COALITION for SUSTAINABLE RAIL

What Steam Pressure for Old Locomotive Boilers?

Ing. Livio Dante Porta

Foreword: Wolf Fengler, MSME

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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 - *a Library of Congress photograph of the John Bull, an 1831-built steam locomotive that has operated as recently as 1981 in the U.S.*

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Foreword

Dear Reader:

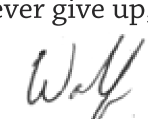
It's funny how life comes full circle sometimes. Back in 2001 I was preparing to undertake my first set of FRA Form 4 calculations. I mentioned this to Dante Porta at the time, and he sent me a copy of this paper as a guide. How appropriate then that 14 years later I was asked to introduce this treatise.

If you have read any of Porta's writings, just a few of which we have published as part of our white paper program, you will have come to understand how much Porta was both a strategic and a tactical thinker when it came to the steam locomotive. The contents of this paper apply that intellect to illuminate the often mysterious world of riveted locomotive boiler construction.

The rapid spread of modern welding techniques after World War II has moved riveted construction further into niche fields like aircraft construction. Porta, in his unique writing style, re-examines this topic from a fresh perspective with a nod toward locomotive preservation as well as new construction.

Of course, CSR isn't just about preserving our steam locomotive heritage and Porta's legacy. It is about advancing that work as well. If you share in that vision, we hope you will consider making a contribution to support our efforts today. To find out more, visit: **csrail.org/support**

Never give up,



Wolf Fengler, MSME
Senior Mechanical Engineer

Summary:

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1. Introduction

There are a number of cases where it is necessary to calculate the maximum allowable working pressure ("MAWP") of locomotive boilers that were built many years ago, and the aim is to set that pressure as high as possible for a number of reasons. Usually, this would have been a matter subject to the jurisdiction of the corresponding authority, but the point is that since 1960 or thereabout, locomotive boiler inspectors having the particular experience in this area no longer exist. Those coming from other areas often feel significant discomfort and tend to adopt conservative criteria which go against the goals and needs of the end user. Furthermore, the vast majority of these boilers are of riveted construction [including that of ATSF 3463], an art about which today's existing knowledge has practically disappeared.

Examples of these situations may be:

a) locomotives which, in large numbers, are apt to receive a process of modernization which include the aim of having the highest possible pressure in the steam chest (example, some 250 locomotives in Cuba);
b) locomotives which for documentation, technical or special purposes, require said highest pressure;
c) locomotives belonging to preservation groups (including museums) which have been built in quite ancient times near the turn of the 20th Century; or
d) locomotives operating on tourist railways.

The Author has been connected with this problem since 1952 when he increased the boiler pressure of twelve locomotives of the 8C class of the FCGR (Argentina) assigned to the Buenos Aires commuter service. The pressure was increased from 11.04 bar to 13.45 bar (160 - 195 PSI) or about ~22%. The locomotives were built in 1915 by BEYER PEACOK (Great Britain). There was no problem with the stringent Argentine Railway Boiler Inspectorate. Same with prototype engine No. 4674, series XIIa, FCGB Argentina whose boiler, built in 1919 by ALCO (USA) was subjected to an increase from 11.73 to 14 bar (170 to 203 PSI) or about 19%. Chapelon increased the pressure of multiple engines of the series 11C (FCGR Argentina) from 13.7 to 14.7 bar (199 to 213 PSI) or about 7% built by ARMSTRONG WITHWORTH (Great Britain) in 1927.

The purpose of this paper is to review the philosophy of historic boiler construction in connection with safety and service EFFICIENCY, not to mention ecological considerations. More than HALF A MILLION of them have been built over 130 years (the most numerous class of all boilers), nearly all of them of riveted construction, which provides evidence of the suitability of said construction as proven by the test of time.

2. Fundamentals

The question is defined as follows: one has a particular boiler in front of them (i.e. materially at sight, not somewhere in the country).

What is the maximum allowable working pressure to be set, when operated by a particular agency or persons, during what period (expressed in time or in distance), under which particular conditions of service, maintenance, inspection, and other precautions?

The boiler steel has endured a history of construction, use, and it often exhibits corrosion (or its abuse), deformation, kinks, etc. But boiler steel has no memory in the sense that it cannot record intentions either concerning design or past use. A number of assumptions and presumptions regarding force must

Lacashire and Yorkshire Railway 0-6-0 No. 1300 *climbs the Kelling Bank on the North Norfolk Railway. Built in 1896, this preserved locomotive is similar to the one which underwent destructive testing in 1912. Photographer Gerry Balding, Creative Commons*

be considered. Perhaps the most important is that the boiler was built according to the rules of the art prevailing at the time of its construction, and that its very existence today after a number of years of service is the very proof of it. In other words, acceptance for service continuation is to be proven. Excluding that of the inner firebox, STEEL DOES NOT AGE, though it may be subjected to fatigue, which may or may not produce damage.

Boiler codes are regarded as a source of knowledge and information. JUST BECAUSE A BOILER COMPLIES WITH ONE OR ALL OF THEM IS NO GUARANTEE OF SAFETY, NOR NON-COMPLIANCE AN UNSAFE BOILER MAKE. Safety is a matter of probability; a 100.000...% safety in any engineering field neither exists nor is possible.

The MAWP of a boiler's design is different from defining the maximum pressure the fabricated boiler is able to withstand. This is due to the actual thickness of the various plates ALWAYS being greater than the calculated one since the plates existing in the market conform to discrete thresholds. Put another way, the manufacturer is forced to choose the next greater thickness available over the calculated figure to ensure sufficient compliance with the requested specifications. Same thing happens with the strength of materials; all of them are above the specified minimum. In other words, *juris et de jure,* a boiler is built to a strength greater than that dictated by design.

All boiler codes of the various industrialized countries are equally respectable, and there is no reason to not check a given boiler against the least stringent one. The Author usually adopts the FRA (U.S. Federal Railroad Administration) or German TÜV (Technische Überwachungs Verein), to which the latest German locomotives have been built (Rheie 10) (*)(#). The common engineering procedure is to check every part and see what pressure each is able to withstand safely. Obviously the element showing the lowest value is the determinant (typically the longitudinal steam of the boiler barrel).

People generally have a poor idea of what strength boilers have against explosion. The Author carried out an informal inquiry related to boilers operating between 12 and 15 bar (175 to 218 PSI) to determine the hypothetical MAWP. The answers varied from 18 to 25 bar (261 to 363 PSI), which in the Author's opinion are still too low. In 1912, the Chief Mechanical Engineer of the Lancashire and Yorkshire Railway ordered his staff to carry out a destructive hydraulic test of a boiler following the failure of a sister locomotive's boiler in service. The designed MAWP was 12 bar (175 PSI); at 42 bar (610 PSI), the test was halted and, upon inspection, just some deformation of the copper firebox plates was found. There is a common feeling that the RED mark on the pressure gauge is a signal for danger: one should note that the FRA code allows 6% extra pressure when the safety valves are popping, while the German code permits 10% (~1.5 bar or ~20 PSI). In Argentina, the latest rule accepted is 5% and it indicates that safety valves should open gradually (not POPPING).

The mode of failure of various boiler parts is different: (a) some components, upon failing, transfer the load to neighboring parts (i.e. staybolts); (b) other components cannot transfer energy to neighboring parts (i.e. the barrel). Therefore, the probability of failure and the resulting damage is not the same, and the design concerning safety cannot be handled under the same philosophy. This concept, although supported by 150 years of experience, has inexplicably never been spoken about! All operating rules state the maximum number of failed stays allowed in a certain area while still keeping a boiler in service, and even the extent of cracked inner or outer plates. But all say that a leakage in the barrel calls for an immediate stopping of the locomotive and demand the pressure fall to zero.

Many regard riveted construction disdainfully, which may result from an insufficient knowledge about what rivets have done, and are still doing, on thousands of constructions and bridges which for decades have been working with far higher stresses and fatigue cycles than in boilers. The reason for the substitution of welding for riveting has not been that of an unsatisfactory service, but rather due to economics and the possibilities concerning lightness and advanced unions. Ref () reports as summary of 1364 papers and studies devoted to riveted construction since 1837 to 1944, which gives an idea of the intensity of research and experience involved in them.

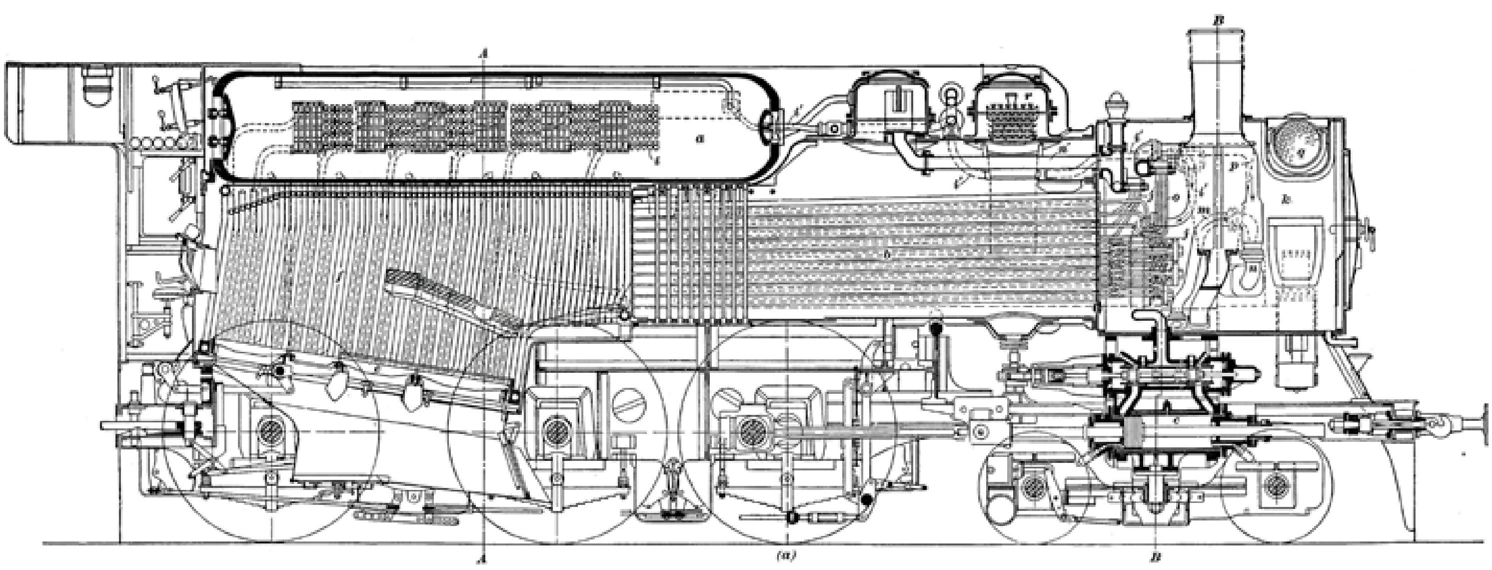
Concerning barrel thickness, one should note that the classic formula for the maximum allowable working pressure in kg/cm2 is:

$$p=(200*v*(s-1)*k^2)/(D*x)$$

Where:
v [-] . . . . is the joint efficiency;
s [mm] . . . . is the barrel thickness
k^2 [kgf mm-2] . . . . tensile strength of the material;
D [mm] . . . . is the inner barrel diameter; and
x [-] . . . safety factor, usually “4” for locomotive boilers.

It is noted that an additional 1 mm is included to account for corrosion, a figure which may be eliminated if either there is no corrosion or if the pressure is adjusted every time the boiler is inspect to account for it.

High Pressure Experimentation. *Railroads underwent a period of experimentation in increased boiler pressure in the early 20th Century that led to the development of prototype, high pressure water tube steam locomotive boilers. These cross sections show the unique design known as the Schmidt Double-Pressure Locomotive Boiler. It employed a 3-stage steam generation system. The primary generator was a fully sealed ultra-high-pressure circuit operating between 1400 and 1800 PSI (9.7 to 12.4 MPa), filled with distilled water that transferred heat from the firebox to the high-pressure drum “a” in section (A). This pressure drum then heated feedwater to high-pressure steam of 900 psi (6.2 MPa) which was taken to power the high pressure center cylinders “c” in section (B). The third steam raising unit was a conventional locomotive fire tube boiler operating at 250 psi (1.7 MPa) heated by combustion gases from the coal fire. Issues with overall mechanical complexity and over-the-road forces damaging the water tube construction plagued this type of locomotive from its inception. Only two locomotives were built with this system - one in Great Britain [see page 7] and one in France - both suffered over the road high pressure tube failures.*



Each type of boiler has particular characteristics resulting from stresses and strains experienced in service. Thus, each one of them should be governed by its specific code, namely MARINE, NAVAL, INDUSTRIAL, LOCOMOTIVE, POWER STATION, SUGAR, REFINERY, etc., boiler codes. A good example of the need to comply with regulations applicable to individual industries is the recurrent failures (at times deserving the qualification of utter) in attempting to replace the STEPHENSONIAN boiler with water tube designs on steam locomotives [SEE BELOW].

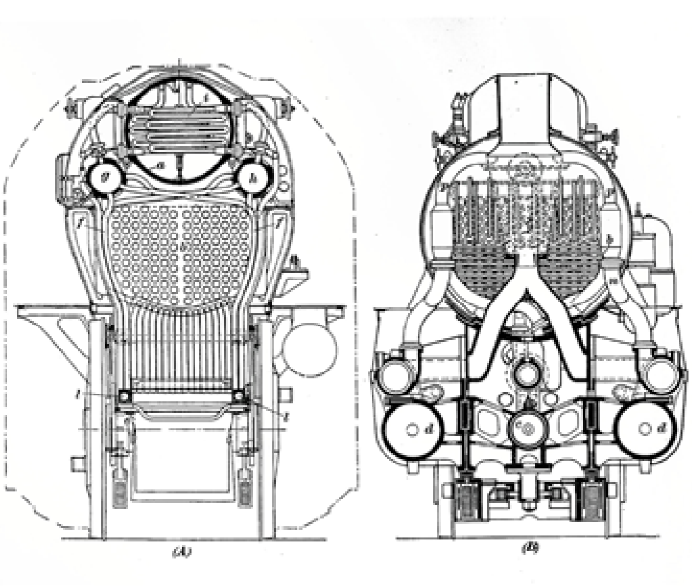
One should note that in the preceding formula, the joint efficiency factor refers to that area of the plate which is affected by the pressure of riveted holes. No corrosion can develop in the portion between the straps; therefore the "corrosion excess" (1 mm) is not to be included in the checking calculations. However, in the case of straps of unequal width, there could be an EXTERNAL corrosion on the surface opposite to the internal strap. Though this is infrequent, in areas where the climate is highly corrosive, as in Cuba, the thickness here is to be checked.

External corrosion can also appear in areas near the firebox where, during the lighting up of oil burning engines, burner flare up may lead to flames exiting damper openings. In those cases, flames can contact parts of the boiler plates where dew has been condensed, thus leading to the formation of CO_2-containing water (carbonic acid or H_2CO_3) which is corrosive.

It is generally the case that, upon checking the various boiler parts, the minimum figure calculated is higher than both the design pressure as indicated in the drawings, and the pressure at which the boiler has been working. For this reason, one should not speak about a pressure increase, but rather of RESTORING THE BOILER TO THE PRESSURE FOR WHICH IT COULD HAVE BEEN DESIGNED. This situation is quite frequent with American boilers; the manufacturer many times used the same boiler with 170 PSI for Cuba, 180 PSI for the Philippines, or 200 PSI for a logging railway out of FRA / ICC jurisdiction.

An ultrasonic survey of the various boiler component thicknesses is a matter of course. If there are corroded areas, a technique is available (and accepted at least in the USA) for pad welding plates. The mechanical engineer should define a minimum thickness for the barrel in areas not neighboring riveted seams. There is also a technique for supplementing the strength of small areas whose thickness is below the previously-defined figure. Furthermore, a technique for recharging such areas by welding also exists, but the Author does not recommend it.

INNER FIREBOXES are to be regarded with different eyes concerning the maximum allowable working pressure. They could fail in service, thus code rules, supposed to have been written for no-failure, are not satisfied. More than 150 years of experience has shown that broken staybolts, plate cracking, riveted joint leakage, bulging sheets and mud ring, stayhead leakage and tubeplate leakage constitute the majority of FOLKLORE concerning locomotive boiler life, yet ALL codes ignore it. This is a tremendous SCANDAL! The best proof of the ridiculousness of code rules is the fact that as soon as a good water treatment is applied, the above failures disappear, even after the metal has been abused by 30 or more years of scaling.



Firebox failures are caused by expansions and contractions resulting from heat transfer variations with the load and washing out [See CSR White Paper on the Thermomechanical Behavior of the Steam Locomotive Firebox]. This is known in full detail after the thorough works of TROSS (5). Indeed, locomotive boiler technology can be said to have two epochs: PRE- and POST-TROSS.

BUT STEAM PEOPLE ALL OVER THE WORLD, EXCEPT IN GERMANY, IGNORE THIS FACT.

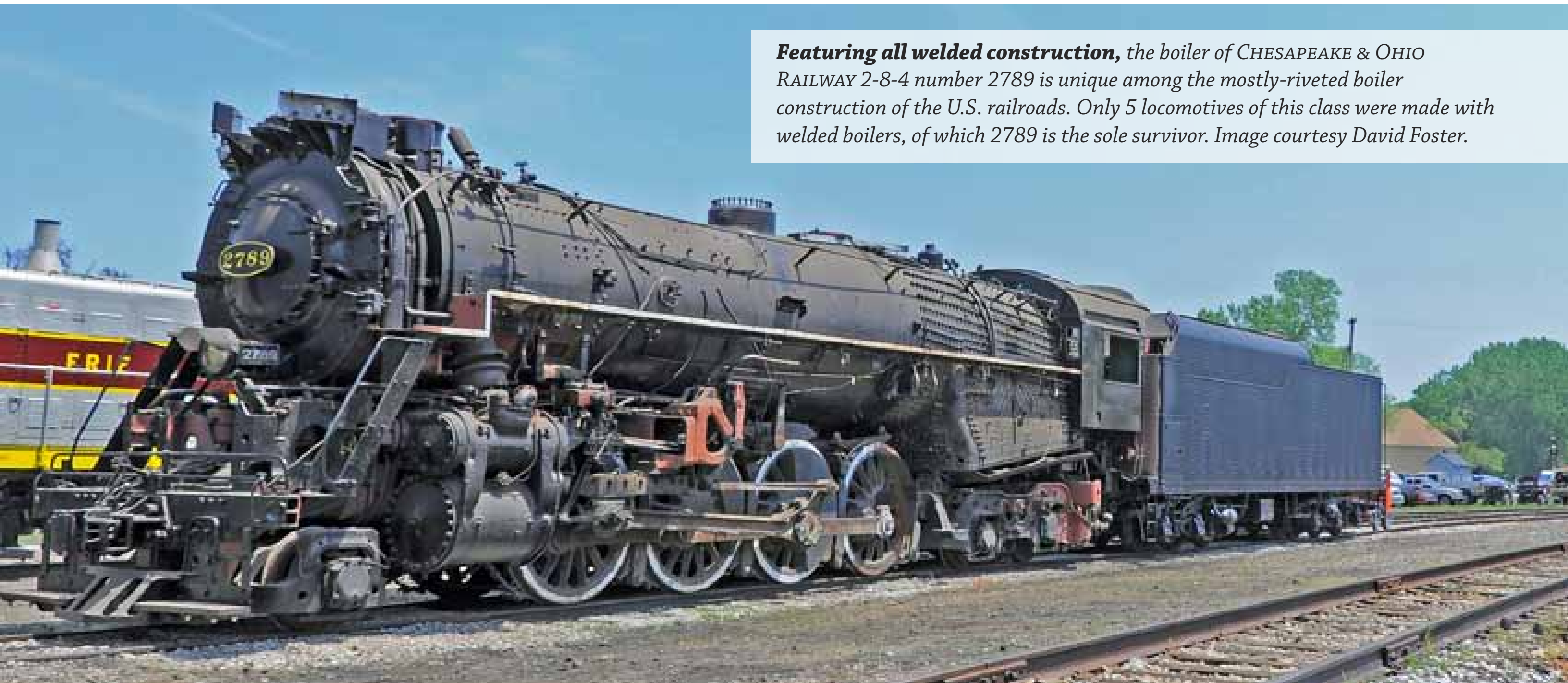
Thus, firebox maintenance does not depend on pressure, rather on thermal strains, which can occur even at zero pressure. So, staybolts and plates should be designed to prevent these kinds of failures, and not according to rules dating to the 1890's!

Firebox steel, and only firebox steel, may age in service because it can encounter, on the fireside, temperatures high enough to cause pearlite spheroidization, which is a metallurgical process in steels by which cementite lamellae decompose into spheroids. This spheroidization is a process accompanied by a decrease of the hardness of the steel. That said, in Germany, steels have been developed to resist this phenomenon.

SNCF rules allow 7mm (7/25 in or 0.28 in) as minimum firebox thickness, whereas general practice in the U.S, dictates 8 mm (5/16 in or 0.3125 in) as a minimum thickness. To the best of the Author's knowledge, no locomotive boiler code in the world prescribes ex-officio a pressure reduction along the years of service for locomotive boilers. Lay people show an untruthful view about boilers. They should be properly reassured, the present treatise does not refer to boilers built prior to 1890 because the steels available don't exhibit properties mandated afterwards. This is not to be interpolated as a disqualification, but simply it is implying that a special study is to be made in each particular case.

On checking the properties of materials employed in the construction of old boilers, one should take into account that ALL specifications refer to their condition previous to their cold (hot in the case of rivets) working as required to get them to the proper shape. Thus, barrels are plastically deformed by force in their outer and inner fibers, hence leading to higher hardness, greater tensile strength, and lower elongation. THIS IS NOT THE EFFECT OF YEARS OF SERVICE.

The Author is aware that the CHARPY toughness test is being incorporated into the material properties required in the standard applying to NEW boilers. Should this test be also demanded for existing boilers? Given that it is possible today to cut a part of the barrel just to make a test and weld a patch under an approved technique, the temptation is to include it in the approval procedure for old boilers. The Author's position is NO. To his best information, no boiler code in the world requires the owner of any type of boiler to buy the latest edition of the corresponding code to check, at given time intervals, his boiler in order to see if it complies with the requirements of said latest edition. However, one should not dismiss the possibility of a major discovery in the field of boiler safety putting all boilers under suspicion. But, such a situation would receive such publicity that is for sure a matter of discussion to be held at *THAT* opportunity.



Featuring all welded construction, *the boiler of Chesapeake & Ohio Railway 2-8-4 number 2789 is unique among the mostly-riveted boiler construction of the U.S. railroads. Only 5 locomotives of this class were made with welded boilers, of which 2789 is the sole survivor. Image courtesy David Foster.*

Chris Combe - Creative Commons

3. Riveted joints in bridges

Superb, majestic bridges embodying millions of rivets have been in use for over 100 years, and at least another 100 years of life are expected from them. Beautiful examples are that over the Firth of Forth [ABOVE] and those over the Rhine River in Germany. What are their design stresses? How do they compare with boiler stresses? The steel is very similar to that used in boilers, though not as finely controlled during manufacture.

In the case of Germany (2), the information available to the author regarding ST37 steel shows a loading of 14 kgf mm-2 for the main forces, 16 kgf mm-2 if accidental forces are included (wind, braking, friction on supports, etc.),the Factor of Safety is as follows :

Factor of Safety = 37 kgf mm-2/14 kgf mm-2 = 2.6

For boilers, there is a standard adoption of a factor of 4 of safety, which would mean

Maximum Load of Bridge using Boiler Code Safety Factor = 37 kgf mm-2/4 = 9.3 kgf mm-2

This means that bridges loaded with the typical load of 14 kgf mm-2 experience a factor of safety that is (4/2.6 = 1.54) or 54% higher than stresses allowed in locomotive boiler design and operation. This factor also includes the aggravating condition that they are subjected to fatigue varying between dead load and dead plus live load on a more frequent and severe basis as opposed to normal locomotive boiler stresses.

That said, locomotive boilers are subjected to fatigue stresses transferred from the frame of the engine (i.e. forces transmitted to the boiler as the engine rocks down the rails at speed). NO LOCOMOTIVE CODE DEMANDS FOR THEIR CONSIDERATION, yet they are present and there is a hypothetical need to clear the point, a matter of which the Author has started to undertake.

It should be noted that according to (3), the factors of safety in the USA have been, for existing or new locomotives:

Up-to 1912	3.25
1919	3.50
1921	3.75
After 1923	4.00

4. Potential mode of failure of riveted joints

Some 1,300,000,000 rivets have been used in locomotive boiler construction, proving that their suitability have stood the test of time, even under conditions of the most serious abuse. Firebox riveting is to be excluded from this discussion because welding has replaced it, although it is good to note that even under conditions of firebox sheet leakage, NEVER has this failure put safety at risk. The reason for this is since the union depends on the friction induced between the plates, the final state before total collapse happens at the sheets due to deformation and rupture by shear. Before final failure occurs, a leak develops which serve as an alarm, making possible the adoption of safeguarding measures. Hence, a riveted firebox could be considered "SAFER" than a welded one because the latter fails by fragile fracturing at a much faster speed.

This "SAFE" mode of failure also occurs in the event a given rivet joint is required to work under conditions which go against the very principal of its union. This is the case of firebox riveting, as mentioned above. Unlike the case of other boiler riveted joints, severe strains in the firebox occur because of the intense heat transfer and the expansion caused thereby on the firebox plates and the rivets themselves. Their eventual failure is never dangerous because of LEAKAGE prior to mechanical failure.

That said, an insidious form of failure has been caustic embrittlement. In the 1930's, caustic embrittlement was a plague of the Baltimore and Ohio Railway. Nowadays, it is known that it is a failure resultant from boiler water. When the concentration of NaOH (Sodium Hydroxide: aka "lye" or "caustic soda") becomes very high in water that contacts metal areas subjected to very high stresses, a crack develops not across the metal crystals but between them, leading to a catastrophic failure if not corrected in time. These failures happened in the case of industrial boilers because in them many times there are seams which are hidden by refractory walls, which is not the case in locomotive boilers.

The following conditions are necessary for caustic embrittlement to occur in locomotive boilers: (a) the metal must be highly stressed; (b) the water has to be embrittling ; and (c) a TINY leak must occur so as to result in the evaporative process, leading to a high concentration of NaOH. These conditions may occur in a riveted joint (of which the only dangerous ones are the main seams of the boiler barrel). In this case, the metal is highly stressed, up to the yield point in the rivets themselves. The water may be embrittling if not treated with inhibitors (tannin or $NaNO_3$ [Sodium nitrate], the latter of which is often present in boiler feedwater) and tiny leaks may occur because of minute imperfections of the riveting procedure. But, also in this case, LEAKAGE comes first, setting up an "alarm" prior to further damage.

Caustic embrittlement does not depend on the steam pressure at which the boiler is operated. Most railway people had never even heard about it; even though all boilers should have been inspected for it (presently done by utlrasonics). The Author does not know of any locomotive boiler inspectorate that requires it, including the FRA in the case of locomotives returned to service after restoration. When performing such an inspection, some rivets should be removed to detect potential hairline cracks on the plates; later the removed rivet can be replaced by a "rivet-bolt" developed by the Author.

Riveted joints may show small leakages in the form of drops showing up during the hydraulic test. This is NOT to be interpreted as weakness and at least a German rule tolerates them (Ref 2). Absolute tightness may be a condition, for example, in the chemical industry if handling acid, but not for locomotive boilers.

Said leaks can be corrected by caulking in the case of new, restored, or repaired boilers.

Millions upon millions of rivets. *This color photograph taken by Jack Delano, and courtesy of the Library of Congress, shows the Topeka shops of the Atchison, Topeka & Santa Fe Railway in March 1943. The railroad thrived on the use of rivets not only in joining boiler seams, but also in fabricating tenders, air compressor tanks, and even the trusses holding up the shop roof.*

5. Conclusory remarks and recommendations

This paper tries to present the subject "in toto," but it is taken for granted that each particular point deserves a thorough discussion taking into account the latest advances in the philosophy of mechanical design. For example, the Author has heard that the latest ASME code allows for higher stresses in designing new equipment if it can be demonstrated that deeper knowledge has been considered. This was unthinkable even a few years ago. The reverse way may also occur: in Cuba, the present safety factor is 5, which seems alright in view of the abuses.

One should realize that all people concerned with boiler safety, much like with railway, refinery, marine or aviation safety, must have professional jurisdiction and knowledge. This might not be necessary for an economical operation, but certainly it is not the case for boilers. Goodwill, intelligence and enthusiasm are no substitute for experience and training, which must include the formation of necessary reflexes and the passing of corresponding examinations. This concept also applies to mechanical engineers all of whom should remember:

NOBODY KNOWS WHAT THEY DO NOT KNOW UNTIL THEY KNOW IT.

A conservative attitude is not a safeguard for not having the desirable expertise: one has to remember the utter failure in Germany in 1914-1918 when copper fireboxes were replaced with steel of the same thickness!

No doubt, the questions treated herein touch on deep aspects of the philosophy of boiler design, and a good discussion seems to be in order. Tourism is the second money-moving industry in the world, and steam locomotives, either rejuvenated or new, are a first rate attraction: they make people HAPPY. There is no reason why they should not be most efficient and pull the maximum tonnage at required speeds.

Kim Nielsen - Smithsonian Institution

The oldest one of them all. *The Camden and Amboy Railroad took delivery of the 4-2-0 locomotive known as "John Bull" in 1831 from Robert Stephenson and Company. The locomotive was manufactured in England, then disassembled and shipped across the Atlantic Ocean. When it arrived, it was the responsibility of C&A Mechanical Engineer Isaac Dripps to reconstruct the locomotive, but it did not have any accompanying drawings and Dripps had never seen a locomotive before!*

The locomotive was delivered by its manufacturer as an 0-4-0, with power transmitted to the driving wheels by two inside cylinders that connected to a rear crank axle with connecting rods to the front axle. The quality of track in the U.S. was much poorer at that time than in England, and the engine was soon found to be prone to derailment.

Mechanical engineers at the C&A retrofitted the locomotive with a lead pony truck (two wheels) to help guide the engine through curves. The design of the lead truck required the removal of the connecting rod between the number two and number one powered axles, effectively making the locomotive a 4-2-0. This was the first implementation of the four wheel lead truck arrangement that eventually morphed into the 4-4-0, or "American Standard" wheel arrangement that was robust enough to support the westward expansion of the U.S.

The C&A used the "John Bull" from 1831 until 1866, at which time it was stored in Bordentown, New Jersey. Through a series of transactions, the C&A was merged into the Pennsylvania Railroad. In 1876, the PRR displayed the locomotive at the Centennial Exposition in Philadelphia. In 1885, the Smithsonian Institution purchased the locomotive.

The locomotive mostly lived indoors at the Smithsonian, traveling on special occasions to outside venues. Most notably was the restoration to operation of the locomotive by William L. Withuhn and John H. White in the 1980's. Beginning in January 1980, the Smithsonian undertook tests with compressed air and, later, ultrasonic equipment to gauge the soundness of the boiler.

In the end, it was determined that John Bull could operate safely at 50 PSI (down from as-manufactured 70 PSI). The locomotive was operated in celebration of its sesquicentennial on a select few excursions on branch lines near Washington, D.C., in 1980 and 1981. It became the oldest operable self-propelled vehicle in the world at these events.

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The Porta Family Foundation provided CSR the raw, scanned version of this white paper. Managed by L.D. Porta's children, Alejandro Dante Porta and Anna Porta, the foundation is led in part by its Vice President, Shaun T. McMahon, who also serves as Director of Engineering of CSR. L.D. Porta placed a great deal of importance in ensuring his "disciples" were in the proper position to carry out a continuation of his life's research after his death. It is following this aspect that McMahon was charged with the responsibility for carrying out that wish. This White Paper is but one manifestation of that bequest.

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Livio D. PORTA.
Consulting Engineer.