Safety Science 152 (2022) 105761

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

Using systems theory for additional risk detection in boiler explosions in Brazil

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ARTICLE INFO

Keywords:
Accident analysis
Boiler
STAMP
CAST
Systems theory
Labour inspection

ABSTRACT

Recent technological advances have allowed some human activities, including those related to safety, to be automated. However, these advances increased the complexity of sociotechnical systems, representing exponential growth of interactions between humans, computers, machines, and the environment. Moreover, growing productive and economic pressures demand safer and more reliable products and projects, at lower costs and time than those practised by competitors. To cope with this complexity and set of conflicting objectives, the STAMP (Systems-Theoretic Accident Model and Processes) emerged as a novel approach to analyse processes and accidents. In this study, an overview of boiler accidents in Brazil is presented and a causal analysis based on STAMP (CAST) is conducted to revisit one of the worst boiler accidents in the Brazilian scenario. Even without direct participation in the investigations, additional and more relevant risk factors are evidenced. Furthermore, it was found that government agencies generally refrain from reviewing their own control actions contributing to the hazard, limiting their potential improvements. This suggests a need for companies and government agencies to adopt new paradigms of risk and accident analysis and to work together for a systemic safety improvement approach.

1. Introduction

Throughout history, inventions and new technology have often advanced ahead of their scientific underpinnings and engineering knowledge, but the result has always been increased risk and accidents until science and engineering caught up (Leveson, 2012). The appearance of the first boiler versions at the beginning of the 18th century was no different, with countless cases of explosions and deaths (Bazzo, 1995).

Currently, there is a reasonable understanding of thermodynamics, the action of steam pressure on walls, the effect of corrosion, among others, and what measures should be taken to prevent accidents. Nevertheless, explosions of this kind of equipment still occur, causing enormous personal and property damage. Therefore, engineers can no longer focus only on technical issues and ignore the social, managerial, and even political factors that impact safety (Leveson, 2012). On this matter, new approaches and techniques of accident analysis can offer to companies and government agencies the means to improve their occupational safety and health (OSH) policies.

In the last decades, there has been a rapid evolution of models using the systems-theoretic approach to understand accident causation (Hulme et al., 2019), like AcciMap (Rasmussen, 1997; Rasmussen and Svedung, 2000), the Human Factors Analysis and Classification System (HFACS) (Wiegmann and Shappell, 2003; Shappell et al., 2007), the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012) and the Systems-Theoretic Accident Model and Processes (STAMP) (Leveson, 2004; Leveson et al., 2009).

The STAMP model, built on Rasmussen's ideas (Leveson, 2017), allows more complex relationships between events to be considered (e.g., feedback loops and other indirect relationships) and also provides a new way to understand why the events occurred (Leveson, 2012). Moreover, several studies relate the adoption of STAMP with a more comprehensive and reliable analysis; more comprehensive because it helps the identification of additional causal factors or recommendations and more

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https://doi.org/10.1016/j.ssci.2022.105761
Received 15 September 2021; Received in revised form 11 March 2022; Accepted 16 March 2022
Available online 24 March 2022

reliable due to the similarity of causal factors identified by different analysts, when compared to other methods and models, such as AcciMap (Goncalves Filho et al., 2019), FRAM (Salmon et al., 2012; Qiao et al., 2019), Swiss Cheese Model (Hickey and Eikema Hommes, 2013), Fault Tree Analysis – FTA (Zhou et al., 2019), Hazard and Operability Study (HAZOP) (Altabbakh et al., 2014), and others (Raman et al., 2016; Mogles et al., 2018).

STAMP (Leveson, 2012, 2019) has been performed in numerous accident analyses, for instance, the loss of the Brazilian space programme's launch vehicle VLS-1 V03 (Johnson and de Almeida, 2008), the Soma mine disaster (Düzgün and Leveson, 2018), the Korean Sewol ferry accident (Kim et al., 2016), the train derailment at Grayrigg (Underwood and Waterson, 2014), the Deepwater Horizon accident (Pereira et al., 2015) and in hospital events (Leveson et al., 2020).

In the literature, there are several references to the analysis of boiler accidents. However, these studies usually focus on virtual simulations of these accidents (Deghal Cheridi et al., 2016; Taimoor et al., 2019) or on the analysis of physical elements – for example, fracture analysis (Kim, 2017) and stress analysis (Pástor et al., 2020). Although some studies recognize the relevance of human and organizational factors in incidents with boilers (Arjunwadkar et al., 2016; Fernández Blanco, 2017; Baalisampang et al., 2018; Hemmatian et al., 2019; Espejo et al., 2021), to the best of our knowledge, no studies have examined boiler accidents through the lens of causal analysis based on STAMP (CAST). This work addresses this gap in the research, developing a STAMP/CAST analysis which provides a more comprehensive framework and process to assist in understanding a boiler accident process and identifying the systemic factors (Leveson, 2012, p. 349). Beyond technical aspects, CAST provides means to government bodies responsible for issuing safety recommendations aimed at preventing future accidents.

In the last two decades, Brazil has experienced 70 explosions and the same number of fatal victims (an average of 3.5 per year), during boiler operation or maintenance (Ml, 2021). Despite successive investigations and reports of their causes, the prevalence of boiler accidents remains high. The year of 2017 proved to be challenging in this subject in Brazil, with 7 boiler incidents, causing 7 fatal and 5 non-fatal victims (Ml, 2021). Moreover, in 2017, one of the worst boiler accidents occurred in a drill ship off the coast of Brazil, being investigated by several government agencies (BN, 2017; ML, 2017; ANP, 2018; BMA, 2020).

Considering this accident prevalence with boilers in Brazil, the aim of this research is to conduct a CAST analysis of a boiler accident reported by the Brazilian National Petroleum Agency (ANP, 2018) as an alternative to the traditional methods. Therefore, the following research questions arise:

RQ1: What additional recommendations can a CAST analysis obtain when performed over an official accident report?

RQ2: Is there room for improvement in the accident analysis carried out by government agencies, in respect of generating additional recommendations to eliminate or reduce the control actions contributing to the hazard?

To answer these questions, first, this study presents an overview of occupational accidents involving boilers in Brazil investigated by labour inspectors of the Ministry of Labour (ML) in the past two decades, with details regarding the main causal factor for these accidents. Subsequently, a CAST analysis of a boiler explosion aboard the Norbe VIII drillship, killing three workers in 2017, is performed based on the ANP official report to determine the weaknesses in the safety control structure that allowed the loss to occur. General accident investigation data from ML and other reports from the same incident serve as a complement to the official report. Finally, the new recommendations originating from the CAST analysis are discussed.

2. Method

2.1. Data extraction of boiler explosion investigations

The first part of this study presents a descriptive overview of occupational accidents involving boilers in Brazil. All the information concerning boiler accidents in Brazil was extracted from the Labour Inspection Federal System – SFIT of the ML, a database that contains investigations of occupational accidents conducted by federal labour inspectors throughout the country (Ml, 2021), and that have already been used in other studies (e.g., Abras et al., 2018; Goncalves Filho et al., 2021). The investigation data were received from ML in text format and then imported into a SQL database.

As a first step, all accidents identified as "boiler explosions", involving at least one victim's injury or death, were selected. Secondly, the contents of the reports were analysed, and accidents erroneously associated with boilers, such as explosions from autoclaves or pressure vessels, were excluded. Then, information tables were generated through the SQL functions *group by*, *count* and *average (avg)* when necessary.

Besides the liability and limitations of using secondary data, they can provide meaningful information to complement the subsequent CAST analysis. For instance, recurrent causal factors may reveal that important systemic factors are not being addressed, primarily at higher levels of the safety control structure. Beyond that, the very description of the causal factors available in the ML accident investigation forms may suggest, or even encourage, the search for blame or human error as a "root cause", both criticized by Leveson et al. (2009).

2.2. Single case study

The subject in this study is the boiler accident analysis of a boiler explosion aboard the Norbe VIII drillship in 2017. Single detailed case studies allow an opportunity for depth of observation, although there are limitations on the generalisability of the conclusions (Voss et al., 2002). Accordingly, the selection of a single case must be justified. The Norbe VIII occurrence was one of the worst boiler incidents in the Brazilian context, killing three workers in 2017. The official accident report was released to the public on the ANP website (ANP, 2018), with detailed information available to researchers and practitioners. To increase the report reliability, the data extracted from ANP were complemented and checked with other sources, such as the reports from the Bahamas Maritime Authority (BMA, 2020), the Brazilian Navy (BN, 2017) and the Ministry of Labour (ML, 2017), which have also investigated this particular accident.

2.3. CAST

Accidents, which in STAMP are defined as unacceptable losses, have traditionally been conceived as occurring from a sequence of directly related failure events, each of which leads to the next event in the chain of events (Ishimatsu et al., 2014). With increased system complexity and the introduction of software, which does not "fail" in the sense that hardware does, new accident processes are arising (Ishimatsu et al., 2014).

CAST is based on STAMP, providing a new theoretical foundation for system safety on which new, more powerful techniques and tools for system safety can be constructed (Leveson, 2012). CAST considers that accidents are not just the result of individual system component failures or errors but more generally result from inadequate enforcement of constraints on the behaviour of the system components (Leveson et al., 2020). The safety constraints are enforced by controls. Controls include physical and logical design to reduce or eliminate common errors, checklists, performance audits, altering the order of steps in a procedure to reduce the risk of skipping some, and changing incentive structures (Leveson et al., 2020).

The boiler accident analysis presented in this study was performed over the official accident report. Despite its potential drawbacks – e.g., absence of crucial information, different models used by investigator – using CAST in the existing accident report can produce a different view of the accident and its causes (Leveson, 2012).

The analysis is divided in five parts, as suggested by the CAST Handbook (Leveson, 2019): (1) Basic information collection to perform the analysis: (2) Modelling of the existing safety control structure. (3) Examination of the components of the control structure to determine why they were not effective in preventing the loss. (4) Identification of flaws in the control structure as a whole (general systemic factors) that contributed to the loss. (5) Recommendations for changes to the control structure to prevent a similar loss in the future.

The basic information to perform the first part were collected from: (1) general information concerning boiler accidents in Brazil; and (2) the ANP official accident report and additional sources.

An overview of the steps undertaken in this study is presented in Fig. 1.

3. Results

3.1. Overview of boiler accidents in Brazil

Between 2002 and 2020 federal labour inspectors investigated 70 fatal and non-fatal work accidents involving boilers. These incidents have caused at least one death per year during boiler operation or maintenance, except in 2011, reaching a peak of 9 deaths in 2015

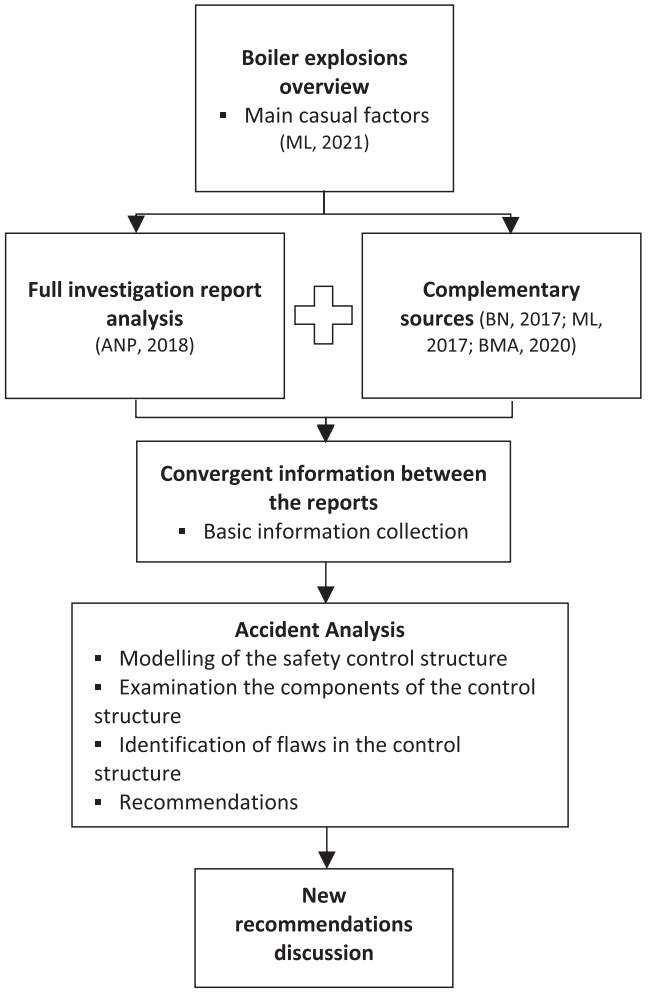

Fig. 1. Steps undertaken in this study.

(Fig. 2). The information presented in this section is based on these investigations (Ml, 2021).

Boiler accidents occurred mainly in the processing industries, accounting for more than 70% of the occurrences. Specifically, the food and beverage industry sector, which comprises dairy products, slaughterhouses, breweries, feed manufacturers, among others, comprised more than half of fatalities (64%) (Table 1).

The boiler accidents killed 70 workers and injured 73, totalling 143 victims. Table 2 reports the distribution of victims according to sex, age, level of education, type of contract, and occupation. Surprisingly, few victims were boiler operators (occupation), indicating that most incidents occur due to boiler operation by unskilled labour or unassisted boilers.

Another point that should be highlighted is the high percentage of accidents with inexperienced workers: almost half of the victims had worked less than one year in the company (Fig. 3). On the other hand, the worker's age does not seem to be significant for the occurrence of these incidents: the groups from 25 to 39 years and 40 to 59 years have similar numbers of victims.

Table 3 shows the top 20 casual factors in boiler accidents in Brazil, according to the Ml, 2021 investigations, and their prevalence in recent accidents (↑), somewhat recent accidents (↗), recent and older accidents (↔), somewhat older accidents (↘), or older accidents (↓).

The lack of preventive or predictive maintenance tops the list, covering more than half of accidents (57%). Absence or insufficiency of safety and health program or document required by regulatory standards, which may include the absence of risk management programs or documentation relating to the boiler (e.g., manufacturer's instructions for operation and maintenance or drawings), is a factor arising in recent investigations. The third on the list, lack or insufficiency of training, may be related to the victim's inexperience, as pointed out earlier (Fig. 3).

All these recurrent causal factors suggests that systemic factors are not being addressed by the companies or by government agencies responsible for regulatory standards enforcement. As will be presented in the next sections, some of these causal factors will reappear on the case study.

It is worth mentioning that the terms and concepts presented in Table 3 were brought as currently used by the ML labour inspectors. These terms are not free from criticism, such as the expression "Failure to anticipate/detect risk/danger", since it makes a judgment of the worker's actions. A common assumption is that most accidents are caused by operator error and rewarding "correct" behaviour and punishing "incorrect" behaviour will eliminate or reduce accidents significantly (Leveson, 2011). Claiming that a worker "failed" to anticipate the risk is just another way to assign blame to the operator. This approach to safety is not as effective as it could be, as it discourages other explanations. Thus, a rephrased blameless expression, e.g. "Worker / Company did not anticipate/detect risk/danger", would demand from the investigator others clarifications, namely: (a) why was the danger not anticipated by the worker? (b) did the system feedbacks allow a different behaviour? Or (c) were the feedbacks adequate? Without changing the environment, human error cannot be reduced for long (Leveson, 2011).

3.2. Original investigation report

The drill ship Norbe VIII (Fig. 4) was in the Marlim Oil Field, off the coast of Brazil, carrying out the annual servicing of the boiler system, by two technicians of the Instituto de Metrologia Industrial Ltd. (IMI), accompanied by the ship's engineer (BN, 2017; ANP, 2018; BMA, 2020). The vessel is owned by Odebrecht Oil and Gas (OOG), a Petróleo Brasileiro SA (Petrobras) contractor. The boiler system on board the Norbe VIII was designed and built by a South Korean company and assisted the following operations: formation testing, well testing or workover (ML, 2017; BMA, 2020). The boiler system had the following characteristics: (i) type: aqua-tubular; (ii) vertical configuration: year of construction: 2009; steam production: 2,000 kg/h; working pressure: 7.14 kgf/cm^2;

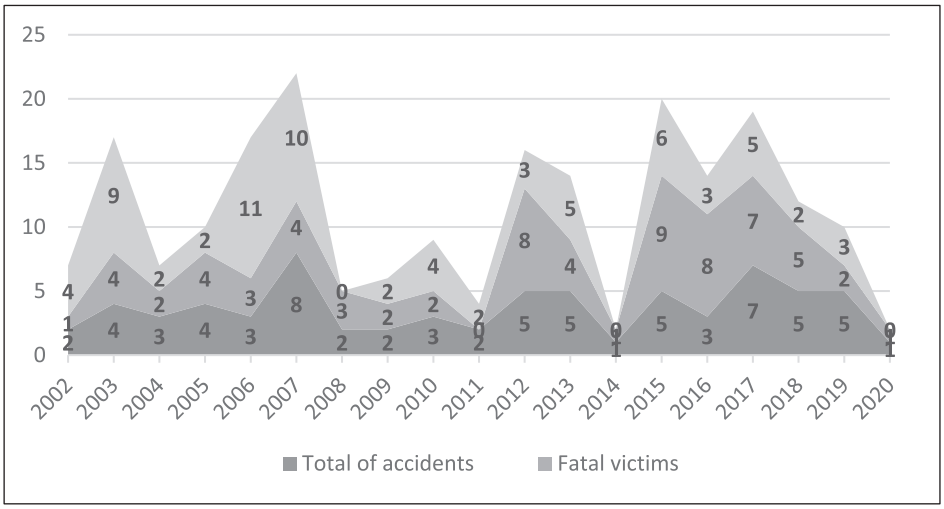

Fig. 2. Boiler accidents investigated by the Ministry of Labour, between 2002 and 2020.

Table 1
Boiler accidents investigated by the Ministry of Labour, between 2002 and 2020, by sector.

Sector	Total of accidents	% of accidents	Fatal victims	% Fatal victims
Food industry	27	39%	36	51%
Laundry	7	10%	2	3%
Chemical industry	6	9%	4	6%
Plastic and rubber products manufacturing	4	6%	3	4%
Pulp and paper industry	4	6%	3	4%
Beverage industry	3	4%	9	13%
Wood industry	3	4%	1	1%
Textile manufacturing	3	4%	1	1%
Wholesale trade, except motor vehicles and motorcycles	2	3%	3	4%
Petroleum coke, oil derivatives, and biofuels production	2	3%	1	1%
Furniture manufacturing industry	1	1%	1	1%
Support activities for mining	1	1%	3	4%
Clothing industry	1	1%	0	0%
Hotels	1	1%	0	0%
Infrastructure construction	1	1%	1	1%
Other activities	4	6%	2	3%

Table 2
Profile of boiler accident victims, investigated by the Ministry of Labour, between 2002 and 2020.

Variable	Total	Percentage
Sex		
Male	132	92%
Female	11	8%
Age		
<18 years	2	1%
18–24 years	19	13%
25–39 years	59	41%
40–59 years	58	41%
≥60 years	5	3%
Education[a]		
Primary education	12	43%
Secondary education	15	54%
Higher education	1	4%
Type of contract		
Permanent employment	122	85%
Temporary	19	13%
Self-employed	1	1%
Public sector	1	1%
Occupation[a]		
Boiler operator	6	18%
Production line operator	4	12%
Welder	2	6%
Repairman	2	6%
Machine operator	2	6%
Electrician	2	6%
Slaughterman	2	6%
Technician	2	6%
Others	12	35%

[a] Data from 2017 onwards; information before 2017 is not available.

maximum allowable working pressure (MAWP): 9.18 kg/cm^2, maximum steam temperature: 420 °C (ML, 2017).

At 07:38 am on 09 June 2017, one of Norbe VIII's boilers exploded. The two shore-based service technicians and the ship's engineer, who were inside the boiler room, received severe burns and respiratory injuries and died later, whilst outside the boiler room, an OOG employee was injured but recovered (ANP, 2018; BMA, 2020). Table 4 reports a summary of the events leading up to the boiler explosion.

According to the ANP (2018), the boiler involved in the incident had several safety mechanisms. For example, a programmable logic controller (PLC) automatically controlled the burner to maintain the pressure between 6.5 and 7.5 kgf/cm^2. If the pressure reached a very high value (8.5 kgf/cm^2), the PLC would perform an interlock (trip) of the boiler. Above this setpoint (8.5 kgf/cm^2), the PSV should relieve the boiler pressure at the MAWP (9.18 kgf/cm^2).

However, after the explosion, an internal investigation found that manual valves in the pressure taps of safety devices (pressure switches) were closed, inhibiting the function of the automatic over pressurization control devices (Fig. 5, a). The pressure gauge manual valve was also closed, but since it was not tight, it allowed the reading of fractions of the actual pressure, giving the false impression of functionality and that the PSV was relieving pressure before the maximum allowable working pressure (MAWP) of 9.18 kgf/cm^2 (ANP, 2018). These interventions in control devices have not been documented. Similarly, the existing work procedure, prepared by OOG, did not help to detect abnormalities as it contained only instructions with reference to how to start and stop the boiler (ANP, 2018). Concerning the security devices, the document was

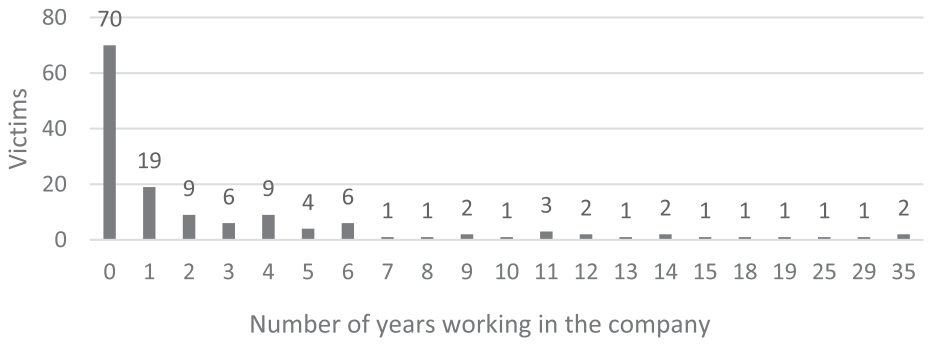

Fig. 3. Number of years working in the company of victims of boiler accidents investigated by the Ministry of Labour between 2002 and 2020.

Table 3
Top 20 casual factors in boiler accidents investigated by the Brazilian Ministry of Labour between 2002 and 2020.

Causal Factor [2]	Quantity	%[a]	Trend
Absence or insufficiency of preventive or predictive maintenance	40	57%	↔
Absence or insufficiency of safety and health program or document required by regulatory standards	24	34%	↑
Lack or insufficiency of training	23	33%	↗
Machine/equipment working poorly or subject to breakdowns	19	27%	↓
Failure to anticipate / detect risk / danger	14	20%	↘
Lack or inadequacy of task risk assessment, when required	14	20%	↔
Designation of unskilled/unqualified/unauthorized worker	14	20%	↔
Absent work procedures or inadequate	13	19%	↔
Other unspecified factors	12	17%	↓
Unsuitable or dangerous workstation	9	13%	↘
Excess of overtime or non-observance of rest intervals	9	13%	↗
Unaware of the job hazard or equipment condition	9	13%	↔
Improvisation / Work around	8	11%	↘
Insufficiency of supervision	8	11%	↗
Insufficient or inadequate materials or equipment for the activity	8	11%	↘
Equipment / tool incorrectly selected or used	7	10%	↑
Means of access inadequate or absent	7	10%	↑
Maintenance of equipment without taking preventive measures	6	9%	↗
Poorly conceived task	6	9%	↗
Insufficient coordination or communication between teams or companies	6	9%	↗

[a] The sum of factors exceeds 100%, as more than one causal factor may affect the same accident.

Fig. 4. The drillship "Norbe VIII" (BN, 2017).

Table 4
Summary of the events onboard Norbe VIII, prior to the boiler explosion (ANP, 2018).

Date	Time	Event
6 June 2016	–	Last periodic safety inspection of boiler #1
6 June 2017	–	The calibration certificate for pressure gauges and safety valves (PSV) and the safety inspection of boilers expires
7 June 2017	Afternoon	Technicians from IMI embark on the Norbe VIII and require the Chief Engineer (day shift) to place the boilers in normal operating conditions
7 June 2017	Afternoon	The Chief Engineer requests the night shift team to heat and start the boilers to carry out the inspection service
7 June 2017	20hs	Heating of the boilers
8 June 2017	2:00–3:00 am	The boilers are started by the Second Engineer (night shift), who identifies that the PSV of both boilers were relieving at pressures below the set pressure.
8 June 2017	Daybreak	The Chief Officer (night shift) starts the boilers and confirms the relief of the PSV below the pressure set. Turn off both boilers and return to the Machine Control Room (ECR).
8 June 2017	Before the shift change	The Chief Officer (night shift) informs the Chief Engineer (day shift) about the PSV problem. Then both go to the boiler room and restart the boilers to confirm the problem. Boilers #1 and #2 PSV were relieved at higher pressures than in the previous test, but still below the set pressure.
8 June 2017	5:30 am	The IMI team was informed that the boilers were not ready for inspection due to the problem found with the PSV.
8 June 2017	Morning	The second Engineer (day shift) and the IMI team enter the boiler room. The boilers were started and the premature actuation of the PSV of boiler #1 was observed.
8 June 2017	5:30 pm	At the shift change meeting, the night team is instructed not to perform boiler service during the shift, as IMI would perform boiler service on the morning of the following day. The Second Engineer (night shift) advises that the PSV would have to be removed and manually tested. The Second Engineer (day shift) informs the Chief Engineer that the following day the boilers would be ready for PSV removal. The Chief Engineer asks the Second Engineer (day shift) to oversee the IMI tasks.
9 June 2017	7:00 am	The boiler heating process starts. The Second Machine Officer and the IMI team are in the boiler room.
9 June 2017	7:38 am	Boiler #1 explodes during the heating process.

superficial and limited to informing: "inspect the security devices", without specifying which ones (ANP, 2018).

Furthermore, investigators discovered that the compression nuts of the boiler #1 pressure safety valves (PSV) were fully tightened and their

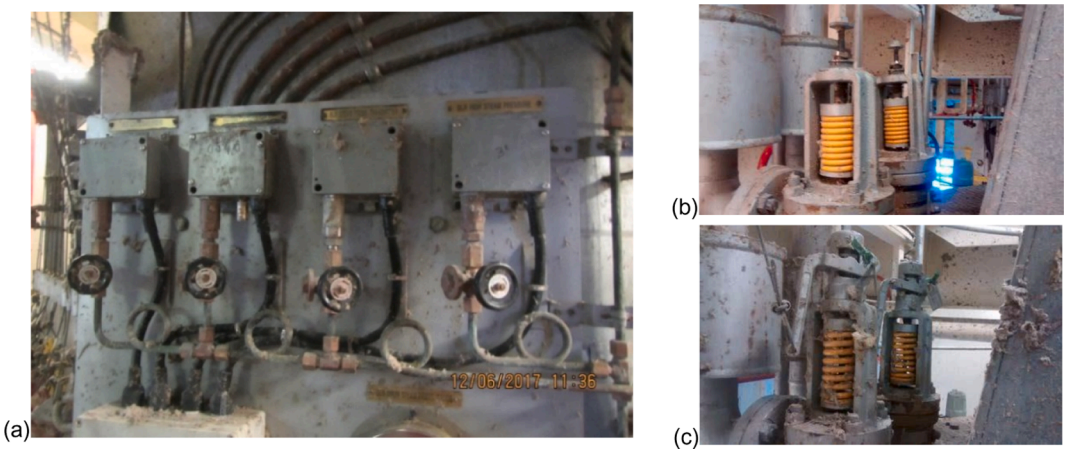

Fig. 5. Boiler system physical components. (a) the manual valves of pressures taps and pressure switches of the boiler (ANP, 2018); (b) Boiler #1 fully compressed PSV springs (BN, 2017); and (c) Boiler #2 PSV (BN, 2017).

anti-tamper seals removed (Fig. 5, b), contrasting with the boiler #2 PSV (Fig. 5, c) (ANP, 2018; BMA, 2020).

This was probably to compensate for the allegedly premature relief of pressure. However, if there were changes in the PSV pressure setting, they were not documented. Further tests indicated that even under pressure between 39 and 41 kgf/cm^2 (more than four times the MAWP) the PSV was not activated (ANP, 2018).

Regarding the IMI selection as a contractor, the original investigation report uncovered that the investigators from OOG did not verify whether the IMI workers were properly trained for the service and made no objections to the maintenance of the boiler by IMI having been carried out without the supervision of a mechanical engineer, mandatory by the national legislation (ML, 2017; ANP, 2018).

On the part of the manufacturer, the boiler manual was provided in English and hence was not fully accessible by the Brazilian onboard team (Portuguese speakers). Also, there was no safe heating procedure for the boiler (ANP, 2018).

Furthermore, the IMI team embarked on the ship without the minimum equipment for the safety devices inspection and calibration. As a result, instead of disassembling the boiler PSV and performing the calibration on a bench, technicians performed the tests with the PSV mounted on a functioning boiler (ANP, 2018).

ANP (2018) made several recommendations (Table 5) based on the identified causes: (i) documental issues (insufficient risk analysis, incomplete procedures, and lack of work permits - PT and boiler operation records), (ii) management (lack of control of contracted services) and (iii) human (insufficient training).

3.3. CAST step 1: basic information collection

After collecting the basic information, the CAST analysis begins describing the hazard that led to the boiler explosion in Norbe VIII and the system-level safety constraints required to prevent the hazard (Fig. 6).

The boundaries of the analysis encompass the equipment (boiler), the workers on board Norbe VIII, OOG, and IMI, as participants in the proximate events. Petrobras and the boiler manufacturer are also important actors to be assessed. Petrobras is the operator of Marlim Field and responsible for selecting OOG (Norbe VIII owner) as a contractor, while including the boiler manufacturer allows analysis of possible design flaws. Moreover, beyond the organizational levels, Labour Inspection, ML, and National Congress were also included in the analysis, to understand how decisions and actions at the level of the government played a role in the accident causation. The National Congress is the legislative body of Brazil's federal government, defining the fundamentals and the parameters within which policy making is delegated to ML, as a regulator. Labour Inspection in Brazil is carried out under the ML and is charged for establishing guidelines and for undertaking inspection activities throughout the country's territory by its decentralized branches for enforcement of labour laws and regulations, including those related to OSH. Labour inspectors are authorized to enter freely and without previous notice at any workplace liable to inspection (ILO, 1947), such as Norbe VIII.

While the event chain does not provide the most important causality

Table 5
ANP (2018) recommendations regarding the accident on board Norbe VIII.

#	Description
1	Provide a qualified professional to oversee the operation and maintenance of the boilers.
2	Improve contractor due diligence, including technical expertise, regulations, and scope of services.
3	Establish audit procedure for contractors
4	Establish procedures for boiler inspection in accordance with the manufacturer's instructions, applicable legislation and validated by the ground engineering support.
5	Implement the use of a checklist for the startup and operation of boilers, complementing R04.
6	Include a specific health and safety culture program in the leadership training matrix.
7	Implement a procedure to perform hazard analysis and control when performing non-routine tasks.
8	Implement a procedure to issue a hazard analysis and control when performing non-routine tasks.
9	Establish a shift change procedure with clear information on the operating conditions of the facility, including changelog, isolation of equipment and systems (lockout & tagout), the status of ongoing interventions, nonroutine tasks performed, and interventions with possible operational impact.
10	Review the boiler start procedure considering the prior verification of valves, instruments, and pressure taps of the control system, through a checklist.
11	Create a procedure for disabling boiler control and protection systems.
12	Implement training in change management and related procedures (operational discipline).
13	Implement a training program to value the safety culture and behavioral attitude of the workforce so as not to initiate any nonroutine activities without first checking all the safety recommendations for each task based on prior planning with an analysis of the risks involved.
14	Establish a documented form of communication between leadership and its team to confirm the participants' understanding of the hazards, safety measures, and task sequence (step by step) of the activities to be performed.
15	Establish a safe work system to keep only qualified professionals directly involved in the activity in the place of execution of operations with high-risk potential.
16	Issue notification to the manufacturer about the failure identified in the Boiler Manual: Lack of a step-by-step procedure to perform the gradual heating of the boiler adequately.
17	Provide updated Boiler Operation Manual in Portuguese.

System Hazard: Boiler explosion (uncontrolled release of energy) and/or fire.

System-level safety constraints:

- Boiler must operate with a pressure equal to or below the maximum allowable working pressure (MAWP).
- Boiler conditions must be routinely evaluated through proper maintenance.
- Boiler must be operated by qualified and experienced personnel in accordance with the manufacturer's procedures.

Fig. 6. System hazard and safety constraints.

information, the basic events related to the loss do need to be identified so that the physical process involved in the loss can be understood (Leveson, 2012). The proximate events leading to the boiler explosion were discussed in detail in the previous section. Briefly, the boiler system was stopped and restarted several times, since the PSV were reportedly operating abnormally each time. Without adequate feedback, workers, unaware that safety devices were inhibited, thought that, according to the pressure gauge, the PSV were relieving pressure before the MAWP. Nonetheless, the PSV were functioning properly. The PSV anti-tamper seals of boiler #1 were removed and had been adjusted so that their springs were fully compressed, setting the pressure to over three times the MAWP. A new boiler heating led to the boiler #1 explosion.

The analysis of the physical loss showed that dysfunctional interactions nullified all safety devices. One basic problem in 'defence-in-depth" approaches is that in such a system having functionally redundant protective defences, a local violation of one of the defences has no immediate, visible effect and then may not be observed in action (Rasmussen, 1997), precisely what happened in this case. As Fig. 7 shows, other people could intervene in the boiler's physical elements (e.g., manual valves and PSV). Moreover, during the servicing, two controllers, the boiler operator from OOG and the servicing team from IMI, controlled the same process. In these cases, control actions may be inadequately coordinated, including unexpected side effects of decisions or actions or conflicting control actions (Leveson, 2012).

3.4. CAST step 2: modelling of the safety control structure

Apart from the pressure gauge valve (not tight), there was no other physical component failure, confirming the CAST premises that safety is as a control problem, instead of a failure problem. To continue the analysis, a safety control structure must be modelled to understand what controls were constructed to prevent the boiler explosion and why they were not effective (Leveson, 2019).

On top of the safety control structure, National Congress holds the authority and responsibility to enact general laws to ensure OSH, to supervise the ML activities through reports, e.g., accident reports and statistics, and to hold committee hearings, usually open to the public, to obtain information and opinions on proposed legislation. ML has been delegated legislative power to create regulatory standards, called "regulatory norms" (NR), to regulate and provide guidance on mandatory procedures related to occupational safety. For instance, NR 13 covers boilers and pressure vessels and sets the minimum requirements for managing the integrity of steam boilers including inspection, operation, and maintenance activities. Also, ML oversees and ensures that the labour inspectorate has enough manpower, means and funding to operate efficiently.

The Labour Inspection must verify whether: (i) companies operate boilers according to technical and legal standards; and (ii) boiler designs from manufacturers comply with standard codes. The manufacturer must design safe boilers that allow adequate monitoring of pressure, temperature, and other variables. Also, the design should make it difficult to neutralize or bypass safety systems.

OOG and Petrobras must oversee the safe operation and maintenance of the boiler, according to the manufacturer's instructions, and ensure the technical expertise of contractors (like IMI) that board the ship for boiler maintenance. In its turn, IMI must perform maintenance with the appropriate procedure and equipment and provide personnel with

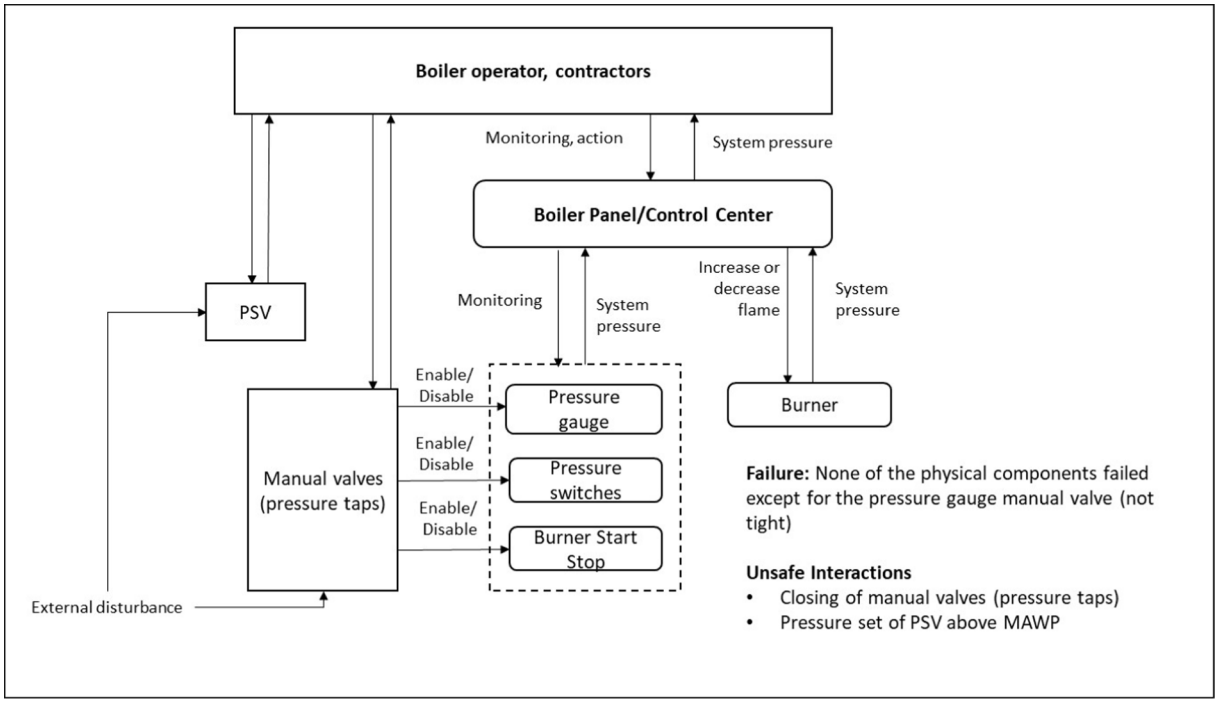

Fig. 7. Safety control structure of the boiler operation process.

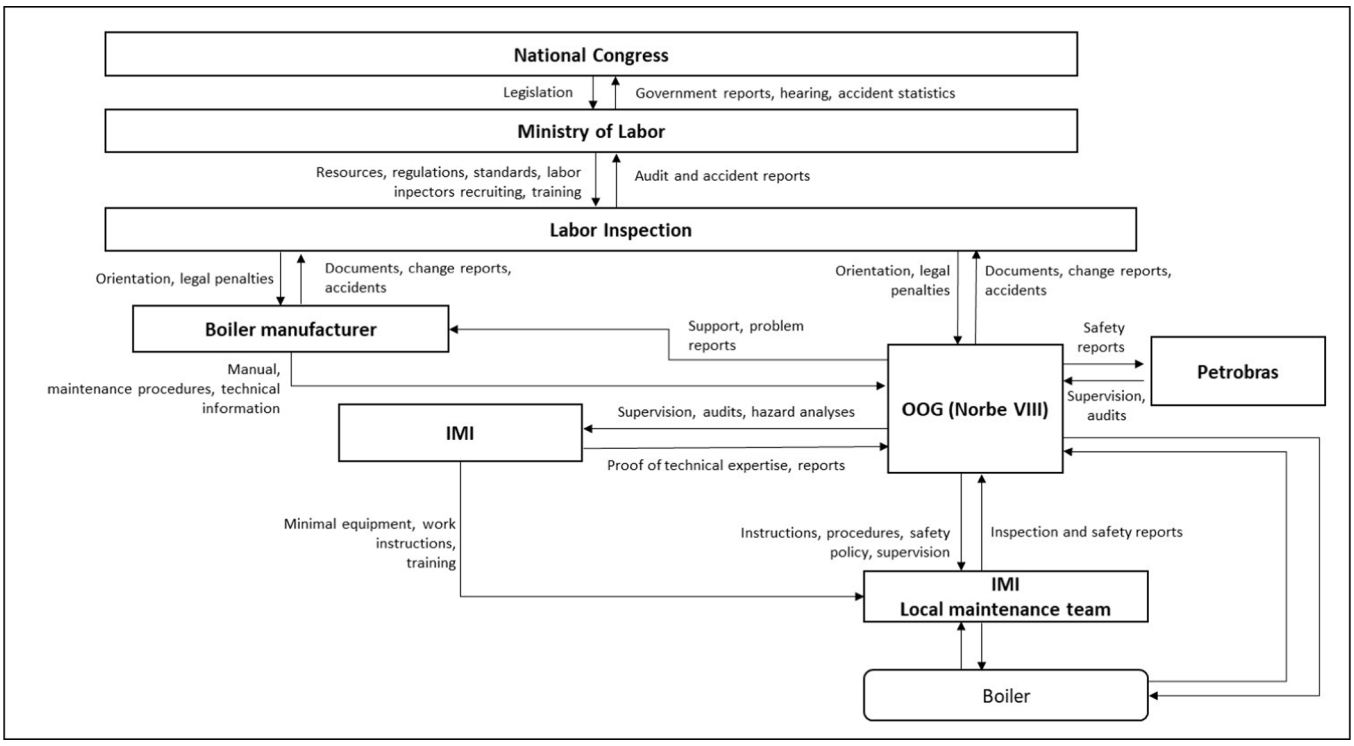

Fig. 8. The system's safety control structure.

technical expertise. The system's safety control structure is depicted in Fig. 8.

3.5. CAST step 3: examination of the components of the control

Although all ANP findings and recommendations (Section 3.2) have their merits, they were limited to behavioural and documentary aspects. In other words, they encompass symbolic (e.g., instructions, procedures) and incorporeal (e.g., training) barriers, classified as low efficiency and reliability, not recommended for safety-critical tasks, difficult to evaluate their effectiveness, and highly dependent on humans during operations (Hollnagel, 2008).

For instance, as stated on the original investigation, external disturbances in the boiler's manual valves and PSV ended up unnoticed by those who successively operated the boiler due to absence of a changelog, suggesting the implementation of a changelog along with personnel training (Table 5, recommendations #9 and #12). However, rather than striving to control behaviour by fighting procedure deviations, to improve safety, the focus should be on control of the behaviour by making the boundaries of safe operations explicit and known to actors (Rasmussen, 1997). In other words, the boiler feedback should be enough to update the operator's mental models about the system migrating toward a higher risk. In this sense, the following question could arise: why didn't the boiler design provide enough feedback to workers to allow them to update their mental models regarding the PSV and the manual valves? Are the risk assessment methods applied to the boiler during the design phase adequate? Was this misuse of the boiler predicted? Could the boiler design be modified to eliminate or reduce the risk of inhibiting safety devices? Were manual valves of pressure taps and gauge strictly necessary for boiler operation and maintenance? These issues, among others, were not addressed in the ANP (2018) report.

Furthermore, regardless of the original investigation which reported that Petrobras' compliance audit of OOG was adequate (ANP, 2018), CAST analysis found an absence of Petrobras controls concerning the OOG's subcontractors in face of the highly fragmented process in traditional contracting. i.e., excess of contractors and subcontractors. Once again, answering these questions will provide information useful for creating recommendations: Did the companies that entered or operated in the Marlim Field, operated by Petrobras, including subcontractors, go through a Petrobras pre-approval process? Is there a pre-approval process? The Table 6 details the analysis of the other components of the control structure.

3.6. CAST step 4: identification of flaws in the control structure

Traditional accident analysis usually concentrates on the proximate events immediately preceding the loss, but the foundation for an accident is often laid years before, stemming from common systemic factors (Leveson, 2012). Rephrasing Reason (1990), the higher an element position within a control structure, the greater is his or her opportunity for generating hazardous states. Higher levels of the control structure, such as government agencies, could be the source of systemic factors that impact the behaviour of several components of the control structure. However, the role or contribution of the inspection agencies to the hazardous state were not addressed in the accident government reports (ML, 2017; ANP, 2018). It is not unusual that initiating events, other events, or explanations are excluded or not examined in-depth because they raise issues that are embarrassing to the organization or its contractors or are politically unacceptable (Leveson, 2012).

As an example, there is no mention, in the reports, of the lack of human resources in government agencies, especially in the ML, responsible for editing safety standards for boilers in the workplace and maintain a body of inspectors. Currently, there are 2,064 labour inspectors in Brazil (Brasil, 2021), an insufficient number in the face of 104.8 million people liable to labour inspection (Filgueiras, 2012; IBGE, 2016). Article 10 of the International Labour Organization (ILO) Convention n° 81, ratified by Brazil, calls for a "sufficient number" of inspectors to do the work required (ILO, 1947). In this context, local research by the Institute of Applied Economic Research - IPEA estimated that at least 8,000 labour inspectors are needed to meet minimal inspection demands (Barbosa et al., 2012). A similar number is

Table 6
Analysis of each component of the control structure.

OOG	IMI (company)	IMI (team on board Norbe VIII)	Petrobras
Safety responsibilities: ■ Ensure that boiler safety devices are functioning accordingly ■ Hire contractors with technical expertise ■ Share boiler's risks and technical data with the contractor ■ Supervise and evaluate contractor maintenance **Decision context:** ■ Contractor's insufficient expertise ■ Insufficient risk documentation ■ Poor feedback from the boiler status **Contributions to the accident:** ■ Insufficient due diligence and supervision regarding the contractor ■ Lack of risk assessment concerning the manual valves of the boiler ■ Simplified boiler operation instructions **Process model flaws:** ■ Believed in the technical expertise of the IMI ■ Unaware of the disturbances in the pressure taps manual valves.	**Safety responsibilities:** ■ Supervise maintenance (engineer)■ Provide adequate maintenance and testing equipment■ Provide an appropriate procedure for boiler maintenance■ Select staff with technical expertise **Decision context:**■ Unskilled leadership (engineer not qualified in mechanical engineering) **Contributions to accident:**■ Lack of supervision of local maintenance activities■ Not providing adequate equipment or training to the maintenance team **Process model flaws:**■ Believed that the Norbe VIII could perform boiler maintenance without adequate equipment, supervision and, training	**Safety responsibilities:** ■ Perform maintenance with an appropriate procedure **Decision context:**■ Adequate maintenance equipment not provided■ Lack of training in boilers■ Lack of proper instructions■ Maintenance leader (engineer) assisting remotely■ Poor feedback from the boiler's status **Contributions to the accident:**■ Improper procedure for PSV calibration (with the safety device connected to a functioning boiler)■ The workers did not check the manual valves of the pressure taps **Mental model flaws:**■ Believed that the manometer indicated the actual pressure of the boiler■ Unaware of the real PSV set pressure■ Believed that the problem was in the premature pressure relief by the PSV	**Safety responsibilities:** ■ Establish a security policy■ Ensure compliance with safety standards by contractors **Decision context:**■ Highly fragmented process in traditional contracting (excess of contractors and subcontractors) **Contributions to the accident:**■ Lack of supervision of the manuals and procedures of contractors and subcontractors **Mental model flaws:**■ Believe that contractors have adequate procedures for hiring other contractors
Ministry of Labour	**Labour Inspection**	**Boiler Manufacturer**	**National Congress**
Safety responsibilities: ■ Regulation (detailing) laws ensuring the safety of boilers■ To adapt the regulations based on accidents investigated by the Labour Tax Audit■ Propose laws to improve safety at work■ Provide human and technical resources to the Labour Inspection **Decision context:**■ Pressure to make regulatory standards more flexible■ Budget constraint. **Contributions to the accident:**■ Absence of new labour inspectors hiring■ Lack of personnel with specific knowledge on occupational safety and health (e.g., absence of open positions exclusively for safety engineers) **Process model flaws:**■ Believe that the shortage of human resources and budget can be fully compensated with the adoption of new technologies and strategies.	**Safety responsibilities:** ■ Ensure compliance with laws and regulations for boiler safety■ Apply penalties in case of non-compliance with laws■ Report accidents to the Ministry of Labour **Decision context:**■ Lack of human resources, vehicles, and equipment.■ Focus on quantitative goals that hinder the reduction of accidentality **Contributions to the accident:**■ Accident investigations hardly reach higher levels of a safety structure (manufacturers, government, etc.) ■ Lack of more targeted preventions inspections of manufacturers (manual inspection, safety of commercialized machinery, machine design, etc.), before the machines reach the market **Process model flaws:**■ Believe that the accident analyses carried out today are sufficiently comprehensive.	**Safety responsibilities:** ■ Design safe boilers that allow adequate monitoring of pressure, temperature, and other variables. ■ Design safe boilers that allow adequate monitoring of pressure, temperature, and other variables. ■ Elaborate manuals, procedures, and technical data for safe operation and maintenance of the boiler **Decision context:** ■ Little oversight of government agencies on manuals, procedures and design **Contributions to the accident:** ■ Poor feedback from the boiler's status **Process model flaws:** ■ Ignore possible dysfunctional interactions among the boiler components ■ Ignore the fact that many workers lack English proficiency ■ Believe that reliability alone will ensure the safety of the boiler operation.	**Safety responsibilities:** ■ Create laws to ensure safety in the manufacture and operation of boilers **Decision context:**■ Pressure for deregulation■ Multiple sources of accidentality information **Contributions to the accident:**■ Monetary fine for safety infringement frozen since the 1990 s■ Lack of laws concerning mandatory release of accident reports by government agencies **Process model flaws:**■ Believe that safety standards slow the country's development by generating unnecessary costs■ Unaware of the cost of accidents for the social security system■ Little public knowledge of the nature of accidents, which end up being treated as misfortunes or unsafe acts (violations) .

recommended by other studies (ILO, 2006; Vasconcelos, 2014; Abras et al., 2018).

However, since 2013, the Brazilian government does not hire labour inspectors. This led to the National Commission for the Eradication of Slave Labour in 2020 to call on the government to hold a public examination for hiring personnel and filling the 1,553 vacant positions (40% of the total) in the labour inspector career (Fagundes, 2020).

Moreover, the knowledge gained from lessons learned during the accident analysis by the Brazilian labour inspectorate has not been shared with inspectors, companies or associations (Botelho, 2018). This explains why none of the 70 boiler accidents investigated by ML had their reports publicized.

Another issue is that the amount of monetary fines imposed as a result of the infringement detected by labour inspectors has not been adjusted for inflation in the last 20 years (Brasil, 2000). If updated by inflation, the fines should be multiplied more than five times (Banco Central do Brasil, 2021).

Moreover, despite the law that requires a specific postgraduate diploma from candidates to labour inspection to work in medicine and occupational safety (Brasil, 2002), since 2003 the government has not made such a requirement, accepting undergraduates from any area of study. Consequently, part of the boiler safety inspections may not be carried out with the proper expertise (Vasconcelos, 2014; Mendeloff, 2015). For example, not surprisingly many labour inspections often identify no safety problems, especially when conducted by lawyers and accountants (Mendeloff, 2015).

3.7. CAST Step 5: additional recommendations

Based on CAST, the following additional recommendations are presented:

(1). **Boiler manufacturer: Change boiler design method**. The ease with which many safety devices have been unnoticeably disabled suggests that the manufacturer's boiler design method is not adequate to detect dysfunctional interactions in its components. A change in this method can avoid not only similar accidents but also unknown ones.
(2). **Boiler manufacturer or OOG: Remove manual valves from pressure taps**. Since OOG had a spare boiler and operating a boiler without its safety devices is an unnecessary risk; there is no need to keep valves in the pressure tap.
(3). **Boiler manufacturer: Install manual valve closing sensors.** As an alternative to the removal of the manual valves, sensors can be installed to interlock the boiler or signal the operator and the boiler control panel in case of the closing of the pressure taps.
(4). **Boiler manufacturer: Improve the design to make it easier to identify the closing of manual valves.** A change to the VA design allows the operator to identify any valve interventions.
(5). **Boiler manufacturer: Change PSV design to allow an approximate estimation of the set pressure.** Boiler operators were unable to identify that the springs on the PSV were fully compressed and set to values equivalent to four times the MAWP. A design change of a PSV would allow the approximate visualization of their set pressure.
(6). **Boiler manufacturer: Add a second pressure gauge.** A second pressure gauge enables the early detection of a failure in any of the devices or the need for calibration.
(7). **OOG: Difficult access to pressure tap valves.** Installing physical barriers can reduce the likelihood of tampering with pressure tap valves.
(8). **Petrobras: Include OOG subcontractors in their audits.** In addition to those directly contracted, audits must also reach subcontractors.
(9). **Labour Inspection: amend the casual factors list available in the accident forms of SFIT.** Terms that suggest blame or judgment should be altered, especially the term "failure" in situations other than physical components, as they can discourage further accident explanations.
(10). **Federal Government: Increase the staff of inspectors in a number compatible with the people liable to labour inspection (worker population).** Currently, the number of inspectors is far below that recommended by national research institutes and by the ILO.
(11). **Federal Government: Hire personnel with specific knowledge on occupational safety and health.** Studies should be carried out on which economic activity the need for technical knowledge is most pressing, based on objective criteria (for example, by the incidence of serious accidents in a certain economic activity or with certain types of equipment). The inclusion of specific technical profiles in the staff (for example, engineers, physicians, among others, with a postgraduate diploma in occupational health and safety engineering or occupational medicine) would enable deeper analysis of documents and reports issued by companies.
(12). **National Congress: readjustment of labour fines.** Today, the current values of the labour fines represent only a fraction of their former value.
(13). **National Congress: mandatory release boiler accidents.** Labour inspection should be obliged to release detailed investigation reports to disseminate lessons learned from the accidents.

4. Discussion

4.1. RQ1: What additional recommendations can a CAST analysis obtain when performed over an official accident report?

As shown in Section 3.7, the CAST analysis presented 13 additional recommendations to the original investigation report (Table 5), raising the total number of recommendations from 17 to 30 (76% increase). In general, recommendations from the official report analysis were restricted to operator's and contractor's procedure deviations. It is not useful and should not be the goal of an accident report to apportion blame or describing causes as being due to human error, but to understand what led to this error, and how this can be avoided in the future (Hailwood, 2016). More important than numbers, the CAST analysis identified systemic causal factors that allow the prevention not only of similar events in the future, but a broader type of accidents that stems from unsafe control actions at higher levels of the safety control structure.

As an example of recommendations that allow the prevention of various types of accidents, in the case of the Federal Government increasing the staff of inspectors with specific knowledge on and dedicated to OSH (CAST recommendations #10 and #11), Brazil will experience an increase of inspection frequency and the likelihood of non-conformity detection, positively impacting the reduction of accidents, related or not with boilers, as reported by other studies in the United States (Viscusi, 1979; Gray and Jones, 1991). The same outcome can be expected through the readjustment of labour fines (CAST recommendation #12).

Moreover, CAST identified the lack of feedback regarding the external disturbances on the boiler's physical components, reflecting design issues. The analysis highlights that the manufacturer's boiler design method is not adequate to detect dysfunctional interactions in its components and, therefore, prone to human error. The new boiler design can allow the boundaries of safe operations to be more explicit to the operator and avoid other classes of human error.

4.2. RQ2: Is there room for improvement in the accident analysis carried out by government agencies, in respect of generating additional recommendations to eliminate or reduce the control actions contributing to the hazard?

With the CAST analysis providing additional recommendations from official investigations, especially on systemic factors, there is a need to rethink the way in which government agencies conduct accident analysis. We noted that analysis of this accident conducted by Brazilian government agencies generally refrain from reviewing their own control actions contributing to the hazard. Criticism and analysis of contributions from government levels to adverse events in Brazil are still restricted to academic literature (e.g., Narciso and Mello, 2017; Fragoso Junior and Garcia, 2019). In this context, the role or contribution of these agencies to the hazardous state were not addressed in the ANP (2018), ML (2017), BN (2017), or BMA (2020) reports, limiting potential improvements in the system as a whole. Using the proper approaches, like CAST in this study, accident analysis carried out by government agencies can reduce the subjectivity in selecting the chaining conditions and provide general recommendations to be absorbed by different levels of the control structure.

The historical background of ML investigations (Section 3.1) also suggests a lack of deeper analysis of the main causal factors involving boiler accidents. Many causal factors used in the accident report form (Table 3) are not clear, such as "Absence or insufficiency of preventive or predictive maintenance" or "Machine/equipment working poorly or subject to breakdowns". Why was preventive maintenance not carried out or why was the equipment working poorly? What control actions contributed to the hazard? These questions were not answered.

Moreover, the dissemination of knowledge obtained from the lessons learned during the accident analysis has not occurred among inspectors, companies, OSH professionals, and society in general (Botelho, 2018), hindering their awareness of main causal factors and recommendations, as overview and detailed reports of boiler accidents are available to the public are scant. The consequences of scarce publications can be noted in Table 3, where several causal factors persist in 20 years of boiler

accidents investigations. For example, "Absence or insufficiency of preventive or predictive maintenance" prevailed in 57% on both recent and older boiler accidents (↔), while "Lack or insufficiency of training" occurred in 33%, raising among the recent accidents (↗). Hailwood (2016) suggests that mandatory publicization of accident reports could clear paths for the dissemination of lessons learned (CAST recommendation #13).

5. Conclusions

The accident analysis over a boiler accident demonstrated that CAST is a new and powerful alternative to the traditional methods, allowing safety advance even of products with centuries of use, such as boilers. Whilst the official accident report propositions were limited to changes in the worker behaviour and documentary aspects, additional recommendations, especially regarding systemic factors and design flaws, were obtained from CAST for each component that played a role in the accident causation. These recommendations may prevent not only of similar events in boiler operation, but a broader type of accidents that stems from managerial and organizational factors and lack of governmental controls, at higher levels of the safety control structure, which can increase the overall system safety in Brazil.

Accident analysis carried out by government agencies can benefit from CAST, as it reduces the subjective in selecting the events and the chaining conditions, resulting in more comprehensive and reliable outcomes. Thus, CAST allows us to overcome the barriers concerning government agencies reviewing their own control actions contributing to the hazard, an issue found in the official report analysed that inhibits the further development of safety in the Brazilian scenario.

Even with the limitations of this research, whose analysis was based on official reports, the CAST analysis brought additional recommendations, contributing to prevent future accidents, and filling the gap existing in the literature for boiler accident analysis. The analysis could be further refined if performed by analysts directly involved in a boiler incident analysis.

CRediT authorship contribution statement

Renan Guimarães Landi: Conceptualization, Methodology, Data Curation, Formal analysis, Writing - Original Draft, Writing - review & editing. **Uiara Bandineli Montedo:** Conceptualization, Writing - review & editing, Supervision. **Carlos H.N. Lahoz:** Writing – review & editing, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the Brazilian Ministry of Labour for granting access to the information on occupational accident investigations.

Disclaimer

The views expressed in this document are those of the authors and do not reflect the official position or policies of the Brazilian Government.

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