Risk control for small pressure vessels: café boilers, bench-top autoclaves, and model steam engines

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Café boilers such as espresso machines are widely used small steam-based pressure vessels, for instance in the hospitality and service sectors. Bench-top autoclaves and miniature steam engines are small steam-based pressure vessels widely used in schools and other educational settings. Duty holders must have effective risk control measures in place to prevent vessel failure and protect the public and workers. Legal requirements are in: the Provision and Use of Work Equipment Regulations (1998), the Pressure Systems Safety Regulations, PSSR (2000) and the Pressure Equipment (Safety) Regulations (2016). Control measures include: correct operation, regular inspection, testing and maintenance. However, there was a lack of engineering evidence about the potential for failure of these small vessels in order to determine proportionate risk controls.

This report describes experimental research on a sample of café boilers, bench-top autoclaves and miniature steam engines. The aim is to understand: (i) the safety devices installed and (ii) the failure modes that could occur if the vessels' safety devices failed. The researchers used a sample of new and second hand vessels. They carried out metallurgical inspection and over-pressurisation of the machines. The researchers identified that overheating and/ or overpressure could result in catastrophic vessel failure and an explosive release of energy with flying fragments and scalding steam and water. This has the potential to cause significant injury or death to people in the vicinity. However, the researchers consider that if effective control measures are in place, catastrophic vessel failure is unlikely. The research findings informed the Safety Assessment Federation's Managing the Risks of Café Boilers (2021) and are informing the approach to inspection within schools of this equipment working in liaison with the Consortium of Local Education Authorities for the Provision of Science Services, CLEAPSS.

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Risk control for small pressure vessels: café boilers, bench-top autoclaves, and model steam engines

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Foreword

The original test work in this research took place in 2016 during changes in UK Regulations for pressure equipment. The Pressure Equipment Regulations (1999) were in place at the time of the work, whereas the Pressure Equipment (Safety) Regulations 2016 are the current requirements for pressure equipment supply. However, this does not alter the technical content or findings of this research.

Following the UK's exit from the European Union, since 01 January 2023 the pressure equipment within the scope of this research (i.e. small steam pressure vessels) has required conformity assessment by a UK Conformity Assessment Body and UKCA marking before being placed on the GB market. For products placed on the market in Northern Ireland, they will require CE marking if an EU Conformity Assessment Body is used; or CE and UKNI marking if a UK Conformity Assessment Body is used.

Key Messages

This report describes experimental research on a sample of small steam pressure vessels (café boilers, bench-top autoclaves, and miniature steam engines). These vessels are used in the hospitality industry, service industry, and in schools. The aim of this project was to understand how the safety control mechanisms of these vessels function, and the consequences if they fail and the machines over-pressurise. A secondary aim was to review the supply legislation and how manufacturers comply with this.

This report will be of interest to café boiler and other small steam vessel manufacturers, pressure vessel inspectors and users.

Café Boilers

- Twelve café boilers were examined (both new and second-hand boilers).
- Hazardous defects were noted in the condition of the electrical systems in two of the second-hand café boilers. This highlighted the critical importance that the café boilers' electrical control systems are examined, tested, and maintained at regular intervals.
- Of the ten relief valves that were tested from the second-hand machines, three did not operate until higher pressures than the relief pressure were applied.
- In eight overpressure tests, the boilers failed at pressures between 18 bar and 28 bar. This was 9 to 14 times higher than the rated pressure on the pressure relief valves.
- In these overpressure tests, five failed catastrophically by ductile overload, fracture and then an energetic release of steam and fragments. The other three boilers all failed by a slow release of steam.
- If a person had been close to a boiler when it failed catastrophically, it is likely they would have been seriously or fatally injured.
- Manufacturing quality has not been implicated as a cause of premature failure during pressure testing.

Autoclaves and Miniature Steam Engines

- The energy released was much lower in the autoclaves than in the café boilers but could still cause harm. Therefore, statutory inspection is still critical.
- For miniature steam engines (three were examined), the water volume is very small, heat cannot be applied continuously, and the fittings leaked at pressures above 2 bar. Therefore, the risk of serious injury to operators of this equipment is low.

If machines are inspected regularly, tested, and maintained under the current statutory requirements, it is very unlikely that all the factors listed above would combine at the same time to cause a catastrophic overpressure.

These research findings informed the Safety Assessment Federation's Managing the Risks of Café Boilers (2021) and are informing the approach to steam vessel inspection within schools.

Executive Summary

Background

Small steam pressure vessels (such as café boilers, steam cleaners, bench-top autoclaves, and miniature steam engines) are commonplace in the hospitality, service, and educational sectors. A serious incident occurred when the boiler of an espresso machine (café boiler) in a café over-pressurised and failed catastrophically, putting staff and customers at risk of serious injury. This incident showed what the consequences of failure of a small steam pressure vessel could be, and the importance of carrying out this work. This report will be of interest to café boiler and other small steam vessel manufacturers, pressure vessel inspectors and users.

Aims

The main aim of this work was to understand how the safety control mechanisms that are installed on small pressure vessels (café boilers, bench-top autoclaves, and miniature steam engines) function; and the consequences if these controls failed and the boilers over-pressurised (as seen in the incident). A secondary aim of the work was to review the supply legislation and manufacturers' response to it in their supply documentation.

Methods

For the café boilers, four manufacturers' machines were assessed, and three machines were obtained from each manufacturer (one new machine and two second-hand machines – 12 machines in total). Where possible the same manufacturers' model was purchased. All were subjected to mechanical, electrical, and metallurgical examination. Four new and four second-hand machines were tested to over-pressure failure. Overpressure was generated by filling the boiler with water, then operating the heating elements continuously until failure. Three bench-top autoclaves from one manufacturer were purchased (one new machine and two second-hand machines) and were examined and tested to failure in a similar way to the café boilers. For the miniature steam engines, one new and two second-hand engines were examined and tested.

Main Findings – Electrical

Café Boilers

All the café boilers complied with a Category 3 control system as defined in the international standard BS EN ISO 13849-1:2015 – Part 1 except for one which used the over-temperature switch to control a contactor which controlled power to the heating elements. This is not monitored so could potentially fail in an energised state and therefore be ineffective. This feature was not present in a newer model from the same manufacturer. In the electrical control system of the second-hand café boilers, in one case the over-temperature switch had failed in a dangerous condition and would not have opened if an over-temperature was present. In another case the condition of the wiring meant that it would have been a potential shock hazard had it been connected to a mains supply.

These defects were not present in any of the new café boilers. This shows the need for the café boilers' electrical control systems to be examined and tested at regular intervals as required by the Pressure Systems Safety Regulations 2000 (the written scheme of examination should include all protective devices).

Autoclaves

Under manufacturer's guidance, the autoclave's electrical control system was over-ridden to ensure continuous heating for the overpressure test. The autoclaves had a fuse in the neutral supply to the heating element. If this fuse was to fail in use, the live supply would have remained intact and would have been a potential shock hazard. This does not comply with current standards.

Main Findings – Mechanical and Metallurgy

Café Boilers

All the boilers were fitted with a pressure relief valve and an anti-vacuum valve: both valves protect the equipment from damage. Ten pressure relief valves (PRVs) were removed from the machines and pressure tested. The manufacturers' rated pressures for these PRVs were from 1.8 to 2.1 bar. Three PRVs did not lift until a pressure above this was applied (2.8 bar, 3.5 bar, > 5.1 bar). For these three valves, after the initial test, the following relief tests showed the valves operating at pressures close to the rated pressure (2.0 to 2.4 bar). In a sample of ten relief valves, three failures are significant.

In eight overpressure tests, the boilers failed at pressures between 18 bar and 28 bar – five failed catastrophically due to ductile overload then fracture and some fragmentation – four were new boilers and one was a second-hand boiler. If a person had been close to a boiler when it failed catastrophically, it is likely they would have been seriously or fatally injured. As the PRVs are designed to relieve the pressure at about 2 bar, and failure pressures were in the range of 18 to 28 bar, all vessels failed at pressures of at least nine times their relief pressures. The other three (second-hand boilers) all failed by a slow leakage of steam.

For the café boilers to be exposed to overpressures of 18 to 28 bar, the following combination of factors would be required:

- the electrical control system would have to have a series of failures depending on the control system type;
- the PRV would have to fail to open, or open insufficiently;
- the ancillary components attached to the boiler, such as the pipe connections, would have to resist the increasing pressure and heat; and
- the boiler would have to be left switched on, without any steam being vented by the user, long enough for the pressure to build within the boiler.

Provided that machines are inspected regularly, tested, and maintained under the current statutory requirements, it is very unlikely that all these factors would combine at the same time to cause a catastrophic overpressure.

Autoclaves

PRVs were removed from the machines and their operation pressure was measured. Both were found to be functional. The new autoclave failed at a pressure and temperature of 5.7 bar and 139 °C respectively. The lid gasket was extruded through a slot, allowing a jet of steam to escape rapidly which overturned the autoclave and moved it a metre. No fragmentation of the autoclave occurred, although some doming of the lid section was observed. The second-hand autoclave failed at a pressure and temperature of 3.5 bar and 140 °C respectively. The lid gasket was displaced between the lid and base adjacent to a slot. This allowed steam to escape beneath the seal and downward in a controlled manner. The autoclave did not move during the release. For the autoclaves to be exposed to pressures of this magnitude the following factors would be required:

- failure of the temperature control system (the temperature sensor (thermistor), the PCB or the triac) so that power is maintained to the heating element regardless of what temperature is achieved;
- the PRV would have to fail to open, or open insufficiently;
- the autoclave would have to be left switched on long enough for the pressure to build within the boiler. From the tests, it took about 18 minutes of continuous heating before failure occurred for the new autoclave. However, as these machines are designed to be set up, switched on then left alone, if there were faults that were leading to overpressure, it is quite possible they would not be detected before failure occurred.

Again, if machines are inspected regularly, tested, and maintained under current the statutory requirements, it is very unlikely that all the factors listed above would combine at the same time and result in an overpressure. Although the energy released is much lower in the autoclaves when compared with the café boilers, there is still potential to cause serious burns and possibly impact injuries if a person is close to an autoclave when it fails.

Miniature Steam Engines

There are no electrical parts on a miniature steam engine and water volumes are very small (100 ml to 200 ml). The steam control valve and piston remained coupled to the boiler as the pipe connections could not be removed. Maximum pressures of 1.6 bar to 1.8 bar were measured with temperatures of around 125 °C. In the models tested heat cannot be applied continuously to the boiler and the boiler fittings do not appear to be designed to withstand pressures above 2 bar. Therefore, the risk of serious injury is low.

Contents

1. Introduction

1.1 Background

The purpose of this work is to assess three different types of small, steam pressure vessel:

- café boilers (can be referred to as coffee machines, espresso machines or coffee boilers);
- bench top autoclaves; and
- miniature steam engines.

These vessels have been chosen for the following reasons:

- In a recent incident, the steam boiler of an espresso machine failed in a café and several people were injured. The only guidance available at the time was an old Safety Assessment Federation (SAFED) publication that told users to rely on the manufacturer's design life if internal inspection of the boiler was not possible. As part of their findings in the investigation, HSE considered that further research work was needed to better understand the risk of an incident like this occurring again, and its consequences.
- For bench top autoclaves and miniature steam engines used in school science laboratories, in 2014 HSE discussed the pressure safety of this equipment with CLEAPSS[1]. This was part of a consultation to revise the *Pressure Systems Safety Regulations* (PSSR) Approved Code of Practice (ACOP)[1]. Schools often use bench top steam autoclaves for cleaning contaminated equipment, and model steam engines for demonstration purposes. There was an interest in the sector to clarify the PSSR requirements in schools. This resulted in an Appendix to the ACOP which explained how schools could comply with PSSR to ensure the risks were being properly assessed and controlled. These pressure vessels have been included within the scope of this work to have a better understanding of the safety risks to staff and pupils if these vessels were to fail in an over-pressurised state.

[1] CLEAPSS is the organisation that provides health and safety advice to school science teachers. It is controlled by its members, which includes all local authorities throughout the British Isles (not Scotland). In Scotland, this service is provided by the Scottish Schools Education Research Centre (SSERC).

1.2 Project Aim

To understand what safety control mechanisms are in place on these machines, and the failure modes that would occur if they failed and the machines were over-pressurised.

To identify the supply legislation the equipment is produced to and assess if the equipment complies with the supply legislation in practice.

1.3 Objectives

To achieve the above aim, several objectives have been defined as follows:

A brief assessment of the equipment that is currently on the market (see Appendix) and obtain examples of new and second-hand equipment for testing.

Identify the relevant supply legislation.

Produce a list showing each relevant part of the supply legislation. Compare this with the information provided by the manufacturers and determine if the manufacturer's information complies with the requirements of the legislation.

Examine and determine the different ways that the safety devices could fail (failure modes).

Establish the level of wear, corrosion, and service damage on second-hand models (a note on internal examination is included in the Appendix).

Undertake overpressure tests to failure and assess the consequences of failure through high-speed video and post-test damage assessment.

Produce a report containing the work for all the above objectives **(this report)**.

The work has been carried out by engineers at HSE's Science Division (HSE SD).

2 Café Boilers – Methodology

2.1 Introduction

Café boilers are manufactured in a variety of different designs; this research has concentrated on professional two-group and three-group[2] espresso machines with steam and hot water outlets. New and second-hand machines from four different manufacturers were purchased for testing and examination. Where possible the same model was purchased for new and second-hand machines. The exceptions were manufacturers A and B where the new machines were the upgraded models of the second-hand machines which were no longer available as new machines.

To produce espresso, ground coffee is placed in a filter holder (brew handle) and secured to the brew head fixture. A metered dose of hot, pressurised water (90 °C to 95 °C and 7 bar to 12 bar pressure) is passed through the ground coffee. This delivers a shot of espresso into a cup placed beneath. Buttons on the machine allow the user to select a single shot, two shots etc. from the brew head. Each brew head is controlled independently, allowing multiple drinks to be dispensed at the same time.

Steam is produced by a central boiler (café boiler) and is delivered to articulated steam pipes known as wands. These are typically used to heat and froth milk and are controlled by a manually operated valve.

A hot water outlet is also provided from the café boiler, typically used for making tea. On the machines selected for examination this was controlled manually by the user (e.g. a press-and-hold; or press-to-start: press-to-stop operation).

A tray beneath the brew heads collects any spills which flow to a central drain port.

For each of the four manufacturers, a new boiler and two second-hand boilers were purchased (12 in total). The new boiler and one of the second-hand boilers were examined, subject to an overpressure test, and then given a further metallurgical examination afterwards. The other second-hand boilers were kept just for metallurgical and electrical inspection.

[2] The ‘group’ is the number of independent brew circuits that are in the machine

2.2 Examination and the Methods to Determine Wear

A visual examination was carried out on the second-hand café boilers from each manufacturer prior to pressure testing. Where possible a borescope was used to inspect the boiler interior through accessible ports, but a more comprehensive visual and photographic log was taken of service-use condition and visible degradation.

Following testing, the boilers were once again examined to determine the failure mechanism and condition. An inspection of the internal condition of the four second-hand but untested boilers, and those boilers which had not failed catastrophically was conducted by circumferentially cutting open the boilers around their mid-point. Wall thickness measurements were taken on all boilers using a calibrated ball head micrometer.

Examination of defects, deposits, fractures, and leak points was carried out using a combination of stereomicroscopy and scanning electron microscopy (SEM). Chemical analysis of corrosion deposits was carried out using Energy Dispersive Spectroscopy (EDS) on the SEM. Metallographic cross-sections were taken through representative samples from the failure points (both overload and leak points) and corrosion defects. These samples were mounted in resin, polished to a 1 µm finish and etched in a solution of ferric chloride with hydrochloric acid in ethanol to reveal the underlying microstructures.

2.3 General Principles of Operation

Figure 1 below provides an overview of the general operation of a two-group café boiler.

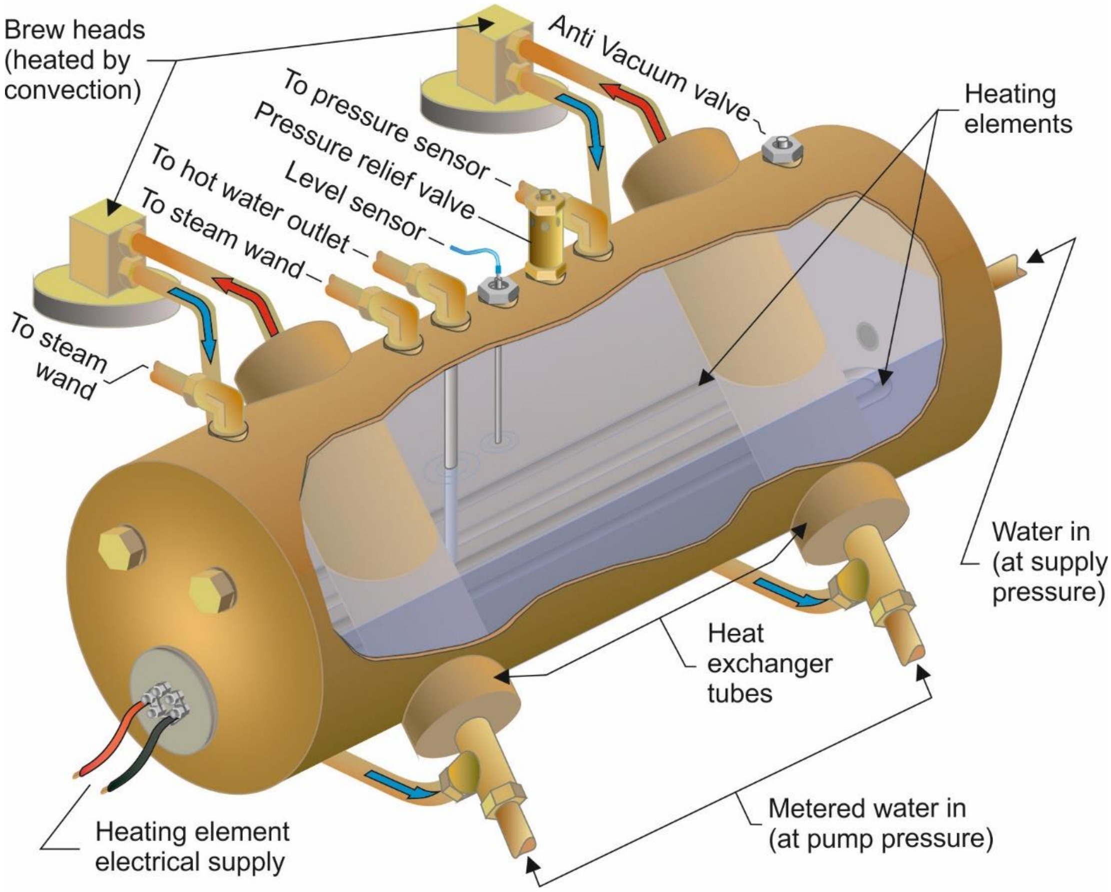


Figure 1 Cut-away view of a typical café boiler in a two-group professional machine

All but one of the café boilers examined for this research utilised a single copper boiler incorporating internal heat exchangers to maintain separation between the coffee water and steam/hot water circuits. The two circuits operate at different pressures, with the steam and hot water circuit ported directly from the boiler and operating at typically 1 – 2 bar. The water for the coffee circuits passes through individual heat exchanger tubes for each brew head circuit and operates at typically 7 to 12 bar pressure. Heating elements installed in the main boiler provide the heat source for the entire machine. However, some machines had additional heating elements for cup warming and one machine had individual boilers for the coffee water and steam/hot water circuits, each incorporating heating elements.

Water within the brew head circuits is typically allowed to circulate through convection, thus warming the heavy brass casting of the brew head and ensuring that water remains hot when passed through to the cup. When dispensing a cup of coffee, a metered dose of water is measured by a flow meter and pumped into the circuit under pressure via a solenoid valve. Heated water is then ejected via the brew head into the cup.

The internal volume of the boiler is occupied by water and steam, typically having a fill level of around 60 % water, which is determined by a level sensor in the boiler. The only outlets for water from this volume are the hot water outlet (via a solenoid valve controlled by a user-activated button) and, on some machines, a drain port. The hot water tap outlet typically consists of an internal dip tube passing from a port at the top of the boiler down towards the bottom of the boiler and into the water. Steam is vented directly from ports situated above the water level, leading to the steam wands and pressure sensor or pressure switch (depending upon the control system employed).

The boilers of all machines were fitted with two types of mechanical safety device acting on the steam volume as follows:

1. **A Pressure Relief Valve (PRV)** This device operates if excessive pressure is present within the boiler, venting steam until the pressure drops back to within normal levels. The pressure relief valve consists of a disc, held against a sealing surface by a spring, which has a spring load matched to the operating pressure of the PRV (typically slightly above the operating pressure of the boiler).

   If pressure in the boiler exceeds the set operating pressure of the PRV, the force of the steam pressure acting against the disc exceeds the reaction force of the spring, and the valve opens which vents steam and relieves pressure from the boiler until the force generated by the steam drops back below the spring force, at which point the valve closes.

   The PRV is not intended to operate in normal usage as boiler pressure is ordinarily controlled by the pressure switch, or via a control circuit acting on data received from pressure and temperature sensors. The operating pressure and flow rate of the PRV must be matched to the boiler to ensure that the boiler does not continue to over-pressurise when the PRV is fully open and venting the boiler. For this reason, some machines with larger boilers are fitted with two PRVs to ensure that there is sufficient venting to ensure the pressure reduces once the PRVs open (checking that the flowrates of the PRVs were adequate for the boiler sizes was not part of this work).

2. **An anti-vacuum valve.** This device prevents a vacuum from occurring within the boiler. This may typically occur when the heat source is switched off and any steam within the boiler returns to the liquid state. Damage may occur to the boiler due to the presence of a vacuum, and operation of the steam wands or hot water outlet when a vacuum is present could lead to air entering the boiler through the outlet. In the case of the steam wands, these are typically placed within a container of milk and then steam is ejected to create hot, frothy milk. If the wand is placed within the milk and operated

when there is a vacuum in the boiler, milk will be drawn into the boiler due to the pressure difference. This could cause serious damage to the machine.
This device operates in reverse to the PRV and consists of a disc suspended within the boiler by a rod, which passes through a port on the top surface of the boiler. A seal fitted to the upper surface of the disc prevents steam from escaping through the port when the disc is in contact with the mating surface of the port.

When there is no positive pressure in the boiler, gravitational force acting on the disc holds the seal away from the mating surface. This allows air from the outside to pass through the port into the boiler, which prevents a vacuum from occurring. As pressure builds within the boiler, this acts upon the surface area of the disc, generating an opposing force. When this force exceeds the gravitational force, the disc is pushed upwards, engaging the seal against the mating surface, and preventing air from entering the boiler and steam from escaping.

The machines typically require an electrical supply of between 4 and 7 kW. Some of the machines purchased were configured for a single-phase 230 V supply (up to 30 A), others were configured for three-phase 415 V. Typically the machines could be converted to operate on either supply.

All machines examined required a mains water supply and connection to a drain. Some machines were fitted or supplied with a water metering device to limit the delivery volume of water in a single operation (to protect against boiler overfilling). The boilers of the machines were filled from the mains water supply via a solenoid valve. Brew head circuits were supplied via a pump to provide the increased water pressure needed for these circuits. Separate hydraulic PRVs were frequently present within these circuits, although the operation of these did not fall within the scope of this research.

2.4 Examination of Electrical Safety Devices

The control of pressure within the boiler ensures that they function correctly and remain safe. The pressure within the boiler is created by applying power to the heating elements within the boiler when the correct level of water is present. As the temperature within the boiler increases so does the pressure. The power to the heating elements is controlled to maintain a pre-set pressure and hence temperature.

In the designs of the café boilers examined in this work, the pressure within the boiler is monitored during operation. How this is achieved varies in complexity and with the type of components used. The electrical power to the heating elements is also controlled. To help to understand the different forms of electrical control, they have been allocated an electrical control type number, this is specific to this report and not used in the café boiler industry.

Type 1 – the pressure is monitored by a mechanical pressure switch that removes power from the heating elements when the desired pressure in the boiler is reached. There was also an over-temperature switch in series with the heating elements. The over-temperature switch could be inserted in two positions on the boiler: into a sleeve in the boiler whose tip is below the normal fill level of the boiler; or in a similar sleeve between heating elements. This over-temperature switch, once operated, had to be manually reset before power could be re-supplied to the elements. If the over-temperature switch is inserted between the heating elements, then the boiler is protected in a boil-dry scenario. Although it is unclear how the over-temperature switch would react if the water level fell below the tip of the sleeve into which it is inserted. However, the end of the sleeve was close to the heating elements and would be exposed to radiant heat. One manufacturer did not position the over-temperature switch between the heating elements, although this was in only one of the second-hand models.

Both the mechanical pressure switch and over-temperature switch could be single-phase – switching ‘live’ and ‘neutral’; or three-phase – switching all three phases. In this type the heating element is either on or off.

Type 2a – the boiler pressure is monitored by an electronic pressure sensor and its output is interpreted by a printed circuit board (PCB). The PCB controls power to the heating elements using electronic switches, generally metal-oxide-semiconductor field-effect transistors (MOSFETs[3]) or triacs[4]. Power to the MOSFETs or triacs is controlled by a contactor[5], whose coil was controlled by the over-temperature switch described in Type 1 and the PCB. So, either the over-temperature switch or the PCB can turn the contactor off, thus removing power to the heating elements. This type can be single or three-phase; however, the power to the heating elements can be proportionally controlled by the PCB using the MOSFETs or triacs to allow better control of the pressure within the boiler and more energy efficiency. The power can be removed from the heating elements by de-energising the contactor which is controlled by the over-temperature switch. The sensor for the over-temperature switch is inserted in a sleeve between the heating elements.

Type 2b – this is the same as Type 2a with the exception that the over-temperature switch can directly disconnect the power from the heating elements if it is triggered, i.e., there is a contactor controlled by the PCB, but this is in series with the over-temperature switch. So both the PCB and the over-temperature switch can isolate the heating elements.

[3] metal-oxide-semiconductor field-effect transistors (MOSFET) have ability to change conductivity (pass current) with the amount of applied voltage, essentially they are an electronically controlled switch that can switch large currents. In this case two would be used back-to-back so that they can switch an a.c. current.

[4] a triac is a voltage bidirectional triode thyristor and can be thought of as a relay that can switch a.c. currents.

[5] a contactor is an electrically controlled switch (relay) used for switching an electrical power circuit.

Type 3 – the boiler pressure is monitored by an electronic pressure sensor and its output is interpreted by a PCB. The PCB controls power to the heating elements using electronic switches in Type 2a and 2b electric control. The MOSFETs or triacs are mounted on the PCB and if they fail the whole PCB must be replaced. These control elements have been replaced by external solid-state relays (SSRs[6]) which in this case are fast acting d.c. controlled switches. This means that if they fail, only the SSR need to be replaced and not the whole PCB. In this type the positive SSR control terminal is supplied by the PCB, and the negative control terminal is supplied by a mechanical pressure switch that monitors the pressure in the boiler. If this pre-set pressure is exceeded the negative supply to the control terminal of the SSR is removed, and this isolates the heating elements. The power can be removed from the heating element by de-energising the contactor, but this is controlled by a switch on the front of the café boiler only – this is a manual action that would require user-intervention to function. As there is type 2b control, the over-temperature switch can directly disconnect the power from the heating elements if it is triggered.

[6] a solid-state relay is an electronic switching device that switches current on and off when a small external voltage is applied across its control terminals.

A schematic of the electrical control circuit types is shown in Figure 2.

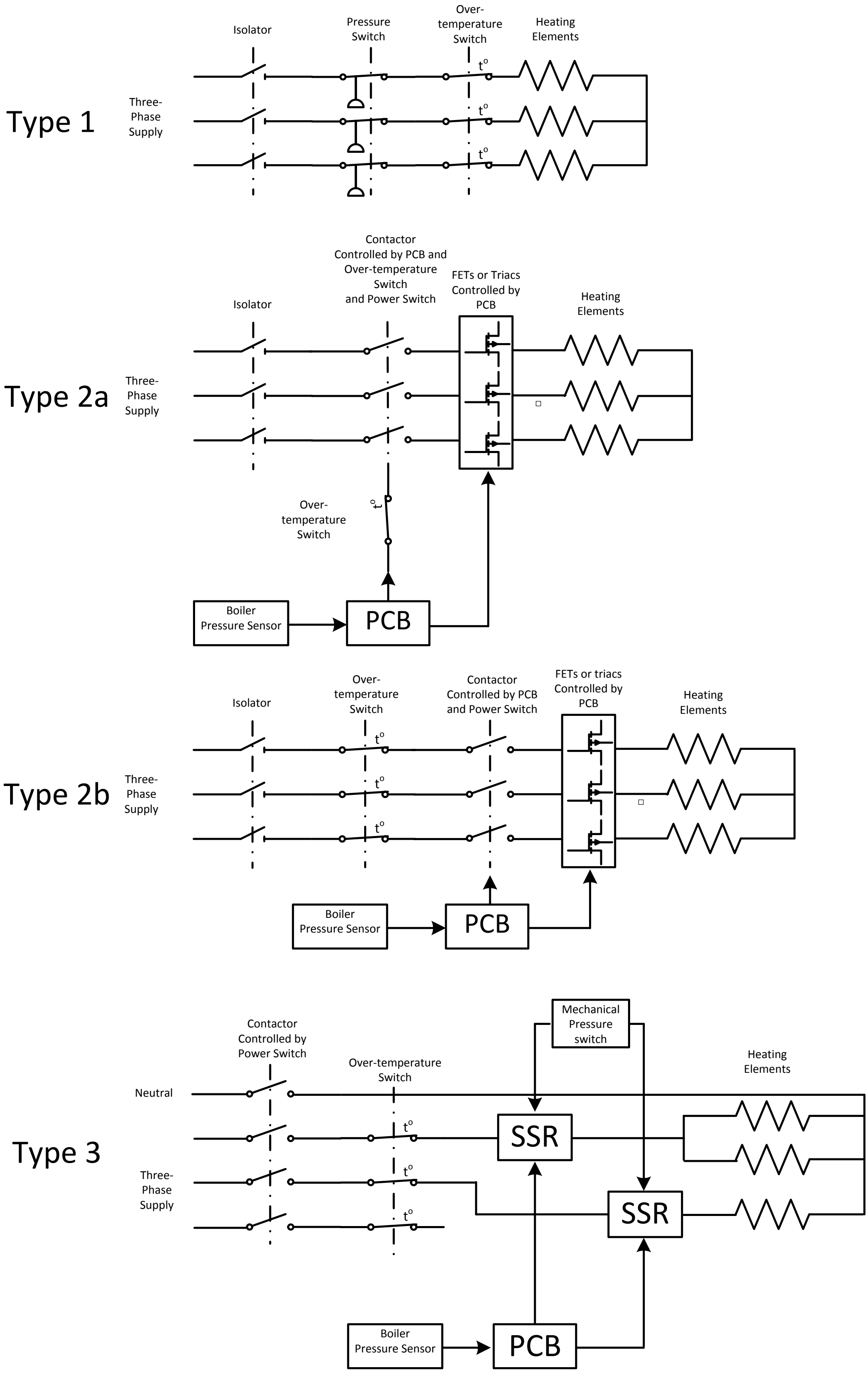


Figure 2 Control type number schematic

The failure mode of MOSFETs, triacs and SSR is not very predictable and depends on the operating conditions, electrical and mechanical, to which they are exposed. However, it is accepted that they could fail in a conducting state, i.e., fail to danger in this application and so they are not considered a safety-component.

It is important to understand that the control methodology of all the types of control system outlined above rely on the over-temperature (manual-reset) switch to remove power from the heating elements if the control system fails to danger. Therefore, this should be considered as a safety device.

Type 2a uses a contactor controlled by the over-temperature switch and PCB which could cause safety issues as operational tests showed that the contactor was not monitored and so could fail in an energised position and not be detected. Subsequent failure of the MOSFETs or triacs could cause power to be continually supplied to the heating elements as the over-temperature switch would have been bypassed by this undetected failure.

2.5 Pressure-to-failure Approach (Including Operational Test Methods)

One second-hand machine from each manufacturer was selected for metallurgical examination based on the condition of the boiler interior or electrical integrity. A borescope was used to view the interior of the boilers to assist with the selection; machines with evidence of significant scale build up and/or verdigris (copper corrosion[7]) were chosen. In one case, the poor condition of the electrical circuit ruled out one machine from operational testing, so this machine was selected for metallurgical examination. The remaining new and second-hand machines from each manufacturer proceeded to operational and overpressure testing.

Prior to any operational testing being carried out, instrumentation was added to the test machines. Pressure measurements were made using an unused port (or the outlet to one of the steam wands if no suitable unused port was available) in the upper, steam portion of the boiler. A 1 m length of high temperature, stainless steel braided test hose was connected between the port and a 100-bar pressure transducer. This remote coupling arrangement was chosen to allow dissipation of heat between the boiler and the pressure transducer.

[7] a bright bluish-green encrustation or patina formed on copper or brass by atmospheric oxidation, consisting of basic copper carbonate.

Four 100-bar pressure transducers were connected to a data logger and calibrated using a Budenburg dead weight pressure calibrator. Each transducer was allocated an individual logger channel, but only one transducer was used per test.

Thermocouples (uncalibrated, for indication only) were fitted to the top and bottom of the boilers as close to halfway along the length of the boilers as access permitted. The thermocouples and the pressure transducer were connected to the data logger to allow monitoring and recording of boiler pressure and temperature throughout all operational and overpressure tests.

2.5.1 Operational Test Methods

Operational tests of the machines were carried out in the laboratory where the electrical and mechanical safety devices were assessed, and operational parameters for temperature and pressure were recorded. PRVs were removed from the machines and their operation pressure was measured using a pressure calibrator which was calibrated to UKAS accredited standards. Any PRVs found to malfunction were replaced prior to powered operational tests being undertaken.

Similarly, the switching pressure of pressure switches (where fitted) was recorded under both increasing and decreasing pressure conditions. An electrical inspection was also undertaken to assess whether the machines' controls were functioning correctly and to ensure wiring was in a safe condition. Any faulty safety-critical components were replaced prior to proceeding with the operational tests.

Instrumentation was connected during operational tests to provide data to the test officers to verify that the machine was operating within safe limits. Where a directly comparable model was available, the new machine was tested first to provide data from which to assess whether the second-hand machines were functioning within the parameters recorded for their new equivalent.

Following testing, the volume of water in the boilers was measured.

2.5.2 Overpressure Test Methods

Prior to overpressure testing, all pipework connections to the boiler were disconnected and replaced with blanking plugs except for the connections to the pressure transducer and the heat exchangers; the latter were left intact to maintain a realistic water pressure within the heat exchanger tubes during testing. The upper limit of this pressure was controlled by PRVs in the brew circuits as would occur in an overpressure scenario during use. It was concluded that the positive pressure within the heat exchanger tubes would help to prevent crushing of the tubes. If this positive pressure was not present, and the heat exchanger tubes were crushed, this would result in a failure mechanism that may not occur in practice[8].

Figure 3 shows these alterations to the boiler.

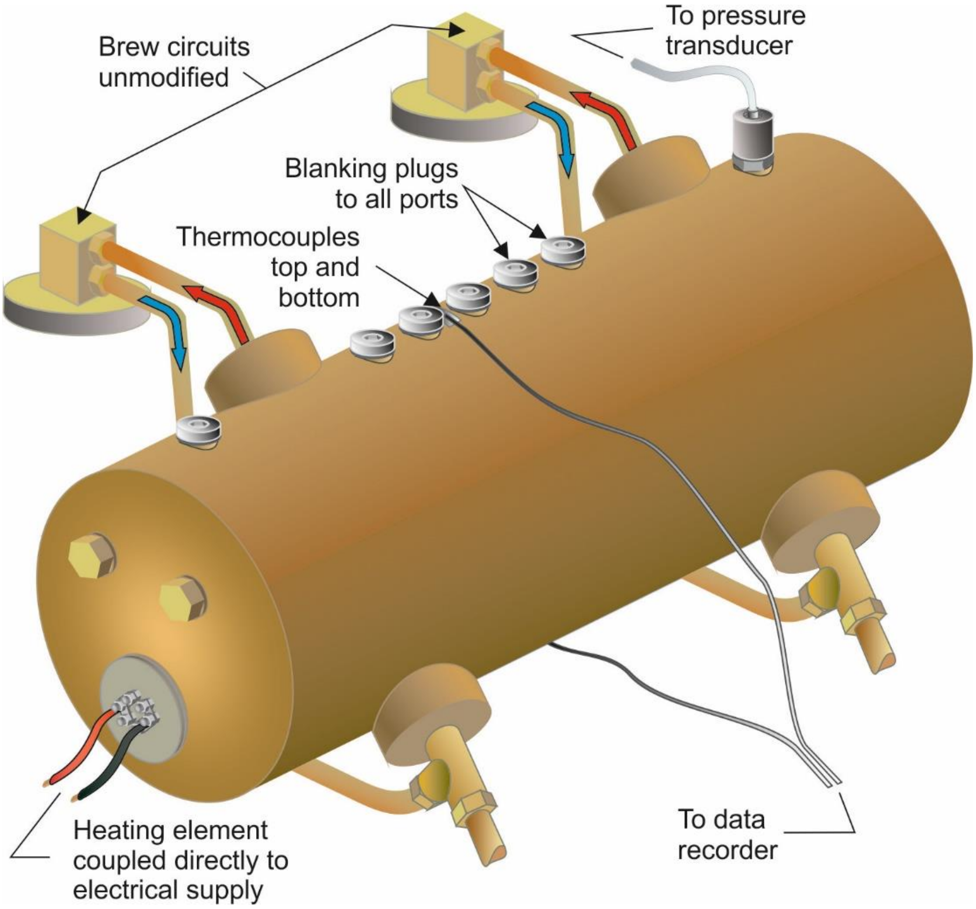


Figure 3 Instrumentation locations and boiler modifications for overpressure testing

PRVs, pressure switches, level sensors and anti-vacuum valves were removed from the boilers and replaced by blanking plugs. Apart from one machine, boilers were refilled with water to the same volume as had been removed following operational testing. One machine had failed to fill to the correct level during operational testing, so was filled to the level recorded upon receipt. The outer casings of the machines and the brew heads were re-fitted in preparation for overpressure testing.

[8] Previous hydraulic overpressure testing by HSE SD, where the heat exchanger tubes were empty showed that the pressure difference between the inside and outside of the tubes caused them to crush and fail at a pressure below what was thought the system could achieve.

The electronic control system was bypassed to ensure that power to the heating elements did not cut out during testing. This was achieved by connecting the heating element directly to the power source, passing only through a purpose-built external remote switching unit. Overpressure was generated within the boiler by operating the heating elements continuously.

Testing was carried out in a large outdoor tunnel manufactured from steel tube which was originally designed to accommodate trains. The tunnel measured approximately 7 m in diameter and 34 m in length; it had one open end and one partially closed end, see Figure 4.

Figure 4 Outdoor tunnel-test facility – viewed from the open end

The machines were placed within the tunnel, approximately 10 m from the open end, and a barrier was located outside, approximately 3.3 m from the open end to prevent debris from exiting the tunnel. Standard and high-speed video cameras were placed within this barrier to record the test. A light coating of white contrast paint was applied to the front face of the machine under test to reduce reflections and glare from the polished surfaces and aid imaging. Where appropriate, the debris spread following the test was recorded, although in many cases, this was restricted by the confines of the tunnel. Data from the pressure transducer and thermocouples was recorded.

Following testing, the boilers were removed from the machines for failure assessment examination.

2.6 External and Internal Visual Examination of the Second-hand, Un-tested Café Boilers

2.6.1 Second-hand Café Boiler (Manufacturer A Sample No. 14034)

Sample 14034 was nominally 610 mm in length and 220 mm external diameter. Service conditions had resulted in this boiler undergoing considerable external tarnishing, with a significant build-up of white and green coloured corrosion deposits at the seals associated with both end plates, Figure 5.

Figure 5 Corrosion deposits at end plate ***(Image No. P2202727.jpg)***

The seals were brittle and flaking. Within the vessel the temperature sensor was significantly corroded, with green corrosion deposits on its surface. Externally, on the underside of the boiler, there was a green-coloured corrosion deposit. Several external fittings also showed indications of corrosion attack.

Internally and below the water level (BWL) there were deposits of loose, flaky, black, and white debris, Figure 6. In the above water level location (AWL) the internal cylinder walls were lightly coated in a very adherent black deposit.

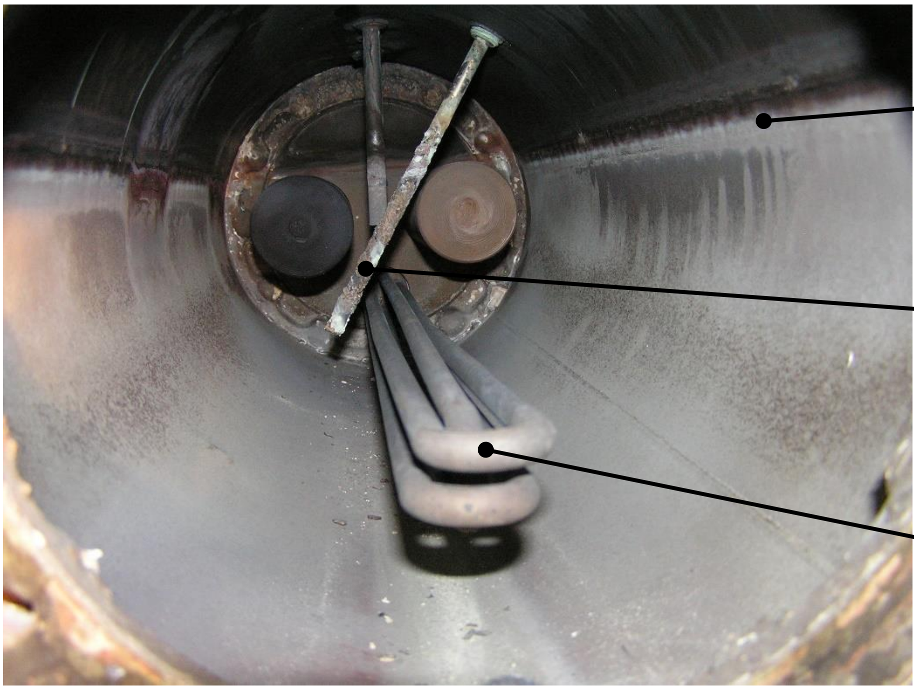


Figure 6 Grey deposits in interior of vessel ***(Image No. P2202740.jpg)***

To assess the depth of corrosion penetration into parts of the boiler, four metallographic samples were prepared from the following areas:

a. a weld between the end plate flange and vessel wall, Figure 7;

b. the underside of the boiler;

c. a transverse section through a fitting attached to the heat exchanger; and

d. a section through one of the brew heads, the interior of which was thickly encrusted with green corrosion deposit, Figure 8.

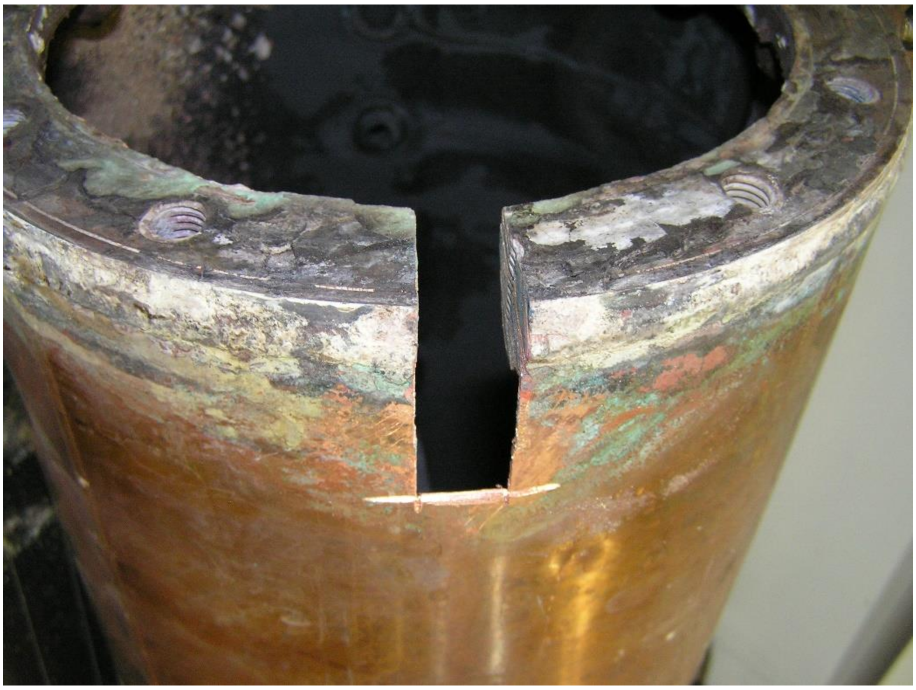


Figure 7 **Section taken through the end plate weld** ***(Image No. P1010834.jpg)***

Figure 8 **Section taken through a group (brew) head** ***(Image No. P1010832.jpg)***

During visual examination, the deposits in the brew head and heat exchanger fitting had appeared to be quite extensive. However, they had only caused slight attack of the walls of the fittings, as shown for example in Figure 8a for the brew head section. The extent of corrosion attack was slightly greater for the end plate flange. Overall, although corrosion was found to have affected all the samples examined, it had not penetrated into the cross-sections to any great extent, and as such its influence was cosmetic and did not compromise the structural integrity of the boiler.

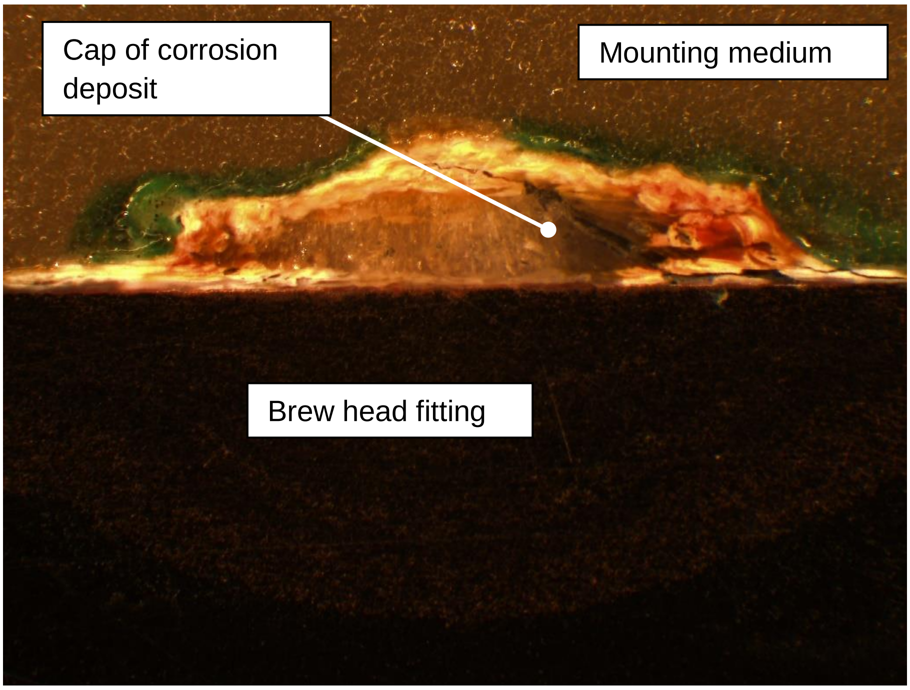


Figure 8a Section through the brew-head showing corrosion deposit sitting above the surface of the fitting ***(Image No. 14260-02x20.jpg)***

Samples of corrosion debris and lime-scale deposit were analysed using EDS on the SEM. External corrosion deposits contained an extensive range of elements of widely varying concentration, but in general the highest concentrations (in descending order) were oxygen, carbon[9], zinc, copper, and calcium. These elements are likely to have been associated with oxides of zinc and copper leached from the café boiler pipework and fittings, and compounds of calcium from the water itself (calcium carbonate or calcium hydroxide). Lower values, generally less than 5 wt %, were obtained for phosphorous, carbon, sodium, silicon, chlorine, and magnesium, while values of less than 1 wt % were observed for iron, nickel sulphur, and aluminium.

The sample of scale taken from the internal body of the vessel was composed primarily of oxygen, calcium, zinc, and copper, with phosphorous, sodium and silicon in smaller quantities. Again, widely varying analyses could give little information other than that a range of elements were present and that their origins would have arisen from the metallic fittings and the water used in the boiler.

[9] It is difficult to make an accurate assessment for carbon using SEM-based EDS due to significant potential for contamination from the mounted sample, and the action of the microscope itself.

A phenomenon known as dezincification was observed at the internal surface of a brass fitting attached to the heat exchanger end of the vessel[10]. The electrochemical process results in the leaching of zinc from the brass. EDS analysis revealed that the zinc content in the surface regions had reduced to 25 %. This was less than the nominal 40 % in the interior of the fitting. The same process was found to have occurred on the inside surface of the brass end plate fitting.

The mean wall thickness for the vessel was 1.56 mm, with a range of values between 1.49 and 1.65 mm.

2.6.2 Second-hand Café Boiler (Manufacturer B Sample no. 14134)

Other than the general staining and tarnishing associated with service use, this boiler was found to be in reasonably good condition with little evidence of corrosion damage on the external surfaces and fittings. Internal examination using a borescope indicated that there was a moderate amount of scale within the water space, on the heater tubes, inside surface of the vessel and the base of the pressure gauge and water level probes.

Cutting open the boiler revealed the accumulated thick plate-like lime-scale deposits in the BWL regions of the vessel, Figure 9. The scale was also observed on fittings such as heating elements, temperature sensors and heat exchangers which lay in the BWL region.

Figure 9 Interior of vessel showing lime-scale deposits ***(Image No. P1010867.jpg)***

[10] dezincification is a corrosive degradation mechanism where the zinc depletes from the brass. This normally leaves a pink-coloured copper-rich material where dezincification has occurred. This may have poor cohesion with the remaining microstructure.

A metallographic cross-section was prepared from the intact longitudinal butt seam weld to demonstrate the range of microstructures and hardness variation across the weld. Distant from the weld, within the parent copper strip, the microstructure comprised a fine equiaxed grain structure, Figure 10.

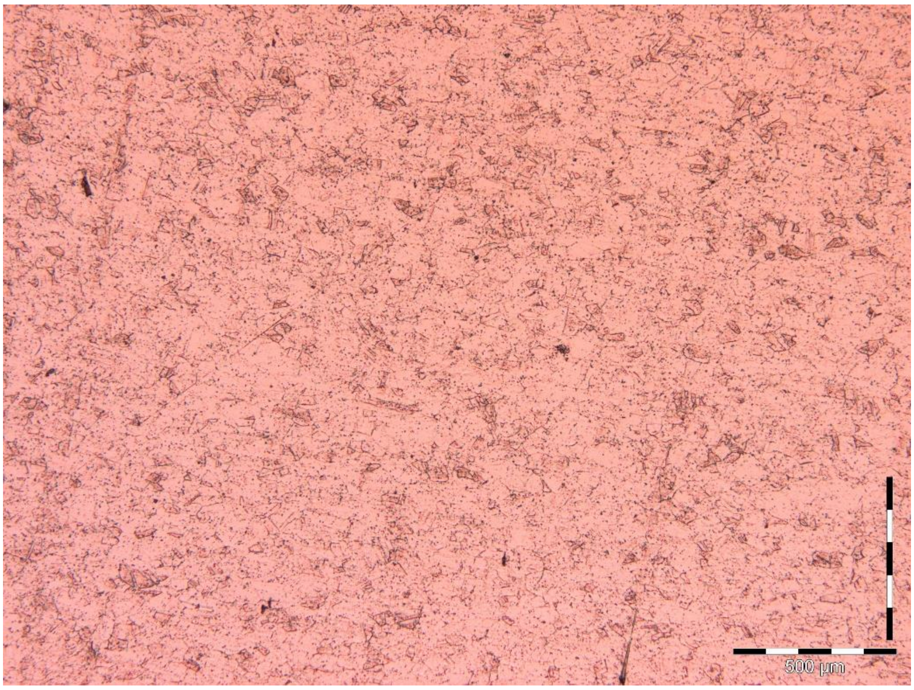


Figure 10 Fine equiaxed grain structure in parent strip ***(Image No. 14134 met1-3.jpg)***

In the heat affected zone (HAZ) either side of the weld, the grain structure had coarsened very significantly, Figure 11. Within the weld metal there were fine, linear, mottled structures indicative of fused copper.

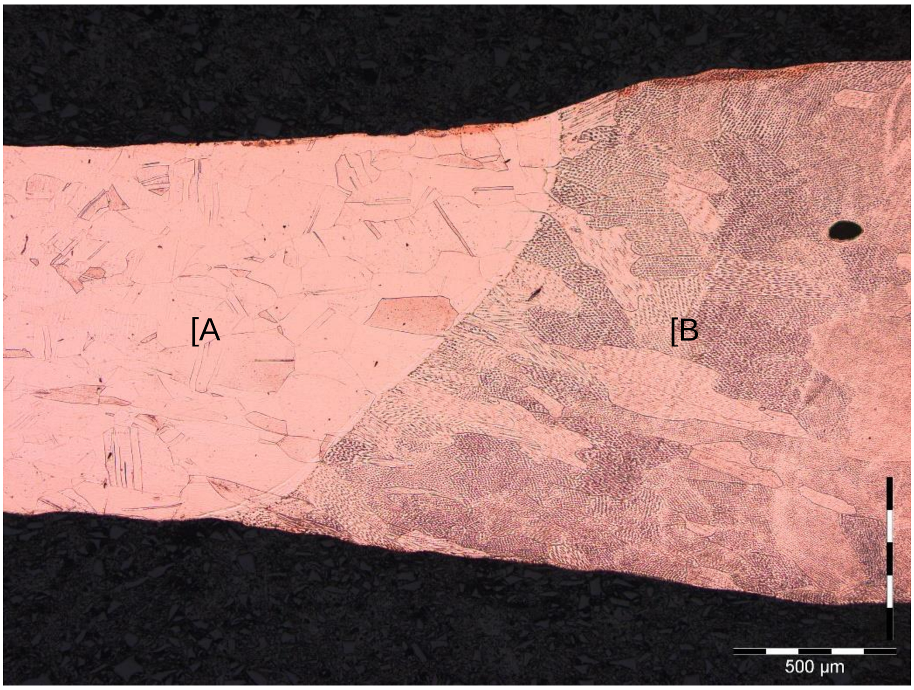


Figure 11 Showing coarse grains in the HAZ of the parent metal [A], and fine structures in fused weld metal [B]. ***(Image No. 14134 met-1-2.jpg)***

The hardness variations across the weld were not very large. Distant from the weld the fine-grained parent metal had a mean Vickers[11] micro-hardness value of 77 HV0.5. Within the HAZ the mean value was 80HV 0.5 whilst within the weld metal a mean value of 72.2 HV0.5 had been measured. This narrow range of hardness values amongst the various microstructures appear to be within the error limits of the micro-hardness technique of ± 8 %. Therefore, it has little significance to the integrity of the vessel.

The mean wall thickness of the vessel, away from the thickly coated BWL locations, was 1.47 mm.

[11] The measurements were made in accordance with BS EN ISO 6507-1:2005, 'Metallic Materials Vickers Hardness Test'. Part 1 Test Method'. The accuracy of individual measurements was within ± 8 %.

2.6.3 Second-hand Café Boiler (Manufacturer C Sample No. 14471)

Boiler sample 14471 from manufacturer C was nominally 600 mm in length and 220 mm in diameter. One end of the vessel comprised a domed pressing which had been welded to the vessel wall. The weld at this and at the opposing end, which was comprised of a ring-shaped flange welded to the vessel wall, was generally uniform. A visual examination showed the weld to be free of defects. The ring-shaped flange permitted a flat brass endplate to be bolted onto it. The longitudinal butt weld running the length of the vessel appeared uniform except towards its proximity to the domed end, where the weld became lumpy and misshapen indicative of over welding having been used in this location, Figure12.

Figure 12 Irregular weld deposit ***(Image No. DSCN5984.jpg)***

From their uneven appearance, the brazed joints associated with the insertion of the brew heads had been made manually. On the weld cap, very occasional, small surface breaking pores could be seen.

The vessel was in good condition with very light tarnishing. The interior of the vessel in the BWL region was only lightly coated with lime-scale deposits, Figure 13. The longitudinal weld was uniform and intact. Consistent with all the other vessels examined the AWL blackening of the wall was present.

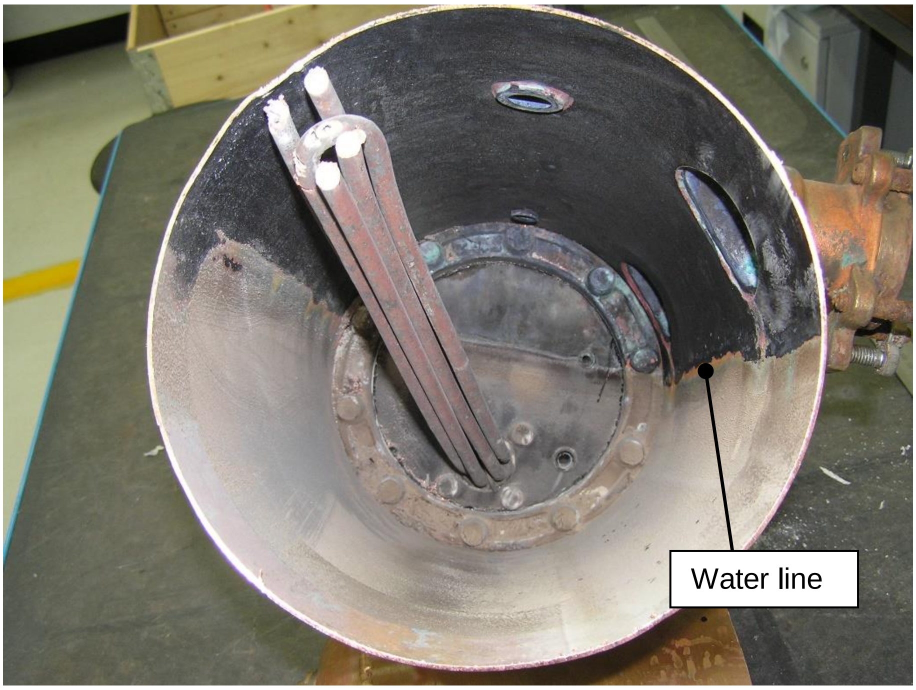


Figure 13 Interior of boiler vessel ***(Image No. P1012987.jpg)***

The bolts on the brew head fittings were badly corroded, showing brown and black coloured rust. This indicated that they had probably been made from carbon steel. When in direct contact with the brass/copper fittings, these bolts would preferentially corrode (galvanic corrosion).

The measured mean wall thickness for this boiler vessel was 1.49 mm with a range of values between 1.47 mm and 1.52 mm.

2.6.4 Second-hand Café Boiler (Manufacturer D Sample No. 14432)

Consistent with all the other café boilers, sample 14432 had been manufactured from copper strip/sheet which was welded to form a cylindrical vessel. Along the length of the vessel was a uniform, intact butt-welded seam and at either end a pressed sheet dome had been welded to the cylinder to complete the boiler unit. The vessel was nominally 430 mm long and 190 mm in diameter.

As received, the boiler vessel was tarnished with an accumulation of surface debris and dirt resulting from its service use (particularly on the top external surface), Figure 14. Other than one or two tiny superficial pits, there were few indications of corrosion on the vessel walls although spot staining was more prevalent. A small quantity of light white coloured deposit was observed on a blanked end cap on the left-hand brew head which may have been indicative of minor leaking. The interior of ports, where accessible, had very slight deposits of a white powdery consistency.

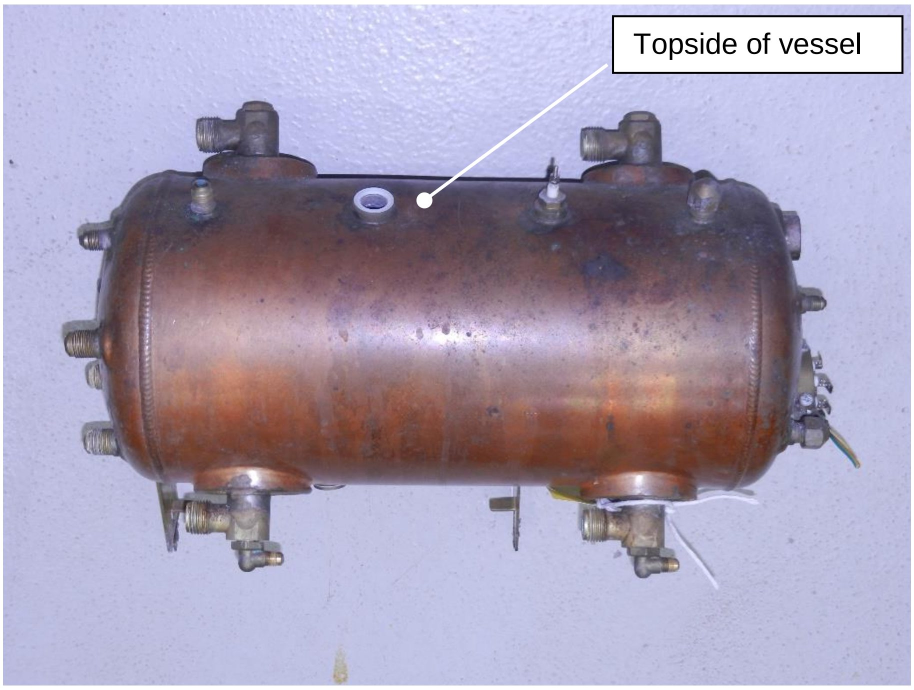


Figure 14 Boiler vessel, manufacturer D. ***(Image No. DSCN 5905.jpg)***

The surface of the vessel around all the fittings and ports was stained and darkened. This was a likely consequence of the brazing process by which they had been affixed. There were no visible indications of defects in the welds/brazed joints.

Internally, in the BWL location, the vessel was found to be heavily contaminated with massive accretions of scale, much of which had spalled off when the vessel was cut to reveal the interior. This created a mass of loose, flaky debris in the base of the vessel, Figure 15. In particular, the heating elements had been severely affected with lime-scale – some of these deposits were 15 mm thick amongst the elements. A sample of this deposit was removed for EDS analysis, Figure 16. Using EDS, four spectra were taken across the surface of the deposit; these indicated the following consistent quantities of elements: oxygen 53 %; Calcium 46 %; 1 % of traces of magnesium, phosphorous, sulphur and copper. This confirmed that the residues had been the result of hard water usage. Carbon was also present but could not be reliably quantified owing to the preparation technique used (as discussed in section 2.6.1).

Figure 15 Lime-scale accumulated in base of vessel ***(Image No. P1012978.jpg)***

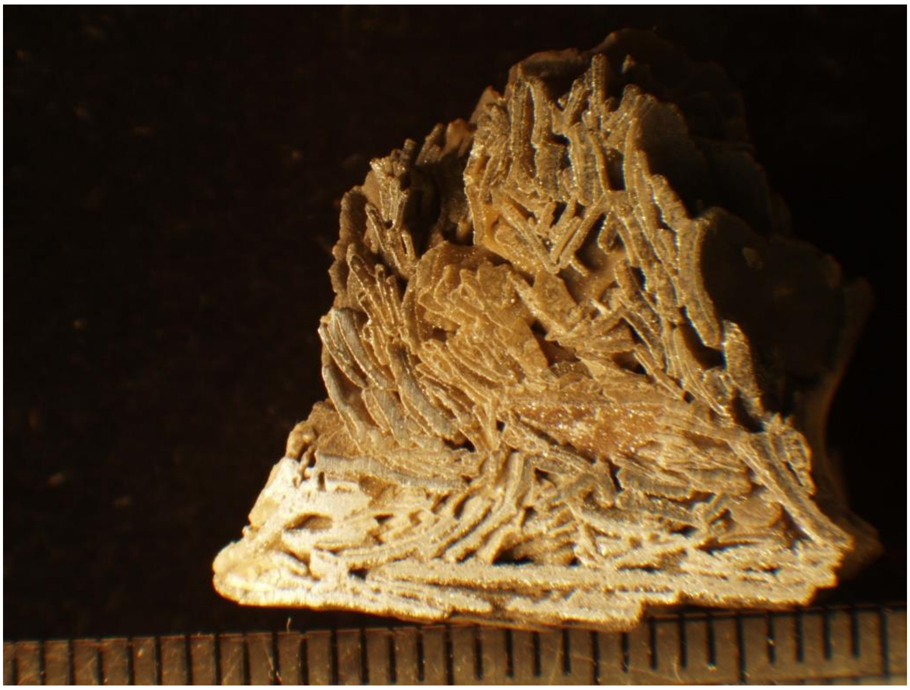


Figure 16 Solid deposit of lime-scale from vicinity of heating element (divisions on scale are millimetres) ***(Image No. 14432 massive scale.jpg)***

Above the water line the vessel wall was black. The ports located in the AWL zone were only lightly coated with black/grey deposits and their orifices were generally free from obstruction. The blanking plug in the drain port in the BWL was affected by a considerable deposit of lime-scale.

3. Café Boilers – Inspections and Test Result Summary

3.1 Pressure Tests

3.1.1 Overpressure Tests

Table 1 shows the units tested and a summary of the overpressure test results. Each test is explained in more detail in section 3.2.

Table 1 Sample Details and Overpressure Test Results

Café boiler HSE SD sample no.	Manufacturer	Number of brew heads	Condition	Boiler volume (litres)	Water volume on arrival (litres)	Water volume after bench test (litres)	Water volume for the overpressure tests (approx.) (litres)	Failure pressure (bar)	Max temp at top thermocouple (°C)	Max temp at bottom thermocouple (°C)	Catastrophic failure	Non-catastrophic failure (gradual release of steam)
14373	A	3	New	13.0	-	7.8	7.8	27.0	243	192	✓	
14035	A	3	2nd hand	21.0	11.76	2.75	13.0	19.9	116	188		✓
14034	A	3	2nd hand[1]	21.0	13.66	NA[5]	NA	NA	NA	NA	NA	NA
14135	B	2	New	11.0	-	5.0	5.0	25.8	122	191	✓	
14133	B	2	2nd hand	11.0[2]	0.0	4.8	5.0	23.6	160	101		✓
14134	B	2	2nd hand[1]	11.0[2]	4.0	NA	NA	NA	NA	NA	NA	NA
14511	C	3	New	21.0	-	11.2	11.2	20.6	204	197	✓	
14418	C	3	2nd hand	21.0	10.9	11.5	11.5	20.2	202	192	✓	
14471	C	3	2nd hand[1]	21.0	9.0	NA	NA	NA	NA	NA	NA	NA
14504	D	2	New	11.0[3]	-	5.7	5.7	19.6	188	191	✓	
14430	D	2	2nd hand	11.0[3]	0.0	5.7	5.7	18.4	297[4]	245[4]		✓
14432	D	2	2nd hand[1]	11.0[3]	5.0	NA	NA	NA	NA	NA	NA	NA

1. machine not tested; dismantled for internal examination as described in Section 2.6
2. information from technical manual (not supplied with machine, no information on the machine)
3. information unsubstantiated (no technical manual provided/available, no information on the machine)

3 temperature was still rising when test was aborted

4 NA – not applicable

In the overpressure tests, much of the metal panelling and covers was distorted due to the pressure release, and some pieces travelled several metres from the machine. Pieces of debris were scattered from about 20 m behind the machine to 15 m in front of the machine. Table 2 gives some more information on how far some of the pieces travelled along the tunnel. Some fragments (particularly those ejected at an angle of around 30° to 60°) would have travelled considerably further than the distances shown in Table 2 as there were scuff marks and imprints on the tunnel wall and ceiling where projectiles had impacted. Some of the panels had twisted and bent, and sharp edges had been formed by this. Also, in some cases, the water pump became free of the carcass, but remained attached by the hose line, and was swinging energetically at the end of this line as the carcass propelled forwards.

Table 2 Summary of machine movements after test (mfr = manufacturer)

Café Machine HSE SD sample ID	Mfr	Condition	Position of the machine after the test	Projectiles in front of the test position	Projectiles to the rear of the test position
14373	A	New	Propelled forwards 4.6 m		Back panel travelled 22 m and struck an obstacle in the tunnel (so may have travelled further)
14035	A	2nd hand	Same position – leak failure (no projectiles)	NA	NA
14135	B	New	Propelled forwards 2 m	An electric switch was propelled 2.5 m outside the tunnel (total distance 14.5 m) Panel twisted and ejected 8 m forward Assortment of brew head handles, panels and mats ejected 2 m to 3 m forward	Back panel travelled 22 m and struck an obstacle in the tunnel (so may have travelled further)
14133	B	2nd hand	Same position – leak failure (no projectiles)	NA	NA
14511	C	New	Propelled forwards 7.3 m	Brass connector 9 m outside the tunnel and 3 m to the side of the track (travelled about 20 m)	Back panel travelled 19 m and struck an obstacle in the tunnel (so may have travelled further)
14418	C	2nd hand	Carcass propelled 5 m forward. Boiler travelled 1.4 m forward	Brew head cluster ejected 5 m	Pieces of the back of the machines travelled 15 m to 17 m
14504	D	New	Carcass propelled forwards 1.5 m. Boiler propelled 4.7 m to the rear. Boiler end plate at the side of the tunnel close to the original position of the machine	Small piece ejected 3 m outside the tunnel. Top panel travelled about 11 m. Other panels travelled approximately 4 m, 6 m, and 8 m	Back panel 17 m behind the boiler
14430	D	2nd hand	Same position – leak failure (no projectiles)	NA	NA

On most machines the boiler tended to travel within the machine carcass at failure. However, in the machine from manufacturer D (new), the boiler detached from the carcass and was propelled to the rear.

All the panels and pallets that were supporting the café boiler underneath were badly damaged by the pressure release. A typical example is shown in Figure 17.

Figure 17 Post-test – Condition of the timber panel and pallet supporting the machine ***(Image No. AIS 1603011_100)***

In one case, one of the thick supporting planks beneath the pallet was also shattered near the centre.

3.1.2 Pressure Relief Valve Tests

Before carrying out the operational tests, the performance of all the pressure relief valves on all second-hand machines was assessed. Table 3 shows the results of these tests.

Table 3 - Results of pressure relief valve (PRV) tests – 2nd hand machines (valves that operated above the rated pressure are shown in bold)

Manufacturer/ Machine	PRV	Initial Relief (bar)	2nd Relief (bar)	3rd Relief (bar)	Rated pressure
A/ 14035*	C	1.688	1.702	1.553	Boiler 2 bar PRV 1.9 - 2.1 bar
A/ 14035*	D	**2.840**	2.028	2.045	As above
A/ 14034	A	1.979	1.903	1.839	Boiler 2 bar PRV 1.9 - 2.1 bar
A/ 14034	B	2.039	2.135	2.086	As above
B/ 14133*		**3.56**	2.258	2.422	165 kPa (1.7 bar)
B/ 14134		<0.03	-	-	180 kPa (1.8 bar)
C/ 14418*		1.841	1.789	1.836	1.8 bar
C/ 14471		2.430	2.012	1.734	No markings
D/ 14430*		2.697	1.96	1.93	No markings
D/ 14432		**>5.01**			2.0 bar

*Machines selected for bench testing

Notes on the PRVs that did not operate in accordance with their rating are as follows:

A/ 14035 – PRV C appeared to vent at a pressure below the indicated operating pressure range. However, it is possible that under greater flow, higher pressures could be generated. After an initial overpressure, PRV D operated within the indicated operating pressure range.

B/ 14133 – PRV operating pressure was significantly greater than the rated pressure, initial operation especially. As this machine was selected for bench testing, it was necessary to replace this PRV prior to bench testing.

B/14134 – PRV did not seal correctly. Using leak detector, bubbles could be seen emerging from the PRV vents at all pressures. It is possible that under greater flow, higher pressures could be generated.

D/ 14432 – PRV operating pressure could not be achieved initially due to a small leakage (possibly interconnecting pipework), although a pressure of 5 bar failed to open the valve. Testing on a higher-pressure system failed to provide a clear initial opening pressure. However, subsequent testing after the initial lift indicated an operating pressure of 2 bar.

Three relief valves failed to operate until they were above their operating range. Of these three, two were significantly higher than their operating range.

3.2 New Café Boiler (Manufacturer A Sample No. 14373)

3.2.1 Initial Metallurgical Examination

No examination was carried out prior to testing.

3.2.2 Examination of Electrical Safety Devices

This was a new café boiler and classed as a Type 3 control circuit that could disconnect the power to the heating elements via the over-temperature switch or SSR. As this was a new café boiler the over-temperature switch and SSRs were not tested. They were in good condition and were wired as per the manufacturer’s information.

The café boiler was prepared for testing by connecting the incoming electrical supply directly to the heating elements.

3.2.3 Overpressure Test

Testing proceeded without interruption although interference to the thermocouples resulted in signal noise. The thermocouple data shown in the graph has had a 49-point running average filter applied to smooth the data (49 points equates to approximately 5 seconds). The pressure transducer data was unaffected, so this has not been filtered.

During the test, pressure and temperature increased steadily until catastrophic failure of the boiler occurred at 27.0 bar as shown in Figure 18.

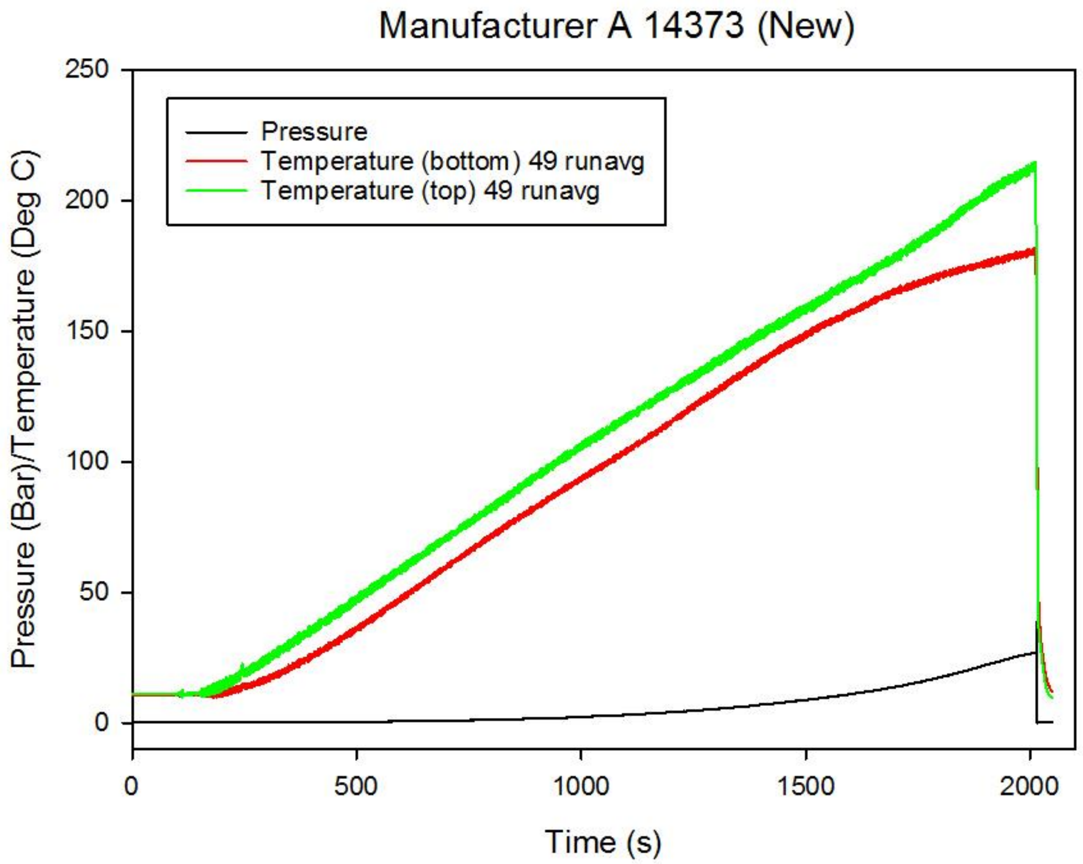


Figure 18 Pressure and Temperature Results – manufacturer A (new)

A momentary peak of 38.9 bar was recorded during failure, however in the preceding data points the pressure had dropped to less than 2 bar, suggesting that failure had already occurred. It is unknown what event caused this secondary peak; however, possible explanations include a pressure wave, or a physical impact experienced by the transducer or cable. A higher logging rate may have provided further information, but the primary purpose of the testing was to determine the pressure within the vessel when failure occurred, rather than to capture pressure events during failure.

The still images (inset a to h) in Figure 19 show the machine before, during and after testing.

Figure 19 Images from the test – manufacturer A (new)

Insets b to g are sequences taken from the high-speed (black and white images) and high-definition video footage (colour images). Note the bright flash in inset image f. This was thought to be due to a severing of the power cable or an internal short circuit that occurred during failure. The residual current device (RCD) protecting the generator had tripped during the failure event.

3.2.4 Post-test Examination

This boiler had been manufactured with pressed domes at both ends. The mean wall thickness of the boiler, taken from five measurements, was 1.38 mm, with individual values ranging from 1.35 mm to 1.41 mm. The boiler had failed catastrophically during testing, resulting in the cylinder almost completely opening out to form a relatively flat, rectangular sheet, Figure 20.

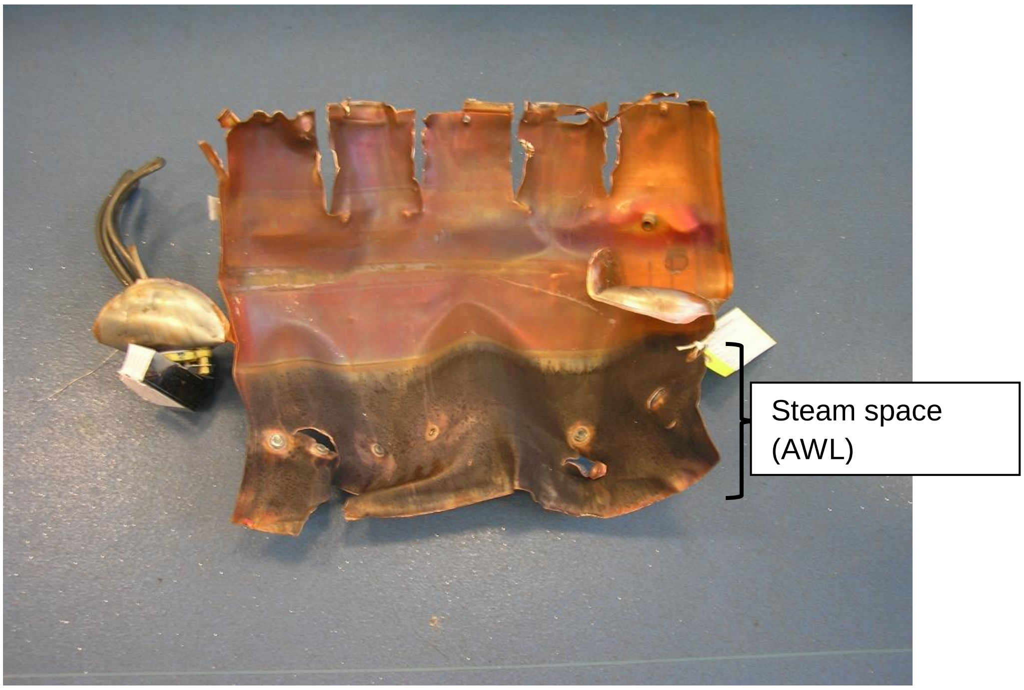


Figure 20 Failed boiler vessel, manufacturer A (new) ***(Image No. P1012778.jpg)***

The fracture had occurred immediately adjacent to and along the length of the longitudinal butt weld, Figure 21.

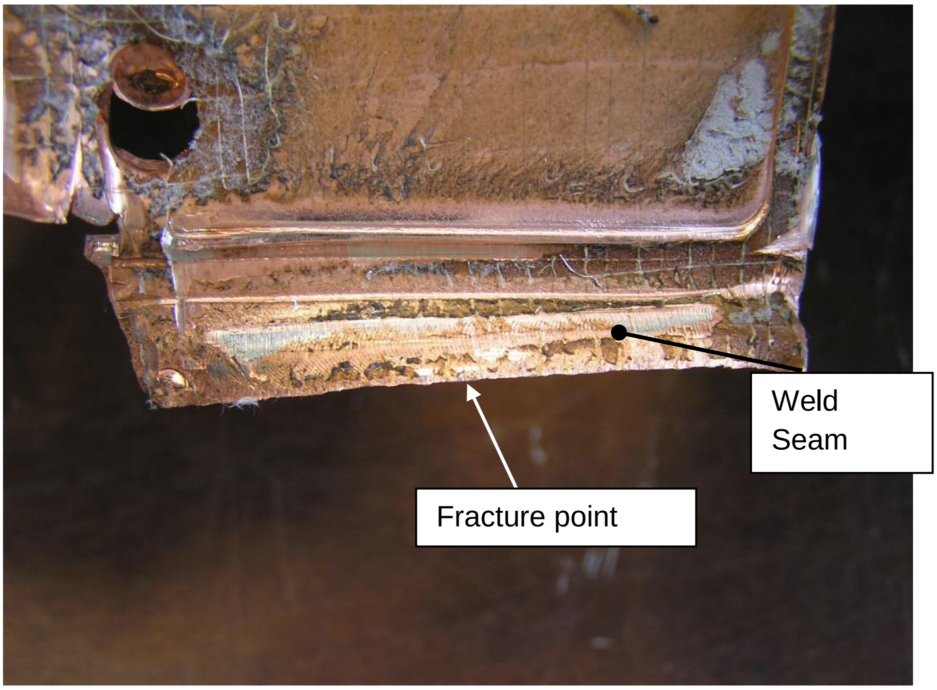


Figure 21 Fracture down one side of longitudinal weld seam ***(Image No. P1012790.jpg)***

The tapering of the fractured edge down to a knife-edge indicated that the failure mechanism had been by ductile overload. The fracture had also travelled around the edge of the joggle weld at the domed ends. There was a series of uniformly spaced, subsidiary, transverse tears along one edge of the failed longitudinal seam. Scrape marks and indents in these locations suggest that this damage had been acquired by the burst boiler wall impinging on the frame of the machine carcass. The internal surface of the boiler vessel was generally bright and defect free, other than consequential mechanical damage arising from the failure event. However, a zone on the internal surface had become blackened as a consequence of oxidation of the copper. This indicated the position of the steam zone AWL in the boiler.

A metallographic sample was taken which incorporated a cross-section through the failure location adjacent to the longitudinal butt weld. Examination at high magnification, following sample preparation, revealed that the failure had occurred in the parent copper metal immediately next to the weld – not within the fused weld metal itself. At the failure point, the metal was heavily deformed. This was exhibited in the elongation of the crystal structures (grains) within the weld and the parent strip, Figure 22.

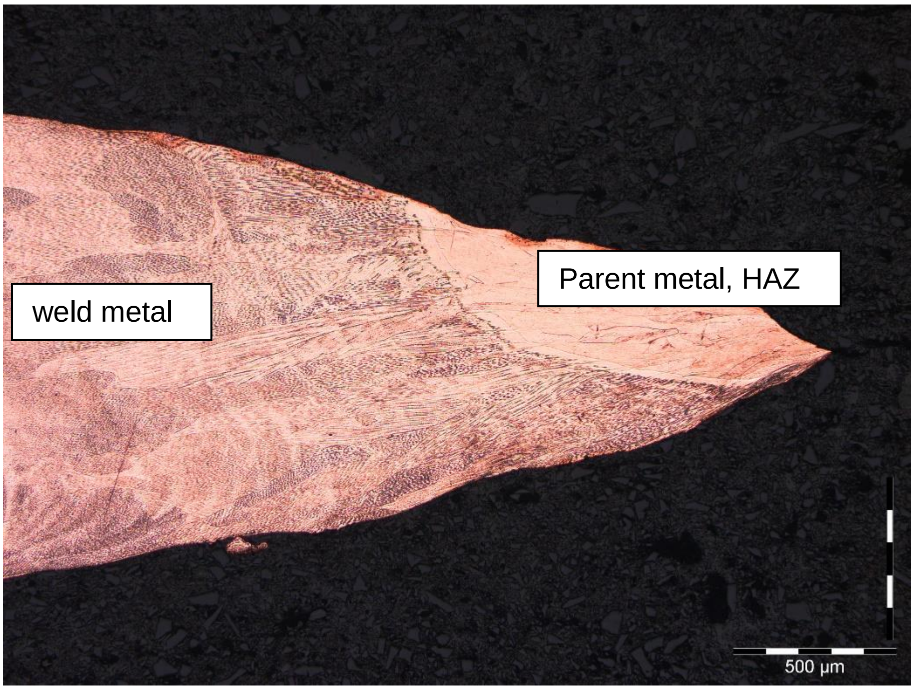


Figure 22 Tapered ductile fracture point of vessel, adjacent to weld. ***(Image No. 14373 met-1-1.jpg)***

To confirm the mode of fracture, a sample was examined at high magnification using the SEM. Figures 23 and 24 show low and high magnification images of the fracture. It was clear that the fracture mode had been by ductile failure, whereby the wall thickness had become progressively thin by plastic deformation under the applied loading until final fracture occurred by microvoid coalescence[12].

There was no evidence either of prior defects being present which may have weakened the vessel, or degradation due, for example, to corrosion thinning of the boiler wall.

[12] Microvoid coalescence occurs when voids form between the interfaces of impurities and the parent metal due to high plastic strain. As the strain continues, the voids enlarge and eventually coalesce to result in the final fracture.

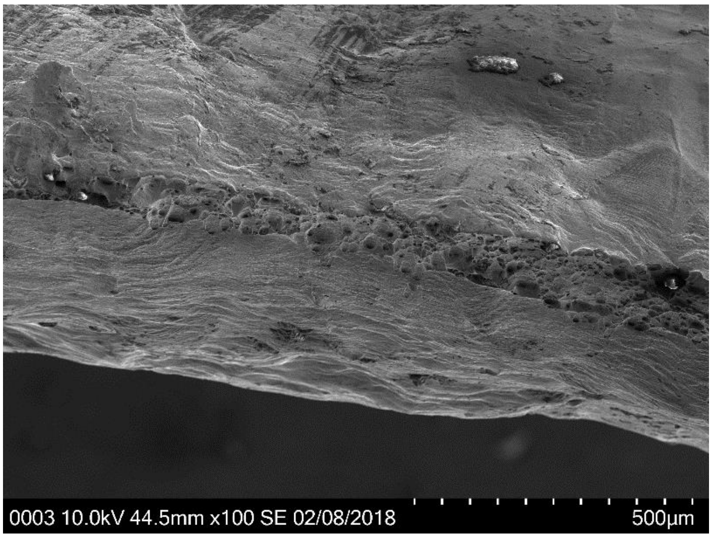


Figure 23 Electron micrograph – looking edge-on to the fracture. ***(Image No. 14373 fract_0003.jpg)***

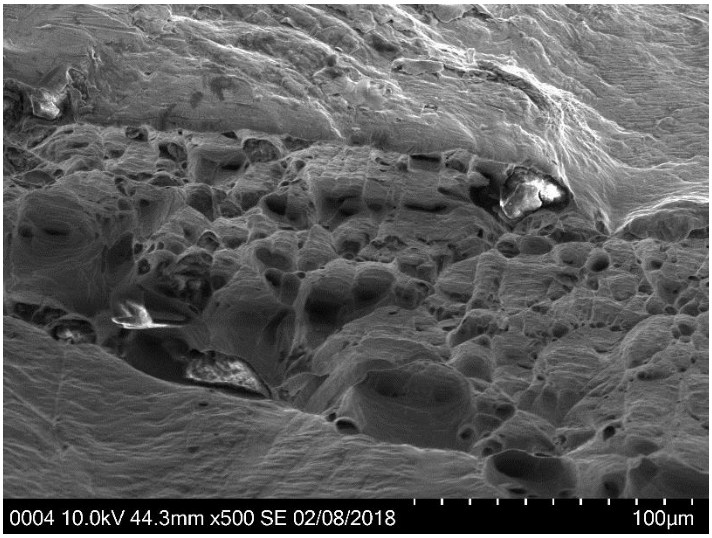


Figure 24 Higher magnification electron micrograph showing ductile microvoid coalescence at failure point. ***(Image No. 14373 fract_0004.jpg)***

3.3 New Café Boiler (Manufacturer B Sample No. 14135)

3.3.1 Initial Metallurgical Examination

No initial examination was carried out, nor any images taken.

3.3.2 Examination of Electrical Safety Devices

This was a new café boiler and classed as a Type 2b control circuit that could disconnect the power to the heating elements via the over-temperature switch, contactor, or MOSFETs/triacs. As this was a new café boiler these items were not tested, were in good condition, and were wired as per the manufacturer's information.

The café boiler was prepared for testing by connecting the incoming electrical supply directly to the heating elements.

3.3.3 Overpressure Test

Testing was interrupted several times during the early heating stages of the test. After a video failure required the replacement of a cable, the data logger was restarted. This initial data has not been analysed, thus the data shown in Figure 25 commences from an elevated temperature. A further interruption to the subsequent file required a pause of approximately 40 seconds, shortly after commencing the new test. This resulted in a slight dip in the temperature reading of the thermocouples. However, no pressure had been generated at this point, so this was unaffected.

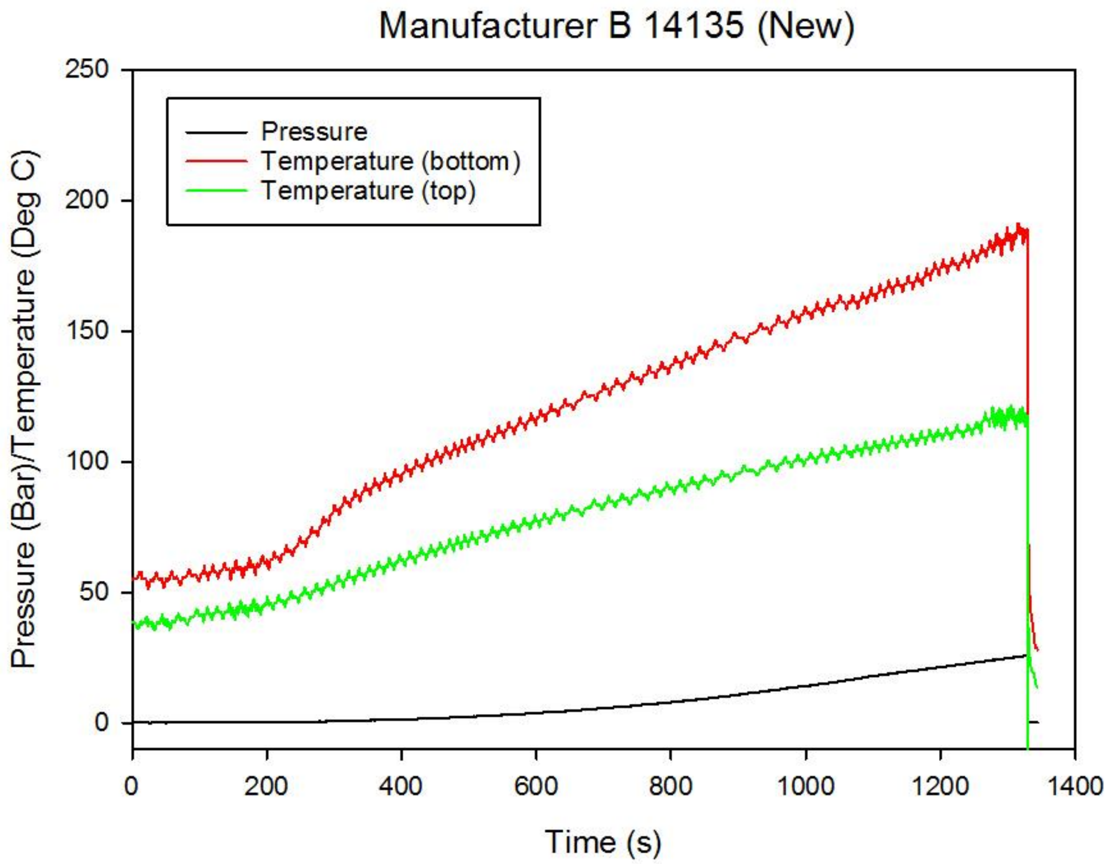


Figure 25 Pressure and Temperature Results – manufacturer B (new)

During the remaining period of the testing, the pressure and temperature increased steadily until catastrophic failure of the boiler occurred at 25.8 bar. A momentary peak of 28.51 bar had been recorded immediately upon failure, but this has been discounted as it was a single value and was also accompanied by a negative temperature spike. Values immediately prior to failure had been steadily rising through 25.7 bar to 25.8 bar.

The still images (inset a to h) in Figure 26 show the machine before, during and after testing.

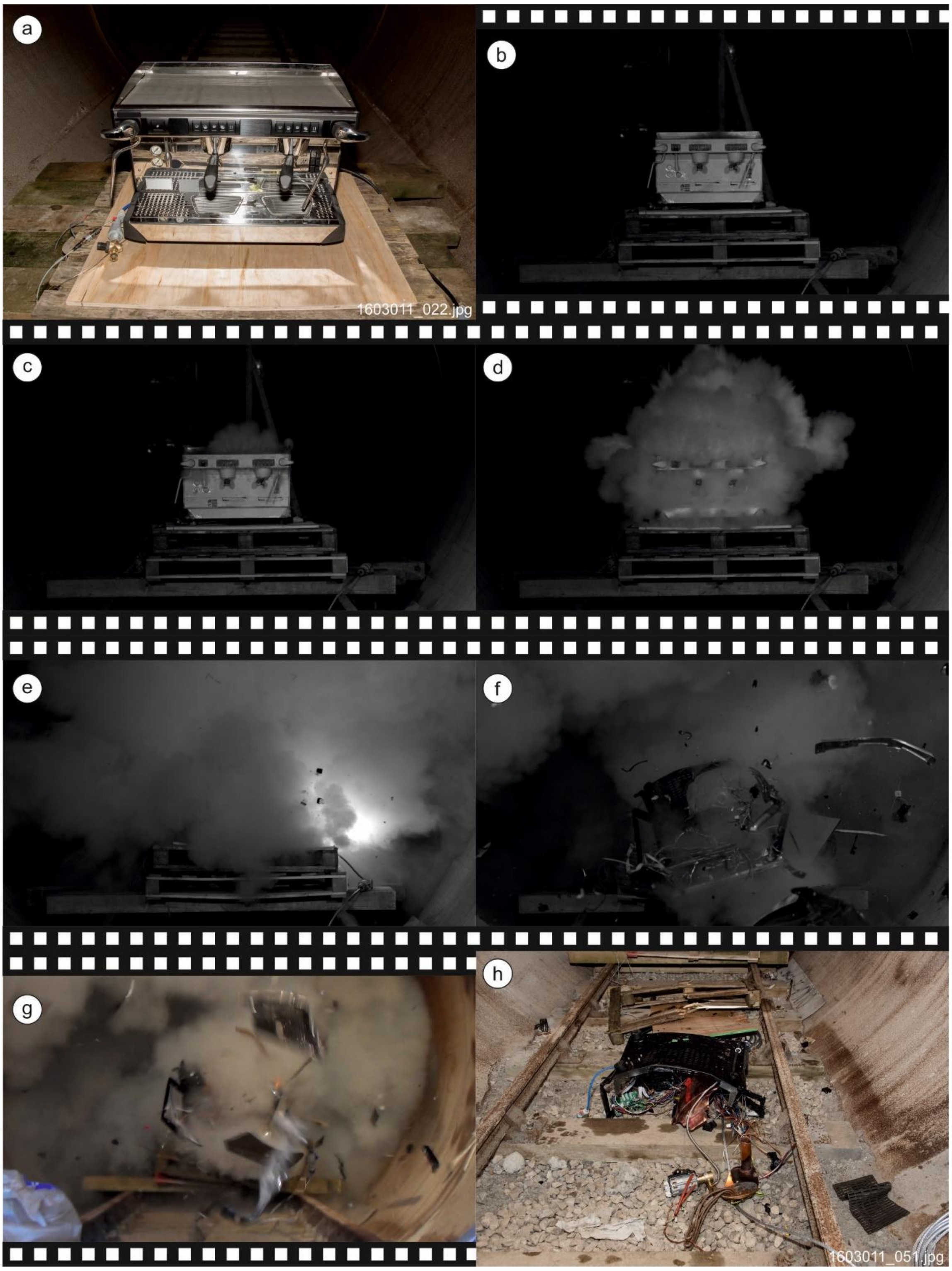


Figure 26 Images from the test – manufacturer B (new)

Insets b to g are sequences taken from the high-speed (black and white images) and high-definition video footage (colour images). Note the bright flash in inset image e. Again, this was thought to be due to a severing of the power cable or an internal short circuit that occurred during failure. The residual current device (RCD) protecting the generator had tripped during the failure event.

3.3.4 Post-test Examination

The boiler had undergone catastrophic failure due to overpressure. On this occasion the vessel had separated into three sections, Figure 27.

Figure 27 Fractured vessel, manufacturer B (new), black zone corresponds to the AWL steam space. ***(Image No. P1012793.jpg)***

The three sections were: the main vessel wall, which had opened out into a flat sheet; a domed end which had been welded to the cylinder; and the opposite, flat end which comprised a disc and had been bolted to a ring plate welded to the cylinder. The longitudinal ductile failure of the boiler wall coincided with the row of eight ports which had been located along the top dead centre of the vessel, above the water line. It is possible that the fittings welded/brazed into the ports had acted as constraining (stiffening) volumes/masses on the adjacent vessel wall, leading to a local rise in strain in the wall in their vicinity, and the occurrence of failure in this location. This was confirmed by wall thickness measurements taken close to, but not at, the failure at the ports, where a mean value of 1.28 mm was measured. In contrast, at a short distance from the ports, the mean wall thickness was 1.38 mm. Another factor contributing to the localisation of the failure along the line of the ports may have been a softening of the copper vessel in the near vicinity of the brazed fitting. The softening would have been a result of heat applied during the brazing process. The failure at both ends of the boiler occurred adjacent to the circumferential weld seams.

The interior of the vessel was generally clean and bright with surface abrasions and indentations associated with the failure event. In the AWL location the internal wall was coloured black with copper oxidation product.

One small weld defect could be seen in the form of lack-of-penetration and lack-of-fusion at the internal wall of the cylinder. This was in the longitudinal butt weld in the 10 mm section adjacent to the domed end of the vessel, Figure 28. This small defect had not contributed to the failure event.

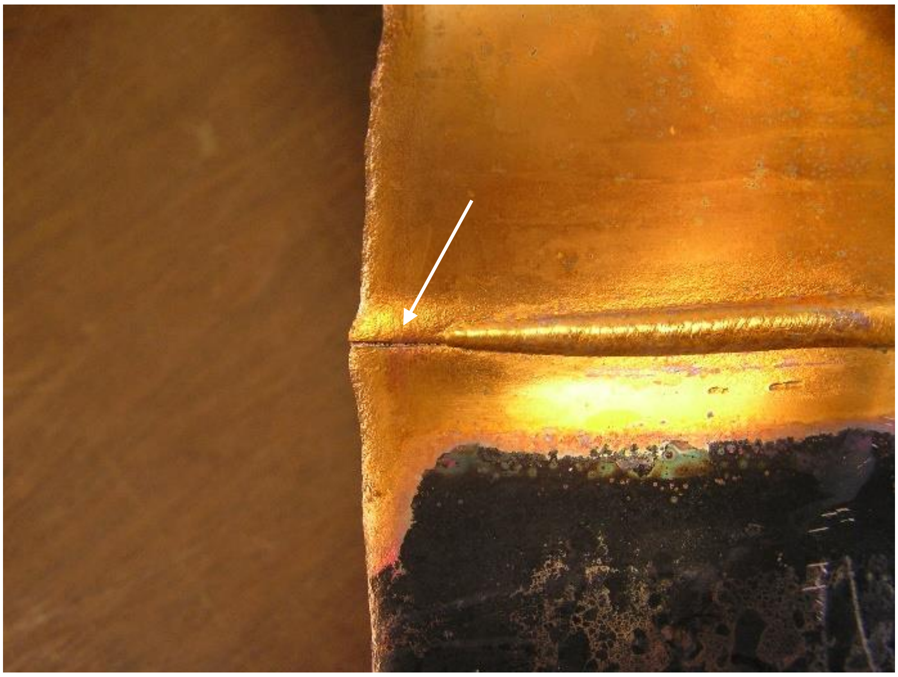


Figure 28 Small lack-of-fusion defect (arrowed) on longitudinal weld on internal wall of vessel (external weld cap was intact). ***(Image No. P1012801.jpg)***

The mean wall thickness for this vessel was 1.38 mm, with a range between 1.28 mm and 1.44 mm.

3.4 New Café Boiler (Manufacturer C Sample No. 14511)

3.4.1 Initial Metallurgical Examination

No initial examination was carried out, nor any images taken.

3.4.2 Examination of Electrical Safety Devices

This was a new café boiler and classed as a Type 1 control circuit that could disconnect the power to the heating elements via the boiler pressure switch and over-temperature switch. As this was a new café boiler it was not tested, was in good condition, and was wired as per the manufacturer’s information.

The café boiler was prepared for testing by connecting the incoming electrical supply directly to the heating elements.

3.4.3 Overpressure Test

Testing proceeded without interruption. Pressure and temperature increased steadily during the test. There was no visible indication of overpressure observed on the video footage prior to catastrophic failure of the boiler (at 20.6 bar) is shown in Figure 29.

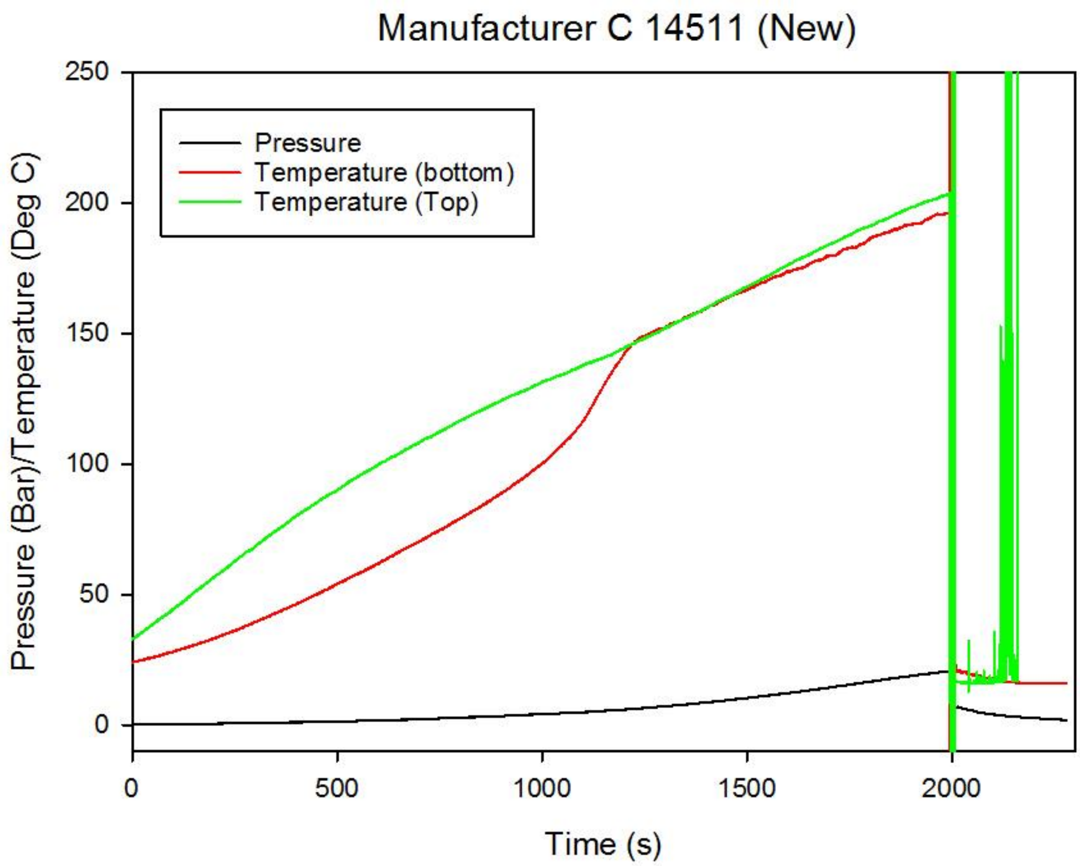


Figure 29 Pressure and Temperature Results – manufacturer C (new)

Severing of cables during the explosion is likely to be the reason for the spikes indicated on the thermocouple readings. The pressure transducer cable had also been severed, but the output did not return to zero immediately. It became clear during post-test examination that the pressure decay indicated after failure did not occur as the interconnecting hose had been severed and was open to atmosphere.

The still images (inset a to h) in Figure 30 show the machine before, during and after testing.

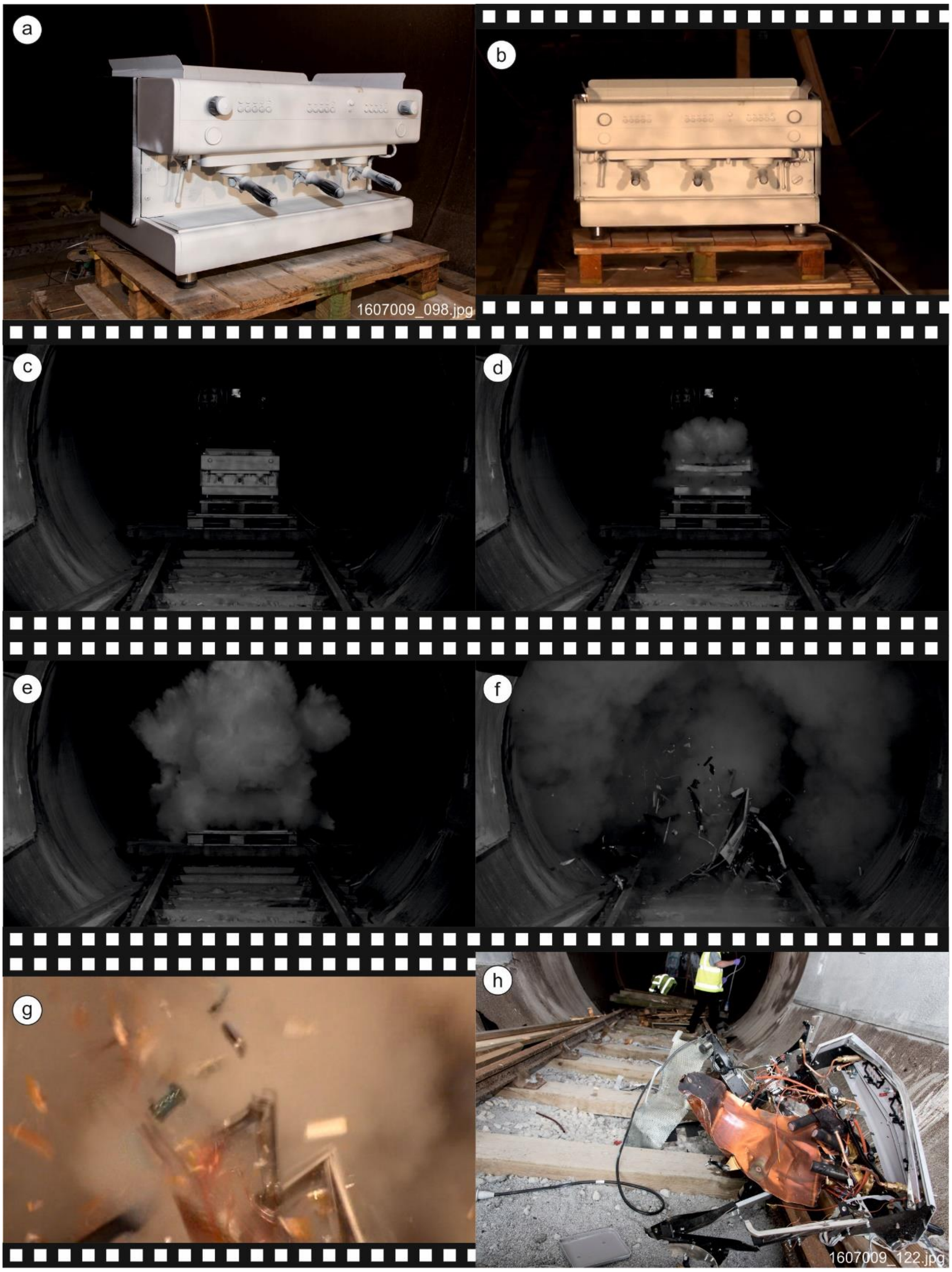


Figure 30 Images from the test – manufacturer C (new)

Insets b to g are sequences taken from the high-speed (black and white images) and high-definition video footage (colour images). There was no evidence of escaping steam prior to the failure of the boiler.

3.4.4 Post-test Examination

Catastrophic failure of this vessel caused it to separate into three sections as shown in Figure 31.

Figure 31 Failure of boiler vessel, manufacturer C (new) ***(Image No. DSCN5973.jpg)***

The primary fracture ran on a path between the three brew heads and three ports in the AWL location of the boiler, tending to run closer to the brew head inserts than the ports. Mechanical damage and deformation were present on the fractured sections because of the failure process. Internal and external surfaces were bright (apart from the blackening of the surface on the AWL location on the internal wall) with small areas of localised discoloration associated with the brazing process used to attach the steam heads and port fittings to the boiler.

Brazed joints, and longitudinal and circumferential butt welds appeared intact and in good condition with no obvious defects such as underfill, porosity or lack-of-fusion.

The mean wall thickness of the vessel was 1.32 mm, ranging between 1.21 mm and 1.42 mm.

3.5 New Café Boiler (Manufacturer D Sample No. 14504)

3.5.1 Initial Metallurgical Examination

No initial examination was carried out, nor any images taken.

3.5.2 Examination of Electrical Safety Devices

This was a new café boiler and classed as a Type 2b control circuit that could disconnect the power to the heating elements via the over-temperature switch, contactor, or MOSFETs/triacs. As this was a new café boiler these were not tested, were in good condition and were wired as per the manufacturer's information.

The café boiler was prepared for testing by connecting the incoming electrical supply directly to the heating elements.

3.5.3 Overpressure Test

Testing proceeded without interruption. During the test, pressure and temperature increased steadily until, at around 13 bar pressure, a small volume of steam could be seen venting. This was possibly due to pressure relief within the brew head circuits. Catastrophic failure of the boiler occurred at 19.6 bar as shown in Figure 32.

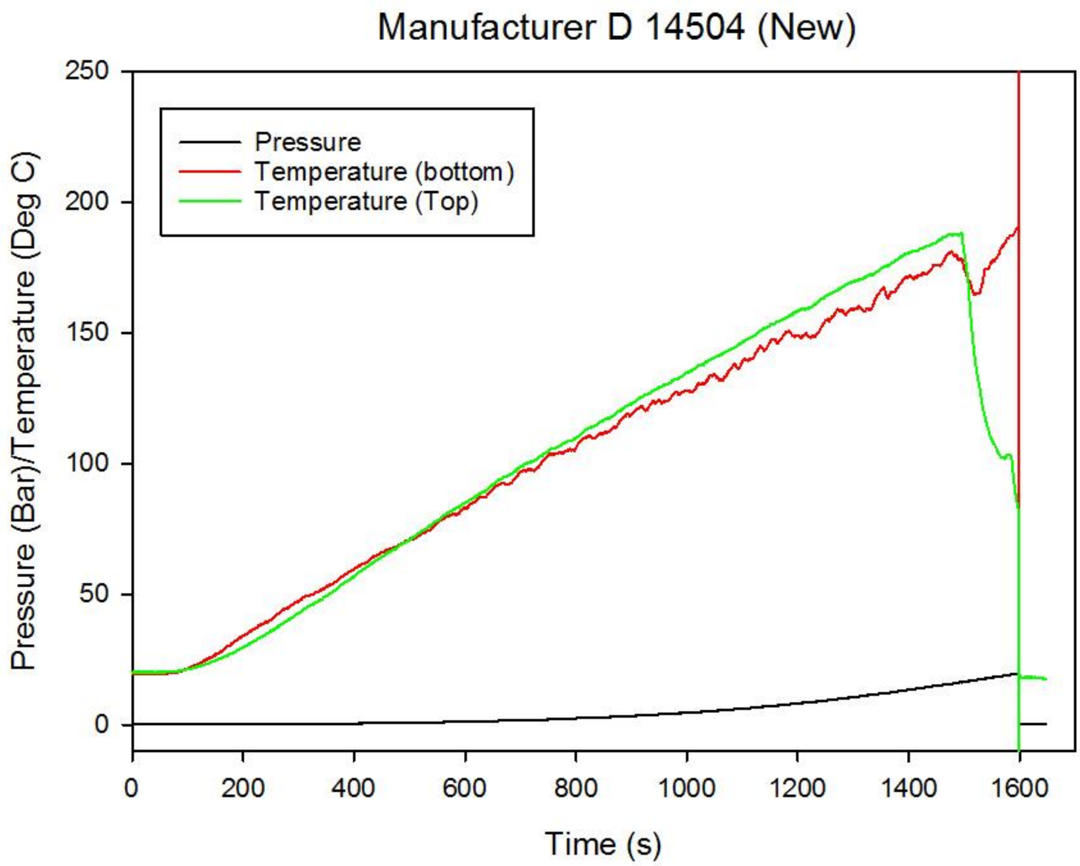


Figure 32 Pressure and Temperature Results – manufacturer D (new)

Shortly before failure, reductions could be seen in both the top and bottom temperature readings (especially the top): the cause of these drops is unknown. However, on this machine the boiler had been supplied with a metal band secured approximately around the centre diameter. The thermocouples were mounted near to, or even beneath this band. Severing of cables during the explosion is likely to be the reason for the spikes indicated on the thermocouple readings.

The still images (inset a to h) in Figure 33 show the machine before, during and after testing.

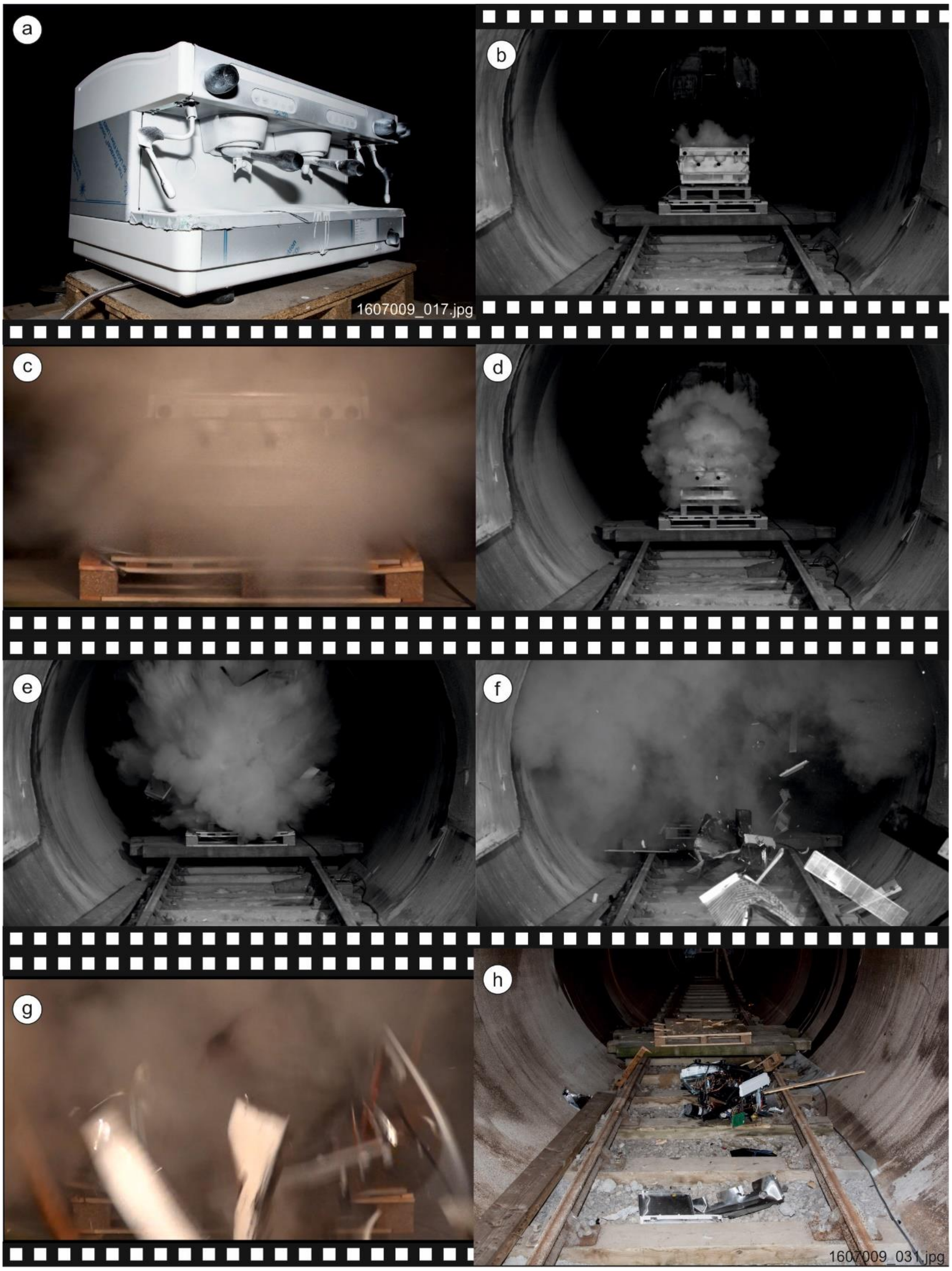


Figure 33 Images from the test – manufacturer D (new)

Insets b to g are sequences taken from the high-speed (black and white images) and high-definition video footage (colour images).

3.5.4 Post-test Examination

Boiler sample 14504 had been manufactured with a pressed dome at either end. Consistent with the other new boilers, sample 14504 failed by catastrophic overload. This caused the boiler to separate into three sections, shown in Figure 34. These were as follows:

a. The main part of the central vessel wall still attached to the two brew head heat exchangers and the domed end through which the heating element entered the vessel.

b. A second section of vessel wall which contained three ports adjacent to one of the failed edges.

c. The other domed end of the boiler.

Figure 34 Fractured boiler vessel, manufacturer D (new) ***(Image No. DSCN5960.jpg)***

The fracture took a complex path in the boiler wall between the AWL ends of the brew heads and four ports, and the BWL ends of the through-boiler heat exchangers. The longitudinal butt weld was intact and in good condition. Around the domed ends the boiler had failed adjacent to the circumferential joggle butt welds. Other than heat tarnishing due to the test conditions and the black AWL coating on the internal surface, the boiler appeared to have been in good condition with no indication of defective brazing of fittings, nor defective butt welding on the longitudinal and circumferential vessel walls.

The mean wall thickness of this vessel was 1.07 mm, with a range of values between 0.92 mm and 1.15 mm.

3.6 Second-hand Café Boiler (Manufacturer A Sample No. 14035)

3.6.1 Initial Metallurgical Examination

This vessel was nominally 610 mm in length and 220 mm in diameter. It had been constructed from a longitudinally butt-welded copper cylinder with a welded brass ring flange at each end. Bolted onto each flange were flat, circular end plates through which various pipework fittings had been inserted including, at one end, a heating element. In the as-received condition, the boiler vessel appeared to be in good condition, although darkened and stained as a normal consequence of service use. The staining was more pronounced in the vicinity of the three brew head attachments and multiple smaller ports, but this was associated with variation in composition, heat effects and residues from the brazing process which had been used to attach them to the vessel.

A borescope examination of the interior of the vessel revealed a small amount of scale in the bottom. The nine ports above the water line at the top of the vessel were relatively clean and free from deposit, as were a further three ports at the 11 ‘o clock position.

3.6.2 Examination of Electrical Safety Devices

This café boiler used a Type 1 control circuit that could disconnect the power to the heating elements via the boiler pressure switch and over-temperature switch. Examination of the pressure switch showed that it was functional although its contacts were quite sooted, indicating it had been used. Both contact pairs had a resistance of 0.3 Ω.

This over-temperature switch had been inserted into a sleeve near the top of the boiler that ends below the normal water fill level within the boiler. The body of the over-temperature switch indicated it should operate, i.e. open its contact pairs at 145°C. The closed resistance of both contacts pairs was less than 0.3Ω.

It was operationally tested by applying heat to its tip using a hot air gun set to approximately 160 °C. Both the line and neutral contacts opened after approximately 10 seconds and, once the over-temperature switch tip had cooled enough, could be reset using the manual reset button. It was noted that the sleeves of the crimp connectors had become brittle, possibly from heat exposure, and crumbled when touched.

The café boiler was prepared for testing by connecting the incoming electrical supply directly to the heating elements.

3.6.3 Overpressure Test

During testing the pressure and temperature increased steadily until a jet of steam was observed exiting the top left-hand side of the machine at 19.9 bar. The test was allowed to continue for some time after this event to observe whether the leakage could be overcome. Temperatures and pressure stabilised with no indication of increasing. After this occurred, the test was stopped. Figure 35 shows the results.

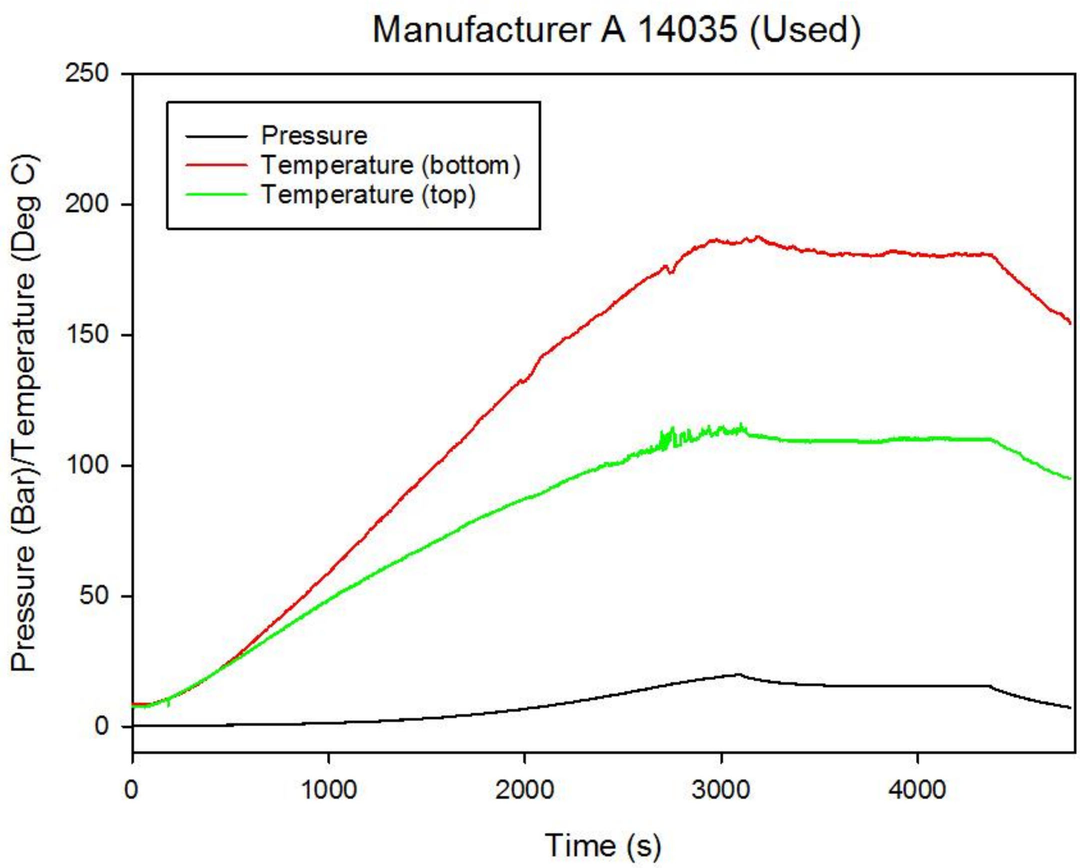


Figure 35 Pressure and Temperature Results – manufacturer A –2nd hand (used)

The still images (inset a to h) in Figure 36 show the machine before, during and after testing.

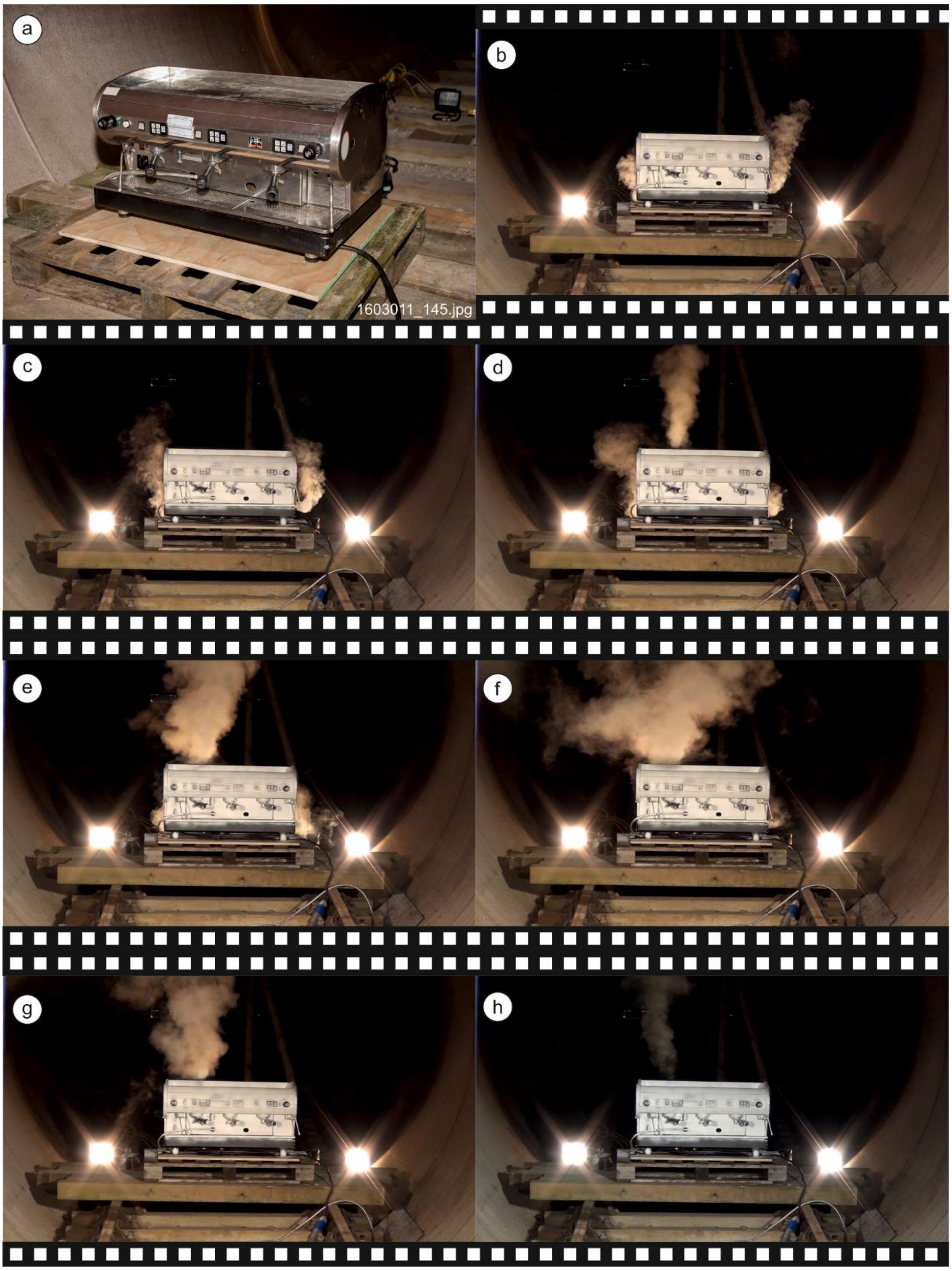


Figure 36 Images from the test – manufacturer A (2nd hand)

As no catastrophic failure occurred, the machine did not look any different (externally) after the test, as can be seen from the sequences in Insets b to h taken from the high-definition video footage. Note the steam escaping from the top left-hand side (inset images d to h). During post-test examinations, a crack was observed to the boss of a port on the top left-hand side of the boiler.

3.6.3 Post-test Examination

During the test the vessel developed a slow leak as mentioned in the previous section. Streak marks on the external surface of the vessel indicated that the location of the leak was through a brazed joint in one of the top ports as shown in Figure 37.

Figure 37 Crack in base of brazed port fitting ***(Image No. DSCN5995.jpg)***

The circumferential crack at the joint was approximately 12 mm in length.

Also, light traces of a black, light green and white deposit could be seen within the brew head ports. The variation in colour indicated the chemistry of the deposit – black being due to copper oxide; green was due to copper sulphides and carbonates; and white was due to lime-scale from the water.

It was evident that the cylinder had dilated during the testing, resulting in an outward bulging of the walls between the ports and brew heads. This is shown in Figure 38.

Figure 38 Showing post-test bulging of vessel (against straight edge of rule) ***(Image No. DSCN5990.jpg)***

A transverse metallographic section was taken through the cracked joint to reveal the fracture path. Figure 39 shows the failed joint with an inset at low magnification.

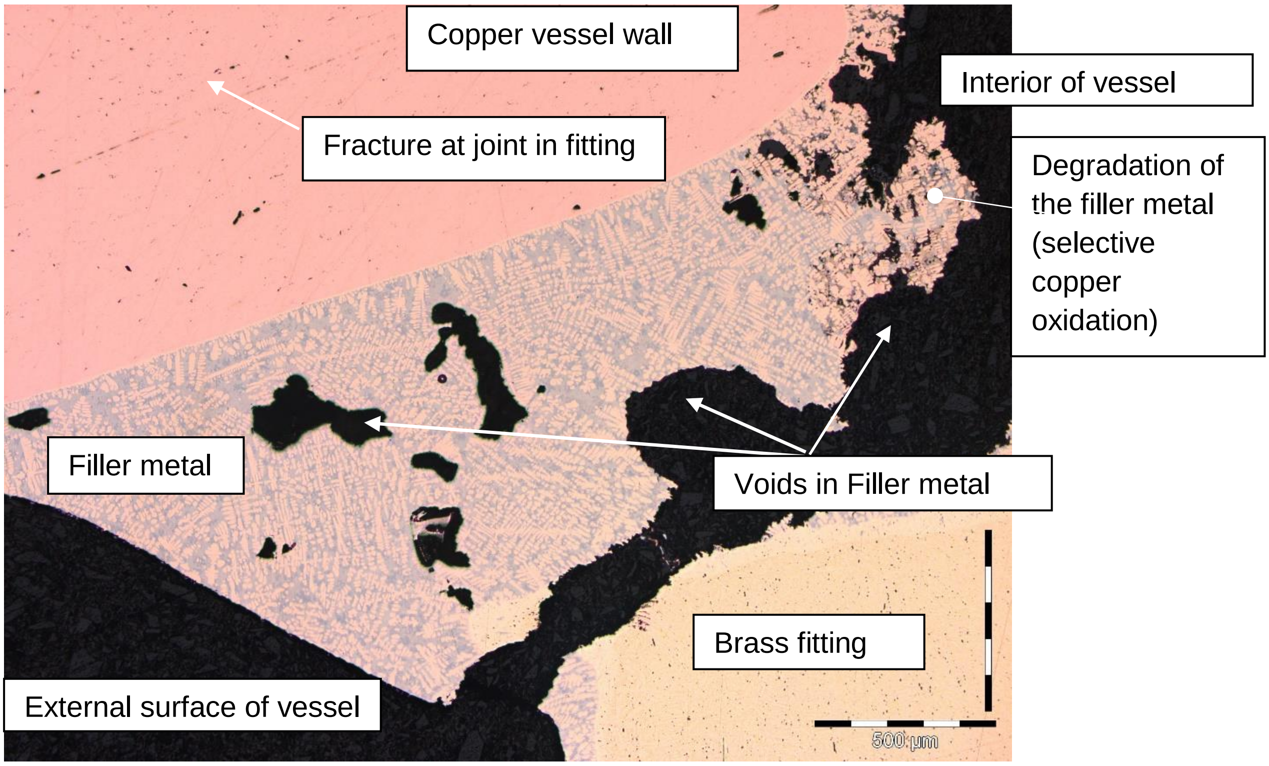


Figure 39 Cross section through cracked brazed joint (inset shows fractured joint at low magnification) ***(Image No. 14035 met1-1.jpg)***

It was evident that the failure had occurred through the filler metal rather than either the brass port fitting or the parent copper strip of the vessel. There were voids within the filler metal – several of which had linked up during the failure process. The filler metal adjacent to the interior of the vessel appeared fragmented and porous, suggesting that a corrosive degradation process had already occurred in this location. A comparison between the chemical composition of the filler metal in the vicinity of the degradation, and distant from this region was carried out using EDS analysis. The composition of the unaffected filler metal was nominally 77 wt % copper, 14 wt % silver, 5 % phosphorous and 4 wt % zinc. In the degraded location there had been a significant reduction in the level of copper from 77 wt % down to 62 wt %, and in phosphorous, from 5 wt % down to 1.3 wt %. Oxygen, absent in the unaffected filler metal, was present in the degraded region. This indicates that the copper and phosphorous had been preferentially oxidised by the environment in the interior of the vessel, and that dezincification[13] had not been the operating degradation mechanism.

The fracture of the port in this location had therefore been a combination of degradation of the filler metal and the presence of voids, both contributing to a weakening of the vessel.

Internally the boiler appeared in good condition with only minor deposits of lime-scale BWL, and the black surface colouration associated with the area AWL. Above the water line, the mean wall thickness value following testing was 1.38 mm.

3.7 Second-hand Café Boiler (Manufacturer B Sample No. 14133)

3.7.1 Initial Metallurgical Examination

Other than a staining and discolouration associated with service-use, the boiler appeared to be in relatively good condition with no indication of poor welding or brazing to the fittings. Some of the joints in the associated pipework had light brown or white deposits on them, which may have been due to water leaks. Internally, the boiler was relatively free of deposits and all the ports were clear.

3.7.2 Examination of Electrical Safety Devices

This café boiler used a Type 2a control circuit and could disconnect the power to the heating elements via the contactor, which was controlled by the over-temperature switch or the MOSFETs/triacs.

Examination of the contactor showed that it had four sets of contacts with contact pair resistances of between 0.2 Ω and 0.4 Ω.

[13] The level of zinc in the filler metal was only 4 wt %, far below the 15 wt % threshold, above which dezincification mechanisms may be active. (Shreir, Corrosion, Volume 1, Edition 2[11])

The over-temperature switch detection bulb had been inserted into a sleeve between the heating elements and was connected by a thin copper tube to the body of the over-temperature switch. To facilitate its testing the detection bulb was removed from its sleeve and heat was applied using a heat gun. This over-temperature switch had only one contact pair with a resistance of 0.3 Ω. This controlled the coil of the contactor.

The body of the over-temperature switch indicated that its operating temperature was 187 °C so the heat gun was set to 200 °C and applied to the bulb. The contacts changed state after approximately 10 seconds and remained in this condition until the detection bulb had cooled and the manual reset button was pressed.

The café boiler was prepared for testing by connecting the incoming electrical supply directly to the heating elements.

3.7.3 Overpressure Test

Testing was paused during the heating phase due to the failure of a generator set powering the lights for the video. This pause can be seen in Figure 40 where the three curves flatten-out after 500 seconds until about 800 seconds. Following the restart, pressure and temperature increased steadily until, at 23.6 bar, a sudden release of steam was observed escaping from the right-hand side of the machine. This failure was accompanied by a rapid loss of pressure, which did not show any indication of re-building, therefore the test was stopped.

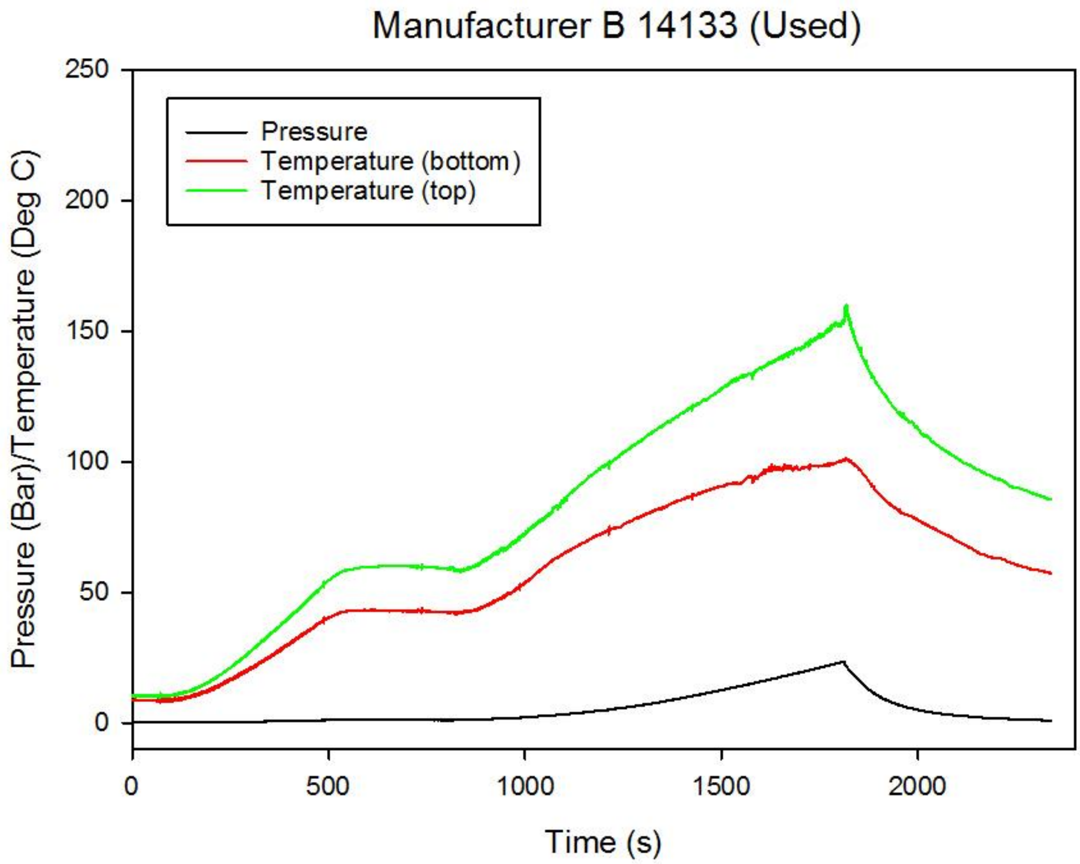


Figure 40 Pressure and Temperature Results – manufacturer B – 2nd hand (used)

The still images (inset a to h) in Figure 41 show the machine before, during and after testing.

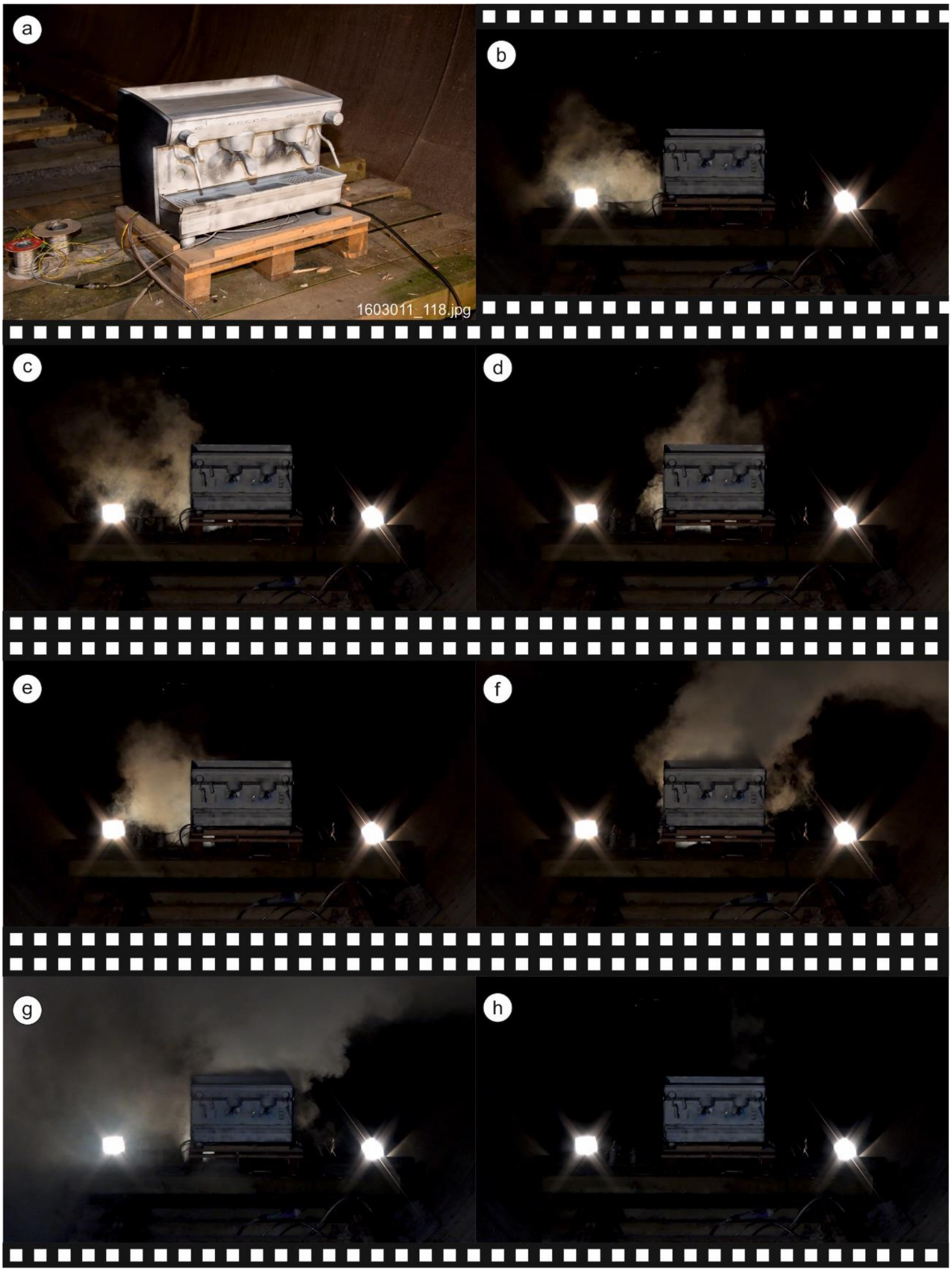


Figure 41 Images from the test – manufacturer B (2nd hand)

As no failure occurred, the machine did not look any different (externally) after the test as can be seen from the sequences in Insets b to h taken from the high-definition video footage. Note the large volume of steam escaping from the top right-hand side (inset images f and g). During post-test examinations, a crack was observed in the boss of a port on the top right-hand side of the boiler.

3.7.4 Post-test Examination

The boiler had undergone a slow-release leak during pressure-to-failure testing. The leak had occurred in the joint between the vessel and the top brass port fitting at the heater element end of the boiler, Figure 42. A metallographic cross-section taken through the crack revealed that the failure had taken place in the filler metal itself and that large spherical voids (gas pores) had been incorporated in the fracture path, Figure 43.

Figure 42 Crack through brazed joint in port fitting ***(Image No. DSCN5938.jpg)***

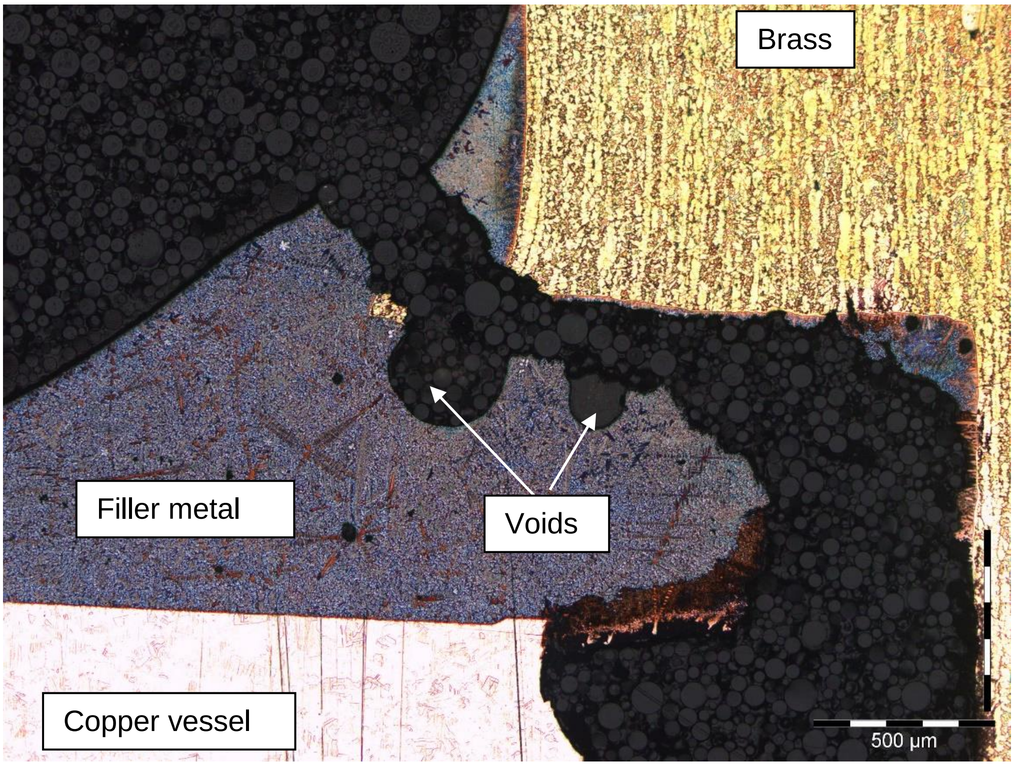


Figure 43 Cross section through fracture in filler metal (sample has been etched)
(Image No. 14133 met-2-2.jpg)

There did not appear to be indications of corrosion/dezincification at the internal wall of the filler metal. The filler metal in this vessel was: 84 wt % copper; 6.6 wt % phosphorous; and 6 wt % tin.

The vessel had dilated during testing. Following testing the boiler dimensions were nominally, 450 mm in length and 196 mm in diameter, this latter value being greater than prior to testing due to the vessel dilation under pressure.

In one of the two heat exchanger inserts in the vessel wall, towards the underside of the vessel, i.e. in the BWL location, there was a build-up of mixed deposits of white and brown powder with some greening of the fitting surface, Figure 44. The deposits appeared to be of some age and were not considered to have developed during the testing. It was not clear whether these deposits had developed due to leaking through the joint or from the deposition and evaporation of externally derived fluids during the service life of the boiler.

Figure 44 Deposits on outer surface of one of the heat exchangers ***(Image No. DSCN5933.jpg)***

Internally, BWL the boiler showed a uniform coating of both grey flaky and spicule-like lime-scale; the flake deposits had adhered to the internal surface. There were white/green coloured deposits on the internal surfaces of the ports. Black surface colouration was present in the AWL locations inside the boiler.

The mean wall thickness value was 1.39 mm. On the scale covered surface BWL, the mean wall thickness value was 1.87 mm.

3.7 Second-hand Café Boiler (Manufacturer C Sample No. 14418)

3.7.1 Initial Metallurgical Examination

No prior examination was carried out.

3.7.2 Examination of Electrical Safety Devices

This café boiler used a Type 1 control circuit that could disconnect the power to the heating elements via the boiler pressure switch and over-temperature switch. Examinations of the pressure switch showed that it was functional, although all three contacts had soot on their surfaces, they had a contact pair resistance of between 0.1 Ω and 0.3 Ω.

The over-temperature switch detection bulb had been inserted into a sleeve between the heating elements and was connected by a thin copper tube to the body of the over-temperature switch. The over-temperature switch had three contact pairs with a resistance between 0.1 Ω and 0.3 Ω. To facilitate its testing the detection bulb was removed from its sleeve and heat was applied using a heat gun.

The operating temperature of the over-temperature switch was indicated on its housing to be 170 °C, so the heat gun was set to 180 °C. When the heat was applied to the bulb the contacts changed state after approximately 8 seconds and remained in this condition until the detection bulb had cooled and the manual reset button was pressed.

The café boiler was prepared for testing by connecting the incoming electrical supply directly to the heating elements.

3.7.3 Overpressure Test

Testing proceeded with only one interruption, when heating was paused during the early phase of the test to allow access across the exclusion zone. This can be observed as a plateau on the top thermocouple trace in Figure 45, at around 600 seconds. During the test, pressure and temperature increased steadily until a small volume of steam could be seen venting at around 18 bar and again at 20 bar. This was in the region of the drip tray and may have been venting from the brew head circuits.

Temperature and pressure continued to rise steadily prior to a short plateau, which occurred shortly before catastrophic failure at 20.2 bar.

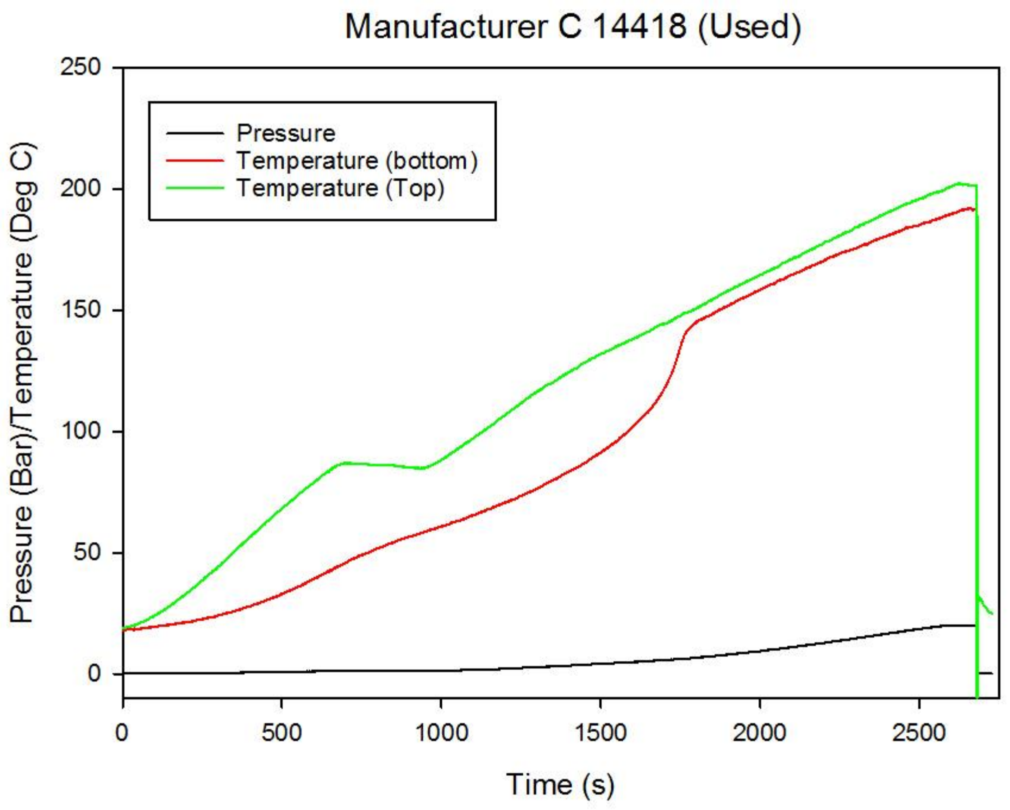


Figure 45 Pressure and Temperature Results – manufacturer C – 2nd hand (used)

The still images (inset a to h) in Figure 46 show the machine before, during and after testing.

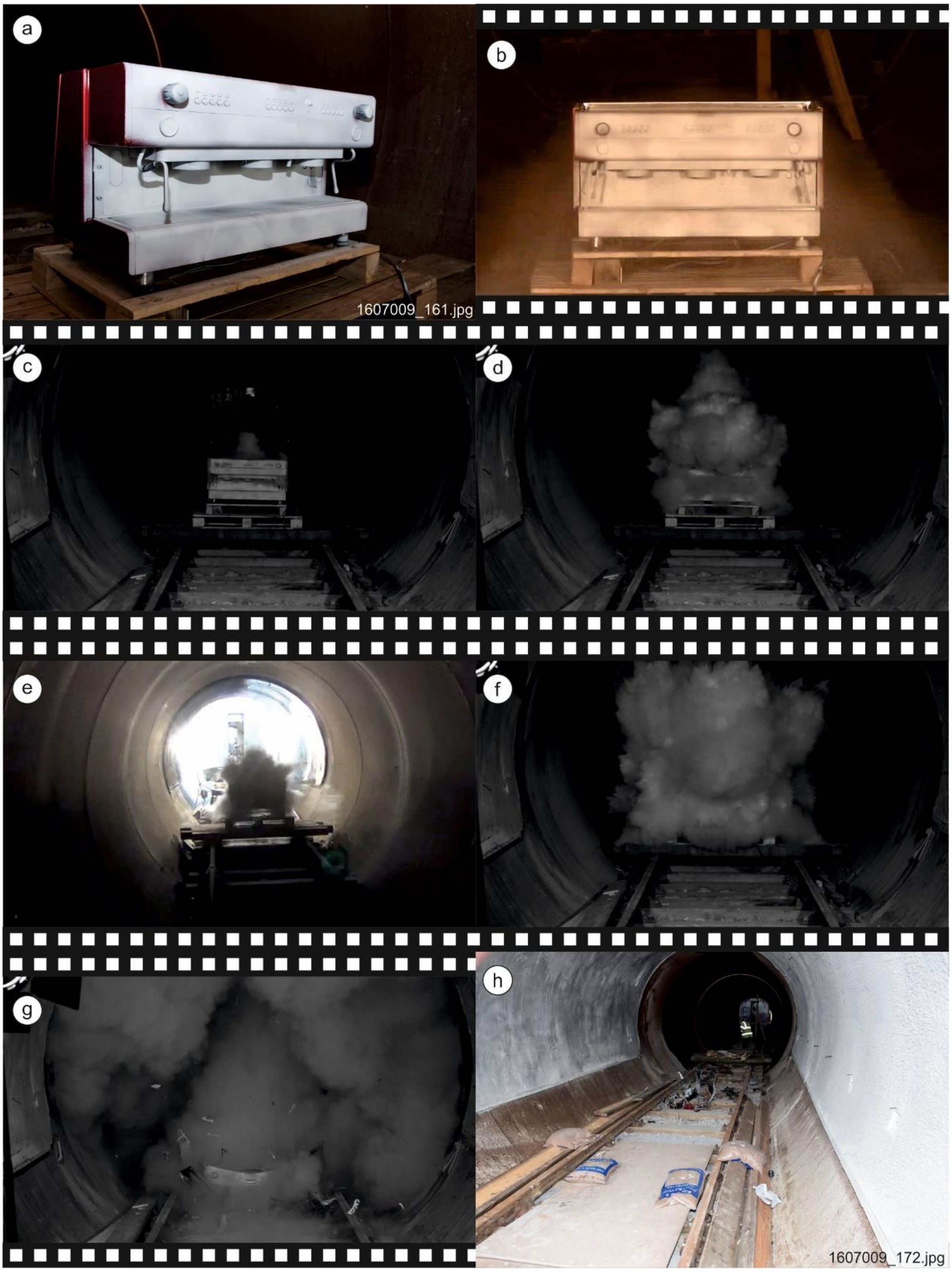


Figure 46 Images from the test – manufacturer C (2nd hand)

Insets b to g are sequences taken from the high-speed (black and white images) and high-definition video footage (colour images). Inset image e was recorded from behind the machine. This was the only second-hand machine to suffer catastrophic boiler failure during the overpressure testing.

3.7.4 Post-test Examination

The vessel had undergone catastrophic overload failure which had resulted in the flattening of part of the vessel to form a near-rectangular shape, Figure 47. The end domes and three heat exchangers and part of the vessel wall were not available for examination. The failure appeared to have occurred in a longitudinal direction and may have been associated with the three brew head heat exchangers and the ports. The longitudinal butt weld seam was intact. There were almost no deposits in the BWL region of the interior of the vessel and blackening of the wall in the AWL location.

Figure 47 Section of fractured boiler vessel ***(Image No. DSCN5957.jpg)***

The mean wall thickness following testing was 1.36 mm, ranging between 1.29 and 1.42 mm.

3.8 Second-hand Café Boiler (Manufacturer D Sample No. 14430)

3.8.1 Initial Metallurgical Examination

No prior metallurgical examination had been undertaken.

3.8.2 Examination of Electrical Safety Devices

This café boiler used a Type 1 control circuit that could disconnect the power to the heating elements via the boiler pressure switch and over-temperature switch. Examination of the pressure switch showed that it was relatively unused and there was no sooting of the contacts. The contacts had a resistance of between 0.1 Ω and 0.2 Ω.

The over-temperature switch detection bulb had been inserted into a sleeve between the heating elements and was connected by a thin copper tube to the body of the over-temperature switch. The over-temperature switch had three contact pairs with a resistance between 0.2 Ω and 0.3 Ω. To facilitate its testing the detection bulb was removed from its sleeve and heat was applied using a heat gun.

The body of the over-temperature switch indicated that its operating temperature was 169 °C. The heat gun was set to 180 °C and applied to the bulb. The contacts changed state after approximately 10 seconds and remained in this condition until the detection bulb had cooled and the manual reset button was pressed.

The café boiler was prepared for testing by connecting the incoming electrical supply directly to the heating elements.

3.8.3 Overpressure Test

Testing proceeded without interruption. During the test, pressure and temperature increased steadily until a small volume of steam could be seen venting at a pressure of around 4 bar. Temperature and pressure continued to rise until steam and water could be observed venting from the machine from around 14 bar (14 bar was achieved at approximately 1340 seconds) as shown in Figure 48.

Venting of water and steam continued until steam was no longer being emitted and temperatures started to climb rapidly. The test was aborted at approximately 300 °C to prevent fire.

Plateauing of the temperature from the upper thermocouple, and reduction of the temperature on the lower thermocouple to approximately 95 °C was observed during the leak phase.

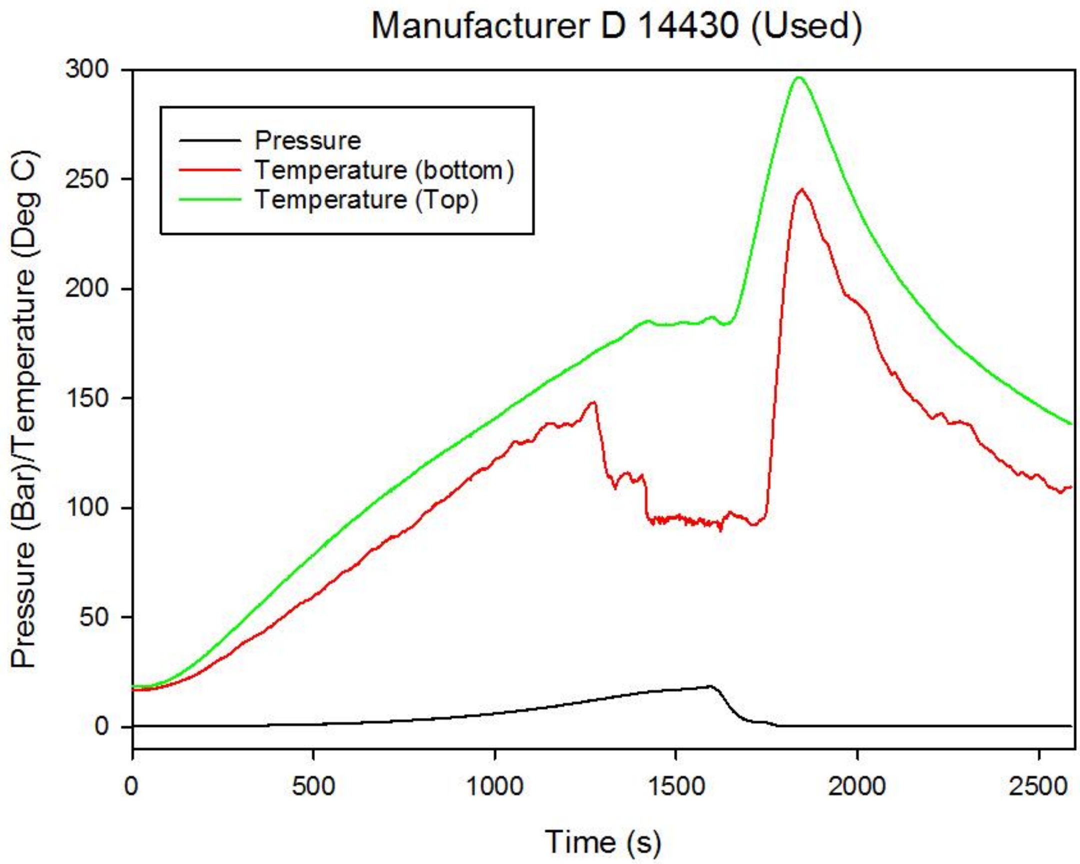


Figure 48 Pressure and Temperature Results – manufacturer D – 2nd hand (used)

The still images (inset a to f) in Figure 49 show the machine before, during and after testing.

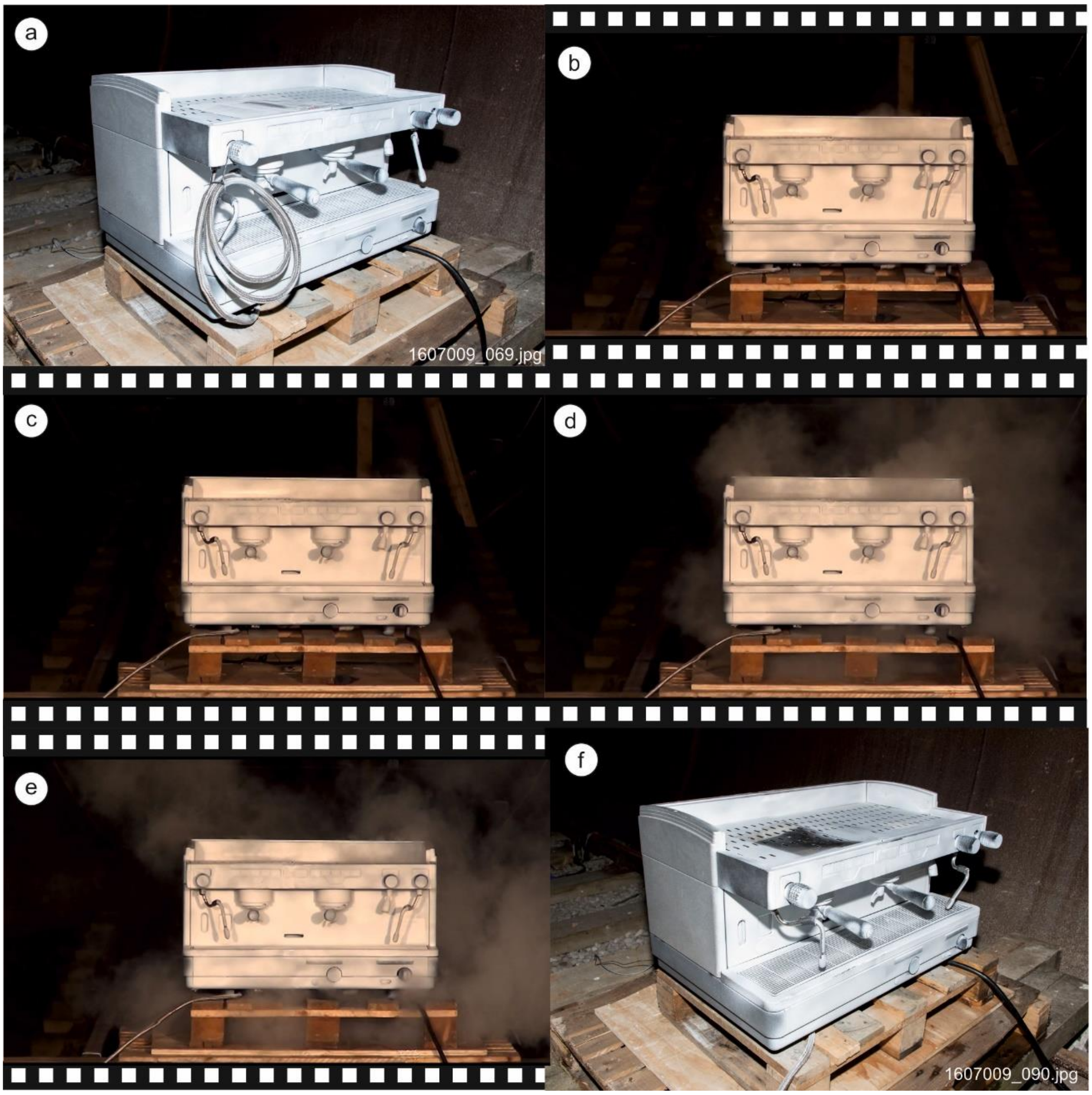


Figure 49 Images from the test – manufacturer D (2nd hand)

Insets b to e are sequences taken from the high-definition video footage. Note the general steam surrounding the machine in inset images d and e, and the areas of standing water on the pallet and base board. During post-test examination, a crack was observed in the drain port boss on the underside of the boiler. Staining of the boiler outer casing was also observed emanating from this failure location.

3.8.4 Post-test Examination

Sample 14430 had undergone a slow release during pressurisation, with dilation of the vessel having occurred. The slow-release leak was associated with the single drain port in the base of the vessel. Clear streak marks could be seen where the steam and fluids had emanated from the crack-like feature in the circumference of the port, Figure 50. In this instance the crack appeared to be within the port fitting itself, not the brazed joint. White powder residue on the port fitting and darker shadowing with green colouration on the surface of the vessel adjacent to the fracture indicated that the leak may have been pre-existent to the testing.

Figure 50 Cracking in wall of fitting at drain port ***(Image No. P1012939.jpg)***

The fracture in the port and a portion of its associated vessel wall was removed for examination. At high magnification using the SEM the crack fracture surfaces appeared fibrous and brittle – with no evidence of plastic deformation, Figure 51.

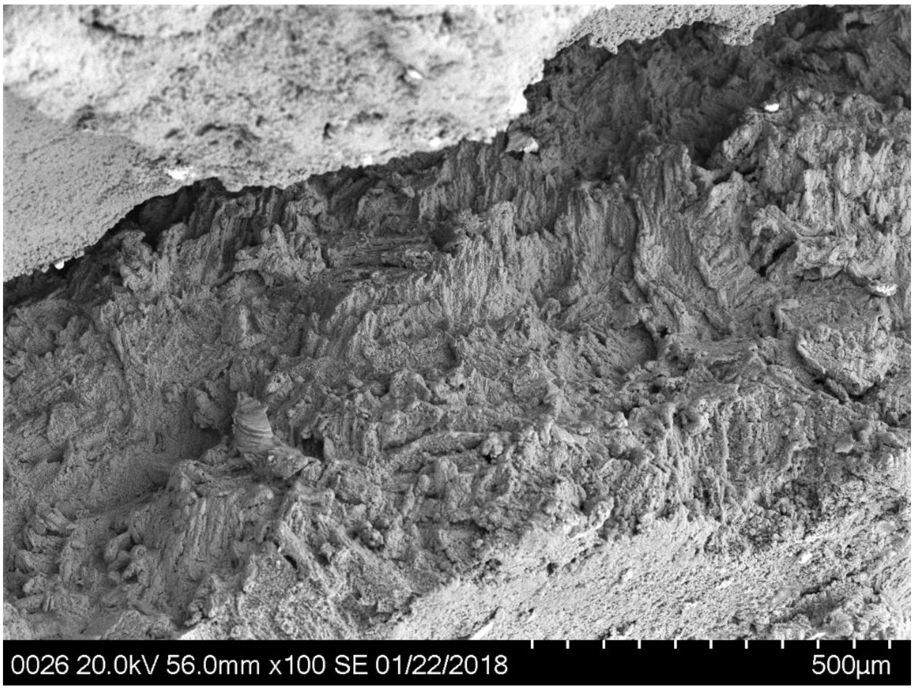


Figure 51 Fracture surface of the crack ***(Image No. 14430_0026.jpg)***

A metallographic sample taken transversely through the fracture revealed that the failure had occurred through the wall of the fitting, which was a two-phase 60:40 brass, Figure 52.

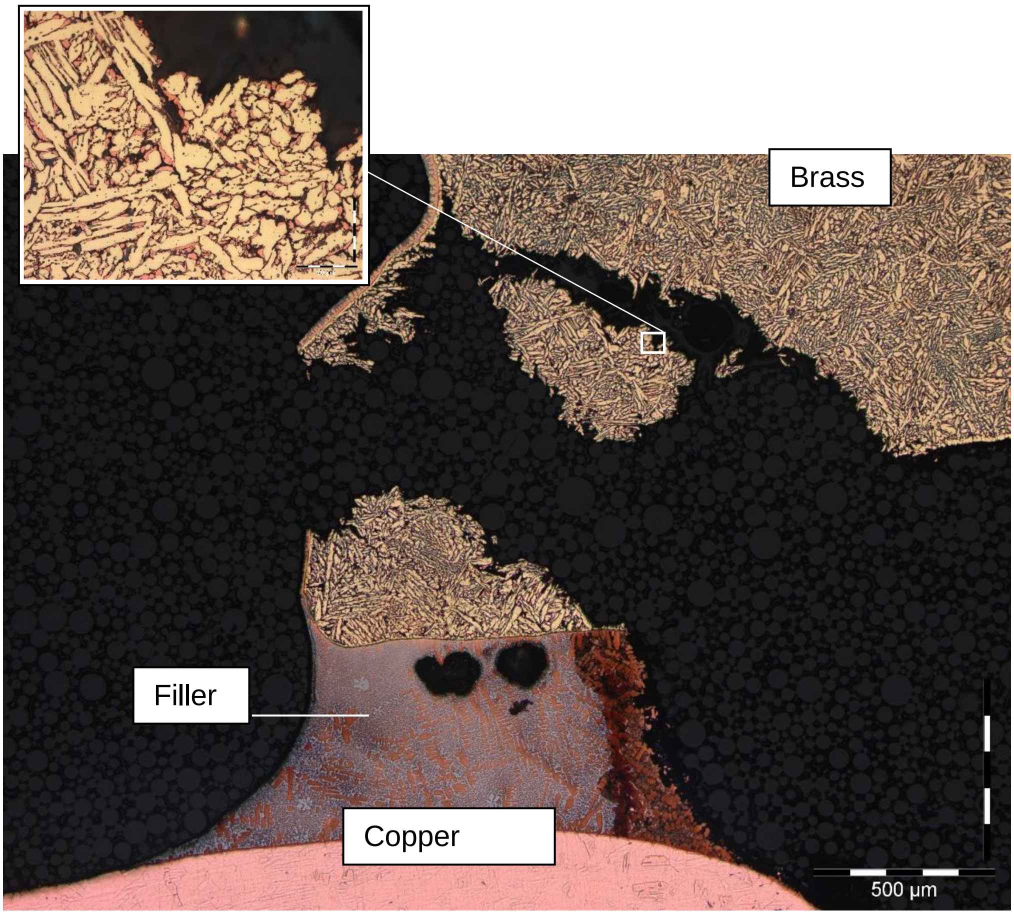


Figure 52 Cross-section through fractured drain port fitting (inset showing pink copper-rich regions due to zinc depletion (dezincification)) ***(Images No. 14430 met 2-1a, 14430 met 2-5.jpg)***

The failure was notable in that it appeared to have resulted from the degradation of the brass. High magnification of the failure location revealed that it had undergone dezincification. The zinc had depleted from the zinc-rich phase leaving behind a pink-coloured copper-rich material with poor cohesion with the remaining microstructure (see inset in Figure 52). This resulted in the fitting being in a weakened condition. The dezincification formed a 2.5 mm wide zone in the fitting, beyond which the brass was unaffected.

Figure 53 shows the interior of the boiler, with light lime-scale deposits BWL, and blackening of the copper wall AWL. The mean wall thickness of the vessel was 1.44 mm.

Figure 53 Interior of boiler

4 Café Boilers Assessment

4.1 Electrical Safety Devices

The main hazard for café boilers is overpressure of the boiler causing it to fail energetically with a rapid release of steam as shown in Figures 19, 26, 30, 33 and 46. It was not possible to calculate the required performance level (PL_r), as the failure rate for the components used was not available. However, the safety function required to control this can be derived using Figure A.1 in BS EN ISO 13849-1[2]. This is the risk graph for determining the required PL_r for the safety function.

There are five categories of risk reduction in Figure A.1: 'a' is the performance level (PL_r) that provides the lowest contribution to risk reduction; and 'e' is the PL_r category that provides the highest contribution to risk reduction.

Using the following parameters described in Figure A.1:

Severity of Injury (S): S2 serious (normally irreversible injury or death).

Frequency and/or exposure to hazard (F): F1 seldom-to-less-often and/or exposure time is short.

Possibility of avoiding hazard or limiting harm (P): P2 scarcely possible (to avoid the hazard).

a PL_r of 'd' is required. As 'd' is the second highest PL_r category, the safety function should be designed to have a high contribution to risk reduction.

In this case it is not possible to empirically calculate the $PL_{r,}$ but these can be mapped across to a Category 3 design architecture, section 6.2.6 of BS EN ISO 13849-1:2015[2]. In summary the safety-related control system should perform in such a way that:

> *'When a single fault occurs, the safety function is always performed.'*
>
> *'Some, but not all, faults will be detected. Accumulation of undetected faults can lead to the loss of the safety function.'*

Each of the café boilers examined had a pressure relief valve (PRV), and so were not relying solely on the electrical components to control the hazard. The operating pressure and flow rate of the PRV must be matched to the boiler to ensure that the boiler is not over-pressurised (checking the ratings of PRVs was not part of this work).

Over-pressurisation will only occur if the PRV fails in a dangerous manner, i.e. it fails to open, or fails to open sufficiently at its design pressure and power continues to be applied to the heating elements. As there were concerns about the performance of the PRV in the incident mentioned in Section 1.1, the electrical control system is an important part of keeping this hazard under control.

Control of power or more specifically removal of power to the heating elements will remove the hazard of the boiler being over-pressurised if the PRV fails. This is achieved in the Types 1, 2a, 2b and 3 control methodologies in a variety of ways described in this report.

Using MOSFETs, triacs, or similar devices to remove power from the heating elements would not be considered to have the required Category behaviour because it uses complex electronic components, i.e., the PCB to interpret the input from the electronic pressure sensor and control these devices. Similarly using SSRs, with their known propensity for failing in the conducting state, should not be used as the sole way for the control system to remove the power to the heating elements if an over pressurisation of the boiler occurs.

Reference [2] states that the safety-related part of the control system can achieve Category 1 using "well-tried" components and the "occurrence of a fault can lead to the loss of the safety function". However, Section 6.2. Category 1 Note 1 states that, "Complex electronic components (e.g., PLC, microprocessor, application specific integrated circuit) cannot be considered as equivalent to "well-tried". Therefore, the use of a PCB with some form of microprocessor as part of the safety-related control circuit limits the control system Category to B.

Using the over-temperature switch to remove power directly from the heating elements, in conjunction with a PRV, would probably allow the control system to behave as a Category 3 design architecture if the over-temperature switch had to be manually reset once activated. From an electrical perspective only, this would encompass control methodologies; Type 1, 2b and 3 described in this report. The only comment would be that one model of the second-hand café boilers did not have the over-temperature switch mounted between the heating elements. Although its behaviour may be slightly different, its sensing tip in the sleeve is very close to the heating elements as illustrated in Figure 6. Therefore, it would be exposed to the radiated heat from the heating elements which would have a similar effect to having the over-temperature switch mounted between the elements. These also had a lower switching temperature of 145 °C compared to 169 °C, 170 °C, and 187 °C for over-temperature switches mounted between the heating elements.

In Type 2a control methodology the over-temperature switch does not directly control power to the heating elements. It controls the power indirectly by operating a contactor, which in turn removes power from the heating elements. The contactor is not monitored by the control circuit and can fail in an energised state and so not be detected. Therefore, a single fault could cause the safety function of the over-temperature switch not to be performed. However, the PRV should still operate and prevent over pressurisation. Type

2a control methodology was only found in one model of the café boilers examined and not in another model from the same manufacturer.

Assessing all the electrical control systems:

Type 1, 2b and 3 achieve Category 3 behaviour; and

Type 2a achieves Category 3 behaviour when the PRV is taken into consideration.

However, maintenance and testing of the over-temperature switch (and PRV) in Types 1, 2b, and 3; and the contactor in Type 2a control systems is essential in maintaining Category 3 behaviour. This should be carried out during regular maintenance and servicing.

Operational tests of the functional over-temperature switches showed that they operated at approximately their design temperature except for one (detailed later in this section). Once operated, they had to be manually reset after they had sufficiently cooled for the café boiler to become operational again.

All the mechanical pressure switches used in Type 1 control circuits operated as expected and the contact pairs were either in good or excellent condition.

Two of the second-hand café boilers not utilised in the pressure testing had serious failures that would have compromised the electrical safety and safe operation if they had been put straight into service in the “as received state”. A third, although electrically safe would not have functioned at all because of the incorrect wiring of the control circuit.

Figure 54 shows an over-temperature switch where it is inserted into the sleeve of the boiler. The sleeve had leaked and as a result the insert of the switch had corroded. The over-temperature switch had mechanically failed in a dangerous (conducting) state and would not have removed power from the heating elements in the boiler if it overheated.

Figure 54 Corroded over-temperature switch ***(Image No. P1050563.jpg)***

Figure 55 shows the power cable to a three-phase café boiler which had been converted to single-phase using the original cable.

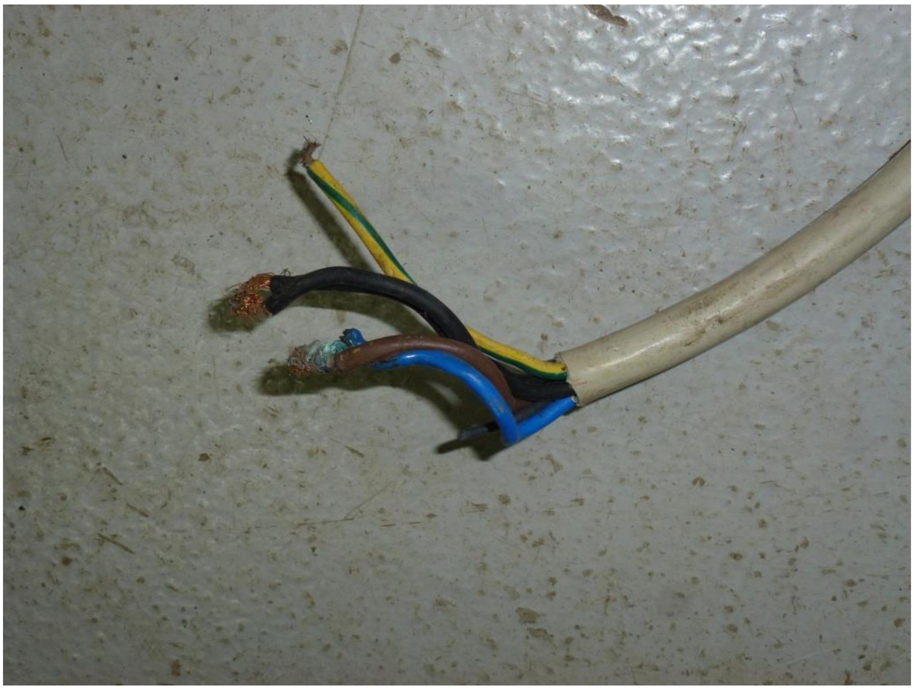


Figure 55 Supply cable conversion three-phase to single phase ***(Image No. P1050957.jpg)***

The conversion at the boiler end, shown in Figure 56 was equally poorly executed with the blue cable almost entirely disconnected. This cable should have been replaced with a suitably rated single-phase cable.

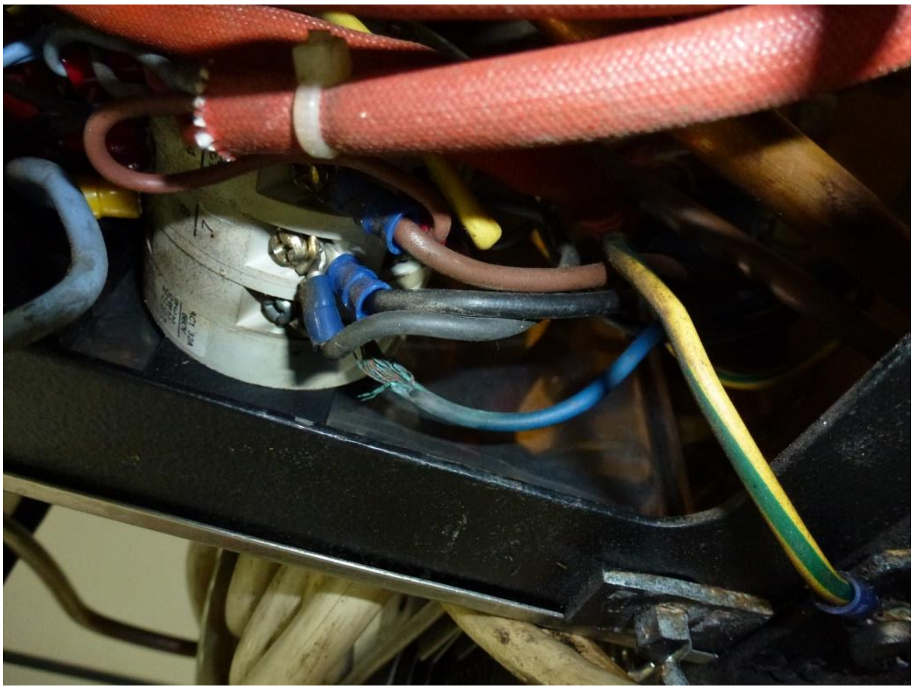


Figure 56 Boiler end conversion three-phase to single phase ***(Image No. P1050979.jpg)***

Figure 57 shows the control PCB, which has 240 V ac present on the PCB, and would have originally been in a plastic enclosure, but was found wrapped in Clingfilm.

Figure 57 Control PCB wrapped in Clingfilm ***(Image No. P1050959.jpg)***

None of the new café boilers had any such defects.

4.2 Mechanical

Previous sections have described the mechanics of the café boilers: this section provides a summary of those key observations.

From Table 3, of the ten pressure relief valves that were tested, three did not lift until a pressure above the rated pressure (1.8 bar to 2.1 bar) was applied (2.8 bar, 3.5 bar, > 5.1 bar). The latter case is significantly higher than the rated pressure. For all three valves, after the initial test, the following relief tests showed the valves operating closer to their rated pressures (2 bar to 2.4 bar). Another relief valve leaked at a low pressure and failed to seal. In a sample of ten relief valves, three failures to relieve pressure is significant. There were concerns about the performance of the relief valve in the café boiler incident mentioned in section 1.1.

In the overpressure tests, of the eight boilers tested, five failed catastrophically at pressures between 19 bar and 28 bar. If a person had been close to these machines when they failed, from the rapid steam release and the movement of the machine and fragments described in Table 2, it is quite possible that there would have been a serious injury or fatality. Of the five that failed catastrophically, four were new machines and one was a second-hand machine.

For the three boilers (Manufacturers A, B and D) that failed through a gradual release of steam, the final pressures were 18 to 23 bar. During post-test examinations, cracks were observed in the boss of a port on the top of the boiler for manufacturers A and B. For manufacturer D, a crack in the drain port boss was observed, which allowed the water to drain out. In this case the steam stopped venting and the temperature measured on the thermocouples began to climb rapidly to 300 °C – at this point the test was stopped. If the test had been continued, and the heating element continued to function, then even higher temperatures may have been reached. The copper boiler would melt at temperatures around 1000 °C, but may soften and lose structural form at temperatures below this. Also, there is a possibility that the heating element could fail and contact the boiler causing the machine to become ‘live’. This could cause a risk of electrocution if someone touched the machine at this time.

At failure, the average internal temperature (average of the two thermocouples for all eight tests) and the average pressure were 189 °C and 22 bar respectively. At 22 bar pressure, water does not boil until a temperature of 218 °C is reached. Therefore, much of the boiler contents would have still been in a liquid state at the point of failure. However, as soon as the failure starts, there is a rapid drop in pressure as the boiler vents to atmosphere. This will cause a sudden change in phase as the water evaporates into steam, and rapid expansion occurs. This is known as a ‘*boiling liquid expanding vapour explosion’* (BLEVE).

For the café boilers to be exposed to pressures of this magnitude the following conditions would first be required:

- the electrical control system would have to have a series of failures depending on the control system Type allocated to it in this report. In this report the electrical safety device has been designated as the over-temperature switch. However, for this to be activated, several concurrent failures would have to occur and remain in place. For example, in a Type 2b control circuit the contactor and MOSFETs or triacs, or the PCB controlling them/pressure sensor, would have to fail AND the over-temperature switch would also have to fail for the power to remain to the heating elements indefinitely.
- the pressure relief valve would have to fail to open, or fail to allow sufficient flow;
- the ancillary components attached to the boiler, such as the pipe connections would have to resist the increasing pressure and heat; and
- the boiler would have to be left switched on, without any steam being vented by the user, long enough for the pressure to build within the boiler. From the tests, it took about 20 to 30 minutes of continuous heating before failure occurred. However, it could take less time than this in use as the tests were outdoors on cool days. Therefore, the rate of heat loss during the tests would have been greater than what it would have been in a restaurant or coffee shop.

It is possible that these failure conditions could arise in-service. However, it is unlikely that all failures would occur at the same time providing the machines are regularly inspected and maintained in a manner where these faults would be detected.

4.3 Materials

All 12 café boilers examined had been manufactured from thin copper sheet welded to form cylindrical vessels. The ends of the vessels had been welded with either pressed copper domes, which had been joggle-welded to the body, or a flat brass ring flange. The ring flanges had flat, brass end plates bolted to them. Inset into the vessels were a range of brazed ports through which operational control and safety instrumentation and supply pipework were fitted. Larger welded inserts were associated with the brew heads.

4.3.1 Failure Mechanisms

In the overpressure tests, all the new café boilers failed by catastrophic overload at pressure values up to and in some instances well over ten times their intended operating pressure, and the operating pressures of the PRVs. The fracture mechanism in all instances had been by ductile overload failure demonstrated by wall thinning and microvoid coalescence at the fracture points. One of the four second-hand machines tested, also failed in this manner.

Failure by slow-release leaks occurred on three of the four second-hand machines pressure tested to failure. Two of the leaks were associated with the brazed joints at ports and showed that failure through the filler metal had occurred. In one case, a potentially significant factor was noted; this was the presence, in the filler metal, of gas porosity generated during the brazing process. The other failure had undergone selective oxidation of the copper and phosphorous in the filler metal at the interior of the vessel which may have contributed to weakening of the joint.

The third leak failure was associated with the brass fitting in the drain plug rather than the filler metal. The fitting had undergone dezincification with a consequent loss of strength. The discoloured appearance of the crack at the external surface of this fitting, and the surrounding vessel wall indicated that this defect had most probably been present, and had been leaking, prior to the overpressure test. The overpressure test would however have widened the gap between the crack faces. The cause of the dezincification is unclear but may have been associated with the fact that the defective fitting would have been under water during the service life of the machine. Dezincification is generally associated with the presence of chlorine, sulphur, oxygen, and carbon dioxide in the environment[3], and under a condition of stagnation and raised temperature. This latter condition could have existed beneath the lime-scale in the base of the boiler vessel, where the drain plug had been located.

4.3.2 Extent of External Degradation

It was evident from the deposits found on the outer surfaces of joints in the fittings and at the seals in the vessels that small amounts of leaking had occurred on some of the second-hand machines. However, only one of the machines, from manufacturer A, showed what appeared to be significant levels of corrosion damage. EDS analysis of the corrosion deposits invariably contained significant quantities of zinc (rather than copper) and as such indicated that corrosion of the brass fittings and in particular selective dezincification of the surface of the fittings had occurred, rather than degradation of the boiler vessel itself. However, following metallographic examination through these regions it was evident that the corrosion deposits, although unsightly, and indicative that refurbishment or maintenance was required, would not have affected the integrity of the vessels.

None of the vessels examined showed signs of degradation processes of sufficient extent, such as corrosion or pre-existing defects e.g., fatigue cracking, to suggest the vessels might fail at or close to normal operational pressures.

4.3.3 Occurrence of Internal Deposits

It is unclear what effect the presence of lime-scale deposits would have had on the integrity of the vessels. In the case of the vessel which leaked due to dezincification of the brass fitting in the drain port, the lime-scale may have led to conditions of stagnation which can enhance a propensity for dezincification, although in this instance the lime-scale was relatively light. The failure of this fitting did not however, result in the vessel failing at significantly lower overpressure than the other vessels examined. The implications for this type of degradation on vessel integrity in circumstances where all other safety features have been defeated are discussed in section 4.3.4.

4.3.4 Implications for Vessel Integrity

Internal examination of the boilers provided information regarding the degree of accumulated lime-scale in the boiler vessel. Lime-scale deposits may have had the potential to increase the likelihood for dezincification of fittings as observed for the drain plug in one of the vessels which failed by slow-release leak. The effect of lime-scale on the operation of the café boiler machine depends on what effect the deposits would have had on the safety and control mechanisms of the machine. Most of the instrumentation was in the void above the water line and as such was likely to have been little affected by deposition. The coating of heating elements and thermocouples beneath the water line may have affected their functioning. Although conjectural it is probable in this case that reduced efficiency may have been the most significant consequence of lime-scale on the machine rather than compromised safety.

The external appearance of the boiler and its attendant fixture and fittings did not provide an indicator of reduced vessel integrity leading to a raising of safety concerns. The accumulation of deposits on external fixtures and fittings signalled that seals and joints had become degraded and that maintenance and refurbishment would be desirable.

Either by catastrophic overload or slow-release leak, the failure pressures were similar for all café boiler vessels in that they were more than ten times the operating and pressure relief valve settings for the machines. Consequently, the defects in brazed joints did not necessarily lead to a significant reduction in failure pressure. Indeed, the differences in failure pressure were more significant between manufacturers than they were between failure modes. Therefore, the manner of slow release, by failure of the joint at the brazed fittings, was a safer failure mode than the energetic separation of the vessel: the latter method being highly energetic and potentially more injurious to bystanders.

4.3.5 Observations on Vessel Manufacture and Materials: Appearance and Welding

No significant defects have been observed in the welds used in the vessel construction on any of the café boilers examined. That the welding has been of adequate quality has been confirmed from the fracture paths of the boiler walls where only one of the 5 boilers which failed catastrophically failed along a longitudinal butt weld. The vessel that failed along the longitudinal butt weld did so at the highest pressure of all the machines tested. Although only a small number of boilers have been tested, manufacturing quality has not been implicated in the failures due to the overpressure tests.

4.4 Supply Information (Includes Benchtop Autoclaves)

This section contains a brief review of manufacturers' and suppliers' duties under the relevant pressure regulations and assesses the supply information provided by the manufacturers for the equipment tested in this project. This is based on the legislation that was current when the machines were supplied which has since been revised. Therefore, a brief discussion is carried out first on the pressure equipment regulations which are now current.

The UK *Pressure Equipment Regulations* (1999) (PER)[4] are the adoption into UK law of the EU Pressure Equipment Directive (PED) 97/23[5]. The PED was revised by the Pressure Equipment Directive 2014/68/EU[6]. This is now part of UK law as the *Pressure Equipment (Safety) Regulations* (2016) (PE(S)R)[7]. The earlier regulations were in force when this work began, and they were superseded by the 2016 regulations during the project. All machines for this work were purchased prior to 8 December 2016 (when PE(S)R came into law). Therefore, the previous regulations (PER) are relevant to assessing the equipment in this project.

Also, since the PE(S)Rs became law, the UK has left the EU. This required PE(S)R to be amended by schedule 24 of *The Product Safety and Metrology etc. (Amendment etc.) (EU exit) Regulations 2019*. The principle aim of these amendment regulations is to revise the wording that was needed regarding CE marking, accreditation, harmonised standards, and declaration etc..

4.4.1 Duty Holder's Requirements when Supplying the System (Current Legislation)

Pressure equipment is defined in regulation 6 of PE(S)R [7]. The relevant parts of regulation 6 for steam pressure vessels are as follows:

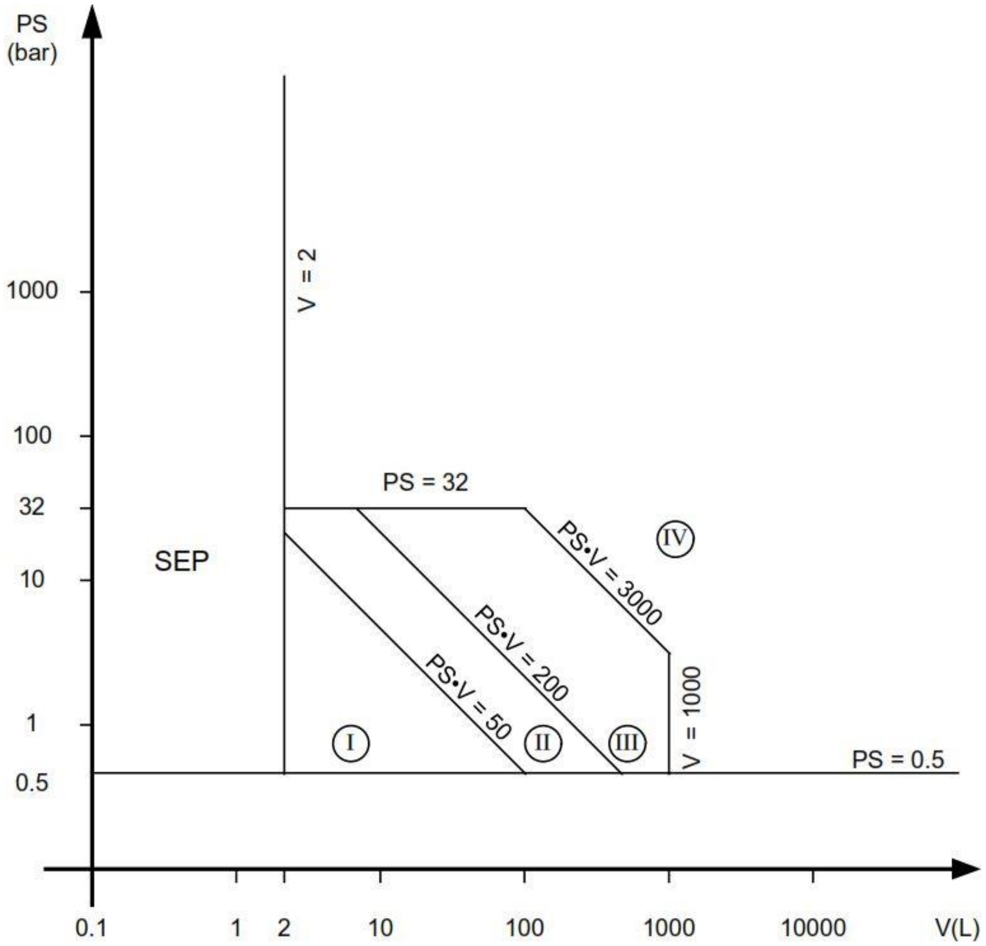
6. *The following pressure equipment must satisfy the essential safety requirements set out in Schedule 2 —….*

(b) fired or otherwise heated pressure equipment with the risk of overheating intended for generation of steam or super-heated water at temperatures higher than 110°C having a volume greater than 2 L, and all pressure cookers;

(this requirement was also in PER)

As all three types of vessels tested in this work are intended for '*generation of steam'*, they come under the requirements of PE(S)R. However, the smaller the volume, the less onerous are the requirements. This can be seen in Table 5 of the conformity assessment tables in schedule 1B in PE(S)R. This shows the chart for steam-generating pressure vessels (Table 3 below).

Table 3 Steam-generating pressure vessel (from Table 5, Schedule 1B PE(S)R[7])



(this table was also in PER – Table 5 schedule 3)

The volume in litres is along the x-axis, and the maximum allowable pressure (PS) in bar is on the y-axis. Any equipment that has a maximum allowable pressure less than 0.5 bar above normal atmospheric pressure is not within the scope of PE(S)R. The UK government guidance on PE(S)R states:

The Regulations (PE(S)R) regulate the design, manufacture and conformity assessment of pressure equipment and assemblies with a maximum allowable pressure PS greater than 0.5 bar[20].

A steam-generating boiler needs to have a minimum pressure of 0.5 bar **and** a minimum volume of 2 litres to be within the categorised areas in PE(S)R[7] (I, II, III and IV in Table 3). Most café boilers will come under category I or II.

Anything above PS = 0.5 bar, but below the category I threshold will still need to be designed using sound engineering practice (SEP) as stated in regulation 8 (2) of PE(S)R[7].

8)….

(2) Pressure equipment and assemblies to which this regulation applies must be—

(a) designed and manufactured in accordance with sound engineering practice (SEP) *in order to ensure safe use; and*

(b) accompanied by adequate instructions for use.

From the DTI Product Standards Pressure Equipment – Guidance Notes on the UK Standards (2005) (ref URN05/1074)[8], in the section on conformity assessment (page 11) it states:

'The higher the category, and therefore the greater the hazards, the more demanding are the requirements. Equipment in Category I will be subject to the manufacturer's own internal production control…

4.4.2 Information from the Pressure Equipment Regulations (PER) for the Equipment Assessment in this Project

In this section, reference is now made to the previous pressure equipment regulations (PER) as these were the regulations at the time that the equipment was obtained.

Therefore, assessment of the equipment received by the suppliers is carried out in accordance with these regulations and not PE(S)R.

In schedule 2, section 3 (Manufacturing) of PER[4], it states:

For pressure equipment in categories II, III and IV, operating procedures and personnel must be approved by a competent third party which, at the manufacturer's discretion, may be:

a notified body,

a third-party organisation recognised by a Member State as provided for in Article 13 of PED

Names of the 3rd party organisations should be published in the Official Journal of the European Union along with the tasks for which they have been recognised.

To carry out these approvals the third party must perform examinations and tests as set out in the appropriate harmonised standards or equivalent examinations and tests or must have them performed.

The 'notified body' is defined in regulation 18 of PER[4] as follows:

18.For the purposes of these Regulations, a notified body is a body which has been appointed to carry out one or more of the conformity assessment procedures mentioned or *referred to in regulation 13 or 14 or to issue a European approval for materials as referred to in regulation 17 and which has been—*

appointed as a notified body in the United Kingdom pursuant to regulation 20; or

appointed by a member State other than the United Kingdom, and has been notified by the member State concerned to the Commission and the other member States pursuant to Article 12 of the Pressure Equipment Directive.

Therefore, the requirements that need to be met under PER for café boilers will vary depending on the category that the machines are in.

Schedule 6 in PER[4] states what must be included in a declaration of conformity as follows:

SCHEDULE 6 Regulations 7(3)(d),

8(3)(a)(iv)

(Annex VII to the Pressure Equipment Directive) EC DECLARATION OF CONFORMITY

The EC declaration of conformity must contain the following particulars:

name and address of the manufacturer or of his authorised representative established within the Community,

description of the pressure equipment or assembly,

conformity assessment procedure followed, (discussed above on regulation 13)

in the case of assemblies, description of the pressure equipment constituting the assembly, and the conformity assessment procedures followed,

where appropriate, name and address of the notified body which carried out the inspection,

where appropriate, a reference to the EC type-examination certificate, EC design-examination certificate or EC certificate of conformity,

where appropriate, name and address of the notified body monitoring the manufacturer's quality assurance system,

where appropriate, the references of the harmonised standards applied,

where appropriate, other technical standards and specifications used, *where appropriate, the references of the other Community Directives applied, particulars of the signatory authorised to sign the legally binding declaration for the manufacturer or his authorised representative established within the Community.*

Any mechanical drives within the machine, such as the pumps, will come under the Supply of Machinery (Safety) regulations[9]. With regard to PER, HSE's website[10] currently states:

'Duties for safety are placed on the manufacturer or their authorised representative, importers and distributors. Machinery may include pressure systems which come within scope of these Regulations. In such cases, the requirements of these Regulations apply to the pressure parts of the machine, alongside those requirements under the Supply of Machinery (Safety) Regulations for the machine.'

The safety-related control system will need to be fit for purpose and follow the requirements of a suitable European standard, for example:

BS EN ISO 13849-1 – *"Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design"* [2]

may be of value as discussed in Section 4.1; although this is a harmonised standard under the Machinery Directive, *not* the Pressure Equipment Directive.

The relevant harmonised standard on safety devices to protect against overpressures (safety valves, pressure relief valves, bursting discs etc.) is BS EN ISO 4126 – *Safety devices for protection against excessive pressure*[11].

A safety accessory is defined in PER[4] as: '*a device designed to protect pressure equipment against the allowable limits being exceeded*'. This will include pressure relief valves.

4.4.3 Information Received from the Suppliers of the Machines Tested

The equipment manuals for the café boilers were reviewed to determine what supply regulations were used to obtain the CE declaration of conformity. Using the information from Schedule 6 of PER[4] (see section 4.4.2 above), each of the requirements is set out in Table 4 below, and the declarations from each of the manufacturers are compared with the requirements from PER. No manuals or declarations of conformity were provided by the sellers for any of the second-hand machines.

Table 4 CE conformity assessment from the information supplied with the machines (includes Autoclaves from Section 5 of this report)

Row No.	PER Schedule 6 Requirements[4]	Manufacturer A (new)	Manufacturer B (new)	Manufacturer C (new)	Manufacturer D (new)	Autoclave
1.	*name and address of the manufacturer or of his authorised representative established within the Community,*	Declaration was provided in a separate certificate (not in the manual) Included Signed and dated by the Managing Director	Declaration was on the back page of the manual Included Signed by the company President.	No manual or DoC was provided with the machine. This had to be requested additionally. The DoC was on the second page of the manual Included Signed and dated (2004)	Included Signed and dated by the R&D Manager and the Operations Manager	Declaration was not included. However, p8 of the manual stated. *Please ask for details of approvals specific to your model:* • *Medical Devices Directive MDD 93/42/EEC* • *Pressure Equipment Directive PED 97/23/EC* • *RoHS2 Directive 2011/65/EU* • *Electricity Safety Standard EN 61010* • *EMC Standard EN 61326* The supplier did provide the DoC when requested. The conformity assessment procedure was in accordance with the Medical Devices Directive (see below). They also provided a 'certificate of compliance' in accordance with PD 5500[14]:

[14] ***PD 5500*** *"Specification for unfired, fusion welded pressure vessels". This is a code of practice that provides rules for the design, fabrication, and inspection of pressure vessels.*

*PD 5500 was formerly a widely used British Standard known as **BS 5500** but was withdrawn from the list of British Standards because it was not harmonized with the Pressure Equipment Directive (97/23/EC). In the United Kingdom it was replaced by EN13445. It is currently published as a "Published Document" (PD)* by the British Standards Institution.

Row No.	PER Schedule 6 Requirements[4]	Manufacturer A (new)	Manufacturer B (new)	Manufacturer C (new)	Manufacturer D (new)	Autoclave
						Name and address were included. Signed by the Managing Director of the Company.
2.	*description of the pressure equipment or assembly,*	Model and serial numbers of the café boiler and PRV are quoted. Year of manufacture included for the PRV For the machine it states *LOT 1/16* which presumably means the date of sale or shipment.	Product defined as: *'Espresso coffee makers for professional use.'* Model and serial numbers were quoted (inside back page of the manual). The label in the manual could be confusing for some as Pmax refers to maximum power as well as maximum pressure.	Model number was quoted and also information on: • The operating pressure range • Max temperature • Boiler capacity • Heat exchanger pressure, max temperature, and capacity However, there was no specific information on the serial number of the machine or the PRV in the manual. Instructions on how to find this information on the machine were included, but they were in Italian, not English.	Model and serial numbers of the café boiler and PRV are quoted. On the valve certificate, it states '*safety valve with helicoid spring and direct action, type:tw1'*	The type and a single-word description are provided.
3.	*conformity assessment procedure followed,*	Included *Classification: Category 1* *Procedure: Form A* Note: form A means module A and is the procedure for category 1 pressure equipment as stated in regulation 13 of PER. This is the procedure where the manufacturer '*ensures and declares that pressure equipment satisfies the requirements of the Directive which apply to it'* (Schedule 4 of PER)	Not included	Not included	No information on the boiler. For the PRV, see below	Included: MDD 93/42/EEC Class IIb, Rule 15. Canadian Medical Device Regulations Rule 13 Class II But it does not include a conformity assessment procedure from PER.

Row No.	PER Schedule 6 Requirements[4]	Manufacturer A (new)	Manufacturer B (new)	Manufacturer C (new)	Manufacturer D (new)	Autoclave
		Therefore a 'Notified Body' (NoBo) is not required unless the manufacturer requests one.				
4.	*in the case of assemblies, description of the pressure equipment constituting the assembly, and the conformity assessment procedures followed,* *where appropriate, name and address of the notified body which carried out the inspection,*	The PRV and boiler are both mentioned separately. No test information on the PRV	The operating pressure of the PRV and maximum static pressure of the boiler are stated in the manual No test information on the PRV	No information on the set pressures of the PRV	The PRV and boiler are both mentioned separately. From the PRV certificate: *CE examination certificate Module B+D* *Certificate Nos:* *Module B – TIS-PED-VI_05-09-007208-1509* *Module D – DRG-0036-QS-1084-12* Module B+D is for category 4 pressure equipment (regulation 13 of PER).	No information, but not necessary as the bar-litre is 1.79 bar x 0.75 litres = 1.34 bar-litre which is below class 1 in Table 3 and comes under SEP.
5.	*where appropriate, a reference to the EC type-examination certificate, EC design-examination certificate or EC certificate of conformity,*	*'as manufacturer of boilers for espresso coffee machines and of security valves for their safety hereby declares that the item described here below is manufactured according to the norms laid down in directive 2014/68/UE.'*	*'…complies with the following directives.'* *2006/42/CE Machinery Directive* *2004/108/CE EMC Directive* *97/23/CE Pressure Equipment Directive* *2011/65/UE RHOS2 Directive*	Manufacturer C *declares that the following product Espresso coffee machines for professional use model XXXX to which this declaration relates is, according to the provisions of the specific directives: 98/37/CE;* (Machinery Directive) *73/23/CE* (Low Voltage Directive); *93/68/CE* (CE Marking Directive)*; 89/336/CE* (Electromagnetic Compatibility Directive)*; 92/31/CE* (Electromagnetic Compatibility Directive)*; 97/23/CE* (Pressure Equipment Directive)	From the valve certificate *EC conformity declaration according to directive 97/23/EC*	*'In accordance with the Medical Device Directive 93/42/EEC and the Pressure Equipment Directive 97/23/EC'.* However, as stated above, a conformity assessment procedure in accordance with PER has not been stated.

Row No.	PER Schedule 6 Requirements[4]	Manufacturer A (new)	Manufacturer B (new)	Manufacturer C (new)	Manufacturer D (new)	Autoclave
6.	*where appropriate, name and address of the notified body* (NoBo) *monitoring the manufacturer's quality assurance system,*	They state on p5 of their manual that their procedure used does not require the intervention of any external body for evaluation of conformity.	No information on the NoBo	No information on the NoBo	The NoBo is mentioned on the PRV certificate, but not on the café boiler certificate	BSI, Hemel Hempstead Health Canada
7.	*where appropriate, the references of the harmonised standards applied,*	*EN 60335-1 Household and similar electrical appliances. Safety. General Requirements* *EN 60335-2-75 Household and similar electrical appliances. Safety. Particular requirements for commercial dispensing appliances and vending machines* *EN 55014-1 Electromagnetic compatibility requirements for household appliances, electric tools and similar apparatus. Emission* *EN 55014-2 Electromagnetic compatibility requirements for household appliances, electric tools and similar apparatus. Immunity. Product Family Standard.* *EN 61000-3-2 Electromagnetic compatibility (EMC) limits. Limits for harmonic current emissions (equipment input current <= 16 A per phase)* *EN 61000-3-3 Electromagnetic compatibility (EMC) limits. Limitation of voltage changes, voltage fluctuations and flicker*	'*Harmonised standards applied* *EN 60335-1 2002-10 + /A1:2004-12 + /A1/EC:2007-01 + /A2:2006-08 + /A11:2004-02 + /A12:2006-03 + /A13:2008-11* *EN 60335-2-75:2004-08 + /A1:2005-02 + /A2:2008-10 + /A11:2006-08* *EN 55014-1:2006-12 + A1:2009-04* *EN 55014-2:1997:02 + EC:1997-12 + /A1:2001-12 + /A2:2008-10* *EN 61000-3-2:2006-04* *EN 61000-3-3:2008/09* *EN 61000-3-11:2000-11* *EN 62233:2008*	It complies with the following norms: *EN 292-1;* Safety of machinery: Basic concepts: General principles for design. Basic terminology, methodology. **(has since been withdrawn and replaced by BS EN ISO 12100-1)** EN 292-2 Safety of machinery: Basic concepts: General principles for design. Technical principles and specifications **(has since been withdrawn and replaced with BS EN ISO 12100-2)** *EN 60335-1;* *IEC 335-2-75 + A1:98* **(the IEC equivalent of EN 60335-2)** *EN 55014-1: 1993 + A1: 1997;* *EN 55014-2:1997* *EN 61000-3-2: 1995 + A13: 1997* *EN 61000-3-3:1995*	None stated	It states: *No harmonised standards*

Row No.	PER Schedule 6 Requirements[4]	Manufacturer A (new)	Manufacturer B (new)	Manufacturer C (new)	Manufacturer D (new)	Autoclave
		in public low-voltage supply systems, for equipment with rated current <= 16 A per phase and not subject to conditional connection				
8.	*where appropriate, other technical standards and specifications used,*	None stated	None stated	None stated		It states: *Market specific approvals*
9.	*where appropriate, the references of the other Community Directives applied, particulars of the signatory authorised to sign the legally binding declaration for the manufacturer or his authorised representative established within the Community.*	Manufacturer A states that the machine *to which this declaration refers, complies with the requirements set forth by the following directives and regulations and subsequent amendments:* *2006/42/CE Machinery Directive* *2014/30/UE Electromagnetic compatibility EMC Directive* *2014/35/UE Low Voltage Directive* *2012/19/UE Waste Electrical and Electronic Equipment (WEEE) Directive* *2011/65/UE Restriction of Hazardous Substances (RoHS) Directive* *2009/142/CE Gas Appliances Directive* 1935/2004 *Regulation on food contact materials*	All directives are stated above	All directives are stated above	*Manufacturer D states that the machine is in compliance with:* 2006/42/EC Machinery Directive 2006/95/EC *Low Voltage Directive* *97/23/EC Pressure Equipment Directive* specifically mentions article 1 and 3.6) *2004/108/EC EMC – EC Electromagnetic Compatibility Directive* *2011/65/UE Restriction of Hazardous Substances (RoHS2) Directive*	*EMC Directive*

Row No.	PER Schedule 6 Requirements[4]	Manufacturer A (new)	Manufacturer B (new)	Manufacturer C (new)	Manufacturer D (new)	Autoclave
10.	**General Comments**	There was an additional *Manufacturer's Declaration* to state that the boiler had passed the necessary hydraulic test in the factory. There is no evidence that the NoBo has carried out any *voluntary assessments* against other sets of supply regulations[15]. However, as the boiler is only 13 litres, the conformity assessment procedure is category 1, Table 3 as stated in row 3. So a NoBo is not required. There is no specific reference to machinery safety harmonised standards such as BS EN ISO 13849-*"Safety of machinery - Safety-related parts of control systems.* Having all the information in six languages, and very small print is confusing to read.	There is no evidence that a NoBo has carried out any *voluntary assessments* against other sets of supply regulations. However, as the boiler is only 13 litres, the conformity assessment procedure is likely to be category 1 in Table 3. In which case there would be no requirement to involve the NoBo. There is no specific reference to machinery safety harmonised standards such as BS EN ISO 13849-*Safety of machinery - Safety-related parts of control systems.*	There is no evidence that a NoBo has carried out any *voluntary assessments* against other sets of supply regulations. However, as the boiler is only 11 litres, the conformity assessment procedure is likely to be category 1 in Table 3. In which case there would be no requirement to involve the NoBo. There is no specific reference to machinery safety harmonised standards such as BS EN ISO 13849-*Safety of machinery - Safety-related parts of control systems.*	There is no evidence that a NoBo has carried out any *voluntary assessments* against other sets of supply regulations. However, as the boiler is only 21 litres, the conformity assessment procedure may be in category 1 in Table 3. In which case there would be no requirement to involve the NoBo. Two DoCs were provided: • A certificate by the safety valve manufacturer (separate to the manual) • The declaration for the café boiler which is on the front page of the manual The valve certificate contained more information than the other manufacturers information on valves (it included performance data at different pressures). This may be due to the valve being supplied by a separate company who provided this information themselves. For the other 3 manufacturers, although the valve may have been manufactured by a separate company, they have included it in their own assemblies with no reference to another	

[15] *This is mainly to check which Directive the products have been made to, and that the manufacturer is supplying all the necessary documents e.g. Declaration of Conformity (DoC), instructions etc. that are required by the Directive, and that these documents have the right information on them- e.g. are the instructions understandable/ in English? Has the DoC got everything on it as listed in the Directive?*

Row No.	PER Schedule 6 Requirements[4]	Manufacturer A (new)	Manufacturer B (new)	Manufacturer C (new)	Manufacturer D (new)	Autoclave
					manufacturer. There is no specific reference to machinery safety harmonised standards such as BS EN ISO 13849-*Safety of machinery - Safety-related parts of control systems.* Having all the information in six languages is confusing to read. The information also includes a ‘factory inspection sheet’ which should be filled in by the authorised distributor and returned to the manufacturer. This appears to be a sheet that is filled in when the machine is first installed for use. The sheet was date-stamped but not completed as HSE SD did not have the machine installed by the distributor.	

4.4.4 Summary on Conformity Assessment

The assessment has been structured around the following four questions:

1. **Are manufacturers using the correct legislation?**
   Manufacturer A stated that manufacture is according to the norms in the current Pressure Equipment Directive (PED) (2014/68/UE)[6]. Manufacturer D and the Autoclave manufacturer refer to the previous PED 97/23/EC[5] (current at the time that they were placed on the market). Manufacturers B and C refer to several directives which included PED 97/23/EC[5], but don't specifically state which directive was used for the conformity assessment.

2. **Have manufacturers categorised their machines correctly within the requirements of the regulations?**
   Manufacturer A has done this. But the other manufacturers do not as they have not referred to the conformity assessment procedure. The autoclave manufacturer has referred to a conformity assessment procedure from the Medical Devices Directive, not the PED.

3. **Did they refer to a notified body?**
   Manufacturer A has noted that their conformity assessment procedure does not require a NoBo. The autoclave manufacturer has referred to two NoBos (one in the UK, one in Canada). This is not needed as a requirement of PED for this size of pressure equipment. However, it may be necessary in accordance with the conformity assessment procedure that they have followed in the Medial Devices Directive[12].

   None of the other manufacturers have referred to a NoBo, although as the machines are probably in category I or below in the PER, there is no duty to involve a NoBo in the conformity assessment procedure.

4. **Has the correct documentation been supplied with the machines as required by the supply regulations?**

i. **DoC instructions**
   Manufacturers B, C and D have not referred to the conformity assessment procedure.

   The autoclave manufacturer states a DoC in accordance with the Pressure Equipment Directive[5] and the Medical Devices Directive (MDD)[12]. The assessment procedure followed was MDD 93/42/EEC Class IIb, Rule 15[12]. The autoclave contains a water volume of 0.75 litres and the operating pressure is 1.05 bar (the maximum design pressure, when the relief valve should operate, is 1.79 bar). By referring to Table 3 above, this would place it below category 1 and into the SEP category in the Pressure Equipment Regulations; therefore, it would be classified as low risk equipment with regard to pressure.

ii. Does the data plate contain the required information?

From PER schedule 2, clause 3.3 (Marking and labelling), the required information is as shown in Table 5. A tick is shown in the manufacturers' column if they have included this information. Only the new machines have been considered. The CE marking and the required information must be given on the pressure equipment or on a data-plate firmly attached to it, (with some exceptions).

Table 5 Information on the data-plate (mfr = manufacturer)

Information required	Mfr A	Mfr B	Mfr C	Mfr D	Auto-clave
the name and address or other means of identification of the manufacturer and, where appropriate, of his authorised representative established within the Community	√	√	√	√	√
the year of manufacture	√	√	√	√	√
identification of the pressure equipment according to its nature, such as type, series or batch identification and serial number	√	√	√	√	√
essential maximum/minimum allowable limits	√	√	√	√	√
depending on the type of pressure equipment, further information necessary for safe installation, operation or use and, where applicable, maintenance and periodic inspection such as:					
○ the volume V of the pressure equipment in L	√	√			
○ the nominal size for piping DN	NA				
○ the test pressure PT applied in bar and date					
○ safety device set pressure in bar	√	√	√	√	
○ output of the pressure equipment in kW	√	√	√	√	√
○ supply voltage in V (volts)	√	√	√	√	√
○ intended use					
○ filling ratio kg/L	√				
○ maximum filling mass in kg	√ (litres)	√ (litres)			
○ tare mass in kg					
○ the product group					
○ where necessary, warnings fixed to the pressure equipment drawing attention to misuse which experience has shown might occur					

4.5 Duty Holder's Requirements When Using the Pressure Systems

For the commercial user, if the machine has a steam-generating boiler, then it will come under the Pressure Systems Safety Regulations (PSSR)[1] which will require a *written scheme of examination (WSE)*.

HSE's current advice on pressure vessels in café boilers is as follows[13]:

'Commercial coffee boilers incorporating a pressure vessel (e.g. cappuccino makers) generate steam and therefore come under the requirements of PSSR. Regulation 8 requires the drafting and completion of a written scheme of examination (WSE), and regulation 9 requires that this examination be carried out by a competent person. Please see other frequently asked questions (FAQs) for further details of the WSE, the examination in accordance with the written scheme, and the role and attributes of the competent person.'

The key duties for owners and users of pressure equipment under PSSR[1] are as follows (from HSE ACOP L122 *Pressure Systems Safety Regulations – Approved Code of Practice and Guidance*)[1]:

The pressure system must contain a relevant fluid, and that fluid must have a bar-litre value greater than 250 (except for steam at any pressure).

The main regulations relevant to operators of pressure systems are regulations 7 to 15. Regulations 4, 5 and 6 are design, supply, and installation duties.

If the pressure system is subject to a lease or hire agreement, then these duties are often carried out by the pressure system owner if they agree to do this in writing (PSSR schedule 2).

Summary information from regulations 7 to 9 is contained in the sub-headings below, and regulations 10 to 15 are listed for information. At the end of each paragraph, it is noted as (*regulatory*) if it is directly from the regulations, (*ACOP*) if it is from the Approved Code of Practice, or (*guidance*) if it is from the guidance accompanying the regulations.

<u>Regulation 7 — Safe operating limits</u>

- The user/owner shall not operate the system before the safe operating limits have been established (*regulatory*).
- A suitable system for recording and retaining information about safe operating limits and any changes to them should be used, and this should be kept up to date (*ACOP*).
- For mobile systems, the owner must provide the user with a written statement detailing the safe operating limits or ensure that this information is clearly marked on the

equipment (*ACOP*). It is recommended that the safe operating limits for mobile systems on hire for short periods are marked on the equipment itself (*guidance*).

<u>Regulation 8 — Written scheme of examination</u>

- The user of an installed system, and owner of a mobile system shall not operate the system or allow it to be operated unless it has a WSE by a competent person (CP), which includes all protective devices, and every pressure vessel and every pipeline where a defect may give rise to danger (*regulatory*).
- The scheme must be drawn up or certified by a CP. The owner shall ensure that the content of the scheme is reviewed at appropriate intervals by a CP, and the content of the scheme is modified in accordance with any recommendations made by the CP arising out of the review (*regulatory*).

<u>Regulation 9 — Examination in accordance with the written scheme</u>

- The user of an installed system and the owner of a mobile system shall ensure that the pressure system in the WSE is examined by a CP within the intervals specified in the scheme and, where the scheme so provides, before the system is used for the first time. They should take all appropriate safety measures to prepare the system for examination (e.g. cooling the system down, isolating the system etc.) and the CP should make a written report of the examination to be provided within 28 days of the examination (*regulatory*).
- The report shall state which parts of the pressure system have been examined, their condition, what repairs or modifications are needed to prevent danger or to ensure the continued effective working of the protective devices, and specify the date by which any such repairs or modifications must be completed or any such changes to the safe operating limits must be made. It should also specify the date within the limits set by the scheme of examination after which the pressure system may not be operated without a further examination under the WSE. There are also further paragraphs about when a postponement of an examination may be considered and appropriate marking on the pressure vessel for when the next inspection is due (*regulatory*).

The other regulations that are most relevant to the user are:

Regulation 10 — Action in case of imminent danger

Regulation 11 — Operation

Regulation 12 — Maintenance

Regulation 14 — Keeping of records

Regulation 15— Precautions to prevent pressurisation of certain vessels

Regarding PSSR issues, Annex 4 of the ACOP (L122)[1] on PSSR states the following:

1. *Very small pressure vessels that are used in educational establishments, e.g. miniature steam engines that are used for demonstration purposes as part of teaching, or pressure cookers and small portable autoclaves used to sterilise equipment and materials for lessons, will usually be classed as 'Minor systems'. Where such pressure vessels are not placed under prolonged duty, it is recognised that proportionate application of PSSR is necessary, however it remains essential that any deterioration in their condition is identified and acted upon in good time.*

2. *Generic written schemes of examination for these pressure vessels are available, for example from educational advisory services such as CLEAPSS (see www.cleapss.org.uk) and the Scottish Schools Education Research Centre, SSERC (see www.sserc.org.uk). If you decide to use a generic scheme, it must still be reviewed individually and certified as suitable by a competent person before the pressure vessels are used. The attributes of the competent person who is certifying the written scheme as suitable should satisfy the practical guidance in paragraph 99(a) for minor systems.*

3. *These pressure vessels must then be examined at the intervals specified in the written scheme. The employer (educational establishment) is responsible for the selection of a suitable person to carry out the inspection to the written scheme. This may include an in-house technician who is suitably knowledgeable and experienced, as described in paragraph 124 of this ACOP. It remains the duty of the employer to ensure that whoever inspects the vessels satisfies the practical guidance in paragraph 124 (this is different from the guidance in paragraph 98), and the general guidance on impartiality set out in paragraph 33.*

Paragraph 124 states:

The competent person should have sufficient practical and theoretical knowledge and actual experience of the type of system under examination to enable defects or weaknesses to be identified and an assessment made of their significance in terms of the integrity and safety of the equipment.

5 Benchtop Autoclaves

The relevant standards on the use of autoclaves in laboratories at the time of this work were: BS 2646:1993 *Autoclaves for Sterilisation in Laboratories* (revised in 2021) [14]; BS EN 12347:1998 *Performance criteria for steam sterilisers and autoclaves* [15]; and PD IEC TR 61010-3-041-2002[16].

CLEAPSS have produced a guidance document for autoclaves and miniature steam engines[17].

Autoclaving is one of the main methods to make inactive the micro-organisms in waste, and to sterilise equipment and media. The process relies on a combination of heat (steam in most cases) and pressure.

Bench-top autoclaves include portable, electric pressure-cooker style autoclaves. The sizes start at volumes of around 5 litres up to the larger, semi-permanent types with volumes around 60 litres. Steam pressures for larger autoclaves are typically 2.5 bar with temperatures up to around 140 °C. For small autoclaves however, the pressures are around 1.15 bar and temperatures around 120 °C.

Benchtop autoclaves are used in laboratories and schools for the sterilisation of small items of equipment, typically surgical implements. The autoclaves examined for this research consist of a pressure vessel, with removable lid, into which a basket containing the equipment to be sterilised can be placed. A small volume of water is added to the vessel, which is heated into steam by an element encapsulated into the base. Once at the appropriate temperature, the autoclave maintains the temperature for a pre-programmed duration, typically 15 to 25 minutes, alerting the user once the cycle has been completed. The scope of this research covered one model of autoclave from one manufacturer, see Figure 58.

Figure 58 Benchtop autoclave, features noted in brackets denote secondary function

Three autoclaves, one new, two second-hand, were purchased for testing and examination. The new machine and one of the second-hand machines were of the same model type, but exhibited slight differences, as may be expected from model evolution over time. The second second-hand machine was fundamentally of the same design, but was of a slightly higher specification, having a thermometer and pressure gauge installed on the lid.

All three machines incorporated the following mechanical safety features:

- Anti-vacuum valve (pressure indicator). This valve remains open when there is no positive pressure in the vessel, preventing the formation of a vacuum in the vessel during cooling and lid removal. A secondary feature of this device is that once positive pressure is present in the vessel the brightly coloured valve stem rises, indicating the presence of positive pressure to the user.
- Pressure relief valve (depressurisation valve). This valve relieves the pressure in the vessel if excessive pressure builds. A secondary feature of this device is that by rotating the actuator, it can be manually overridden to vent pressure from the vessel. The instructions advise that this should be opened when removing or refitting the lid and closed during testing.
- Steam relief port. In the event of operation of the pressure relief valve (manually or automatically), steam is ducted through the handle to a port situated to the side of the lid, away from the manual control of the pressure relief valve and handle.
- Gasket extrusion slot. A circumferential slot cut into the rim of the gasket groove provides a weak point in the circumferential support of the sealing gasket, which lies between the upper (lid) and lower (base) portions of the vessel. If the pressure relief valve fails to operate, the gasket is forced through this slot (extruded) by the internal pressure acting upon it, relieving the pressure in the vessel.

  The new machine also incorporated the following safety feature:

- Thermal interlock. A locking pin situated in the handle on one side of the base section which prevents the lid from being opened until the base has cooled sufficiently for all steam to have been relieved. As this feature was only present in the new machine, it was not possible to observe the functionality of this device in the second-hand machines.

5.1 Electrical Safety Devices

The power to the heating element is controlled using a triac, which is in turn controlled by a PCB that measures the temperature of the Benchtop autoclave using a temperature dependant resistor (thermistor). The thermistor is located on the base of the Bench autoclave where the heating element is permanently moulded into the bottom of the autoclave chamber.

The electrical control system has no way of measuring the pressure within the autoclave chamber and infers the pressure within the autoclave chamber by measuring the temperature of its metal base and the fixed volume of the chamber.

The non-resettable thermal fuse is crimped in series with the brown (line) supply wire from the kettle plug and the markings on the device indicated that it was rated for 220/240 V and would melt at 152 °C. The non-resettable thermal fuse was in contact with the metal base of the autoclave close to the embedded heating element. The instructions state that the non-resettable thermal fuse would *‘melt at a pre-determined temperature, disconnecting the power’*.

There were also two 10 A ceramic fuses in the line and neutral to the PCB.

In summary, the line (brown) side of the heating elements are supplied with power via a kettle lead socket then:

a. a non-resettable thermal fuse in the supply; then

b. a 10 A ceramic fuse on the PCB; then

c. a triac mounted on the PCB to the line side of the heating element.

The neutral side of the heating element is supplied with power from the kettle lead socket then:

a. a 10 A ceramic fuse on the PCB; then

b. the PCB to the neutral side of the heating element.

The non-resettable thermal fuse should be considered as an electrical safety device in this case as it provides a function similar to the over-temperature switch in café boilers.

BS 2646[14] defines this type of Benchtop autoclave as a type 4, *“Steam produced from water contained within the autoclave chamber and heated by means of an electric immersion heater”*. This standard gives guidance on the control of the door safety mechanisms by electrical and electronic (programmable) means but not the overall control of the pressure within the autoclave using electrical control. This is achieved with mechanical devices, i.e. a PRV.

In PD IEC TR 61010-3-041-2002[16] in Section 13.2 Explosions and implosion, it states:

> *“13.2.1 Components - Components liable to explode: – pressure release device or – the apparatus incorporates OPERATOR protection (see also 7.5) Pressure release device: – discharge without danger – not obstructable”*

This does not state anything about electrical control so it would not be required for CE marking.

However, the non-resettable thermal fuse would prevent excessive build-up of pressure by melting if the temperature of the base of the autoclave reached approximately 152 °C. Therefore, this is an additional safety feature above what is required.

The autoclaves were prepared electrically by connecting the heating elements directly to a single-phase 240 V a.c. supply, thus bypassing the non-resettable thermal fuse.

5.2 Pressure-to-failure Approach (Including Operational Tests)

One second-hand autoclave was selected for metallurgical examination and was not subjected to operational or overpressure testing.

5.2.1 Operational Test Methods

Due to the lack of accessible ports on the new autoclave, it was not possible to connect a pressure transducer to this machine for the operational test without making significant modifications. Therefore, it was decided to carry out the test without the pressure transducer as the machine was brand new and unmodified. While available ports were present on the second-hand machine, one of these was already fitted with a thermometer and one with a pressure gauge. However, as there would be no data from the test from the new machine to compare with pressure data from the second-hand machine, it was decided not to fit a pressure transducer to the second-hand machine as well. Both machines were fitted with a thermocouple (uncalibrated for indication only) to the base, prior to operational testing.

Operational testing of the machines was carried out in the laboratory, during which the function of electrical and mechanical safety devices was assessed, and operational parameters for temperature were recorded. PRVs were removed from the machines and their operation pressure was measured using a pressure calibrator which was calibrated to UKAS accredited standards. The pressure rating for these PRVs is around 1.8 bar. The PRVs for all three autoclaves were found to be functional and lifted at pressures between 1.74 and 2.0 bar. They were reinstalled on the two autoclaves that were to undergo operational and overpressure tests. An electrical inspection was also undertaken to assess whether the machines' controls were functioning correctly and whether wiring was in a safe condition. Any faulty safety-critical components were replaced if necessary. Operational testing was only carried out if all assessments were passed (or could be passed by replacing components).

Instrumentation was connected during operational tests to provide data for the test officers to ensure that the machines were operating within safe limits. The new machine was tested first to provide data from which to assess whether the second-hand machine was functioning within the parameters recorded for the new machine.

5.2.2 Overpressure Test Methods

For the overpressure tests, the PRV was removed, and a pressure test point was fitted to this port, which is situated on the lid in the upper, steam portion of the vessel. A 1 m length of high temperature, stainless steel braided test hose was connected between the test point and a 100-bar pressure transducer. This remote coupling arrangement was chosen to allow dissipation of heat between the vessel and the pressure transducer.

The manufacturer had informed the authors that the electrical control system could be over-ridden by removing the thermistor from the base of the autoclave. With no means of detecting the temperature of the vessel, the heating element would remain live as the control circuit would not be informed when the target temperature had been achieved. The thermistor was secured on two studs by nuts and washers with flexible putty between the thermistor and surface. The cable to the thermistor was also secured by a clamp fitted to a third stud. The thermistor and clamp were removed, as instructed by the manufacturer, but no other modifications were carried out.

An additional thermocouple (uncalibrated, for indication only) was fitted to the lid of the autoclaves, and the thermocouple previously fitted to the base was relocated to allow it to be clamped to the base by the cable clamp which had previously been used to secure the thermistor cable. These and the pressure transducer were connected to the data logger to allow monitoring and recording of boiler pressure and temperature throughout both overpressure tests.

A 100-bar pressure transducer was connected to a data logger and calibrated using a Budenburg dead weight pressure calibrator which was calibrated to UKAS accredited standards. This transducer had been used previously for overpressure testing of the café boilers. It was re-calibrated to ensure that it had remained fully operational prior to the test being undertaken.

Both machines were filled with water to the fill-level marking within the interior of the vessel (750 ml). To commence testing it was necessary to manually press the cycle start switch on the autoclaves. No other intervention was required to generate the overpressure within the autoclaves.

Testing was carried out using the same outdoor facility as was used for the café boilers as described in section 2.4.2. A standard speed video camera was used to video the test. Data from the pressure transducer and thermocouples was recorded.

5.2.3 Overpressure Test Results

Autoclave 14427 (new)

Maximum pressure at failure: 5.68 bar (0.38 bar offset at zero)

Maximum temperature of lid: 139.4 °C (at failure)

Maximum temperature of base: 97.1 °C (96.1 °C at failure)

Images taken from the video of the test are shown in Figure 59.

The autoclave was placed in the test facility, and for safety reasons, secured using a loose fitted fabric sling (inset a). The lid gasket extrusion slot is shown prior to the test in inset b. The sequence of frames from the video footage, shown in insets c, d, e, and f depict the failure. The lid gasket was extruded through the gasket extrusion slot, which allowed a jet of steam to escape rapidly, overturning the autoclave and displacing it from its original position. This distance was not measured, although the board upon which the autoclave was positioned at the start of the test measured approximately 1 m along the longest edge (left to right in the images). The final resting position is shown in inset g, note that the restraint remains slack. Note also the dark patch resulting from the ejected water and steam on the right-hand wall of the test facility.

Observation immediately after the test revealed that the lid gasket had split when it was extruded through the gasket extrusion slot (inset h).

Figure 59 Overpressure testing of new autoclave 14427

Upon removal of the lid after the test, it was found that the internal basket had also been reshaped, see Figure 60. No fragmentation of the autoclave occurred, although visually some doming of the lid section was observed.

Figure 60 **Deformation of internal carrier basket, new autoclave 14427** ***(Image No. AIS 1604043_024)***

Autoclave 14426 (second-hand)

Maximum pressure at failure: 3.556 bar (0.39 bar offset at zero)

Maximum temperature of lid: 133.1 °C (133.0 °C at failure)

Maximum temperature of base: 140.5 °C (at failure)

Images taken from the video of the test are shown in Figure 61. The second-hand autoclave was placed in the test facility (inset a) and was not secured, as the previous test had demonstrated that the risk of the lid section becoming detached was low. The gasket extrusion slot is shown, prior to the test, in inset b. The sequence of frames from the video footage, shown in insets c, d, and e, depict the failure as the lid gasket was displaced between the lid and base into the gasket extrusion slot. This allowed steam to escape beneath the seal in a controlled manner. Steam was observed exhausting in a downward direction, displacing the insulated jacket (inset f). The autoclave did not move during the release. Observation after the test revealed that the seal had remained largely intact but was partially ejected through the gasket extrusion slot (inset g). However, a small split was evident to one portion of the seal at the point at which it had displaced (inset h).

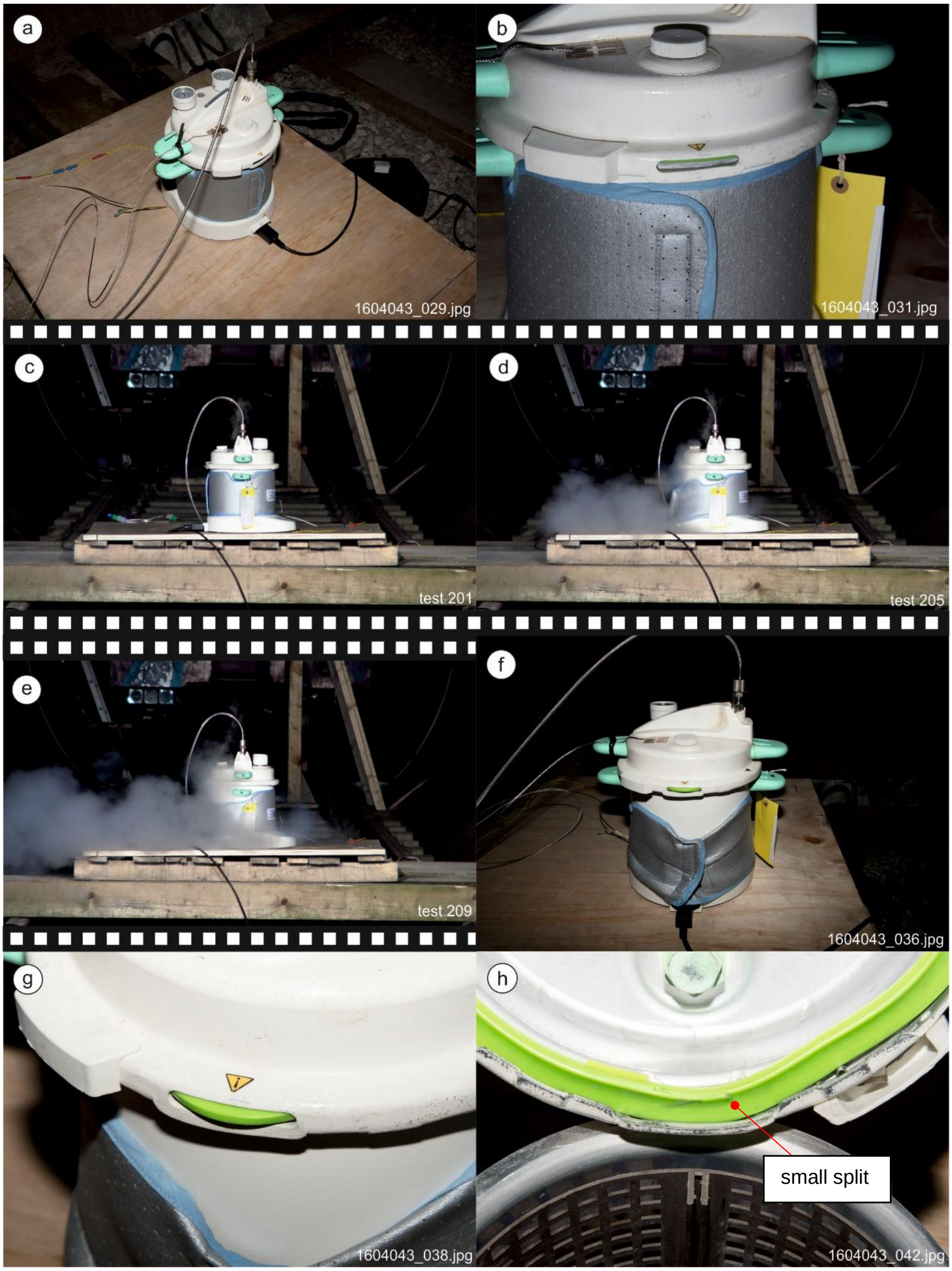


Figure 61 Overpressure testing of 2nd hand autoclave 14426

For the autoclaves to be exposed to pressures of this magnitude the following conditions would first be required:

- failure of the temperature control system (the temperature sensor (thermistor), the PCB or the triac) so that power is continued to be supplied to the heating element no matter what temperature is achieved;
- the pressure relief valve would have to fail to open, or fail to open sufficiently;
- the autoclave would have to be left switched on long enough for the pressure to build within the boiler. From the tests, it took about 18 minutes of continuous heating before failure occurred for the new autoclave.

It is possible that these failure conditions could arise in-service. However, it is unlikely that all failures could occur at the same time providing the machines are regularly inspected and maintained by a competent person.

Although the energy released is much lower in this type of autoclave when compared with the café boilers, there is still potential to cause serious burns and impact injuries if a person is close to one of the autoclaves when it fails.

5.3 External and Internal Visual Examination of the Autoclaves

5.3.1 New Tested Autoclave (Sample no. 14427)

The autoclave comprised a cast aluminium chamber, with an integrated heating element. The mean wall thickness of the chamber was 2.86 mm and nominal internal diameter 210 mm. On the outer rim of the chamber were six outward facing lugs which were the means of securing it to the cast aluminium lid by engagement with the six reciprocal, inward-facing lugs on the lid. After testing, the interior of the vessel was smooth and matt grey with slight speckle staining on the base. The whole assembly was bright and clean and mounted within a moulded plastic base with no measurable distortion to the metal components.

Two components from within the autoclave had been damaged during pressure-to-failure testing. These were the reinforced polymer basket within which instruments for sterilising would have been placed, and the green elastomeric gasket used to create the steam proof pressure seal between the lid and chamber. The gasket had ruptured in one location at an oblique angle, Figure 62. The basket had become heavily distorted at one location on its top edge into a spout shape, Figure 63. From the shape of the deformation it was evident that the distortion had been generated by impingement/extrusion of the basket with a slot in the lid, understood to be part of the pressure relief mechanism.

Figure 62 Ruptured gasket from autoclave 14427 ***(Image No. P1012991.jpg)***

Figure 63 Distorted basket from autoclave 14427 ***(Image No. P1012985.jpg)***

5.3.2 Second-hand Tested Autoclave (Sample no. 14426)

The chamber and lid for autoclave 14426 was identical in design and construction to the new one, although the mean wall thickness was slightly larger being 3.00 mm. Only with respect to the plastic base and basket design did it differ to any great extent. The machine is shown (post-test) in Figure 64. The base of the chamber was coated with localised powder deposits and more general staining and deposit, Figure 65.

Figure 64 Components of 2nd hand autoclave 14426 after overpressure testing ***(Image No. P1013005.jpg)***

Figure 65 Base of 2nd hand autoclave 14426 after overpressure testing ***(Image No. P1012998.jpg)***

Using stereo microscope examination, small corrosion pitting features could be seen at the water line of the chamber and underneath the localised white powder caps on the base, Figure 66 and inset.

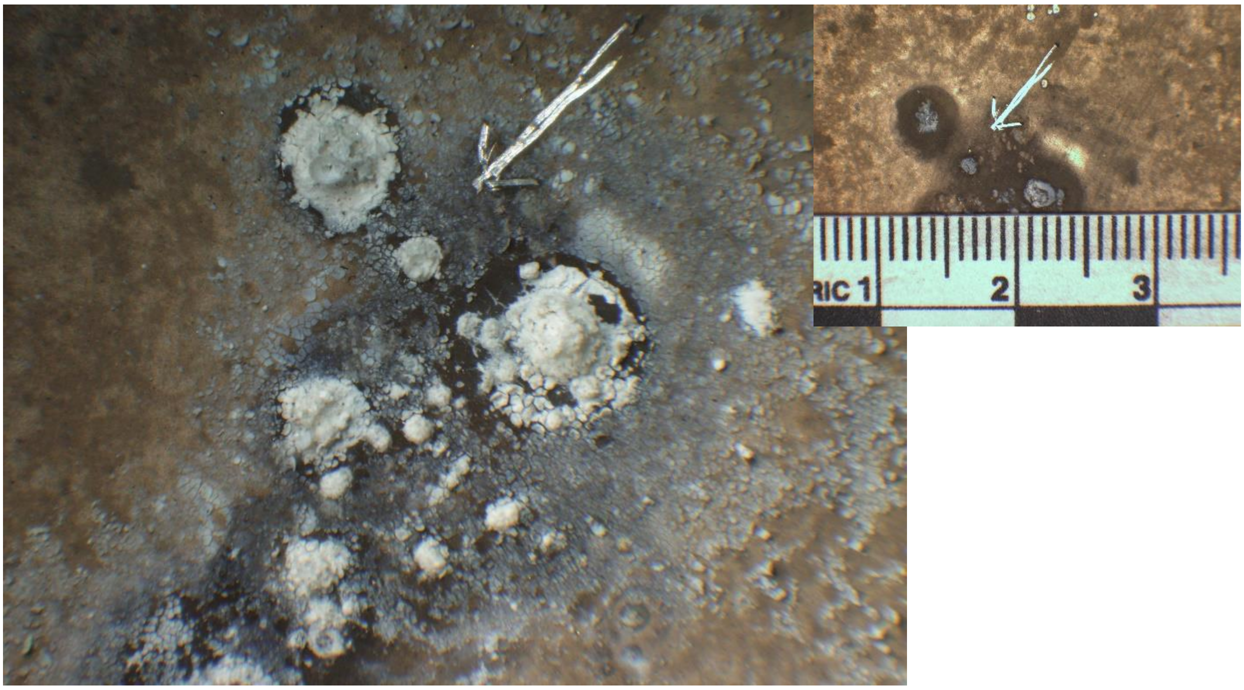


Figure 66 Showing powdery caps overlying pits (inset) in base of autoclave 14426
(Image No. 14426-5,and -7.jpg)

EDS analysis of both the localised white powder residues and the more widespread deposits revealed them to be primarily oxides (or more probably hydrated oxides) of aluminium, with significant percentages of sulphur between 2.2 wt % and 3.7 wt %.

The pressure-to-failure test on this machine produced less damage than in the new machine. In this instance the basket had remained intact, but the seal had acquired a small 7 mm long slit in its underside.

The electrical supply fittings in the plastic base of the machine appeared to have been subject to heat damage as shown in Figure 67.

Figure 67 **Heat damage to electrical fitting (arrow) in plastic base of autoclave 14426** ***(Image No. P1013001.jpg)***

5.3.3 Second-hand Un-tested Autoclave (Sample no. 14425)

This vessel was identical in design and construction to the new machine, sample 14427, which had been tested. The interior of the chamber was smooth, with only minor yellowing of the surface and negligible deposits on the base. The basket and green gasket were intact and in good condition.

5.4 Autoclave Failure and Degradation Mechanisms

Both tested machines underwent overpressure release by the design mechanism that was intended – the extrusion of the elastomer gasket through the overpressure slot in the lid. Both autoclave chambers and lids remained intact and, other than damage to the gaskets (and for the new autoclave, its basket) the machines failed in what would be construed as the designed manner. Whether the pressure at which the failure occurred was appropriate in terms of its reach and implication to personnel in its vicinity to the reach of the released steam is a matter for further discussion.

Internal degradation has been observed in the form of pitting corrosion in the base of the vessel. This has most likely arisen as a consequence of not using distilled water; so mineral compounds containing sulphur[16] have been deposited out of the evaporated water.

[16] As identified by EDS analysis of the corrosion product

5.5 Implications for Safety (Electrical)

The mechanical safety features, i.e., the lid gasket failed releasing the pressure within the benchtop autoclave in both operational tests before the base temperature reached the 152 °C required to melt the non-resettable thermal fuse.

The autoclave has metal parts of the product that could potentially have a hazardous voltage present if the basic insulation fails. In Class I products all the exposed metal parts need to be bonded to a protective earth, which in this case they are. However, in these autoclaves there is a fuse in both the line and neutral supplies to the PCB and heating element. This is predominantly associated with appliances where the polarity (line and neutral) can potentially be reversed. However, in this case this is not possible due to the UK having polarized sockets/plugs and loss of the neutral fuse, under certain fault conditions, i.e., the neutral fuse has blown, the appliance would appear to be disconnected but would still be connected to the line supply. This could lead the metal parts of the autoclave becoming live and therefore creating an electric shock hazard. This does not comply with BS EN 60204-1:2018 - Safety of machinery – Electrical equipment of machines – General requirements - Section 7.2.3 (Power circuits), which states:

‘Devices for detection and interruption of overcurrent, selected in accordance with 7.2.10, shall be applied to each live conductor including circuits supplying control circuit transformers.

The following conductors, as applicable, shall not be disconnected without disconnecting all associated live conductors:

- *– the neutral conductor of AC power circuits;*
- *– the earthed conductor of DC power circuits;*
- *– DC power conductors bonded to exposed conductive parts of mobile machines.’*

5.6 Supply Information

The supply information for the autoclaves is included with the information on café boilers in Table 4 in section 4.4.3.

6 Miniature Steam Engines

One observation in assessing model miniature steam engines is that the pressure relief valve (PRV) is an *operational* rather than a *safety critical* component. When the water is being heated in the boiler, the operator waits until the PRV is ‘blowing’; then they open the steam valve to operate the cylinder and drive.

Manufacturers often recommend filling the boilers with a large syringe (this gives an indication of water volumes in a model steam engine).

From the Scottish Schools Education Research Centre (SSERC) website, a bulletin written in 1986[19] noted that three serious accidents with miniature steam engines had occurred in the 1980s. However, they were due to liquid fuel fires causing burns, rather than the boiler failing under pressure. The bulletin noted an accident that occurred when a teacher was refilling the fuel trough with methylated spirits thinking the burner had gone out. However, the trough was still hot and the fuel immediately ignited causing a flash fire and burns to a pupil sitting nearby. The bulletin’s recommendation was to only use solid fuel, as recommended by the manufacturers, and not to use liquid fuel in any circumstances.

In the domestic market, miniature steam tractors are owned by enthusiasts, or used as toys. However, they are also used by schools for scientific demonstrations. To provide an indication of the potential risks they may pose in this environment, operational tests and overpressure tests of new and second-hand models were carried out. Only one design of steam model, from one manufacturer, was selected and only three models were purchased: one new, and two second-hand. With such a small sample range, any findings relating to these models should be viewed as indicative only. Figure 68 shows the new model steam engine.

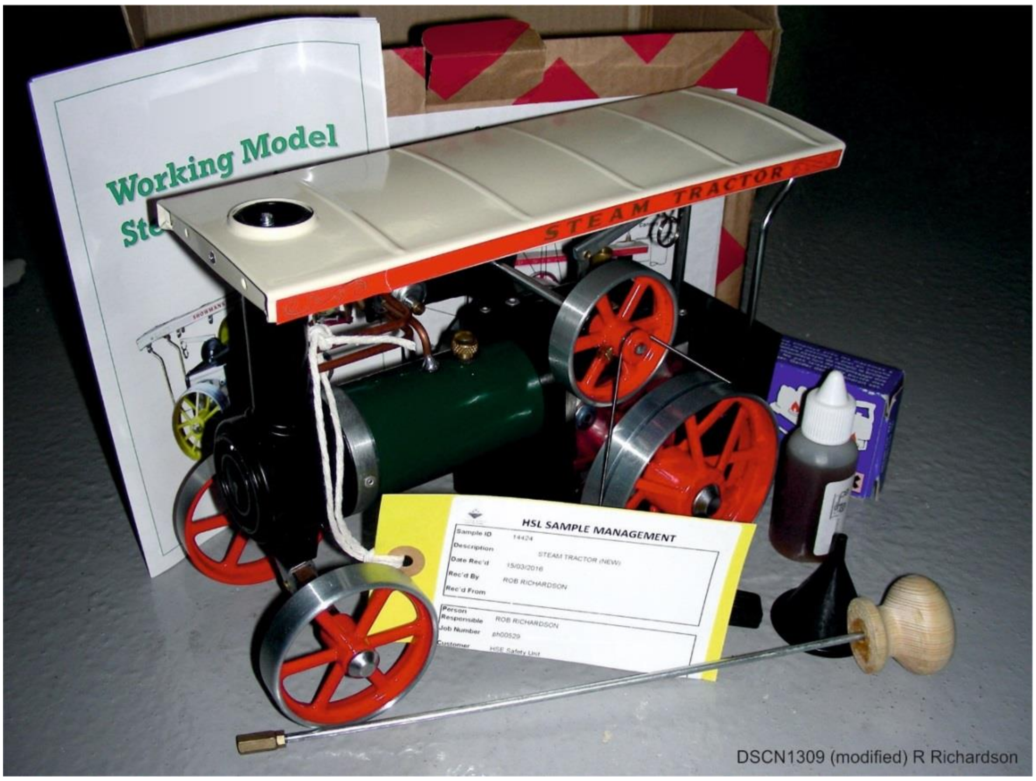


Figure 68 Miniature Steam Tractor (new model 14424), as received

The steam tractors are powered by a small boiler, heated by waxed coated solid fuel tablets (Hexamine), and a single cylinder steam engine, coupled via a sliding interface control valve. The boiler is fitted with a Pressure Relief Valve (PRV), rated at 1.5 bar, and a whistle. The PRV doubles as the filler plug for the boiler.

6.1 Pressure-to-failure Approach (Including Operational Testing)

The packaging for the new model (14424) states the boiler capacity to be 199 cm^3 (0.199 l), however, the test certificate states it to be 1.74 cm^3 (0.00174 l), with a filling volume of 135 ml. The capacity stated on the test certificate is clearly wrong, as 1 cm^3 = 1 ml, therefore the boiler capacity must, at the very least, exceed the 135 ml filling volume. Even if the number should read 174 cm^3 instead of 1.74 cm^3, there is still a discrepancy of 25 ml.

During operational testing, it was found that filling to a volume of approximately 100 ml was sufficient to reach the maximum level mark on the sight glass of the new model (14424). The second-hand models were not fitted with a sight glass, but instead have an overflow port. When the water level reaches the port, water flows out, preventing overfilling (assuming the model to be level). This was also found to occur at around 100 ml on model 14423.

Using fuel tablets (the user instructions state *'two only'* should be used) a finite resource of fuel is available to heat the boiler. This is quite different to the continuous supply of electricity available to café boilers and autoclaves. Therefore, to provide the greatest opportunity for excessive pressure within the boiler within the burn time of the fuel tablets, some advice was taken from the instructions.

The instructions supplied with the new model (HSE SD sample no. 14424) recommend that the boiler is flushed out with boiling water prior to each run. The instructions supplied with one of the second-hand models (HSE SD sample no. 14423) recommend that for a longer run, the boiler can be filled with boiling water. These two recommendations were followed, prior to both operational and overpressure testing. It was considered that flushing the boiler with boiling water would pre-heat the boiler. However, as this process would also cool the water, this water was then drained out and replaced with fresh near boiling water. In this way the least amount of energy would be required from the fuel tablet to heat the water to the required temperature for steam to be produced.

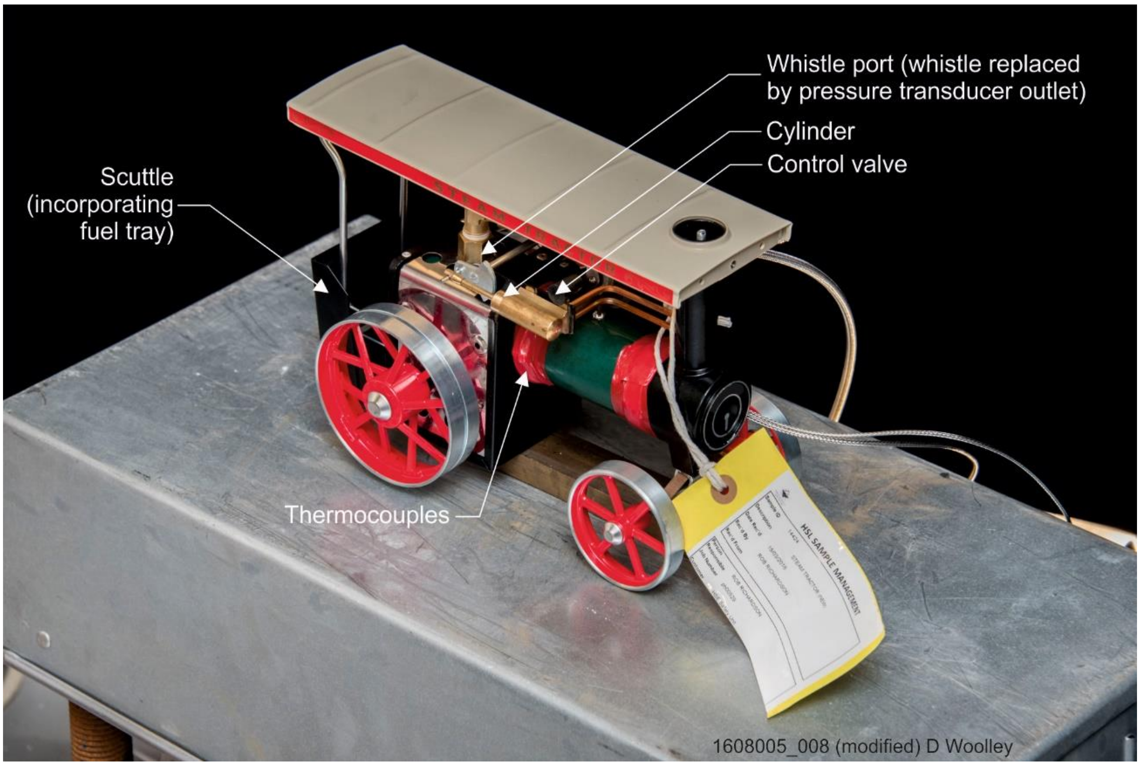


Figure 69 Miniature Steam Tractor (new model 14424), prepared for testing

Both models allocated for operation and overpressure testing were fitted with thermocouples. One was fitted to the top surface of the boiler, between the PRV (filler) and the bulkhead. A second thermocouple was fitted to the bottom surface of the boiler, directly beneath the first.

The whistle was removed from both models and the port into which it had been attached was used to attach a pressure test point, allowing a pressure transducer to be coupled via a test hose.

6.1.1 Operational Test, New Model (HSE SD Sample No. 14424)

The new model was oiled, as directed by the instructions, and the piston placed at top-dead-centre, to prevent operation of the steam engine. The boiler was preheated and filled as described in Section 6.1 to the maximum level of the sight glass. With the PRV (filler) replaced, two fuel tablets (supplied with the new machine (14424)) were installed in the fuel tray and ignited using a small gas torch.

The fuel tray and scuttle were inserted into the firebox and the data logger was started. After some time, the model achieved a pressure of approximately 1 bar, at which point a minor vent of steam was observed from the piston and valve.

Pressure continued to build, despite small volumes of steam and water escaping from the piston. PRV leakage occurred from approximately 1.3 bar, with venting occurring from approximately 1.4 bar.[17] Temperatures of approximately 123 °C and 115 °C occurred at the bottom and top of the boiler respectively. No further pressure increase was observed, so the engine was run to check operation.

The engine was stopped, and pressure rebuilt to approximately 1.1 bar. At this point leakage through the PRV and depletion of fuel tablets prevented further pressure from building.

6.1.2 Operational Test, Second-hand Model (HSE SD Sample No. 14423)

The second-hand model was oiled, as directed by the instructions, and the piston placed at top-dead-centre, to prevent operation of the steam engine. The boiler was preheated and filled as described in Section 6.1 until excess water drained from the overflow port. With fill ports replaced, two fuel tablets (supplied with the new machine (14424)) were installed in the fuel tray and ignited using a small gas torch.

The fuel tray and scuttle were inserted into the firebox and the data logger was started. After some time, the model achieved a pressure of approximately 0.9 bar, at which point a minor vent of steam was observed from the piston and valve.

The pressure reached approximately 0.94 bar before it started to vent through the PRV. Maximum temperatures of approximately 114°C and 88.4°C were observed at the bottom and top thermocouples respectively. The engine was run to reduce the pressure, and in so doing allow the PRV to reseal. Despite this, after the engine was stopped, pressure failed

[17] In this work, leaking is defined as minor incidental expulsions of water (‘popping’ and ‘spitting’); venting is defined as a continuous expulsion of steam at a regular rate

to build beyond approximately 0.78 bar. This process was repeated, but a pressure of approximately 0.84 bar was the maximum achieved, with leakage observed at the PRV.

After the fuel tablets had burnt out, and the model cooled, the pressure test point and PRV seals were replaced. The test was repeated, but a maximum pressure of approximately 0.7 bar was achieved before venting through the PRV was observed. A peak pressure of approximately 0.84 bar was achieved throughout the test, and leakage through the PRV was still observed as pressure dropped to approximately 0.3 bar as the fuel tablets burnt out.

6.1.3 Overpressure Test, New Model (HSE SD Sample No. 14424)

Overpressure testing was carried out in a similar manner to the bench testing, with the exception that the PRVs were replaced with M6 socket cap head screws. Unlike the café boilers, these blanking plugs could not be sealed with thread lock as it was necessary to remove and replace them to fill the models with hot water during testing. Also, as the pipework had been attached to the boiler directly by welding, the pipes could not be removed and replaced with blanking plugs as they had been during the café boiler testing, thus the steam control valve and piston remained coupled to the boiler.

As the safety device had been removed, testing was carried out in one of HSE SD's blast chambers. In the blast chamber the model could not be observed by eye, and no interaction with the models could take place after the tests had commenced. The piston was placed at top-dead-centre to prevent operation of the engine during testing.

The boiler was preheated using a flush of hot water, which was then drained and the boiler filled with 100 ml of near-boiling water. The blanking plug was replaced and the fuel tablets lit and placed within the firebox.

Temperature and pressure data were recorded and monitored using the data logger. A video camera was set to record the test from within the chamber, however, on this first test the camera failed to provide an image to the monitor in the control room, so the test could not be observed live.

During this first test the model failed to generate pressure over 1.1 bar, which was lower than the pressure it had generated during operational testing. The exact cause was unknown, but after the test, the blanking plug was removed and fitted with some PTFE tape and a new rubber washer. The test was then repeated from the beginning.

Temperature and pressure data were recorded and monitored by the data logger and a live visual feed was observed from the video camera. Upon achieving working pressure (1.5 bar), some steam was seen to be venting from the chimney and passing the piston to vent from the cylinder. As pressure continued to build, steam was observed to be continuously venting through the exhaust from approximately 1.7 bar. A maximum pressure of 1.82 bar was recorded, with temperatures of 127 °C and 124 °C at the bottom and top of the boiler respectively.

6.1.4 Overpressure Test, Second-hand Model (HSE SD Sample No. 14423)

The boiler was preheated using a flush of hot water, which was then drained and the boiler filled with 100 ml of near-boiling water. The blanking plug, which had been pre-fitted with PTFE tape, was replaced and the fuel tablets lit and placed within the firebox.

Temperature and pressure data were recorded and monitored using the data logger. A video camera was set to record the test from within the chamber and the footage was observed live on a monitor in the control room.

Upon achieving working pressure (1.5 bar), some steam was seen to be venting from the control valve and passing the piston to vent from the cylinder. As pressure continued to build, steam was observed to be venting continuously through the exhaust from approximately 1.6 bar. A maximum pressure of 1.66 bar was recorded, with temperatures of 129 °C and 123 °C at the bottom and top of the boiler respectively.

6.2 External and Internal Visual Examination of a Second-hand Miniature Steam Engine (HSE SD Sample No. 14422)

From the test results in section 6.1, it is considered that there are no significant safety concerns from overpressure of these miniature engines. This is because a situation of dangerous overpressure cannot be reached as fuel supply is finite and not continuous, the boiler vessel has a small capacity, and inherent leaks in the steam lines prevent the build-up of pressure.

In the light of these observations, internal examination of a steam engine was not carried out.

7 Conclusions

Small steam pressure vessels (such as café boilers, steam cleaners, bench-top autoclaves, and miniature steam engines) are commonplace in the hospitality, service, and educational sectors. A serious incident occurred when the boiler of an espresso machine (café boiler) in a café over-pressurised and failed catastrophically, putting staff and customers at risk of serious injury. This incident showed what the consequences of failure of a small steam pressure vessel could be, and the importance of carrying out this work. The aims of the work are to understand how the safety control mechanisms function on three small types of pressure vessel (café boilers, bench-top autoclaves, and miniature steam engines), and the failures that would occur if these controls did not operate and the machines over-pressurised (as happened in the incident). Overpressure was generated within each boiler by filling them with water, then operating the heating elements continuously. Bench-top autoclaves and miniature steam engines are often used in schools. These were included in the work scope to better understand the safety risks to staff and pupils if they were to fail in an over-pressurised state.

A secondary aim was to review the supply legislation and manufacturers' response to it in their documentation.

For the café boilers, four manufacturers were selected: one new machine and two second-hand machines were purchased from each manufacturer (12 machines in total). One second-hand machine from each manufacturer was selected for metallurgical examination; the remaining new and second-hand machines (eight in total) were over-pressurised to failure in a confined space (a tunnel), and then given a metallurgical examination after the tests. In one case, the dangerous condition of the electrical circuit of the second-hand machine that had been selected for pressure testing meant that it had to be changed for the other second-hand machine of the same manufacturer, and the machine with the unsafe electrics was used for metallurgical examination instead. The remaining new and second-hand machines from each manufacturer (eight in total) were pressure tested.

Three bench-top autoclaves from one manufacturer were purchased: one was new, and the other two were second-hand. One second-hand autoclave was selected for metallurgical examination; the other two were pressure tested and then given metallurgical examinations. Likewise, for the miniature steam engines, one new and two second-hand engines were purchased from one manufacturer.

7.1 Electrical

7.1.1 Café Boilers

The machines typically required an electrical supply of between 4 kW and 7 kW. Some of the machines purchased were configured for a single-phase 230 V supply (up to 30 A), others were configured for three-phase 415 V. Typically the machines could be converted to operate on either supply.

The electronic control system was bypassed to ensure that power to the heating elements did not cut out during testing. This was achieved by connecting the heating element directly to the power source, passing only through a purpose-built external remote switching unit. Overpressure was generated within the boiler by operating the heating elements continuously.

The over-temperature switch, that disconnects the power directly from the heating elements, appears to be part of the safety circuit, which also includes the PRV.

It was not possible to calculate the required performance level (PL_r) as the failure rate for the components was not available. However, using Figure A.1 — Risk graph for determining required PL_r for safety function in BS EN ISO 13849-1:2015 – Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design, then the following observations can be made:

All the café boilers except one complied with a Category 3 control system as defined in BS EN ISO 13849-1:2002015 – “Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design.” The one that did not comply had a Type 2a control system.

The control methodology of the Type 2a machine used the over-temperature switch to control a contactor that could then control power to the heating elements. This is not ideal as it is not monitored and could potentially fail in an energised state thus rendering the over-temperature switch ineffective. This appeared in only one manufacturer’s model assessed and was not present in a newer model in the same range.

Operational tests of all but one of the over-temperature switches proved that they were functional at approximately the operating temperature stated on the devices.

There were some defects in the electrical control and safety of some of the second-hand café boilers that were examined. In one case the over-temperature switch had failed in a dangerous condition, i.e., it would not open if an over-temperature was present. In another case the condition of the café boiler would have led to a potential shock hazard due to the condition of its wiring if it had been connected to a mains supply. These defects were not present in any of the new café boilers. This highlights the importance of the café boilers’ electrical control systems being examined and tested at regular intervals. Regulation 8 of the Pressure Systems Safety Regulations requires that the written scheme of examination includes all protective devices.

7.1.2 Autoclaves

Under manufacturer's guidance, the autoclave's electrical control system was over-ridden by removing the thermistor from its base. With no means of detecting the temperature of the vessel, the heating element would remain live as the control circuit would not be informed when the target temperature had been reached.

Only three autoclaves were examined, and all had non-resettable thermal fuses in the line supply to the PCB that supplied the heating elements. The autoclaves have a PRV and a gasket (which is designed to extrude through a slot on the lid) to protect against over-pressurisation.

However, inclusion of a fuse in the neutral supply to the heating element could give rise to a potential shock hazard if the neutral fuse blows leaving the live supply to the autoclave intact. This does not comply with BS EN 60204-1:2018 - Safety of machinery. Electrical equipment of machines. General requirements - Section 7.2.3.

7.2 Mechanical

7.2.1 Café Boilers

All the boilers were fitted with two types of mechanical safety device:

- a pressure relief valve – the operating pressure and flow rate of the PRV must be matched to the boiler. For this reason, some machines with larger boilers were fitted with two PRVs to ensure that sufficient flow rate was provided to adequately dump the required volume of steam.
- an anti-vacuum valve **–** this device prevents a vacuum from occurring within the boiler, and its purpose is to protect the equipment from damage rather than protecting people.

Before overpressure testing, a pressure transducer was fitted to each machine. Thermocouples were fitted to the top and bottom of the boilers. The thermocouples and the pressure transducer were connected to the data logger to allow monitoring and recording of boiler pressure and temperature throughout the tests.

Operational tests were carried out first to assess the electrical and mechanical safety devices.

PRVs were removed from the machines and their operation pressure was measured. The manufacturers' rated pressures for these PRVs were from 1.8 to 2.1 bar. Of the ten pressure relief valves that were tested, three did not lift until a pressure above the rated pressure was applied (2.8 bar, 3.5 bar, > 5.1 bar). The latter case is significantly higher than the rated pressure. For two valves, after the initial test, the following relief tests showed the valves operating closer to their rated pressures (2 bar to 2.4 bar). In a sample of ten relief valves, three failures are significant. As it is likely that the relief valve in the café boiler incident did not function, or did function but not sufficiently to allow sufficient steam flow to relieve the pressure in the boiler, then assessing the function and condition of PRVs during vessel inspection is clearly very important.

In the eight overpressure tests, five boilers failed catastrophically at pressures between 19 bar and 28 bar. If a person had been close to these machines when they failed, it is quite possible they would have suffered serious or fatal injuries. Of the five that failed catastrophically, four were new machines and one was a second-hand machine.

For the five boilers that failed catastrophically, much of the metal panelling and covers had been distorted due to the pressure release, and some pieces had travelled several metres from the machine. Pieces of debris were scattered from about 20 m behind the machine to 15 m in front of the machine. Some fragments (particularly those ejected at an angle of around 30° to 60°) would have travelled considerably further if they hadn't struck the tunnel wall.

For the three boilers that failed through a gradual release of steam, the final pressures were 18 bar to 23 bar. During post-test examinations, cracks were observed near the ports (discussed further in Section 7.3).

As the PRVs are designed to relieve the pressure at about 2 bar, and failure pressures were in the range of 18 bar to 28 bar for all the boilers tested, all vessels failed at pressures at and above ten times their relief pressures.

For the café boilers to be exposed to pressures of this magnitude the following conditions would first be required:

- the electrical control system would have to have a series of failures depending on the control system Type allocated to it in this report. The electrical safety device has been designated as the over-temperature switch. However, for this to be activated several concurrent failures would have to occur and remain in place. For example, in a Type 2b control circuit the contactor and MOSFETs or triacs (or the PCB controlling them/pressure sensor), would have to fail AND then the over-temperature switch fail for the power to remain to the heating elements indefinitely;
- the pressure relief valve would have to fail to open, or open insufficiently;
- the ancillary components attached to the boiler, such as the pipe connections would have to resist the increasing pressure and heat; and
- the boiler would have to be left switched on, without any steam being vented by the user, long enough for the pressure to build within the boiler. From the tests, it took about 20 to 30 minutes of continuous heating before failure occurred. However, it could take less time than this in use as the tests were outdoors on cool days. So the heat

losses during the tests would have been greater than what they would be in a restaurant or coffee shop.

It is unlikely that all failures would occur at the same time providing the machines are regularly inspected and maintained in a manner where these faults are detected and dealt with.

7.2.2 Autoclaves

As mentioned earlier, three autoclaves were selected from one manufacturer (one was new and two were second-hand). One of the second-hand autoclaves was selected for metallurgical examination and was not pressure tested.

PRVs were removed from the machines and their operational pressure was measured. Both PRVs were found to be functional.

For the overpressure tests, the PRV was removed, and a pressure transducer was fitted to this port, which is located on the lid of the vessel. Thermocouples were fitted to the lid and base of the autoclave. Data from the pressure transducer and thermocouples was recorded.

The new autoclave failed at a pressure and temperature of 5.7 bar and 139 °C. The lid gasket was extruded through the gasket extrusion slot, allowing a jet of steam to escape rapidly, overturning the autoclave and moving it a little less than a metre from its original position. Observation immediately after the test revealed that the lid gasket had split when it was extruded through the gasket extrusion slot. No fragmentation of the autoclave occurred, although some doming of the lid section had occurred.

The second-hand autoclave failed at a pressure and temperature of 3.5 bar and 140 °C. The lid gasket between the lid and base was displaced into the gasket extrusion slot. This allowed steam to escape beneath the seal and downward in a controlled manner. The autoclave did not move during the release. Observation after the test revealed that the seal had remained largely intact but was partially ejected through the gasket extrusion slot. However, a small split was evident to one portion of the seal at the point at which it had displaced.

For the autoclaves to be exposed to pressures of this magnitude the following conditions would first be required;

- failure of the temperature control system – either the temperature sensor (thermistor), PCB, or triac – so that power is supplied continuously to the heating element;
- the pressure relief valve would have to fail to open, or open insufficiently;
- the autoclave would have to be left switched on long enough for the pressure to build within the boiler. From the tests, it took about 18 minutes of continuous heating before failure occurred for the new autoclave.

It is unlikely that all failures would occur at the same time providing the machines are regularly inspected and maintained in a manner where these faults would be detected and dealt with.

Although the energy released is much lower in this type of autoclave when compared with the café boilers, there is still potential to cause serious burns and possibly impact injuries if a person is close to one of the autoclaves when it fails.

7.2.3 Miniature Steam Engines

One design of steam model from one manufacturer was selected and only three models were purchased: one new, and two second-hand.

One observation in assessing model miniature steam engines is that the pressure relief valve (PRV) is an *operational* rather than a *safety critical* component. When the water is being heated in the boiler, the operator waits until the PRV is 'blowing' before opening the steam valve to operate the cylinder and drive.

Manufacturers often recommend filling the boilers with a large syringe. This gives an indication of water volumes (100 to 200 ml) in a model steam engine.

Recommendations are to use a small amount of solid fuel in the fire tray, which will give a finite amount of thermal energy; so once the fuel has burnt, no further energy can be added to the boiler without the operator being involved.

The new model and one of the second-hand models were allocated for operation and overpressure testing and were fitted with thermocouples. The whistle was removed from both models and the port into which it had been attached was used to attach a pressure test point, allowing a pressure transducer to be coupled via a test hose.

The PRVs were replaced with cap head screws. The steam control valve and piston remained coupled to the boiler as the pipe connections could not be removed.

Temperature and pressure data were recorded and monitored using the data logger.

For both models, upon achieving working pressure (1.5 bar), some steam was seen to be venting from the chimney and passing the piston to vent from the cylinder. As pressure continued to build, steam was observed to be continuously venting through the exhaust from approximately 1.6 to 1.7 bar. Maximum pressures of 1.6 to 1.8 bar were recorded, with temperatures of around 125 °C.

In the models tested, as heat cannot be applied continuously to the boiler, and as the boiler fittings do not appear to be designed to withstand pressures above 2 bar, the risk of serious injury to operators of this equipment, under normal circumstances, is low.

7.3 Materials

7.3.1 Café Boilers

The boiler wall thicknesses varied from 1 mm to 1.65 mm. The smaller wall thicknesses were measured on the boilers that had catastrophically failed.

For the pressure testing, five of the eight vessels (four new vessels and one second-hand vessel) failed catastrophically by ductile overload.

The other three second-hand vessels all failed by a slow release of steam. Two of the leaks were associated with the brazed joints at ports and showed that failure through the filler metal had occurred. In one case, a potentially significant factor was noted; this was the presence in the filler metal of gas porosity generated during the brazing process. The other failure had undergone selective oxidation of the copper and phosphorous in the filler metal at the interior of the vessel which may have contributed to weakening of the joint. The third leak failure was associated with the brass fitting in the drain plug rather than the filler metal. The fitting had undergone dezincification with a consequent loss of strength. The discoloured appearance of the crack at the external surface of this fitting, and the surrounding vessel wall indicated that this defect had most probably been present, and had been leaking, prior to the testing. The overpressure testing would however have widened the gap between the crack faces.

Degradation in the form of external corrosion at seals and joints was observed, but it has not been implicated in the failure during overpressure testing.

Unsightly external deposits could be used more as an indicator that the machine requires maintenance or refurbishment, rather than a sign of failure.

Manufacturing quality has not been implicated as a cause of premature failure during pressure testing.

The build-up of lime-scale in the interior of the boiler vessels has not been found, in this exercise, to have had any significant implication for the material integrity of the boiler. Its influence on the control/operation of machine when coating ports, heaters and control instrumentation remains unclear.

7.3.2 Autoclaves

The wall thickness of the two autoclaves tested was 2.8 mm to 3 mm.

When a state of overpressure was reached in both autoclave machines tested, they released the pressure in their designed manner, by extrusion of the gasket through a slot in the autoclave lid.

Corrosion pitting and lime-scale in the base of the second-hand autoclave was indicative that distilled water had not been used in-service.

7.4 Supply Information

The UK *Pressure Equipment Regulations* (1999) (PER) are the adoption into UK law of the EU Pressure Equipment Directive (PED) 97/23. The PED has since been revised by the Pressure Equipment Directive 2014/68/EU. This is now part of UK law as the *Pressure Equipment (Safety) Regulations* (PE(S)R) (2016). However, as this equipment was obtained prior to PE(S)R coming into law, assessment was carried out in accordance with PER.

The equipment manuals for the café boilers were reviewed to determine what supply regulations were used to obtain the CE declaration of conformity.

Three café boilers manufacturers referred to several directives which included the Pressure Equipment Directive PED 97/23/EC, but they did not specifically state which directive was used for the conformity assessment procedure. The autoclave manufacturer has referred to a conformity assessment procedure from the Medical Devices Directive.

One manufacturer has noted that their conformity assessment procedure does not require a (NoBo). This is probably correct as their boiler will probably be in category I, which does not require a NoBo. None of the other three café boiler manufacturers have referred to a NoBo, although as the machines are also likely to be in category I, this is not an issue. The autoclave manufacturer's declaration of conformity states that it is in accordance with the Medical Devices Directive and the Pressure Equipment Directive. They have referred to two Notified Bodies (NoBos) – one in the UK, and one in Canada, but this is not a requirement of the PED for autoclaves of this size.

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9 Glossary

3-Group machine	a café boiler with the ability to dispense coffee through three independent brew heads
ACOP	Approved Code of Practice
Autoclave	a pressure chamber used to sterilize equipment and supplies by subjecting them to high-pressure saturated steam
AWL	above water level
BLEVE	boiling liquid expanding vapour explosion
Brew temperature	the temperature of the water as it is filtered through the coffee. The ideal temperature is 91 to 96°C
BWL	below water level
CLEAPSS	the trade name of the organisation which provides health and safety advice to schools' science departments in England and Wales
CP	Competent Person
Crema	the foam on freshly-brewed coffee (like the head on a pint of beer)
DoC	Declaration of Conformity
EDS	Energy dispersive spectroscopy
Group head or brew head	the coffee outlet on the machine. The hot water passes through a brew handle which consists of a small pot containing the ground coffee
HAZ	Heat affected zone
HSE SD	The Science Division of the Health and Safety Executive
ITC	independent temperature control – this allows a certain amount of cold water to be added to the brewing water. This gives the barista the option to control the brewing temperature and experiment until the ideal temperature has been reached. It also means the café boiler can be run extra hot to give better

	steam and hot water. This can be done because the ITC will cool down the brewing water ensuring that it is not too hot.
MOSFET	Metal-oxide semi-conductor field effect transistor
NoBo	Notified Body
PCB	Printed circuit board
PED	Pressure Equipment Directive 97/23/EC and then revised in 2014 by 2014/68/EU
PER	Pressure Equipment Regulations (1997) – the UK Regulations that enacted the PED 97/23/EC
PE(S)R	Pressure Equipment (Safety) Regulations (2016) – the UK regulations that enacted the revised PED 2014/68/EU
PLC	Programmable logic controller
PL_r	The required performance level of an electrical safety component (BS EN ISO 13849-1)
PRV	pressure relief valve
PS	maximum allowable pressure (bar) as defined in PER and PED
PSSR	Pressure Systems Safety Regulations
SAFED	Safety Assessment Federation
Safety valve	Term used to describe the PRV on a miniature steam engine. When the valve starts to ‘lift’ and relieve the pressure, this indicates the steam is at operational pressure.
SEM	Scanning electron microscopy
SEP	Sound engineering practice (defined in the Pressure Equipment Regulations)
SSERC	Scottish Schools Education Research Centre (Scottish version of CLEAPSS)
SSR	Solid-state relay
Steam wand	A small hose-like device fitted to the front of the café boiler that provides steam to froth the milk for lattes, cappuccinos etc.

Thermistor	an electrical resistor whose resistance is greatly reduced by heating. They are used for measurement and control. In this work they were used by the manufacturers as over-temperature safety switches
Triac	a triac is a voltage bidirectional triode thyristor and can be thought of as relay that can switch a.c. currents.
WSE	Written Scheme of Examination

10 Appendix – Background Information on Café Boilers

10.1 Café Boilers Sold in the UK

Many of the machines sold in the UK are manufactured in Italy. Café boilers have single steam-generating boilers with heat exchanger tubes passing through the boiler to heat the water for the coffee. There are also machines that have dual boilers: one for steam, one for hot water for the coffee. This allows independent control of steam and water pressures and temperatures.

There are machines for lower volume coffee production that produce steam and hot water on demand in a vessel with a pressure below 0.5 bar. The boiler is about the size of a pair of 'cupped' hands. These machines are not widely distributed in commercial premises and are not within the scope of this work

Most coffee retailers lease their machines and the typical lease period is around five to ten years. As part of the lease agreement, the supply company will often take responsibility for servicing the machines. However, they may not provide a written scheme of examination, nor carry out an examination under PSSR. Some suppliers recommend that their customers contact their insurance company for PSSR-related issues. The supplier may carry out joint visits with inspectors to ensure the machine is opened up and re-fitted correctly after examination as they will have the right specification of seals, gaskets etc. that may need to be replaced as a result of the examination. Once the lease period is concluded, then a new or refurbished machine is normally supplied.

Some café boiler suppliers have refurbishing departments to extend the life of machines for as long as it is practical. After that they scrap their machines, and do not normally sell into the second- hand market.

Many of the machines that are beyond the lease period, and beyond refurbishment, will have the valuable metals removed for recycling, and then will go for scrap. One machine supplier stated:

'Once a machine has gone beyond its normal economic usefulness… we use a WEEE-compliance company who strip them down to the component parts and dispose of the parts in the correct manner. They then certify to us the complete disposal of each asset, so we have a complete audit trail of the life of each machine.'

New machines cost between £6k to £9k (2020 prices) depending on the size and sophistication of the control system: some will cost more than this.

On eBay, some companies offer short-term and long-term rental deals for commercial espresso machines for events like parties and conferences.

However, there does appear to be a second-hand market for café boilers that are supplied by some companies, and by individual traders.

10.2 Internal Examination of Pressure Equipment

In clause 8 of schedule 2, part 2 of the current regulations, i.e. the Pressure Equipment (Safety) Regulations (2016)[7], it states:

Means of examination

(1) Pressure equipment must be designed and constructed so that all necessary examinations to ensure safety can be carried out.

(2) Where it is necessary to ensure the continued safety of the equipment, means of determining the internal condition of the equipment must be available (such as access openings allowing physical access to the inside of the pressure equipment) so that appropriate examinations can be carried out safely and ergonomically.

(3) Other means of ensuring the safe condition of the pressure equipment may be applied in any of the following situations—

(a) where the pressure equipment is too small for physical internal access;

(b) where opening the pressure equipment would adversely affect the inside; or

(c) where the substance contained has been shown not to be harmful to the material from which the pressure equipment is made and no other internal degradation mechanisms are reasonably foreseeable.

Therefore, whether a steam-generating boiler should be inspected internally will be a matter for the manufacturer and the notified body (if the vessel is category II or above). The regulations are not prescriptive about this for smaller boilers.

Café boilers such as espresso machines are widely used small steam-based pressure vessels, for instance in the hospitality and service sectors. Bench-top

autoclaves and miniature steam engines are small steam-based pressure vessels widely used in schools and other educational settings. Duty holders must have effective risk control measures in place to prevent vessel failure and protect the public and workers. Legal requirements are in: the Provision and Use of Work Equipment Regulations (1998), the Pressure Systems Safety Regulations, PSSR (2000) and the Pressure Equipment (Safety) Regulations (2016). Control measures include: correct operation, regular inspection, testing and maintenance. However, there was a lack of engineering evidence about the potential for failure of these small vessels in order to determine proportionate risk controls.

This report describes experimental research on a sample of café boilers, bench-top autoclaves and miniature steam engines. The aim is to understand: (i) the safety devices installed and (ii) the failure modes that could occur if the vessels' safety devices failed. The researchers used a sample of new and second hand vessels. They carried out metallurgical inspection and over-pressurisation of the machines. The researchers identified that overheating and/ or overpressure could result in catastrophic vessel failure and an explosive release of energy with flying fragments and scalding steam and water. This has the potential to cause significant injury or death to people in the vicinity. However, the researchers consider that if effective control measures are in place, catastrophic vessel failure is unlikely. The research findings informed the Safety Assessment Federation's Managing the Risks of Café Boilers (2021) and are informing the approach to inspection within schools of this equipment working in liaison with the Consortium of Local Education Authorities for the Provision of Science Services, CLEAPSS.

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