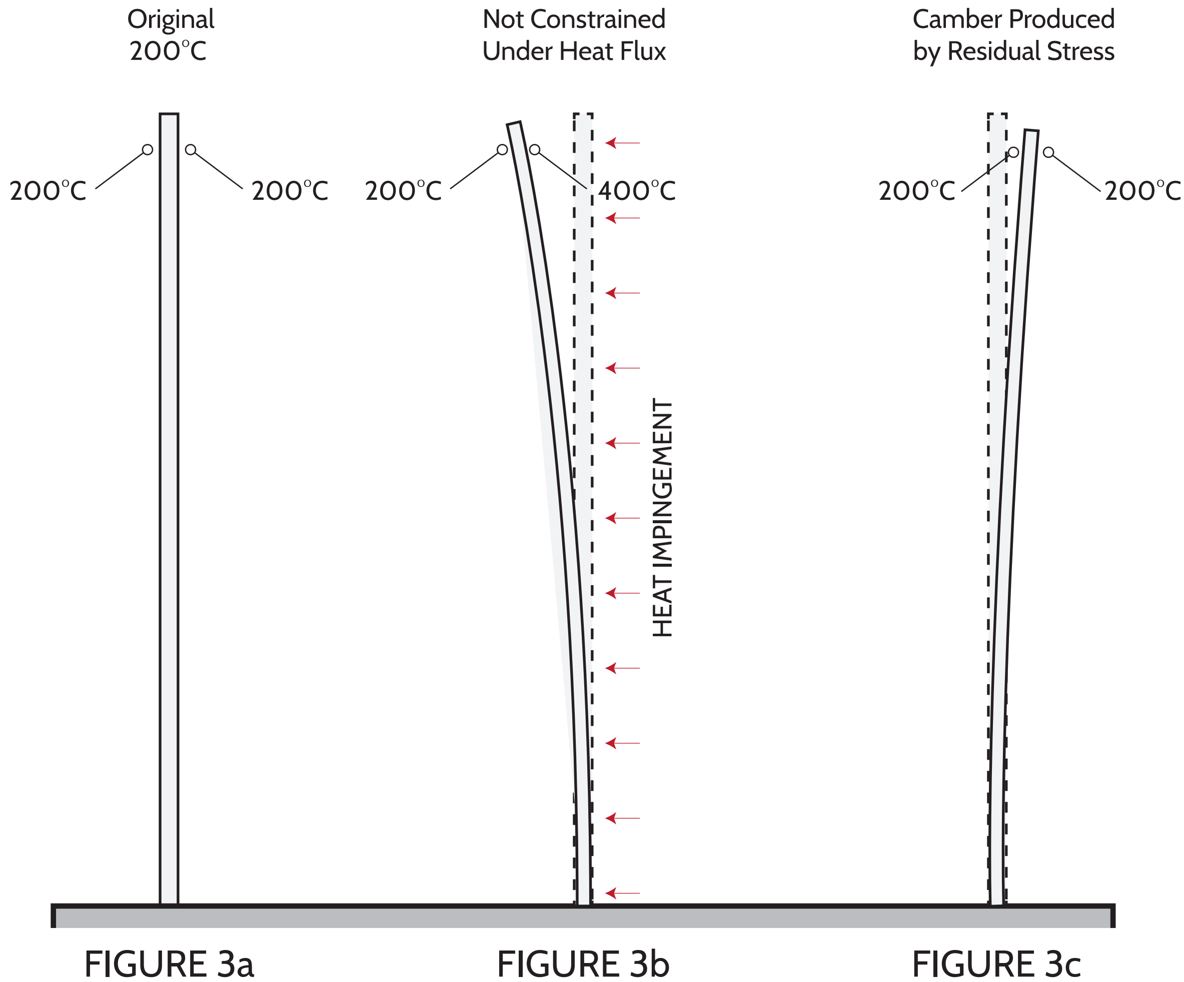
the last figure corresponding to the (higher) yield point at 200°C (392°F).

Each time the heating-cooling cycle occurs, if the rod is allowed to expand freely only a fraction of what would be required, plastic “squeezing-in” and plastic “stretching” will occur, thus leading to fatigue. This is a simplified picture of what happens with the firebox side plates. Referring to Fig 1, the highly heated area “a” expands and contracts following the heat flux variations occurring in correspondence with boiler load variation. Its expansion is severely constrained by the stiff foundation ring (mud ring) “f,” and to a lesser degree, by the adjacent area “b,” which also expands, but to a lower temperature because of a lower heat flux.

When a plate is subjected to a heat flux (Fig 3a), the face receiving the heat impingement will be heated up to, say, 400°C, while the other side will keep, say, at 200°C. The plate will expand lengthwise, but also will bend because of the longer length of the expanded hot fibers as compared to the unexpanded cooler fibers (Fig 3b). When the heat flux ceases, the temperature of both faces will equalize and the plate will return to its original plane condition.

Should the plate be constrained to keep plane, compressive stresses develop in the hotter side and tensile stresses on the cooler side. If the temperature difference between both sides keeps within the limits,

Heat flux much? *Locomotive 614 pulls with all of its worth at Miflin, Pennsylvania, on September 28, 1980. The engine stalled just a few hundred feet further down the rails. Photograph by John F. Bjorklund and courtesy of the Center for Railroad Photography and Art - www.railphoto-art.org*



Figures 3a-3c *Effect of temperature differences between the faces of a plate subjected to a heat flux.*

the resulting stresses will be below the yield points.[5] Upon ceasing the heat flux (the temperature returning to the original 200°C), both compressive and tensile stresses will disappear and the plate will remain planar without reacting on the constraints. But if the heat flux resulted in temperatures leading to stresses above the yield point, plastic deformations will occur in the material near both sides: the hotter side will be "squeezed-in" and the cooler one will be "stretched." If the heat flow ceases, the hotter side will shrink (as per the rod before) and the cooler side will expand, thus resulting in a camber (Fig 3c) whose size is contrary to that obtained when the plate is free (compare Fig 3c with Fig 3a). The camber is permanent unless the constraints are such that the plate is forced to keep the plane. In that case, a residual tensile stress will appear in the hotter side and a compressive stress will do so in the cooler side. Provided that the heat flux is high enough, both stresses will reach the yield point.

5 - In tension and compression, which are not necessarily equal

Both stresses (the formerly spoken about resulting from constrained linear expansions and the latter resulting from the heat flux) combine, and depend on the intensity of the heat flux). Since the latter follows the cyclic boiler load variations, the stresses also do the same, thus leading to fatigue.

The cyclically heated-cooled inner firebox plate is forced to keep plane because of linkage provided by the staybolts. If the latter are of the ordinary, not the articulated ("flexible") type with both ends clamped (fixed) on their respective plates, the assembly is very stiff, and its moment of inertia is very large. However, said assembly does not behave as an ideal solid because (i) the stays bend to an S-shape, and (ii) both plates assume a local inclination around the stay clamping because of the clamping moment (Fig 7).

When the area "a" (Fig 1) is subjected to expansions constrained by the surrounding, cooler, area "b" and the foundation ring "f," it would tend to buckle were

Where the magic (of combustion) happens. *This image, taken from the flue sheet of an operable 4-8-4 locomotive, shows the view through the combustion chamber and of the T-style safety circulators of the locomotive. Many thousands of staybolts are evident as the circular dots spaced in a grid across the sheets.*

it not for the support given by the stays. This buckling tendency also shows locally in the area between the stays on the sheets. Under the influence of the pressure and the expanding tendencies of the hotter fiber, the buckling takes place between the stays, assuming the form of a bulge (Fig 4). At times, two or more bulges lying one before and one above the other form an elongated, vertical bulge; several vertical bulges can appear on a firebox side, leading to the so-called "undulations." The bulges and undulations are a natural escape for the constrained expansions and **are not due to a reduction of the resistance of the metal** due to overheating, as is many times supposed. On the French Railways, a say up-to 7mm (1/4") is tolerated. Of course, they can also result from a heavy overheating obtaining in a heavily sealed plate. Bulges are prone to be found on heavily heated areas. For example, in the back part of the crown sheet in oil burning engines where the flame, coming from the bottom, impinges said crown sheet. On oil burning engines they also appear at the rear part of the side sheets where the heat flux is very intense.

The relative movements between the inner and outer plates are small in the neighborhood of the foundation ring because of its great stiffness, and increase with the distance from it. Expansion associated with heat flux translates into high stresses when constrained near the mud ring (hence leading to cracks), and into movements affecting the stays when the plates are free to displace.[6] This, the danger of displacements, obtaining far from the ring, in the area "c" (Fig 1), result in a greater frequency in stay breakages (in the aptly named breakage zones).

Again, the failure is through fatigue and occurs (in the stay) where stresses are the highest, i.e. near the clamped ends. To absorb larger relative displacements between the plates, articulated ("flexible") stays are provided. They are more flexible because of the ball-and-socket articulation transmitting quite low clamping moment (that due to friction only).

In the case of the horizontal stresses developing in the zone "a" (Fig. 1), the inner plate can only absorb them by a plastic tensile yield (as already said) or by an outward bulging of the whole firebox (see LEFT). But, since the constraints in the vertical direction are mild, the shrinkage results in a **downward** permanent deflection of the stays (Fig 8). Those of the front and back rows, for the same reason, tend to bend outwards towards the center of the area "a" (Fig 1).

The permanent shrinkage of the inner plate leads to a

6 - This was not true in the case of 614T January 85 tests. Hence, leaks could not be stopped!

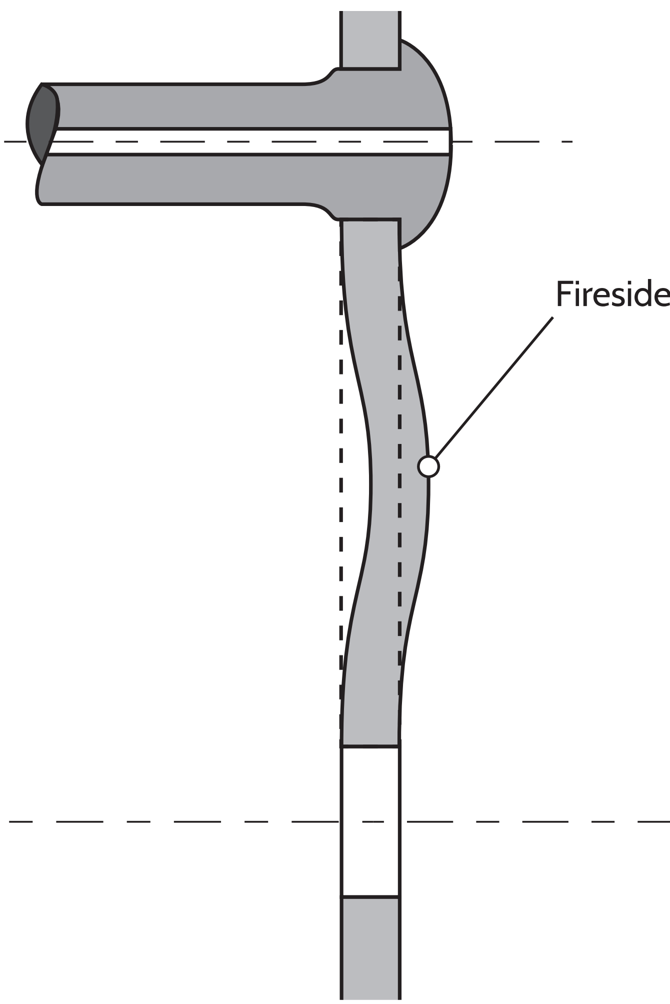


FIGURE 4

Figure 4 *Inner firebox plate bulging between the stays*

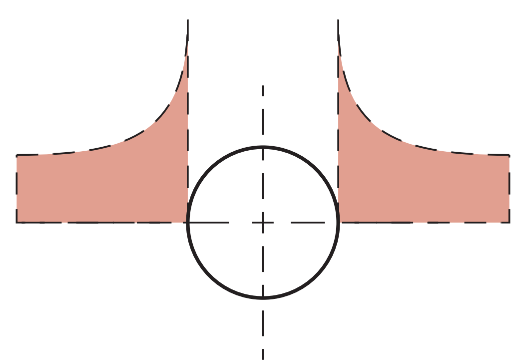


FIGURE 5

Figure 5 *Tensile stress concentration around the stayhole* permanent outward bulging of the whole firebox. The foundation ring increases its width (some 3" in the case of the German Class 44's). This permanent bulging leads to increased, cyclic S-deflections in the stays. By the same token, the inward pre-bulging proposed by TROSS (standard in Germany) works favorably.

Stay leakage, together with side plate cracks and staybolt breakages, is the third plague affecting firebox maintenance. It is the result of strains and stresses altering the good fit of threads and stay heads. CHAPELON ((Ref 4), p. 65) says that:

> *Contrary to what can be thought, it is very difficult, perhaps impossible, to practically make stay heads leakage free by the sole accuracy of the fitting. It is absolutely necessary to get it through riveting or by expanding the head made hollow (Germany).*"[7]

This is not surprising in view of the kind of stresses affecting the fit, as said above. Instead of riveting, seal welding was also practiced as a result of empirical development. Stay leakage is more apparent when the hole is deformed by the kind of horizontal-wise stresses also causing the cracks. This is why they show with greater frequency on the area "a" (Fig. 1) as for said cracks. Bulging and undulations, in that they contribute to the deformation of the plate in the vicinity of the head, also lead to leakages (Fig. 6). In the U.S.A., the simultaneity of leakage and plate cracks was linked by a cause-effect relationship: cracks were attributed to "Fatigue-under corrosion."

Since the tensile stresses on the plate are the highest when the heat flux is zero, leakage is more apparent (and also more easily seen!) when the boiler is cooled down. For the same reason, cracks take place under such circumstances, at times triggered off by the blow of a hammer.

Experience has proven that, by far, water treatment is the largest influencing factor, namely:

1. Scale, acting as a heat insulator, increases the temperature of the firebox plates significantly, thus leading to increased expansionisms, their effects "proportional" to them;
2. Corrosion reduces the fatigue resistance on both plate and stay metal;
3. Caustic embrittlement leads to accelerated inter-granual cracking in all metal subjected to yield point stresses. The three conditions necessary for the caustic embrittlement are present: (a) concentrating leaks (in this case formed by the heat impingement); (b) high stresses and (c) the embrittiling (e.g. not inhibited) water.

The latest internal treatment techniques (e.g. Porta Treatment) do provide appropriate control in connection with this aspect of the problem. In France, the 141R of American design attained 2,000,000 km (1,250,000 miles) with less than 200 man hours charged to firebox maintenance. **A scale layer 1/16 inch thick produces more damage than doubling the evaporation rate**.

Abuse and mishandling are large factors in aggravating the herein considered difficulties. It takes several forms:

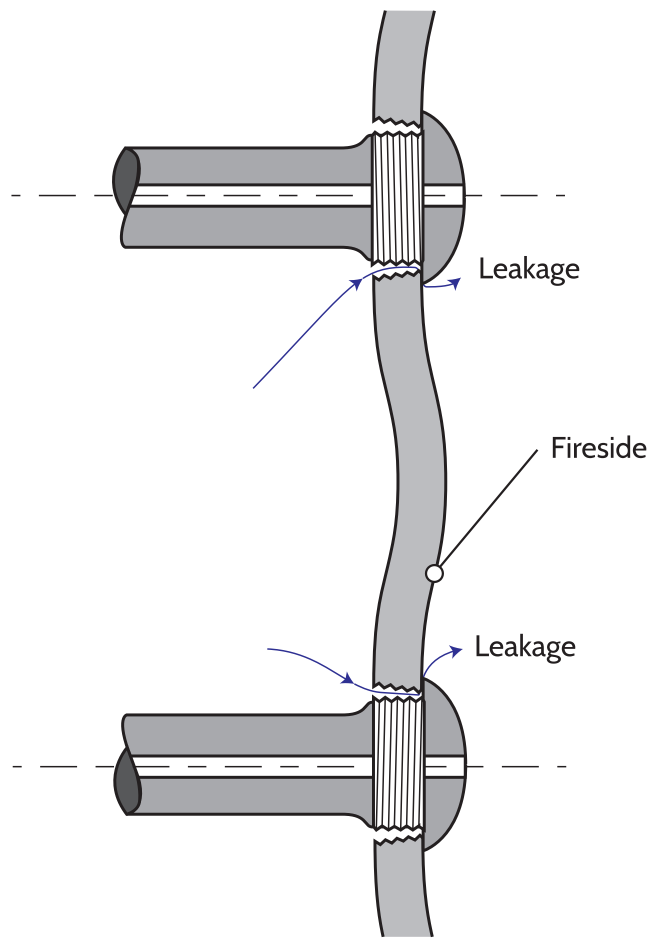


Figure 6

Figure 6 *Stay leakage produced by large bulging (not to scale)*

7 - *Relatively free.*

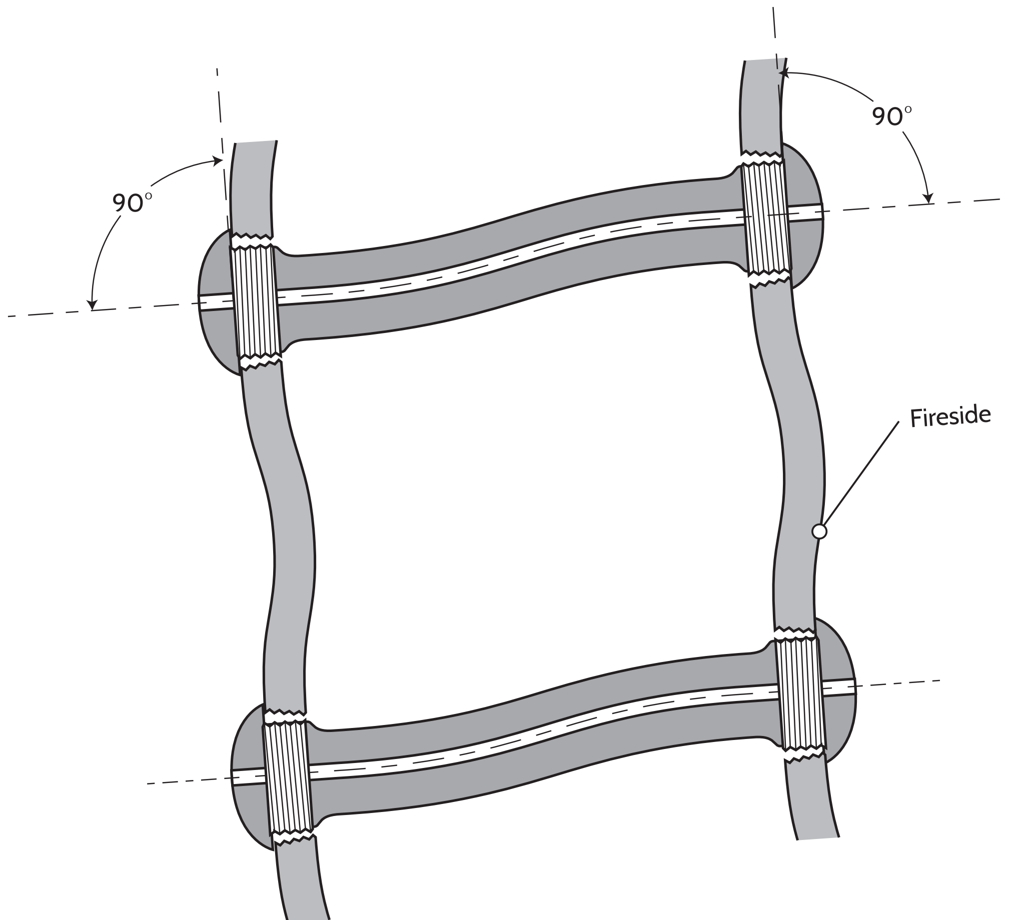


Figure 7 *Deformation of the stays in S and inclination of the plates at the clamping ends due to a displacement of the inner relative to outer firebox.*

1. Reversing the flow of heat so that it goes from the water towards the fireside. This occurs when:
    - Cold air is sucked by the blower with little or no fire on the grate. Also when moving engines under such conditions on its own steam;
    - Improper cooling down practices
    - Boiler washing out (or filling up) with water hotter than the metal, etc.;
2. Pumping large quantities of cold water immediately after the throttle is closed following a heavy steaming; and
3. Inferior shop and roundhouse repair and maintenance practice, etc.

All cyclic, fatigue-producing effects (as said) increase with the temperature difference occurring between both sides of the inner firebox. This difference is proportional to plate thickness; thus the tendency should be to adopt thinner plates. Increasing the thickness is not a way to reduce failures, as proven by the already-mentioned German failure in 1914-1918 when switching from copper to steel inner firebox sheets. Reducing this thickness increases the more or less constant pressure-related stresses, but these are lower and far from the yield point attained during every steaming load cycle.

Metal conductivity has insufficiencies similar to thickness: alloying elements **decreases** that conductivity, and therefor this aspect must be watched.

Since water side corrosion can now be reduced to negligible proportions, no extra thickness is to be added on this account. Same concerning the mechanical erosion cause by char particle impingement on the fireside. Thanks to the GPCS, this impingement is largely reduced, and therefore the extra thickness included on this account can be reduced. To this writer's best knowledge, the minimum thickness accepted for plates in worn-down condition is 7mm (a little less than 5/16") on the French Railways.

Longer stays provide increased flexibility and are therefore favorable; both the American empirical development and the German one based on Tross' work (hence largely including the herein spoken considerations) point towards longer stays. But

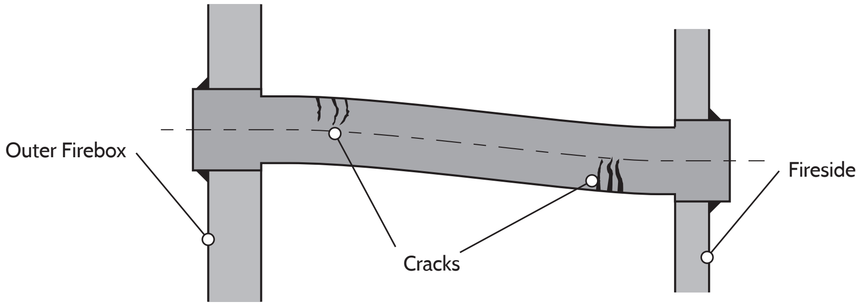


FIGURE 8

Figure 8 *Form taken by stays of the breakage zone as a result of the inner firebox shrinkage (from TROSS Ref (2)). Note downward bending.*

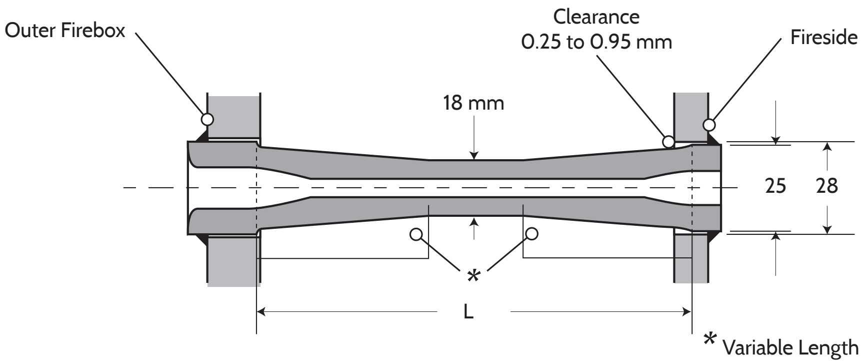


FIGURE 9

Figure 9 *The TROSS - HENSCHEL stay adopted as standard in Germany.*

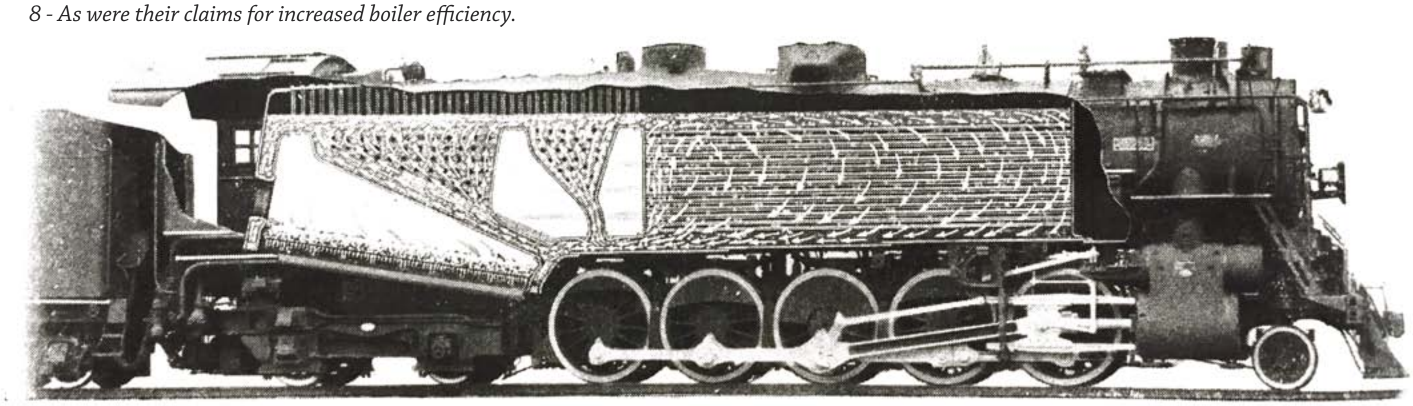
longer stays are not synonymous of larger water passages. Water circulation is ample in locomotive type boilers (water/steam mass ration on the order of 500) and has **no** influence on firebox difficulties. The staybolt breakage reduction claimed by NICHOLSON syphon proposers is false.[8] The wasted shape of the shaft of the TROSS – HENSCHEL stays do provide the best combination of flexibility and uniformity in the overall stresses (Fig 9), and has proven its worth in service.

Same for the threadless, welded-until-clearance stay head, which is superior to the various forms of seal-welded heads (Fig. 9). Laboratory experiences showed great promise for the configuration shown in Fig. 10. All kind of welds introduce important residual stress that must be taken into account. Note that stress relieving is not possible for existing boilers.

The tube plate is an element which, in the past, led to considerate maintenance. Leakage was a plague, and in the U.S.A. erosion too. Its design proceeded along an historical, empirical path. Nobody tried to understand the mechanisms associated with its strength to withstand the handling of thermal stresses. Why does the front tube sheet never leak?

Tightness was attained by tube rolling. Beading-over permitted to dispense with stay tubes which were used in other fire tube boilers. Rolling is a more efficient way of connecting the tubes to a plate or drum, however, in the latter case the connection is not subjected to heat impingement, hence not to thermal stresses. Tube rolling sets up severe stress, up to the yield point, both in the tube and the plate; same for beading over. These stresses produce a severe strain hardening on both

8 - As were their claims for increased boiler efficiency.



Nicholson Sypons *(polygons in the firebox)are shown in this promotional image from 1941.*

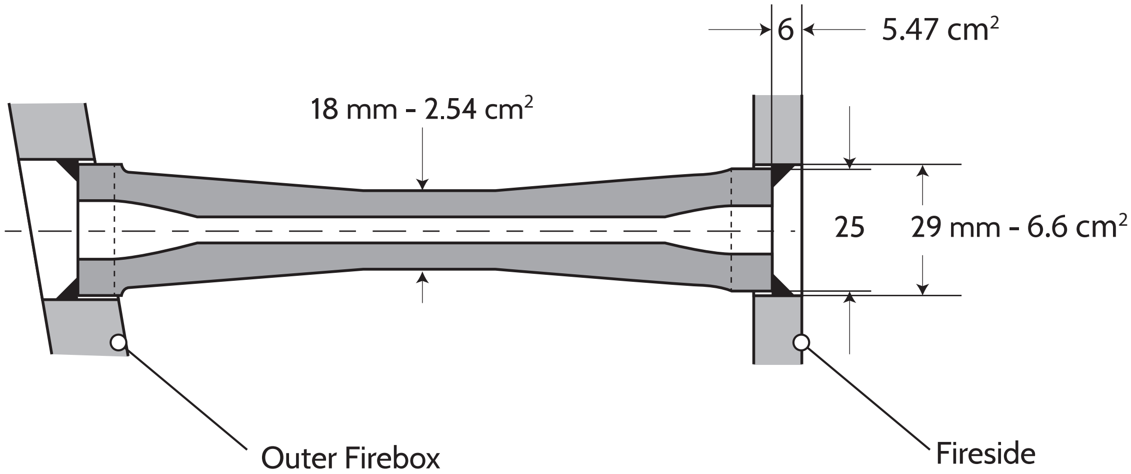


FIGURE 10

Figure 10 *Latest form of stayhead proposed by TROSS.*

metals. Leakage is produced because the contacting pressure is lost; maintenance restores the contacting pressure time and again by further rolling, on its turn increasing time and again the plastic deformation of both members.

Plate thickness cannot go below a certain minimum established by experience if an effective seal is to be kept by rolling. Same with the minimum amount of metal left between the tubes. Both are not fixed by stresses related to safety; a simple calculation for the area left between the tubes shows that, were it not because of rolling requirements, it would be very small (say 1/8"), far less than the customary 5/8" (16 mm).

A 1/8" thick copper ferrule was introduced between the tube and the plate as an empirical development to improve tightness. Then a light seal weld was included, which weld was performed with the boiler filled up with water. By the very definition of rolling, no stress relieving is possible.

The tube plate fails because of thermal stresses resulting from flame impingement, in a manner similar to that leading to stay leakage. The plate can expand more or less freely both vertical and horizontal-wise, but cannot bulge because of the heavy linkage established by the tubes to the front tube plate. The latter is thicker, and **never** leaks. As for firebox plates, thermal stresses reach the yield point in a cyclical manner, thus leading to fatigue. Cracks develop both circumferentially and radially; in the latter case, they continue lengthwise on the tube. They also develop on the plate metal in radial form, and terminate by connecting one hole with its neighbor. Cracks are repaired by welding, but they last fewer and fewer miles until the boiler has to be retubed, a most costly operation.

Tubeplate leakage leads to (i) poor steaming and (ii) **makes impossible the control of the water treatment** because it works as a large, unwanted blowdown.

As a result of cyclic stresses getting over the yield point, the tubeplate shrinks by a process similar to that evidenced in firebox plates; this led to various forms of articulations for some rows of neighboring roof stays.

As for the other firebox plates, water treatment imperfections (scale and corrosion) severely affect tube plate upkeep. Same concerning the severity of heat impingement and abuse. The already-mentioned French experience with the TIA water treatment showed that tube plates keep very well with rolling, beading over and seal welding arrangement.[9] In Germany, the substitution of steel for copper after WWII led to a development derived from TROSS stay heads; the tubes were welded with **clearance** (hence no rolling) in the tube plate.

The tube plate must absorb the forces caused by the lengthwise expansion of the tube bundle, and also that of the combustion chamber (if present). Both increase with their length. The Pennsylvania Railroad introduced a corrugation between the combustion chamber and the firebox, and at the bottom of the front tube plate (Fig 11). How both tube plates accommodate to absorb these forces is not known, and its mechanism must be disclosed. Again, tube sealing increases tube temperatures and therefore the amount of expansion that must be cyclically absorbed.

Gas area is a cardinal point in boiler design: all

9 As per the USA current practice.

Rolling along at track speed with a clean stack, *C&O 614 pulls a Chessie Safety Express train Eastbound at Rockwood, Pennsylvania, on September 27, 1980. Photograph by John F. Bjorklund and courtesy of the Center for Railroad Photography and Art - www.railphoto-art.org*

available means must be sought to increase it as far as possible. The available room left between the firebox or combustion chamber plates must be utilized to the maximum. This requires the tubes to approach as much as possible the corners; leading to difficulties in connection with rolling, beading over and seal welding. Attention is also called to the unbalanced forces resulting from more parallel arrangements of the tubes, as is frequent in German designs.

There is no need to keep to a system for tube attachment which is unnecessarily tied to empirical development. As is the case for tubular heat exchanger technique, new configurations based on relying on welding as a uniting procedure must be taken advantage of.

Fireboxes never fail catastrophically (except in the case of low water) because (i) a leakage always shows first, (ii) no brittle fracture occurs, and (iii) in case of failure (stay breakage or plate crack) a safe load transference to the adjacent members is always possible. Therefore, safety criteria can include more “risky” hypotheses.

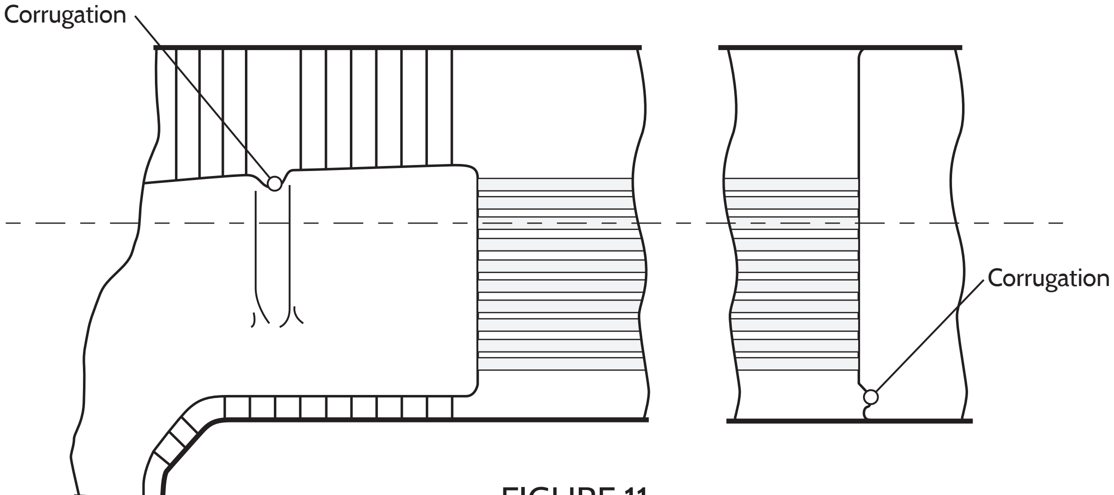


FIGURE 11

Figure 11 *Showing the corrugation introduced by the PRR in the firebox-combustion chamber union and at the bottom of the front tubeplate.*

3. Concluding Remarks and Recommendations

As said, this paper purposely avoids the proof of the advanced statements. Neither is its object to get into the complex analysis of details, nor to list answers to the posed questions. It tries to make a broad synthesis of the problematics of firebox design. It may be that there are completely different approaches, like the Lawford FRY or BROTAN water tube fireboxes. Their discussion is also outside the scope here.

Four reasons are accepted for continuing the study of the STEPHENSONIAN firebox:

1. That its ills vanished as a result of the advances in water treatment;
2. That it integrates very well in making the boiler serve as an elegant backbone for the whole locomotive;
3. That it answers the problems involved in the premises included in locomotive rebuilding ; and
4. Because it is felt that it offers considerable room for progress as required by the more ambitious targets aimed at in third generation steam technology.

As said in the introduction, the present effort is no more than a synthesis experience. TROSS (2) is half way in the process aiming at getting a rational firebox design, not to mention the questions associated with the GPCS and the extension of the locomotive boiler technology to areas like tour boat, bagasse and refuse burning, and the industrial field generally, and with pressures in the 60 ATM (882 PSI) range for which the stayed construction has proven its capabilities.

Tube bundles, in which the gas flow is parallel to the heating surface development, are at an advantage with respect to cross flow, water tube arrangements in connection with draft pumping work, erosion and fouling. Very high drafts, produced either by efficient ejectors (whose development is not as yet attained its climax) or by tail-steam turbine driven faces, open the door to use them both to increase the heat transfer productivity of convective surfaces, and the intensity of gas phase combustion. The GPCS with cyclonic particle separation offers great possibilities for an efficient increase in the capabilities of a given grate surface.

Given plenty of draft, where is the limit for the maximum evaporation of a given hardware? Which means, where is the limit between steam production / investments and operating costs?

The development of the steam locomotive boiler did not exhaust its possibilities. Its design proceeded along an historical path which was largely empirical in nature. The endurance of its conception can be taken as proof of its intrinsic merits. That development ceased because of the development of the steam locomotive ceased, and full advantage of major potential contributions like those of water treatment, welding and the science of materials did come into being. This shows a clear path for progress.

Two fundamental conceptions of firebox design are to be explored: (i) the traditional scheme in which both fireboxes are made solidary by rigid stays (with additional elasticity in breakage areas) and (ii) one in which the inner firebox “hangs” ideally suspended from the outer firebox by means of double-articulated stays (or their equivalent). The span between them can include intermediate solutions. **The proper choice can only be made by predicting the behaviors in quantitative terms**, and related to the science of the strength of materials. This writing is no more than a first step down the road.

It may be that speaking about cyclic stresses getting above the yield point horrifies the engineer. Perhaps they may tolerate them in connection with maintenance, but not with safety. But the fact is that some HALF A MILLION locomotive boilers have been built and proven to be safe in spite of stresses which in the past, because of poor water treatment, were far lighter than they were by the end of steam locomotive development in the 1950’s. This is so in spite of the engineer not being aware of it. But such stresses are possible because the parts contained herein are not required to work an infinite number of cycles (i.e. they are subjected to low cycle fatigue) and because the failure is **never** catastrophic. The proposed philosophy is not one of avoiding them, but one **quantitatively** mastering them. After all, one has to remember that riveted structures, like those of airplanes, do work, in certain parts, with stresses well into the plastic range!

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THE THERMO-MECHANICAL BEHAVIOUR OF THE STEAM LOCOMOTIVE BOILER FIREBOX - AN OVERALL VIEW.

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L.D. PORTA