NDT Requirements Workshop

Report from the Workshop on NDT Requirements for Heritage Railway Boilers

13 February 2018

Alresford Goods Shed, Mid Hants Railway

BINDT
THE BRITISH INSTITUTE OF NON-DESTRUCTIVE TESTING

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Workshop on NDT Requirements for Heritage Railway Boilers

Chair: Robert Smith, Professor of NDT, University of Bristol, and Past President of BINDT.
Co-sponsors: Mid Hants Railway and BINDT.

The cost of meeting safety requirements when restoring a steam locomotive that has been repaired and life-extended several times is proving difficult to estimate due to inadequate non-destructive testing (NDT) information on the current corrosion state of the boiler. The result has been some significant (over £100k) overspends and delays (> one year) on recent restoration projects.

This workshop was aimed at defining requirements for NDT to bring benefit in terms of high-quality information to guide restoration decisions and improve cost estimates for funding applications. Following engagement with the British Institute of Non-Destructive Testing (BINDT) by the Mid Hants Railway regarding its 'Canadian Pacific' (Merchant Navy class) restoration project, which included a plenary presentation and a tour of NDT stands at the Materials Testing 2017 exhibition, it became clear that modern NDT methods have the potential to provide suitable boiler 'survey' information in terms of maps of remaining wall thickness and rapid assessment of corroded stays.

The workshop brought together regulators, inspecting authorities, heritage railway operators and the non-destructive testing (NDT) community to:

- learn about the inspection problems faced by the heritage railways in the UK; and
- establish the requirements for an improved NDT solution for pressurised heritage locomotive boilers so that there will no longer be unexpected additional costs when restoring locomotives with apparently sound boilers or fireboxes that turn out to need replacing once work has started.

The ability to survey the state of a boiler/firebox prior to deciding whether to restore the locomotive is a crucial driver in this exercise.

For the purposes of this workshop, the main risk that needs to be mitigated is a boiler explosion: a catastrophic failure of a boiler due to a failure of the pressure parts of the steam and water sides. There can be many different causes, such as structural failure of critical parts of the boiler, failure of the safety valve or a low water level. This workshop only considered the former: structural failure (see Appendix A).

A list of delegates attending the workshop is given in Appendix B.

Session 1: Landscape and background

Introduction

Professor Robert Smith, University of Bristol

Professor Robert Smith welcomed the attendees and explained his involvement as a facilitator for 'NDT Requirements Workshops' of this kind for various industries. He introduced Dr Becky Peacock and Andy Netherwood, from the Mid Hants Railway, with whom he had convened the workshop. He then presented the potential benefits of improved NDT solutions and the desired outcomes of the workshop. During discussions prior to the workshop, Professor Smith had identified that the primary benefit of improved NDT for boiler restoration will be in better-informed choices between the restoration of original components and fabrication of new ones, as illustrated in Figure 1.

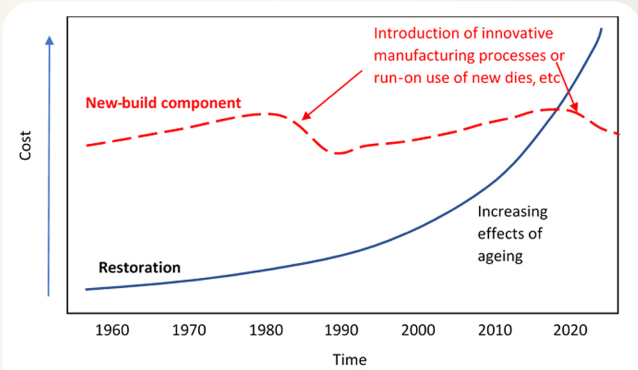


Figure 1. Diagram indicating the cost factors involved in deciding whether to restore an original component or fabricate a new one

All original British steam railway boilers are now over 50 years old and some are considerably older, but they were generally only designed to last ten years at most, so they often contain numerous repairs and sometimes repairs of repairs! This is causing exponentially increasing costs of restoration, which are already comparable to the costs of new fabrication in many cases.

New fabrication methods, such as additive layer manufacturing (ALM), are already offering step-change reductions in the cost of new-build. On the other hand, there is also a new industry called 'remanufacturing', where worn-out components may be restored to their original condition and performance using advanced

ALM methods. While remanufacturing is primarily driven by the aerospace industry at present, the knock-on benefits for the heritage industry are considerable and could result in a reduction in the cost of restoration of some less critical components.

Professor Smith described the potential benefits of improved, more advanced NDT in terms of the five- and ten-year inspections, as shown in Figure 2. There are three benefit areas: preservation, certification and business. These can be summarised as follows:

Large-area corrosion mapping:

- Full assessment of boiler plate condition
- Informed repair/replacement decisions
- Informed cost of refurbishment
- Less expensive to achieve acceptable risk.

Customised inspections:

- Reduced preparation (removal of corrosion product, lagging, etc)
- Reduced cost of inspection.

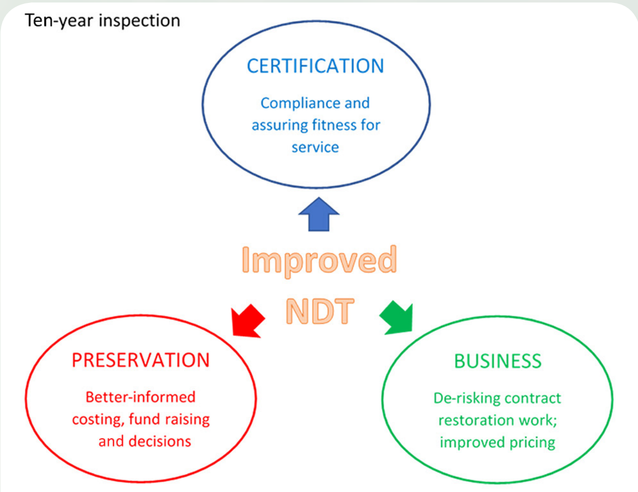


Figure 2. Diagram explaining the potential benefits of improved NDT, particularly at the ten-year boiler inspection period

During the Materials Testing 2017 exhibition, an initial survey of potential NDT improvements identified the following categories:

- Mapping remaining wall thickness due to corrosion:
  - Large-area non-contact ultrasonic scanning from smooth side, avoiding stay heads, using either electromagnetic acoustic transducers (EMATs) or laser ultrasound.
  - Pulsed eddy currents as used for corrosion mapping for one inch-thick steel pipes under up to three inches of lagging.
- Stay inspection:
  - Use of different ultrasonic coupling methods to inspect without first treating the surface of the head.
  - Instrumented 'tap' or resonance testing.

Professor Smith then described the desired outcomes for this requirements workshop:

- To bound the scope of the NDT requirements:
  - Material types and geometries
  - Defect types and sizes
  - Access restrictions (lagging, rivet head spacing, etc)
  - Cost of inspection *versus* benefit of de-risking refurbishment.
- To plan a way forward:
  - Maybe form a working group – BINDT-based, HRA-based or joint
  - Samples for technique validation – number, size, etc
  - Trials of new techniques on samples – funding unlikely
  - Technique writing, validation and technical justification exercise
  - Technique sign-off and implementation.

The steam locomotive boiler

Andy Netherwood, Mid Hants Railway

Andy Netherwood gave a brief overview of steam locomotive boiler workings and configuration for the benefit of NDT sector attendees who may be unfamiliar. Figure 3 shows the locomotive boiler of the type being considered: a cylindrical or tapered steel barrel section closed off with a tubeplate at the front end, extending to the outer firebox where the backplate closes off the back of the firebox and where the firing door is located, forming a pressure vessel containing water and steam. The inner firebox, surrounded by water and containing the fire, can be made from steel or copper; it is closed off at the bottom by a solid forged foundation ring and held in position by several hundred firebox stays, which are about 4" apart. Hot combustion gases from the firebox pass through the tubes attached to the firebox tubeplate (the water surrounding the tubes is heated on the way to the smokebox tubeplate) from where they pass out through the chimney. The boilers generally operate in the range of 160-250 lb/in^2 (10.8-17.2 bar) steam pressure. Inspection of the critical areas of the water spaces is difficult due to the restricted openings, accumulated scale and the presence, most of the time, of lagging, the outer casing and the boiler being located within the locomotive frames.

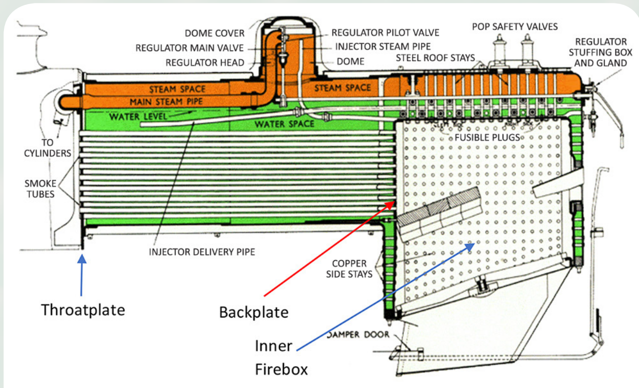
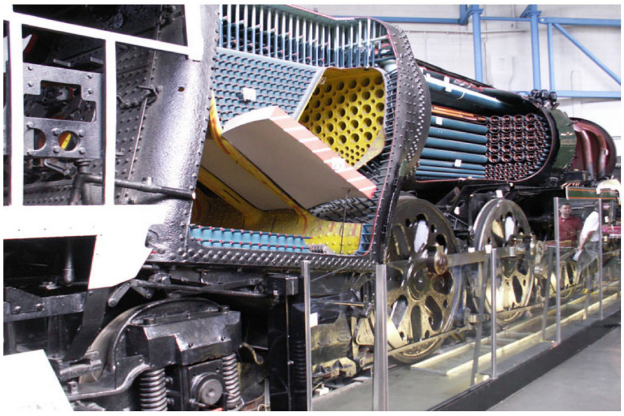


Figure 3. Schematic of a locomotive boiler and firebox. Water is shown as green and steam as brown

While there are numerous types of defect that can affect a boiler, three main types will be concentrated on in this workshop: internal boiler corrosion (water side) in the firebox area, cracking and fracture of stays, cracking between stay bolts and grooving near to the foundation plate or at lap joints. Only steel fireboxes will be discussed, not copper, concentrating on the throatplate, outer firebox, backplate and the stays. While Figure 3 shows a simple firebox, the more complex type shown in Figure 4 is the focus of this discussion and contains the same problem areas.

(a)



(b)

Figure 4. (a) Merchant Navy class boiler; and (b) sectioned Merchant Navy class locomotive at the National Railway Museum

Mitigating health & safety risks for heritage railways

Rob Le Chevalier, South Devon Railway Engineering Ltd

Rob Le Chevalier, Engineering Manager at the South Devon Railway (SDR), deals with both new and old boilers and was also representing the Heritage Railway Association (HRA). He presented an analysis of regulations for pressure boilers, although he pointed out that there is very little in the regulations applicable to NDT of heritage boilers.

The earliest regulations were the Boiler Explosion Acts in 1882 and 1890, which were eventually withdrawn in the mid-1970s. The 1964 Factories Act specifically excluded a range of boilers, including locomotive boilers, mainly because the nationalised railway was self-regulating and had its own safety management system and risk assessments.

The 1974 Health and Safety at Work Act is often quoted as it ensures protection of all people from harm due to work but it is very high level. The more specific regulations have more detail, although nothing really applies to historic pressure vessels. However, the Pressure Systems Safety Regulation 2000 (PSSR) (SI 2000/128, Second Edition, 2014, amended by SI 2015/16) does have an applicable section. It is a working document of the Pressure Equipment Directive (PED) and provides a code of practice and guidance notes that apply to heritage railway boilers (Figure 5).

Regarding inspection, guidance is given on determining when and how to inspect, based on the risk assessment, good practice and the original railway inspection regimes. The owner has the responsibility to produce and maintain a written scheme of examination (regulation 8), carry out inspections in accordance with it (regulation 9) and keep records of those inspections (regulation 14). The Provision and Use of Work Equipment Regulations 1998 (PUWER) is a generic statutory instrument ensuring that every employer maintains equipment in a safe state and nobody is hurt. The basis is to determine what is safe, what is the experience of others, good practice and guidance notes in order to prepare a risk assessment.

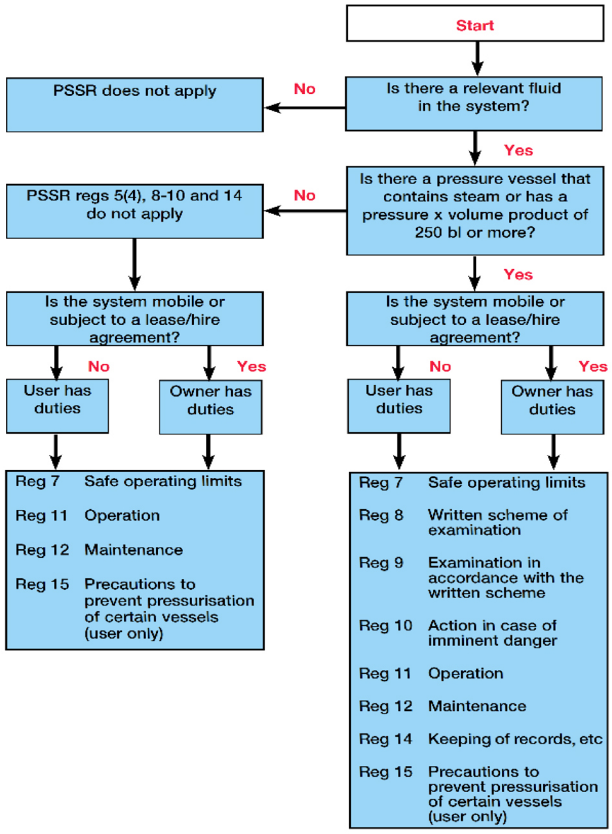


Figure 5. Applicability of the PSSR 2000 working document can be determined using this flow diagram. Specifically, regulations 8, 9 and 14 apply to heritage railway boilers. Taken from PSSR 2000

Network Rail's Railway Group Standard GM/RT2003 (1996) 'Certification Requirements for Registration of Steam Locomotives' applies to main line running but is good practice in all cases. Both this and the new RSSB engineering requirements document for steam locomotives (RIS-4472-RST, November 2017) prescribe a seven-yearly general boiler examination referring to British Rail document MT/276; however, this does not give a non-destructive examination (NDE) requirement for boilers beyond visual, pressure and hammer testing. Railway Safety Publication (RSP) 6 (HSG 29) 'The Management of Steam Locomotive Boilers' has guidance on testing but nothing on NDE of boilers.

The key is the written scheme of examination required by PSSR 2000, compiled by the 'competent person' (boiler inspector). It should include the nature of the examination required, including inspection, testing and NDE requirements. It is owned by the railway and should be edited to suit the boiler it belongs to, explaining what should be inspected, how, by whom and what records must be kept.

There are many occasions when NDE should be considered, as boiler life is often long compared to original design life. There are four main inspection periods considered:

- At in-service washouts, inspections performed mainly in house are visual: flair lamp (LED), endoscope (borescope) and use of mirrors; acoustic resonance by hammer test; and monitoring the sound while in steam. Periods between washouts have been increased due to improvements of water quality; however, this reduces the frequency of inspections.
- At the annual service and examination, all of the same in-house inspections are performed as at washout plus ultrasonic thickness testing, dye penetrant testing and magnetic particle inspection (MPI). It must also be examined by the competent person to verify thickness checks and provide an independent view.
- At the seven-to-ten-year general boiler examination, the boiler is taken out of the frames for detailed examination and the same in-house inspections are carried out as for the annual examination, plus any areas included in the written scheme of examination, as determined by the competent person. However, these can be brief on NDE. An approved NDE engineer is required to carry out the list of inspections provided in the written scheme of examination, but experience is mixed due to lack of knowledge of the boiler by the NDE inspector.
- New components are inspected as required by the competent person. There is a lot of guidance on new construction, but when these are for restoration of old locomotives it is less clear. All new welds are 100% inspected at SDR by MPI and ultrasonic testing for peace of mind, however this is not an official requirement.

The main sources of guidance at present are the HRA Guidance Notes: HGR-B9220 'Materials and Non-Destructive Testing' and HGR-B9160 'Examination in Service of Steam Locomotive Boilers', which do describe the NDE processes but not where to use them or to what standard. These need to be revised following consideration of the outcome of this workshop.

Currently, the heritage railways are very dependent on the views of the competent person (Figure 6). Regarding NDE, a uniformity of approach is required for both traditional and new NDE techniques. Rob Le Chevalier finished by recommending the alignment of expectations of the insurance companies' competent persons and the HRA to capture best practice for steam locomotive boilers for future operations.

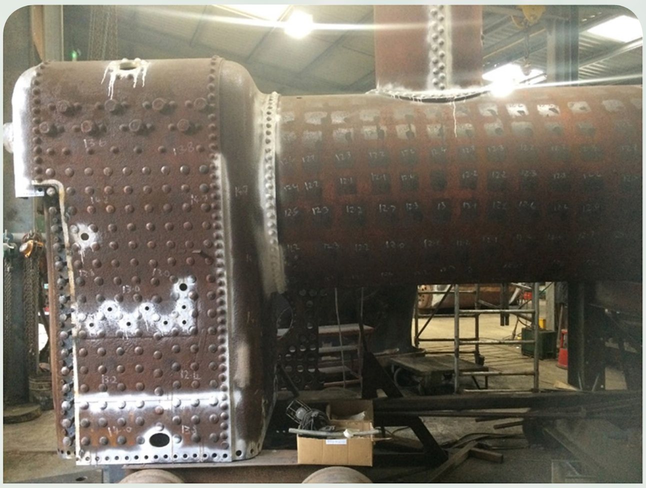


Figure 6. Boiler of GWR 1369 after inspection with MPI in locations that were not obviously the most significant for this particular boiler

NDT: Supporting tests for risk-based inspection

John Haigh, Allianz UK

John Haigh, representing the insurer Allianz, explained what Inspection Bodies do and how they use NDT. Three documents are used for guidance: (1) PSSR 2000, which details the statutory inspection and how it is carried out; (2) the written scheme of examination, as referenced in PSSR 2000; and (3) SAFed PSG 15, for modifications and repairs.

When a boiler goes into service after an overhaul, annual inspections are statutory and carried out by a competent person, as defined in PSSR 2000. For Allianz, the competent person is the company, not an individual, and they carry out a thorough annual examination in accordance with the written scheme of examination. A hammer test of the stays will be included, as well as some spot thickness tests. If anything raises concerns the inspector can ask for supplementary testing, which is where NDT comes in, incurring an additional cost. After five years, the boiler will be examined according to the written scheme of examination. Boiler tubes may be taken out and some additional NDT may be called for, but the boiler is still in its frames so there are access limitations. Again, if something is found of concern, then supplementary testing will be called for and may require the boiler to be removed from the frames. The competent person is signing the report to say the boiler is fit for use for a certain number of years, up to a maximum of ten since the last full overhaul, so they need to be confident. At the end of that period, the boiler is removed from the frames and everything is detached from it. When it goes in for overhaul, it falls out of PSSR 2000 Section 9 'Examination in accordance with the written scheme' and falls under PSSR 2000 Section 13 'Modification and repair' and then NDT is crucial. An initial visual inspection is carried out and a decision is made between the owner, the repairer and the competent person on a range of further work that is required before it will be deemed fit for return to service for a number of years, assuming proper maintenance. Any NDT that can enhance the information on unseen locations will benefit the decisions made about the boiler. The engineer should instruct the NDT practitioner about what he/she wants to see. Attention is focused on known areas of concern from generic boiler experience, extending to other locations such as old repairs. In PSG 15 'Repairs or Modifications to Pressure Systems', required documents are specified, such as welder qualifications, materials and consumables, as well as NDT reports. At the end of the overhaul, all documentation is reviewed by the competent person and other tests are performed, such as a hydraulic testing and out-of-frame steaming testing. When the boiler is put back in the frames it falls under PSSR 2000 Section 9 'Examination in accordance with the written scheme' so the written scheme is reviewed reflecting the current state of the boiler. A final examination is carried out according to the new written scheme before the boiler goes back into service.

NDT is expensive and comprehensive, but it produces a report on the condition of the boiler that is measured, defined and documented so that, in the future, there is a reference providing a better understanding of the condition of the boiler.

In response to questions, John Haigh said that competence of NDT inspectors is provided by the SAFed boiler qualification. It was then pointed out that appreciation of in-service failure modes is really required to develop and assess NDT techniques in each location. The qualification of techniques has been carried out on an *ad hoc* basis in the past, where a defect can be seen visually, but there is not a rigorous method using a set of test-pieces with defects and a probability of detection study so there is a requirement for sets of test samples. There was a suggestion that annual NDT is applied with thickness readings recorded to build a body of knowledge. This was welcomed by the insurers but it is expensive. The idea that railways could purchase their own NDT equipment is fine, but competence to use it needs to be demonstrated before any weight is put on the results because it is not always straightforward to carry out NDT tests and measurements.

Session 2: Specific boiler inspection problems

Introduction

Andy Netherwood, Mid Hants Railway

The examples shown in Andy Netherwood's introductory presentation were sections cut from West Country and Merchant Navy classes of locomotive. At the ten-year inspection, the boiler is examined by works boilersmiths and the inspecting authority. A package of work that has to be carried out is drawn up and there is an informed discussion as to the extent of NDT and the extent of repair that has to be carried out to meet the requirements. Traditionally, railway workshops had their own boiler inspectors with a lifetime of experience of knowing where the issues were. The throughput of boilers was considerable and they would come across these problems daily. A big problem for heritage railways is the lack of people with this kind of experience in workshops. We are having to look to alternative methods for determining whether a defect is critical and will require immediate repair, will last without being disturbed or becoming marginal for the next ten years, or should be repaired giving a 30-year permanent repair, for example. Determining the condition acceptance level for a ten-year period is very difficult to quantify due to a boiler's use, out-of-use condition and long- and short-term storage conditions.

Internal boiler corrosion

Andy Netherwood, Mid Hants Railway

The internal corrosion problems cause concern at the outer firebox and inner firebox on steel boilers. Originally, railway boilers were designed for a relatively short ten-year life, but some of the heritage boilers are over 60 years old. We are used to external visible corrosion caused by wet lagging while resting in scrapyards, but the real problem is internal corrosion. This could be where mapping of remaining wall thickness could be really useful, rather than the current method of random spot measurements of wall thickness. It is a common problem that the measurements are not taken at the most corroded areas because they cannot be accessed from the outside (Figure 7). Much of the cause is due to poor water quality and the build-up of hard-water scale as well as corrosion products. Also, the adhered scale prevents observation of the corroded surface visually unless it is removed mechanically or chemically by the action of modern boiler water treatments. Ultrasonic thickness readings can be confusing, especially to the untrained operator, and some low readings are thought to be spurious and caused by poor surface finish, but it is possible that what is being measured are deep and extensive corrosion pits: oxygen corrosion. The improved water quality in recent years includes water treatment to remove scale, occasionally revealing extensive corrosion pits that seem to favour these areas. However, it is difficult to maintain water quality on mainline locomotives as their water is sourced from unpredictable locations. The exterior corrosion makes ultrasonic coupling difficult (Figure 8) and grinding the surface would just reduce an already marginal plate thickness yet again. Radiography is generally too big a health & safety problem due to the requirement to clear the area – the Mid Hants workshops are located near residential housing and fields with cattle! Welds can be difficult to inspect due to the geometry, which also makes it difficult to reach 100% thickness-mapping coverage with ultrasound; stay heads, overlap joints and riveted seams cause a big challenge. NDT is usually unable to achieve a 100% scan report. Heavy concretions of hard scale around the thread roots of stays (Figure 7) obscures the actual corroded surface. There is difficulty in getting a probe close enough to the stay hole due to the riveted-over stay head.

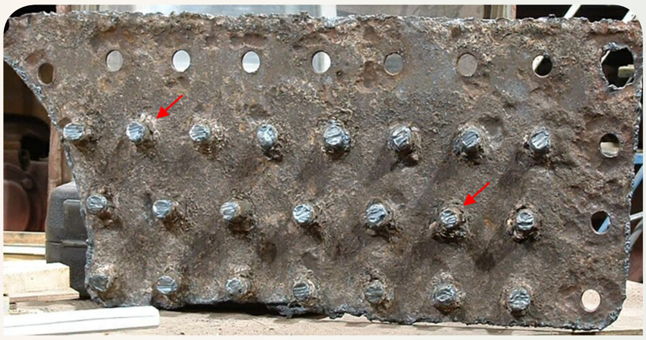


Figure 7. Inner firebox corrosion from a Merchant Navy class locomotive. The red arrows mark some locations of scale that are obscuring the actual corroded surface

Figure 8. Exterior corrosion making ultrasonic coupling difficult

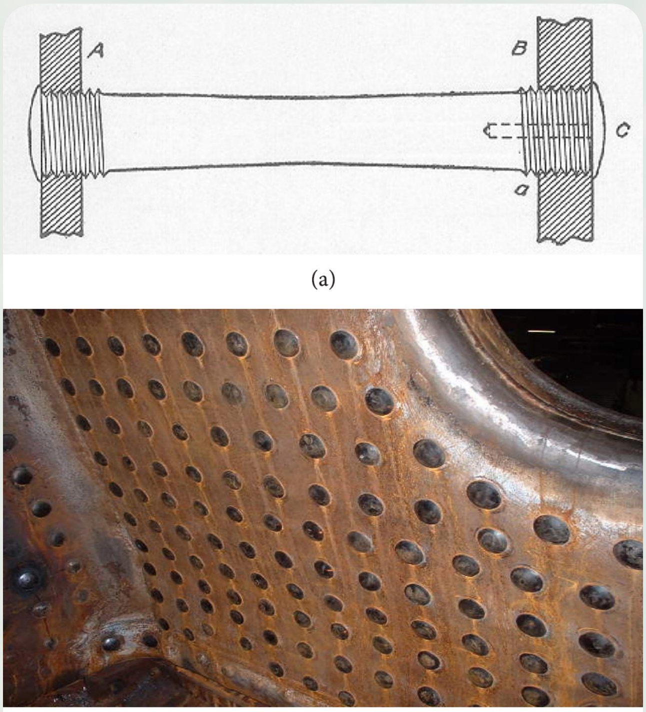
If you examine a boiler that is 60 or 70 years old, you will definitely find something. We need to be aware of NDT techniques that are out there, what benefit they can provide, what their limitations are and whether we can improve on the NDT we use. Repairers are always looking for new ways of inspecting and providing more information to avoid cutting out large sections for repair. So, we need to improve our quantifying NDT to keep costs down but, at the same time, ensure that we do not miss any critical problems.

There is also a need to define and agree an acceptance standard for NDT findings on old and repaired boilers. 'No defects permitted' would render all restored or repaired components to the scrap heap but reporting and then monitoring defects could help to manage the risk. However, the original designs had in-built safety factors exceeding present-day factors through increased plate thicknesses, oversized riveted seams, rivets, thicknessing liners and doubling plates, resulting in very few explosions in the last 60 years in the UK, while other countries have fared much worse. Only when boiler weight started to become an issue did the heavy designs become more of a problem. Experiments and production of boilers with high tensile and alloy steels were used to reduce thickness and save weight. These materials then started to develop other metallurgical issues later on; these are still encountered where those boilers remain in existence today.

Broken firebox stays

Andy Netherwood, Mid Hants Railway

Andy Netherwood stood in for Chris Shepherd from the Bluebell Railway who, unfortunately, was unwell, to talk about firebox-stay breakages and how to detect them. This is one of the most contentious inspections. Figure 9 shows the stay and the large number of them required for a firebox. Testing each of these at the washout exam, every ten to 20 days when in continuous service, is onerous. Traditionally, this was achieved through hammer testing by people with a lifetime of experience of testing stays in this way. They were able to detect the different resonance of a cracked stay from the sound, despite the background noise in a locomotive works, but this takes a very keen ear. Figure 10 shows another test where, if both sides are accessible, hammer A is used to hit one side with enough force to open any crack, in which case the impact is not transmitted to hammer B. The one-hammer method is more common at washout intervals because the lagging is covering the outer firebox; it is still the most widely used method and generally finds the completely broken stays, but it is subject to the right interpretation on behalf of the boilersmith. A better method is needed.



(a)

(b)

Figure 9. (a) Typical screw stay bolt – not all stays are threaded, they may be riveted; and (b) firebox stays on a West Country class locomotive

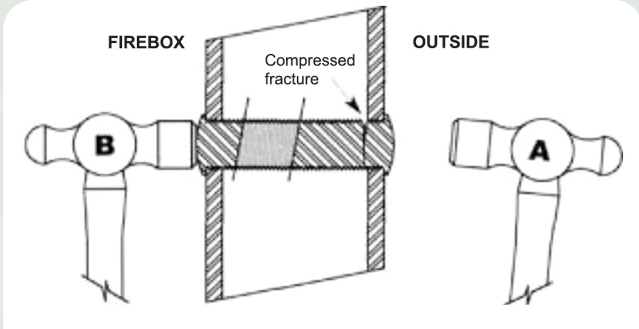


Figure 10. Hammer test where access is possible from both sides. One hammer is tapped and the person holding the other one to the stay will feel and hear a different response for cracked stays

Another detection method is the use of 'tell-tales' on steel stays, where a hole is drilled into the centre of the stay to beyond where the crack is likely to occur (Figure 11). If this starts to weep water, it indicates a crack. The problem with this is that the hole can get riveted or corroded over. This method is more common in the USA and on the continent than in the UK.

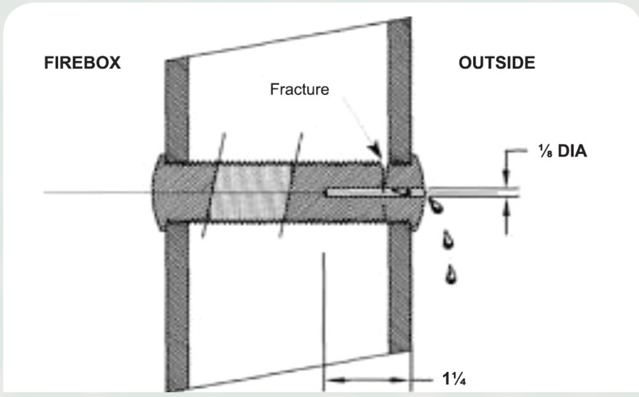


Figure 11. Illustration of the use of a tell-tale hole drilled into the centre of a stay

Recently, ultrasound has been used on both steel and copper stays (Figure 12) but the process is painfully slow because of the surface preparation required. Interpretation of the ultrasound response is crucial and false calls are costly because the boiler lagging then needs to be removed. Therefore, well trained and qualified staff are required. However, washout intervals are too short to employ NDT technicians, so training of in-house personnel is required. (Note: This could be an NDT 'Level 1 limited' activity where people are trained on a very limited number of inspections.)

On the tour of the Materials Testing Exhibition in 2017, it was clear that one or two NDT equipment suppliers have newer coupling methods in which it is not necessary to grind the surface prior to inspection and there are also resonance methods that instrument the response to a tap.

Not all broken stay bolts have to be repaired immediately, although this is a contentious subject too. There are recommendations for the number that can exist in a local region before they have to be replaced. However, when one stay is broken it increases the load on the surrounding stays, potentially

Figure 12. Ultrasonic testing of stays after surface preparation

causing them to also fail; consequently, an avalanche effect can be created causing bulging of the flat plates until the load tears off the plate from the supporting stays, which is what led to the boiler explosion in Figure 13. Therefore, broken stays need to be detected early and cannot wait until the annual, five-year or ten-year examinations. Increasing the reliability of NDT methods would increase confidence in the map of broken stays and may reduce the costly replacement of stays between out-of-frame maintenance periods.

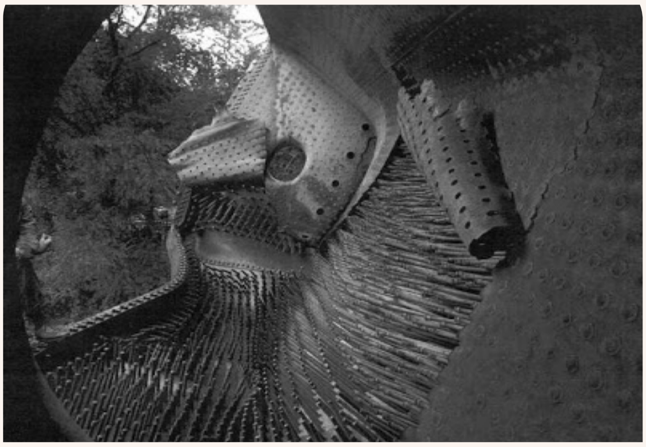


Figure 13. A firebox after a boiler explosion in the USA

A question was asked about the reliability of hammer testing, for example corroded stays that will still ring on a hammer tap. Ultrasound, however, can detect and characterise stay cracks. Also, the density of multiple broken stays is an issue; there are instances of numerous broken stays but the over-engineered design still retained its integrity. There is only one company that never had a boiler explosion: the London and North Eastern Railway (LNER)[1].

Grooving of boiler plates – experience with NDE defect assessment

Chris Greatley, Kent and East Sussex Railway

Chris Greatley is responsible for water treatment and water chemistry at the Kent and East Sussex Railway. When a defect is identified it is repaired, but no metallurgy is carried out to determine the cause. Hence, the cause of grooving is not proven but Chris favours the fatigue explanation rather than the stress-corrosion cracking theory[1]. The inner firebox is around 120° hotter than the outer firebox; differential expansion causes stress concentrations typically just above the foundation ring (Figure 14), resulting in fatigue damage due to the thermal cycles of the boiler. This starts as micro-cracking and the corrosion can easily take advantage. When these boilers were in constant use between washouts, the rate of thermal cycling was much lower than on preserved railways, where the cycle can often last just one day. In addition (Figure 14), washout openings are about one inch above the foundation ring, so a pool of water will remain along with scale debris when the boiler is drained, resulting in continuous wetness that is open to the air. In lap seams, any bending stress at the joint can cause fatigue damage, which is then followed by corrosion. Figure 15 shows grooving above the foundation ring, where the groove width is about 20 mm and the depth is 8.5 mm. The plate thickness is 12.5 mm, with up to 0.5 mm thickness loss on the outside. Rust scaling is also present, not water-hardness scaling. Tenacious hard scale can be seen in the inset image and has started to tunnel below the foundation ring and up the vertical seam.

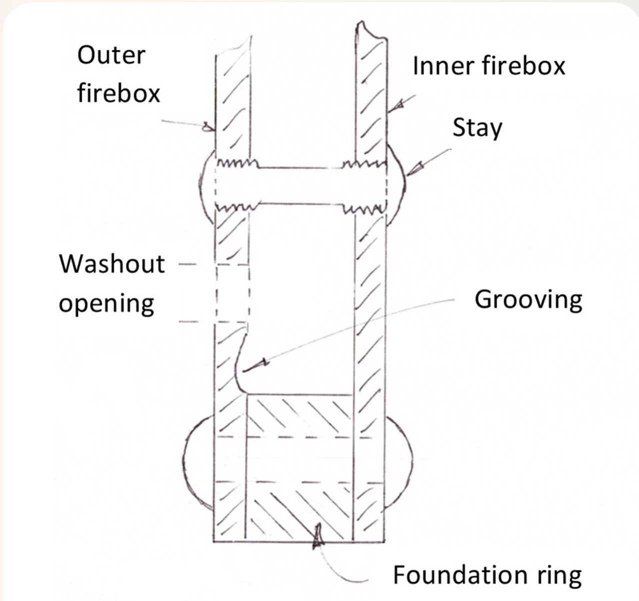
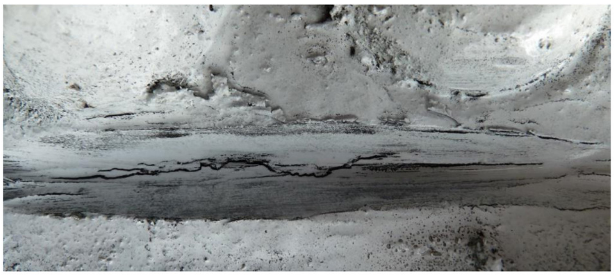


Figure 14. Diagram showing the location of grooving relative to the foundation ring and the washout plug hole

Ultrasound thickness gauging can be used after surface preparation of the outside and does not get confused by the rust scale on the inside. However, sometimes a crack can precede the corrosion (Figure 16) and these are difficult to detect and quantify with normal incidence ultrasound. Both normal incidence and 60° angle probe inspections were used to detect the grooving and cracking, but it is difficult to know which it is. Note: angle probe ultrasound or time-of-flight diffraction (TOFD) may detect and size a crack, while phased array ultrasound or, preferably, full matrix capture (FMC) with the total focusing method (TFM) should be able to image the whole groove and crack. Ultrasound showed deeper grooving near the corners of the firebox, which is consistent with a fatigue cause as the stresses will be greater there.

Figure 15. Grooving above the foundation ring on an 80-year-old outer firebox



(a)

(b)

Figure 16. Evidence of cracks that have preceded the grooving: (a) this example has been ground out from the outside, towards the groove on the inside, but the crack was encountered before the groove. The foundation-ring rivets can be seen above the crack; and (b) 10 mm-wide, 5 mm-deep groove where MPI shows three short (1.5-2 mm) radial cracks. The boiler was 52 years old

Chris finished by saying that, if the water chemistry and laying up procedures were improved, he believes the corrosion rates would be reduced, which in turn may reduce the crack propagation; any layer of rust scale tends to enhance corrosion rates underneath it.

In the questions, the point was made that these levels of grooving have been accumulated over several decades. Even though they are massively over-engineered, there still need to be acceptance limits. Chris thought that the rate of corrosion grows as the corrosion itself grows. A suggestion was that new plates are lasting a fraction of the time of old plates, so there is a question about the quality of the steel obtainable today. Rob Le Chevalier said that they have monitored thickness of corrosion and on old plate it is about 0.2 mm per year, but on new plate it is a lot faster. Protection regimes are also widely variable on new and refurbished boilers.

Session 3: NDT experiences

NDT experiences

Andy Wright, British Engineering Services

Andy Wright is a technical specialist managing 20 heritage boiler inspectors at British Engineering Services (BES). If there is an accident, the written schemes of examination, any current reports and subsequent NDT reports will all be investigated. They prove that everything possible has been done to avoid an accident. Regulations about NDT are quite open-ended, with the onus being on the competent person. There is a massive variety in NDT experience of this type of structure, so the competent person is often relied upon. NDT inspectors need to be qualified and should have experience of these boilers; comprehensive reports have to be produced. Initial NDT should involve a conversation between the competent person and the NDT company. It will not find every defect, but gives a rough idea of the cost of the overhaul and attempts to ensure there are no surprises. Depending on the repairs undertaken, there will be other NDT visits. Boilersmiths need a specification for preparation prior to NDT: what NDT will be taking place and in what areas. NDT operators may not be knowledgeable about the locomotive type so they rely on the owner/user, but really they need to speak to the competent person so that the right NDT test is performed. A scope of work is required whenever NDT is needed, so the boiler is fully prepared in advance. NDT specialists know areas of common defects and boilersmiths find defects supplemented by visual inspection by a surveyor, such as dry tracking round the fire hole and firebox. The smokebox tubeplate is an area for inspection with thickness checks (Figure 17). Grooving at lap joints has been found in areas other than those expected. The workshop did not include discussion of fixtures and fittings other than stays, such as boiler tubes, steam pipes, bottle-neck welds in flue tubes, etc. Some NDT examinations should be of 100% of these items due to the consequence of a single failure. Other issues are often found when plates are removed. NDT cannot find everything (Figure 18).

Andy proposed an HRA-led central information repository to pool experiences for different boiler types and share these with other people owning boilers of the same type.

In summary, suitably-qualified, experienced NDT operators are required and approval of the scope of NDT examinations is by the competent person. The boiler needs to be prepared properly before the NDT operator arrives but the NDT operator should really be on site at the same time as the boiler inspector to avoid confusion about the NDT required, because sometimes they do not meet and this needs to be sorted. The owner must be kept informed, but Andy proposed a closer liaison between NDT operators, the owner and the competent person. The production of comprehensive NDT reports is essential.

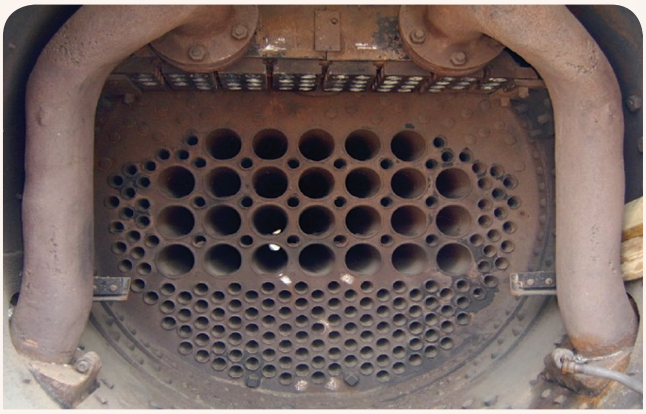


Figure 17. NDT examinations are also often required for the superheater header and the main steam pipes

Image courtesy of Jim Baker

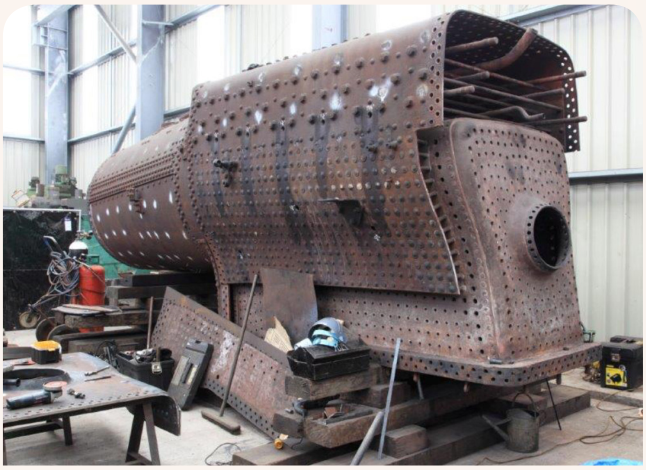


Figure 18. Ongoing repairs will require further NDT examinations. Removal of plates may reveal further defects. NDT does not reveal the full picture

General discussion

A lively discussion followed the presentations, with several suggestions being put forward. Regarding the dissemination of knowledge about known faults and defects using a central repository, we were told that the mainline has something called National Industry Reports (NIRs). These are aimed at the same goal but have not been taken up by the heritage railways, partly because there are lots of individuals with a lot of knowledge, but they will not last forever. The collation of this knowledge needs to start very soon and be accelerated. We need to get past the competitive nature of the heritage railway world.

There is a need to review the boiler codes of practice and include special requirements in the written scheme that are based on an assessment of information in a central repository and are then specific to the boiler type. Common standardised methods for NDT should be identified and recommended as best practice (but not mandated). More knowledge is required about NDT and allowables. It was stated that we should be careful about mandating certain inspections. All we can do is to make the information available and then the competent person can be expected to review the information and put into the written scheme all relevant inspections. Standardising NDT methodology should reduce the burden of validating the reliability of a non-destructive inspection. HRA could lead on recommended repairs and NDT for specific boiler types, developing a best practice guide from which any deviation can be approved by the competent person but it is at their risk. These are similar to the codes of practice (guidance notes) from HRA.

There seems to be a shortage of SAFed-qualified NDT engineers. Maybe there is a need for more or for in-house staff to be trained to a higher NDT skill level.

There is a desire to implement NDT for information purposes using in-house staff for the easier inspections. This can be used to make the decision to replace or repair a component without the need for a costly NDT engineer. However, training and validation of NDT inspectors is crucial and a PCN scheme for this field would be welcomed. The basic NDT could be carried out locally to give a rough idea of the quality of the component, but there is potential for error if the local operator is not properly trained. There is a case for a 'Level 1 limited' qualification for specific inspections to be carried out by in-house staff in order to satisfy the competent person of the competence of the in-house NDT inspector.

We are not looking for one silver-bullet solution but more a regime change that incorporates many of these improvements. Similarly to the Americans, Her Majesty's Railway Inspectorate (HMRI) could mandate 'tell-tales', which would not solve everything but does increase confidence and reduce risk. We do not necessarily need highly skilled solutions; some good engineering low-tech solutions, supplemented by proper NDT inspection and calling on NDT operators when needed, would suffice.

Breakout session (workshop tour)

The delegates formed six groups that were pre-planned by Dr Becky Peacock so that each group contained a mix of NDT, insurance, regulation and railway operator delegates. The following notes are just some examples of the kinds of discussions in the groups. The discussions that followed this breakout session were clearly better informed as a result.

- Effective water treatment can limit hardness scale formation.
- Steaming cycles affect corrosion and fatigue due to cyclic stressing. Used to stay in steam for a month, now only a day or so. Stays at the top of the firebox are in the steam envelope and a lot is going on at this level.
- Borescopes with anti-scratch removable tips are a requirement (there are new types that allow for a great deal of control over the path they take).
- Washouts are generally carried out by paid staff but, while volunteers can be trained, it is not the kind of job most volunteers signed up to do.
- Use NDT to track the ends of cracks, etc.
- A pinhole can give a tell-tale wisp of steam or water without reducing boiler pressure enough to cause an explosion. These witness the slow degradation so that defects might be picked up earlier or monitoring may be possible.
- Stress corrosion cracking develops between rivet holes, particularly just above the foundation ring, and at stay holes in the pressed plates on the first row beyond the radius. Angle probe ultrasonic inspections are used at ten-year overhaul and, if there is an indication, it should be added to the written scheme of examination.

- An inspection plug is screwed in but can act as a stress raiser on a radius, so is often replaced with a boss.
- In the days of steam, a boiler would be replaced every five or ten years.
- Some repairs involve riveting a plate over the top.
- Effects of defects – need acceptance advice – there is a lack of organisation – BES could help.
- First-line NDT needs to be effective and cheap. Training on interpretation of findings is needed.
- HRA guidance notes – NDT needs to be included and there is not enough detail on problem areas.
- Grooving (Figure 19) appears to be a function of the boiler design, operating conditions and maintenance history. There is a need to establish the extent and monitor it over years to determine the rate of metal loss.
- Grooving at seams can occur even on the non-water side as it is initially a fatigue effect.
- Waterside corrosion of thermic syphon sections. Sample inspections can be recorded and can then feed into annual inspections. Day-to-day use of NDT?

Figure 19. Andy Netherwood (left) explaining the evolution of grooving in the outer firebox

Panel session

The panel comprised: John Haigh (Allianz), Andy Wright (British Engineering Services), Rob Le Chevalier (South Devon Railway), Andy Nertherwood (Mid Hants Railway) and Steve Turner (HMRI). The session chair, Professor Robert Smith, began by asking each panel member to state their top priority requirement to increase the benefit and effectiveness of NDT for heritage boilers.

- John Haigh gave top priority to defining and validating suitable NDT methods to detect and size small defects in the known problem areas and surrounding environment.
- John also felt that monitoring of defects should be undertaken.
- Andy Wright raised the importance of using suitably trained NDT operators and suggested a list of recognised companies and NDT operators who have the required approvals and experience, such as the list for industrial steam boilers. This would require regulated training and certification.
- Rob Le Chevalier proposed a review of the HRA guidance notes to include NDT and coordinate major insurers to follow the same practice, so this should be undertaken by a group, including the insurers, who agree a process.
- Rob also proposed establishing a central repository for sharing experiences of working with boilers of specific types.
- Andy Netherwood noted that it is important to review the defect allowables, acceptance standards and ongoing inspection requirements for the heritage sector to encompass these defects, allowing for the long period of generation of defects and the potential for monitoring defects. A body that reviews current practice and HRA guidance could be responsible for this and needs to be broader than NDT to include defect propagation rates, etc. (Reporting of defects is different to mitigation of the risk they cause.)
- Steve Turner prioritised the repository and database for types of defects seen by class of locomotive, preferably an illustrated guide.
- Steve also wanted to see some guidance on the advantages and disadvantages of different NDT methods for the uninitiated. There are 215 heritage railways and they do not all have a large body of knowledge and cannot all afford qualified NDT staff or NDT equipment. Some guidance would be useful for those railways wishing to do their own inspections for their information.

As the discussion was continued by the rest of the delegates, it became clear that two working groups were needed:

- A reconstituted group for revising the HRA boiler codes of practice (Guidance Notes on Materials and NDT), including the effect of defects, acceptance standards, allowables for defect types, safety factors going beyond original design documents and a substantial section on NDT, with input from the following NDT subgroup.
- A BINDT/HRA 'NDT of Heritage Railway Boilers' working group recommending: potential improved NDT methods and their development and evaluation, NDT training and qualifications, validation of NDT techniques, samples required for validation and pre-inspection calibration. This group will also input to the above group to help with the NDT section of the HRA guidance notes.

A question was raised about which body has the authority to set up the repository and dictate how things will be done, and how this will be carried out in a way that does not exclude a large proportion of the inspection community. It was suggested that the HRA should be approached to establish a repository and database for types of defects seen by class of locomotive, preferably an illustrated guide.

Boiler explosion and third-party insurance is usually covered by an insurance company or underwriter, which accepts the statutory inspection certificate from the inspecting authority. There was a comment that insurance companies are in a powerful position because they can choose whether to accept the statutory inspection certificate from the inspecting authority and, if the insurance company is also an inspecting authority, they may choose to accept only their own certificates. There needs to be a way for independent NDT inspectors to obtain accreditation such that work carried out by them for owners is accepted by insurance companies, inspecting authorities and notified bodies. This is insurance-led or inspection authority-led, *ie* competent person-led. This needs to be taken through SAFed but also needs to provide a way for independent NDT inspectors to join in and be raised to an approved level. Independent inspectors can be included in the working groups. Insurers and inspecting authorities will only underwrite the work of inspection bodies that they have accredited and audited.

Another requirement is for the provision of test samples, not only for technique reliability validation but also test-blocks for proving the correct operation of the equipment before and after the inspection.

For current NDT technologies, best practice needs to be captured and documented. Validation of NDT procedures must be tightened up and the requirement for a written NDT procedure established.

A process for validation of NDT procedures (techniques) is required, as is the case in aerospace, where a responsible Level III is approved for each company but may be contracted in. It may be that a competent person can provide that role, but it is unlikely because of the high level of NDT training for approving NDT techniques.

For new NDT technologies that may offer benefit, there is a need for a study of their applicability to solve the problems described in this workshop.

There is unlikely to be funding or studies for these groups, so as much as possible will need to be done by volunteers and as in-kind support from the heritage railways with a view to the continued ability to operate steam locomotives.

HRA will be looking to BINDT to move this forward and should be included in the working group on NDT.

There was a general feeling in the room that this conversation and investigation needs to happen, even if it is eventually decided that not much has to change.

Summary of requirements

- Define new NDT methods to find small defects in the known problem areas and surrounding environment. Monitoring of defects should be undertaken.
- It is important to use suitably trained NDT operators and a list of those who have the required training, qualifications and experience in each method should be considered.
- A review of the HRA guidance notes is required to include NDT and this review should be undertaken by a group that includes the insurers, who agree a process and establish a central repository for sharing experiences of working with boilers of specific types.
- It is important to review the defect allowables standards for the heritage sector to encompass these defects, allowing for the long period of generation of defects and the potential for monitoring defects.
- A central illustrated repository for shared information about failure modes and NDT inspections on specific boiler types/locomotive types would future proof the heritage sector as we lose the first-hand experience. HRA is to be approached to host this.
- Guidance on the advantages and disadvantages of different NDT methods.
- Guidance on NDT best practice, where possible, would provide a starting point – a validated NDT solution – allowing the competent person to consider it as their recommended inspection.
- Training and certification of in-house staff, for example to NDT 'Level 1 limited' just for ultrasonic stay inspection.
- Two working groups are needed:
  - An HRA group reviewing the HRA boiler codes of practice (guidance notes), including allowables for defect types, safety factors going beyond original design documents and including more on NDT and requesting input from the following NDT group.
  - A BINDT/HRA 'NDT of Heritage Railway Boilers' working group recommending: potential improved NDT methods; NDT training and qualifications; validation of NDT techniques; samples required for validation; and pre-inspection calibration. This group will also input to the above group to help with the NDT section.
- Provision of test samples both for validation and for proving the functionality of the equipment at the time of inspection.
- A process for validation of the reliability of NDT procedures (techniques) is required.

Summary of potential new NDT solutions

The following is a summary of NDT developments that revealed themselves during the workshop and should be investigated by a new NDT working group:

- Improved coupling system for ultrasonic stay inspection to avoid the need for surface preparation.
- Non-contact EMAT system for stay inspection, groove detection and characterisation and spot measurements of plate.
- Use of angle probe ultrasound or TOFD for detecting and sizing cracks preceding grooving.
- Use of phased array, FMC/TFM with adaptive focusing to image grooving and cracks from a rough front surface using a water stand-off and membrane.

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1. C H Hewison, Locomotive Boiler Explosions, 1983.
2. 'Result of Boiler Explosion', Locomotive Engineering, Vol 10, No 6, June 1897.
3. The Colliery Engineers Company (1900) Locomotive Boilers, ICS Reference Library #59, Stationer's Hall, London: International Textbook Company, section 12, p 76.

Appendix A: Thermodynamic principles of boiler explosions

Although a boiler explosion – a catastrophic failure of the pressure vessel – can have many causes, this workshop only considered the structural failure of critical parts of the boiler. This appendix provides a brief summary of the mechanism by which a potential small defect can cause a massive catastrophic failure that can release a considerable amount of energy, causing death or serious injury to people and damage to property (Figure 20).

While it might appear that a small defect could cause a slow release of pressure, in a similar way to the safety valves that are used to limit the pressure, the thermodynamic effects are more complicated than that for a pressure drop.

The water in a pressure boiler is held at a much higher temperature than its boiling point at atmospheric pressure. At elevated temperatures, the boiling process produces steam, which increases the pressure, until an equilibrium is reached and boiling ceases. It only boils again in order to restore the equilibrium, such as if the pressure falls, due to the use of the steam, or the temperature rises. Thus, a rapid drop in pressure, due to even a small failure, will cause the water to suddenly boil. The rapidly created steam bubbles displace the remaining water. The potential energy is released with enough force to peel back the structure surrounding the break in the vessel and can cause a 'water hammer' effect where 'slugs' of water are projected at high velocity towards the opening in the boiler, enlarging the original rupture or even tearing the shell in two[3].

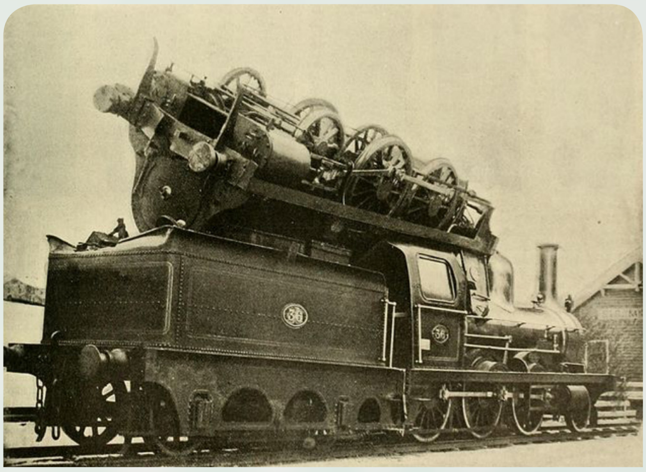

Figure 20. The aftermath of a boiler explosion near Oslo, Norway, in 1893. One locomotive was thrown into the air and landed on the roof of another; the crews of both escaped without injury[2]

Appendix B: Delegate list

Robert van Agthoven*	Stoom Stichting Nederland
Alex Beasley*	Great Western Society
Chris Birmingham*	Swanage Railway
Darren Boakes*	Resolution NDT
Gary Brown*	West Somerset Railway
Chris Burden	AePS (Applied engineering Prognostic Science)
Matthew Cay*	British Engineering Services
Martin Clarke*	Chairman of the Association of Independent Boiler Inspectors (AIBI)
Lawrence Donaldson	Kent and East Sussex Railway
Rory Edwards*	Dartmouth Steam Railway
Graham Froud*	Swanage Railway
Chris Greatley*	Kent and East Sussex Railway
John Haigh*	Allianz UK
Martin Hillier*	AWE
Richard Hiscox	West Somerset Railway
Dave Horton*	West Somerset Railway
Richard Johnson*	Lloyd's Register
Chris Kelley*	North Yorkshire Moors Railway
Alan Kirkham*	
Rob Le Chevalier*	South Devon Railway/HRA
Stede Marsh*	British Engineering Services
Edward Meakes*	Great Western Society
Bob Meanley	Tyseley Locomotive Works
Paul Merrington*	Dartmouth Steam Railway
John Moorhouse*	Dartmouth Steam Railway
Graham Morris*	Graham Morris Engineering Ltd
Andy Murray*	TSSNDT, RAF Wittering
Andrew Netherwood*	Mid Hants Railway
Mark O'Brien*	North Yorkshire Moors Railway
Christopher O'Neill*	Ultrascan Ltd
Keith Philips †	Testia Ltd
Pete Pickering*	P J Engineering Ltd
Ryan Pope	West Somerset Railway
Bob Rollason*	Minton
Hiddo Schultz*	Stoom Stichting Nederland
Chris Shepherd	Bluebell Railway
Nick Smith*	AWE
Robert Smith*	BINDT
Andy Summers*	Isle of Wight Railway
Martin Sutton*	Baugh & Weedon Ltd
David Taylor	MinstNDT
Dave Tibble*	Baugh & Weedon Ltd
Steve Turner*	HMRI
Martin Turner*	Talylln Railway
Andy Webber*	Resolution NDT
David Wothers*	
Matthew Wothers	
Andy Wright*	British Engineering Services

* Attended
† Deputy attended instead.

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