DUTCH
SAFETY BOARD

Fatal accident after rupture of expansion joint in steam pipe

Lessons learned from the occurrence on board the Nieuw Amsterdam

Fatal accident after rupture of expansion joint in steam pipe

Lessons learned from the occurrence on board the Nieuw Amsterdam

The Hague, October 2025

The Dutch Safety Board's reports are public and are available at www.safetyboard.nl.

Cover photo: Dutch Safety Board

The Dutch Safety Board

When accidents or disasters happen, the Dutch Safety Board investigates how it was possible for these to occur, with the aim of learning lessons for the future and, ultimately, improving safety in the Netherlands. The Dutch Safety Board is independent and is free to decide which incidents to investigate. In particular, it focuses on situations in which people's personal safety is dependent on third parties, such as the government or companies. In certain cases, the Dutch Safety Board is under an obligation to carry out an investigation. Its investigations do not consider issues of blame or liability.

Visiting address: Lange Voorhout 9, 2514 EA The Hague, The Netherlands
Postal address: PO Box 95404, 2509 CK The Hague, The Netherlands

Telephone: +31 (0)70 333 7000

Website: safetyboard.nl
Email: info@safetyboard.nl

N.B.: This report has been published in the Dutch and English language. If there are differences in interpretation the Dutch report prevails.

CONTENTS

1 INTRODUCTION

1.1 The occurrence

At about 09.15 hours local time[1] on the morning of 22 March 2024, a fatal accident occurred on board the Dutch cruise ship Nieuw Amsterdam when it was calling at Half Moon Cay in the Bahamas. In an area of the engine room, an expansion joint in the main steam pipe ruptured. Through the resulting hole in the steam system, the room quickly filled up with steam at a temperature exceeding 100 °C.

The steam[2] was released on the port side, while two crew members were working in the same room on the starboard side. Because the vessel was not alongside the quay, the doors at the forward and aft of this room were closed in accordance with the procedure.[3] Due to the speed with which the room filled up with the hot steam, the two crew members could no longer reach the doors and the emergency exit and sustained fatal injuries.

1.2 Classification

The accident concerned here is classified as a 'Very Serious Marine Casualty' within the meaning of the Casualty Investigation Code of the International Maritime Organization (IMO) and EU Directive 2009/18/EC. Pursuant to the Dutch Safety Board Decree (*Besluit Onderzoeksraad voor Veiligheid*), which is based on the Casualty Investigation Code, the Dutch Safety Board has the obligation to investigate this occurrence.

1.3 Objective and investigation questions

The Dutch Safety Board's intention with this investigation is to determine how the safety risks associated with the vessel's steam system were managed and how the expansion joint could rupture. This is so as to prevent the occurrence being repeated or to limit its consequences.

1 The times in this report are local time; local time Bahamas = UTC -5 hours.
2 Steam is water in gas form and is not visible. Visible 'steam' is a mist of tiny droplets of water that form when water vapour cools and condenses. In the present report, we use the word 'steam' for both phases.
3 In accordance with MSC.1/Circular.1564 – Revised Guidance for Watertight Doors on Passenger Ships Which may be Opened During Navigation – (16 July 2017).

The investigation therefore focusses on the following investigation questions:

1. How could the expansion joint rupture?
2. Which factors played a key role in the rupture of the expansion joint?
3. Which underlying factors played a key role in the death of the two crew members as a consequence of the escaping steam?

1.4 Investigation approach

The Dutch Safety Board received the notification of the accident that same evening. Two Safety Board investigators went to the scene and conducted an investigation on board the vessel in the days following the accident. They conducted a number of interviews on board. The accident site in the engine room was investigated, as was the safety centre on the vessel's bridge. The ruptured component was taken to the Netherlands for technical examination. Back in the Netherlands, discussions took place with various other parties involved.

On 15 December 2024, two Safety Board investigators paid a follow-up visit to the vessel to gather supplementary investigation information (including from an examination of the steam system and inspection of the maintenance logs) and to conduct additional interviews.

The Safety Board had the expansion joint examined by the Element Material Technology materials science firm. We requested the firm to determine the condition of the expansion joint and to pay particular attention to any abnormalities in and around the area of the rupture. We have incorporated the results of these analyses into the present report. The report by Element Material Technology is included in Appendix C.

1.5 Demarcation

The investigation focuses on three main aspects:
- The rupture of the expansion joint.
- The reason for the presence of the expansion joint.
- The risks associated with a steam system on board a vessel, including the options for controlling them.

2 COURSE OF EVENTS

2.1 Introduction

This chapter describes the course of events in the occurrence. In Section 2.2, we begin with a brief description of the occurrence. In Section 2.3 we describe the rescue operation undertaken by the crew. In Section 2.4, we conclude this chapter with a description of the extent of the damage.

2.2 Course of events in the occurrence

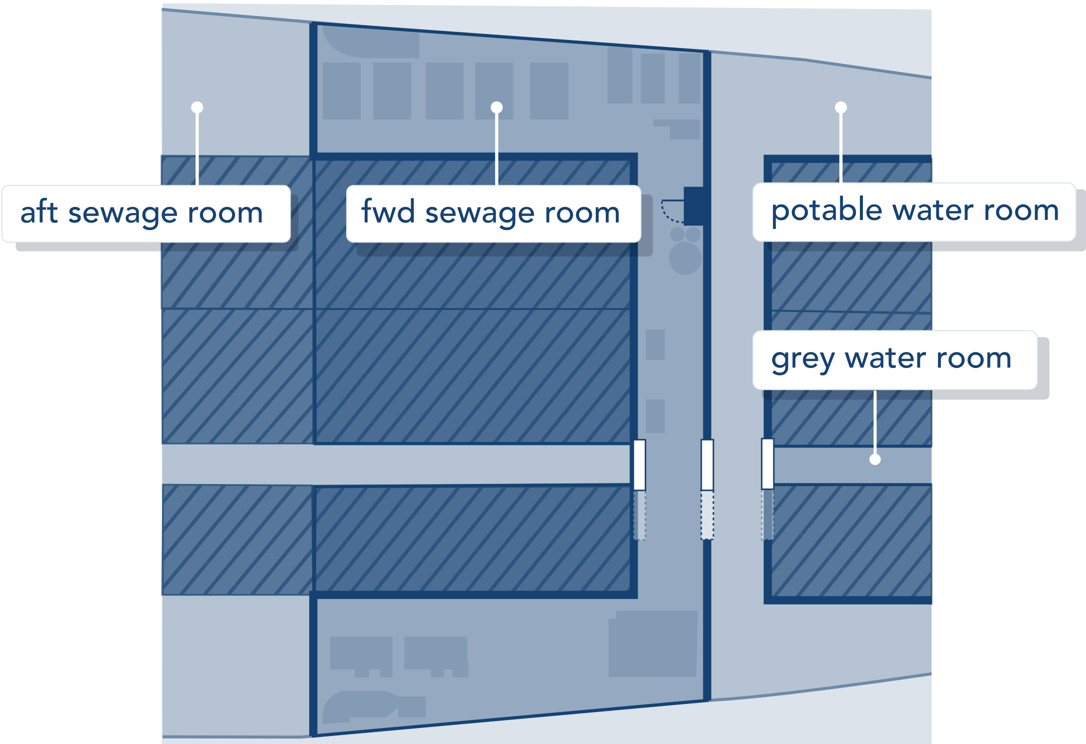
The Nieuw Amsterdam arrived at Half Moon Cay in the Bahamas at about 08.00 hours on 22 March 2024. The vessel remained off the coast without anchoring, held in position with the aid of its Azipods.[4] Because the vessel was not moored in a port, all the watertight doors in the engine room remained closed, in accordance with the procedure.[5]

Prior to the occurrence on 22 March, a repair was made on 17 March to an accommodation water heater that was leaking. The heater had to be removed for the repair. In order to be able to remove it, a valve in the steam inlet pipe that was slightly open was fully closed. Following the repair, the heater was reinstalled on 21 March, but the valve in the steam inlet pipe remained closed.

At about 08.30 hours, a third engineer officer and a motorman went to work in the forward sewage room (see Figure 1). They were carrying out routine maintenance on the sewage system[6] on the starboard side of this room.

At 09.13 hours, a number of loud bangs were heard at the bulkhead between the forward sewage room and the adjacent potable water room on the port side. At the same moment, the first engineer officer in the aft engine room was working on one of the steam system feed pumps.[7] This pump suddenly started to rotate, as if a large pressure difference had arisen between the two sides of the pump. At that point, the forward sewage room filled up with steam.

4 An Azipod is a rudder propeller, i.e. a ship's propeller installed in a pod that can be rotated to any horizontal angle, making a rudder superfluous.
5 In accordance with MSC.1/Circular.1564 – Revised Guidance for Watertight Doors on Passenger Ships Which may be Opened During Navigation – (16 July 2017).
6 The sewage system is a advanced waste water treatment plant that purifies sewage and greywater that pumps overboard in designated locations.
7 These pumps pump water to steam boilers so as to produce steam.



▲ *Figure 1: Top view of the layout of the forward sewage room (source: Dutch Safety Board).*

At about 09.13 hours – i.e. the same time as the bangs were heard – a low insulation alarm[8] went off in the engine control room, as did the engine room fire alarm. The *Safety Management and Control System* (SMCS)[9] indicated that all the smoke alarms in the forward sewage room had been activated.

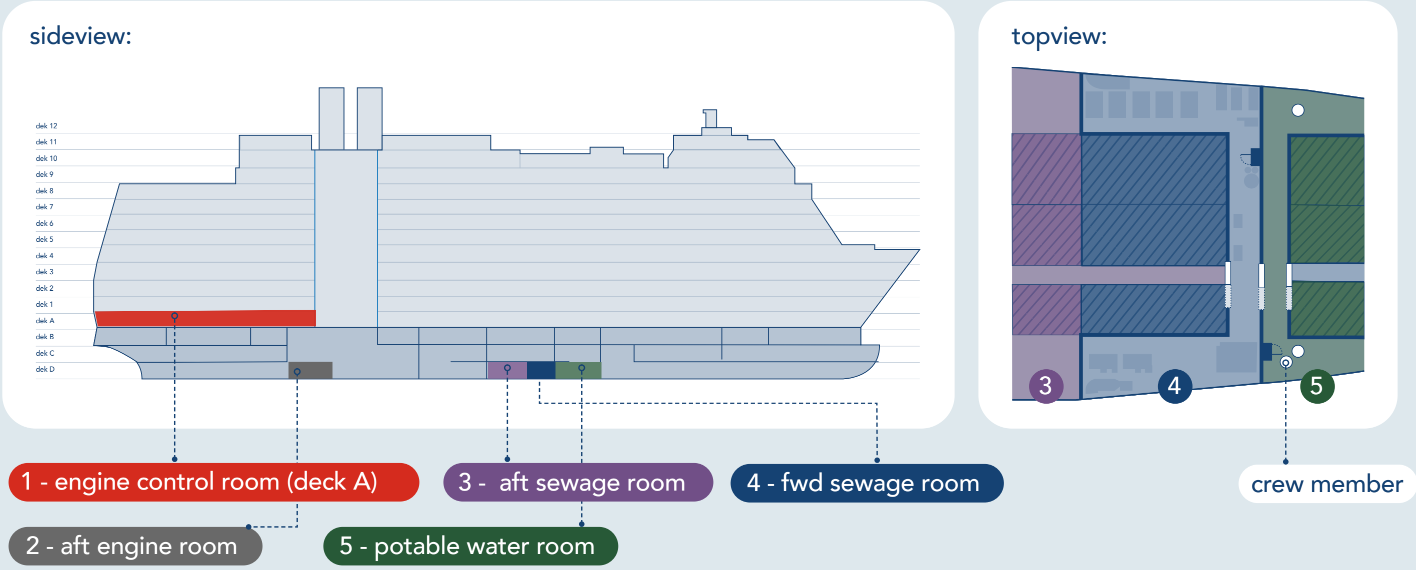
At 09.14 hours, the staff captain initiated emergency first stage response alarm as per company procedures to the crew based on the reports from the SMCS. This initiated the fire response[10] and alerted the crew that all four fire teams had to assemble.

In the engine control room, the *Integrated Alarm Monitoring and Control System* (IAMCS)[11] indicated at 09.14 hours that the pressure in the steam system had dropped from 8 to 5 bar. The engineer officer of the watch (EOOW) and the chief engineer who were present then determined that it was a steam leak and not a fire. The chief engineer therefore gave the order to shut the steam isolation valve (S39; see Figure 7 in Section 3.3) in the air-conditioning compressor room so as to shut off the flow of steam to the leak. The chief engineer also informed the bridge that there was a steam leak in the forward sewage room and not a fire.

8 A low insulation alarm indicates that a considerable amount of electrical current is leaking past the insulation, with an increased risk of a short circuit.
9 The SMCS is a digital information supply system designed for crisis management on cruise ships. It assists the crew in managing safety during the various phases of an emergency, from the initial alarm to when the event is resolved.
10 On merchant and passenger vessels, this is the procedure for the general and individual duties of the crew in the event of fire.
11 The IAMCS is a digital system that provides an overview of the status of the vessel's technical systems, and from which these systems can be controlled.

Sequence of events Nieuw Amsterdam

Location:



Events:

March 17

- the crew shut off the steam supply to heaters in the potable water room
- the crew start repair of the heater

March 21

- repair completed, steam supply remains shut off

March 22

08.00

- the passenger ship arrives at Half Moon Cay

08.30

- 2 crew members begin working in the forward sewage room

09.13

- 3 crew members in the potable water room hear five loud bangs from the forward sewage room
- a pump in the aft engine room starts rotating unexpectedly
- a expansion joint ruptures and steam fills the forward sewage room
- the *low insulation* alarm goes off in the engine control room
- the engine room fire alarm in the forward sewage room goes off

09.14

- the crew assembles for fire response

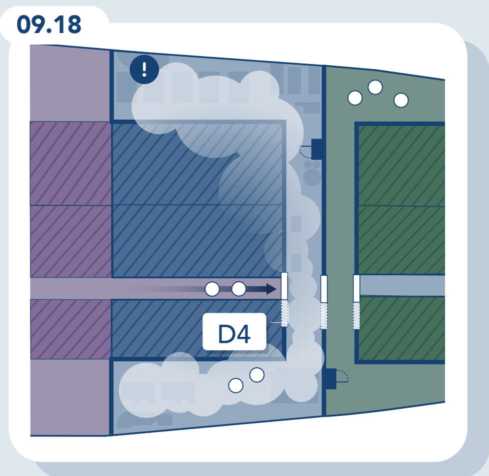
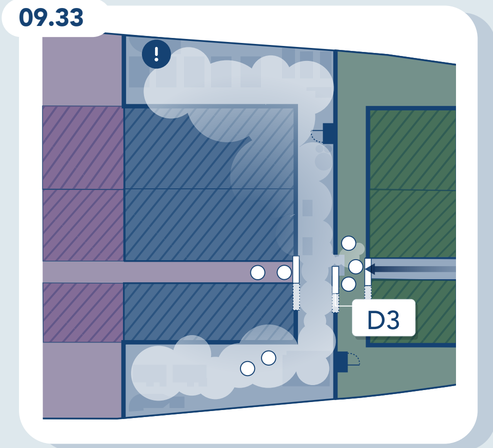
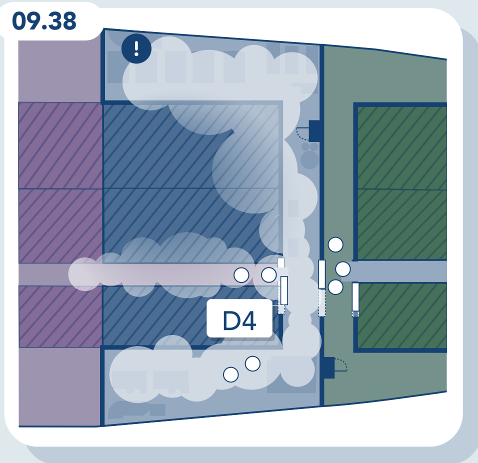


Figure 2: Timeline (source: Dutch Safety Board).

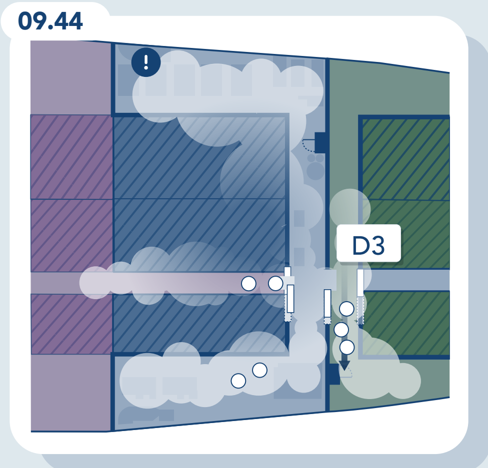
- **09.18** — 2 crew members open door D4 from the aft sewage room
- steam escapes from the forward sewage room and hits the crew members. They step back and the door slams shut
- **09.20** — A 3rd engineer officer is reported missing
- **09.22** — the *On Scene Commander* (OSC) is requested to initiate search
- **09.26** — the OSC attempts to open door D4, but fails
- **09.30** — the motorman is reported missing



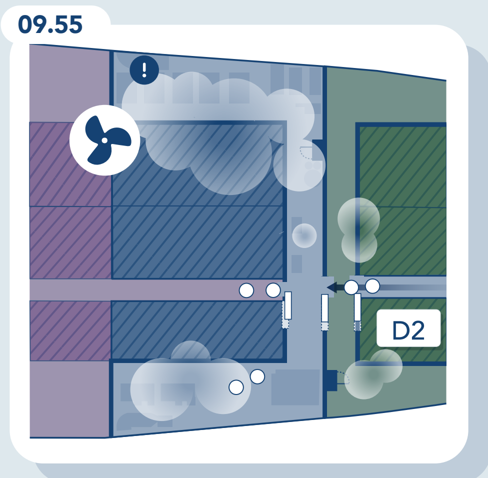
- **09.33** — fire team 2 opens door D3 from the potable water room. Steam escapes and hits the fire team. They step back and the door slams shut



- **09.38** — fire team 3 opens door D4 slightly. Aft sewage room fills with steam. Fire team 3 retreats to the air conditioning room



- **09.44** — fire team 4 opens door D3 slightly. The potable water room fills with steam. Fire team 4 is forced to retreat through an emergency exit
- **09.55** — fire team 1 opens door D1 and then D2 from the forward engine room
- the crew increases the ventilation in the forward engine room spaces to remove the steam



- **10.08** — fire team 1 fully opens door D3 and finds the first victim in the forward sewage room
- **10.13** — first victim is evacuated
- **10.16** — fire teams 3 and 4 begin opening door D4 further
- **10.22** — door D4 is open enough, the second victim is found in the forward sewage room
- **11.13** — the forward sewage room is inspected. Crew finds the ruptured expansion joint

▲ *Figure 2: Timeline (source: Dutch Safety Board).*

2.3 Rescue operation

After the staff captain initiated emergency first stage response alarm as per company procedures at 09.14 hours, the crew mustered at the designated assembly points. The four fire teams assumed there was a fire in the engine room and put on their fire suits and self-contained breathing apparatus (SCBA).

At 09.18 hours, a number of crew members attempted to open door D4 from the adjoining aft sewage room. As soon as they opened the door slightly, steam escaped from the forward sewage room. The crew members were struck by the steam and were forced to let go of the door control levers. The door then immediately slammed shut again.

At 09.20 hours it became clear that the third engineer officer was missing; he had not reported to his muster point. The first engineer officer was appointed On Scene Commander and began a search with the fire teams, starting at the forward sewage room. He arrived in the aft sewage room at 09.26 hours and attempted to open the door to the forward sewage room. Using a thermal camera, the temperature of this door was measured at 100 °C. At 09.30 hours, all the crew members had been accounted for and it became apparent that the motorman was also missing.

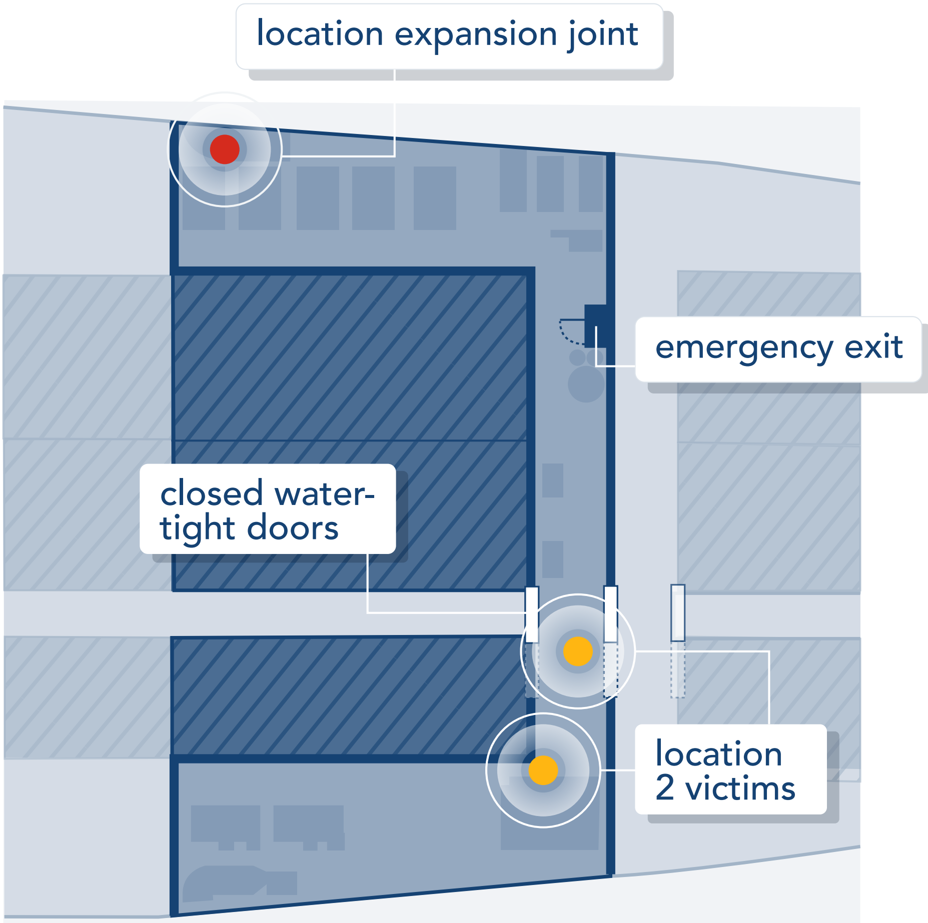
The four fire teams attempted to open the forward sewage room from both the forward (door D3) and the aft (door D4). Each time they opened the door slightly, steam escaped and forced them to let go of the door control levers. At 09.33 hours, it was possible to open door D3 a little, causing the adjoining potable water room to fill up with steam. The fire team present there then withdrew via an emergency exit. At 09.38 hours, a team managed to open door D4 slightly and hold it open, after which the room in which they were filled up with steam. The fire teams left this room.

One of the fire teams opened doors D1 and D2 from the forward room in the engine room, so that the remaining steam in the various engine room areas was removed through ventilation. At 10.08 hours, it was possible to fully open door D3. The first casualty was then found and evacuated; see Figure 4 for his location. At 10.22 hours, it was also possible to open door D4 sufficiently and the second casualty was found and evacuated. Neither casualty survived the incident. Based on data from the automatic fire detection system, it appears that the room filled up with steam within 86 seconds after the initial alarm.

2.4 Extent of the damage

About two hours after the occurrence, it was possible to inspect the forward sewage room. On the port side, there was a great deal of damage to the insulation of the steam piping (see Figure 3, left), the paint, ventilation ducts, and other equipment. At the back of the room, on the port side, there was a ruptured expansion joint in the steam pipe that ran there (see Figure 3, right). Various plastic components had been deformed by the heat and the smoke detectors and lighting covers had melted. On the starboard side, a fibreglass tank had cracked. See Figure 4 for an overview of the room.

▲ *Figure 3: Left: The situation in the forward sewage room after the occurrence (source: Dutch Safety Board). Right: The expansion joint as it was found (source: Holland America Line).*



▲ *Figure 4: Locations of the two casualties and the expansion joint (source: Dutch Safety Board).*

3 BACKGROUND INFORMATION

3.1 Introduction

In this chapter, we provide background information on the occurrence. We begin in Section 3.2 with information about the vessel and its operation by the owner. We explain the steam system in Section 3.3. Section 3.4 describes the composition of the crew. Finally, Section 3.5 covers the various procedures and relevant training on board.

3.2 The vessel

3.2.1 Owner

The Nieuw Amsterdam is part of the fleet of the Holland America Line (HAL), an originally Dutch shipping company. The company was established in Rotterdam in 1873 and for decades operated passenger and cargo services between the Netherlands and America. From the 1970s onwards, it focused more on cruises, divesting itself of all other activities. At the time when the occurrence took place, HAL had a fleet of eleven passenger vessels (see Table 1). Since 1989, HAL has been a subsidiary of the Carnival Corporation & plc, which also has an office establishment in Rotterdam. Carnival Corporation & plc manages more than 90 passenger vessels from various shipping companies including HAL, Carnival Cruise Line, Costa Cruises, P&O Cruises, and Cunard Lines. HAL's vessels operate under the flag of the Netherlands.

▼ *Table 1: The Holland America Line fleet (with year of commissioning).*

Class	Name	Year of commissioning
R class	Volendam	1999
	Zaandam	2000
Vista class	Zuiderdam	2002
	Oosterdam	2003
	Westerdam	2004
	Noordam	2005
Signature class	Eurodam	2008
	Nieuw Amsterdam	2010
Pinnacle class	Koningsdam	2016
	Nieuw Statendam	2018
	Rotterdam	2021

3.2.2 Construction

The Nieuw Amsterdam was one of the owner's newer vessels. Its keel was laid on 15 July 2008 at Fincantieri's Marghera shipyard in Venice, Italy, as the second vessel in the Signature class, which consists of two vessels based on the same design. Its sister ship in this class, the Eurodam, had been delivered previously. The passenger vessel was the fourteenth vessel that the owner had built by the Italian Fincantieri company at the Marghera shipyard. In November 2009, the passenger vessel was towed out of the dry dock for further fitting-out alongside a fitting-out quay. It entered service in 2010.

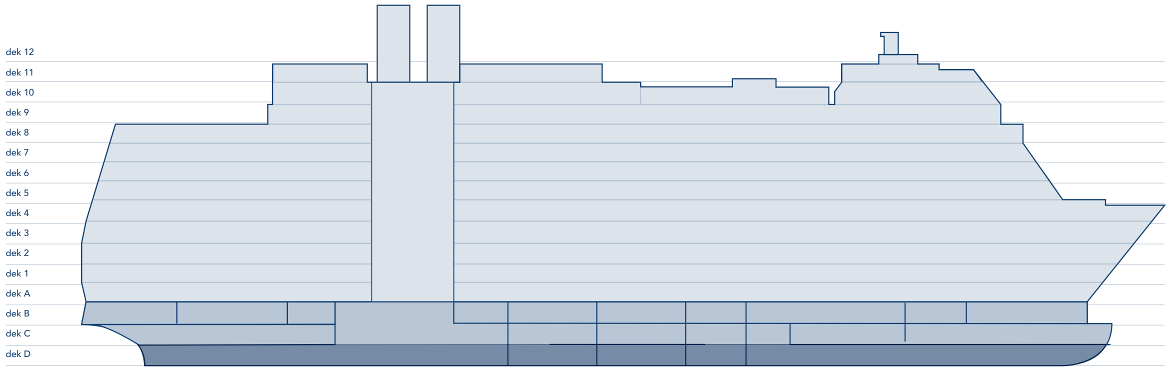
The vessel was built in sections at several different shipyards. The sections were then connected together at the Marghera shipyard. This is a customary method when building vessels of this size. The sections are not only constructed from the necessary steel, but are also equipped as far as possible with piping systems for fuel, water and steam, among other things. This means that the pipework must also be connected up when the sections are joined together.

The electricity for the vessel is supplied by six diesel generators, namely four MaK 12 M 43 C engines and two MaK 8 M 43 C engines, which together can generate 64,000 kW. The vessel is propelled by electrically powered Azipods and is equipped with a dynamic positioning system.[12]

12 A dynamic positioning system is a system that automatically controls the position and course of a vessel by using its own propellers, usually rudder propellers.

3.2.3 The vessel's decks

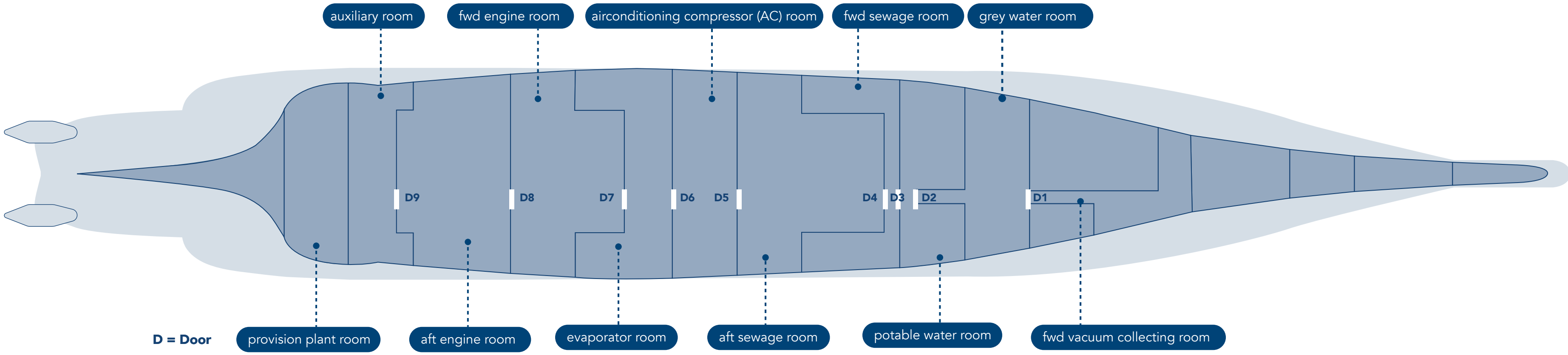
The vessel has passenger accommodation across 14 decks and can accommodate 2,106 passengers. Below those 14 decks are four decks with technical rooms and accommodation for a maximum of 874 crew members. These decks are labelled from the top down as decks A to D. The engine control room is located on deck A. Decks B and C contain the crew quarters. The engine room itself is located at the very bottom of the vessel, on deck D. Figure 5 provides a schematic overview of the vessel's decks.



▲ *Figure 5: The vessel's decks (source: Dutch Safety Board).*

3.2.4 Layout of the engine room

The engine room is divided into 11 watertight sections. These are shown in Figure 6.



▲ *Figure 6: Layout of the engine room (source: Dutch Safety Board).*

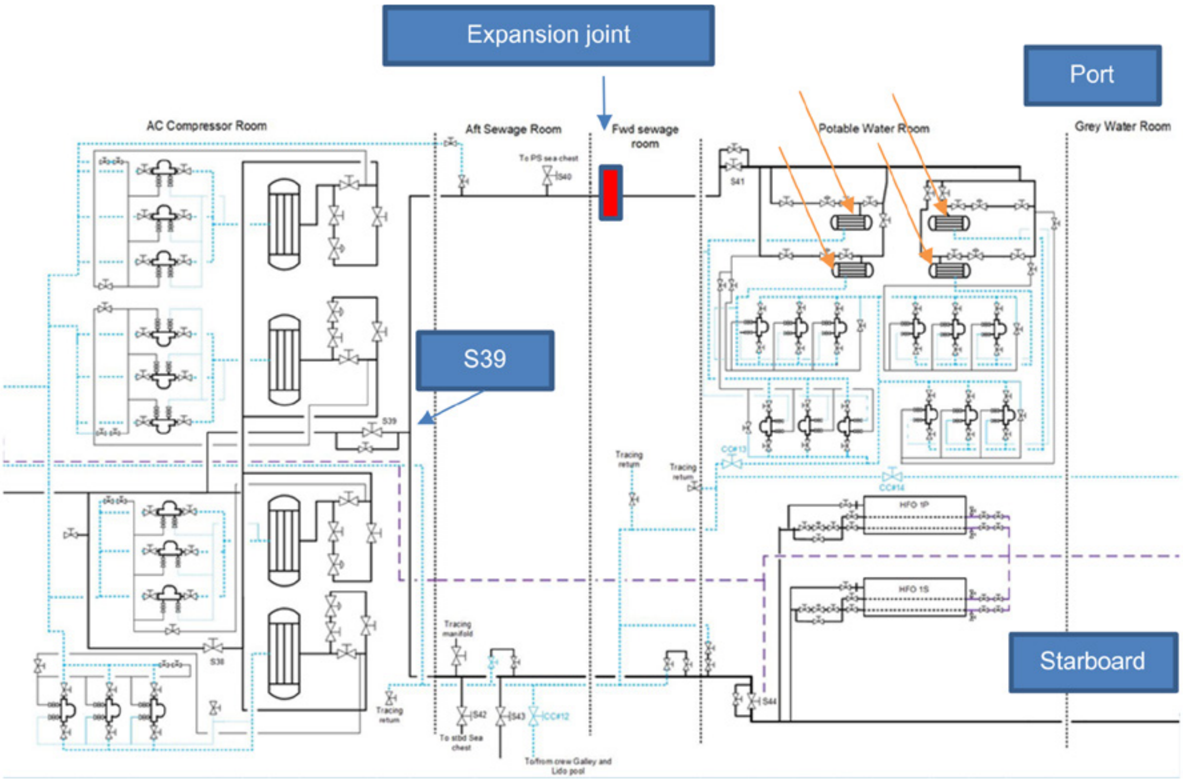
3.3 Steam system

A steam system is used on board the passenger vessel as a means of transporting heat. It operates at a pressure of 8 bar and a temperature of 170 °C. After being generated, the steam is distributed to the various users. This includes for heating the fuel tanks, the accommodation, the hot water system, the swimming pools, the (steam) laundry, and the various galleys on board.

3.3.1 Operation of the system on board

The steam is generated in the two rooms in the engine room where the diesel generators are located. When the engines of these generators are running, exhaust gas boilers are used to generate the steam, i.e. the heat from the exhaust gases of the engines is used to produce steam. Besides the exhaust gas boilers, two oil-fired auxiliary boilers are also available to generate steam.

A main steam pipe runs forward from the two rooms in the engine room where the steam is generated. In the air-conditioning compressor room, there is a steam isolation valve in the main steam pipe (labelled S39 in Figure 7). Beyond that valve, the system separates into two branches. One branch runs from the centre to starboard and then forward, through the aft and forward sewage rooms. This pipe then supplies steam to the laundry. The second branch runs to port and then also forward through the aft and forward sewage rooms and on to the potable water room, where there are four heaters for the hot water supply. At the time of the occurrence, there was an expansion joint in this branch at the back of the forward sewage room (see also Section 3.3.4). In the potable water room, the main port side pipe separates into two smaller pipes, one for the accommodation heaters and one for the galley heaters. In Figure 7, which provides an overview of the steam system between the air-conditioning compressor room and the potable water room, a red block indicates approximately where the expansion joint was positioned in the steam pipe. The heaters are indicated by the orange arrows.



▲ *Figure 7: Schematic diagram of the branches of the steam system. The steam pipes are shown in black, with the condensate (return) pipes in blue. S39 indicates the steam isolation valve in the main steam pipe (source: Holland America Line).*

3.3.2 Use of the steam pipe to the heaters

In normal operation (most of the year), the water for the accommodation and the galleys is heated using cooling water from the main engines (cooling water heaters). One of the exceptions is when the main engines are shut down, in which case the water is heated with steam (steam heaters). Consequently, the pipe with the expansion joint is only in use when the main engines are completely shut down. That only happens a few days a year, which in practice means that the pipe with the expansion joint is 'not in use'. In this case, however, the phrase 'not in use' does not mean 'closed'. To prevent the pipe from cooling down, two[13] valves to the steam heaters were always left slightly open.

Dangers of steam

Under normal atmospheric conditions, steam is at a temperature of 100 °C. Direct contact can cause serious and permanent injury, in some cases even resulting in death. Inhaling steam can burn the pulmonary alveoli, which severely impairs lung function.

If a litre of water is heated until it turns into steam, its volume becomes approximately 1,600 times greater. If water comes into contact with an extremely hot surface, the water evaporates extremely rapidly and the pressure increases exponentially, as a result of which a steam explosion can occur.

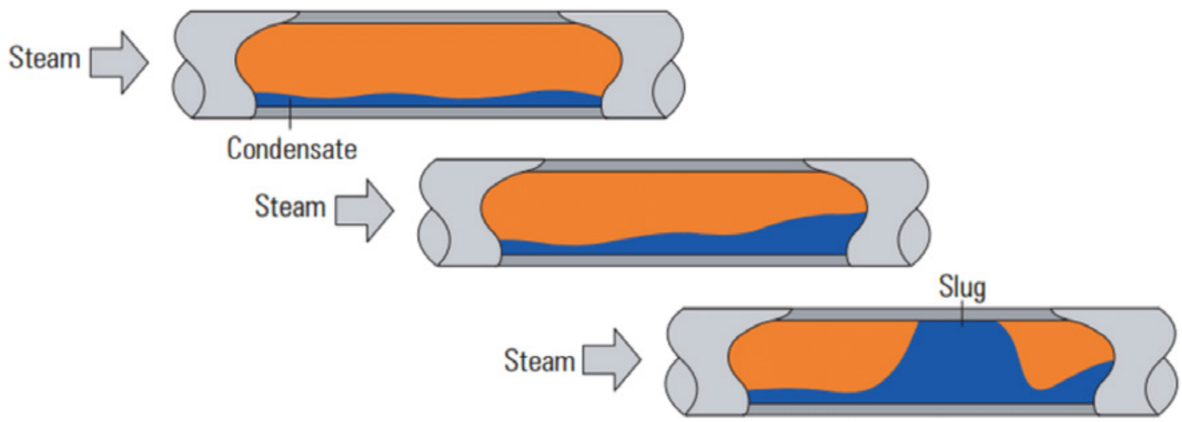
13 One valve to the accommodation heaters and one to the galley heaters.

3.3.3 Condensate

When the steam releases its heat, it cools down and water forms in the steam pipes. This also happens in a steam system. The water that is formed is referred to as 'condensate'. In the steam system on board, the condensate is drained using steam traps, which separate the condensate from the steam. The condensate is then channelled back to a tank, from where it is returned to the boilers to be heated up and turned into steam again.

Condensate in a steam system can be dangerous. Among other things, it can lead to thermal shock. When steam comes into contact with a cold surface, such as a steel pipe, it condenses rapidly, drastically reducing its volume and creating a vacuum. This vacuum sucks in water, which can lead to a chain reaction of further condensation and rapid water movements. These rapid movements can cause pipes to rupture or even explode. To prevent this, procedures are followed when starting up steam systems by which the pressure is gradually increased and vent valves are opened to safely drain away condensate.

Another danger of condensate in a steam system is differential shock. This can occur in properly functioning steam systems because a certain amount of condensate is always produced in steam systems due to heat loss. That condensate is generally drained away via steam traps and by installing the steam pipes in a sloping position (with a downward slope) to allow the water to drain away. However, if the steam traps are closed, clogged or defective, there can be a build-up of condensation. The rapidly flowing steam above the standing water can cause waves that eventually form a mass of water known as a 'slug'. The steam pressure forces the slug through the pipe like a projectile, which can cause enormous pressure spikes when it encounters obstacles or bends (see Figure 8).



▲ *Figure 8: Slug formed by rapidly flowing steam above standing water (source: Spiraxsarco).*

The pressure peaks that can occur due to thermal or differential shock mostly result in loud bangs in the system. Peaks in pressure caused by the presence of condensate are therefore referred to as 'steam hammer'.

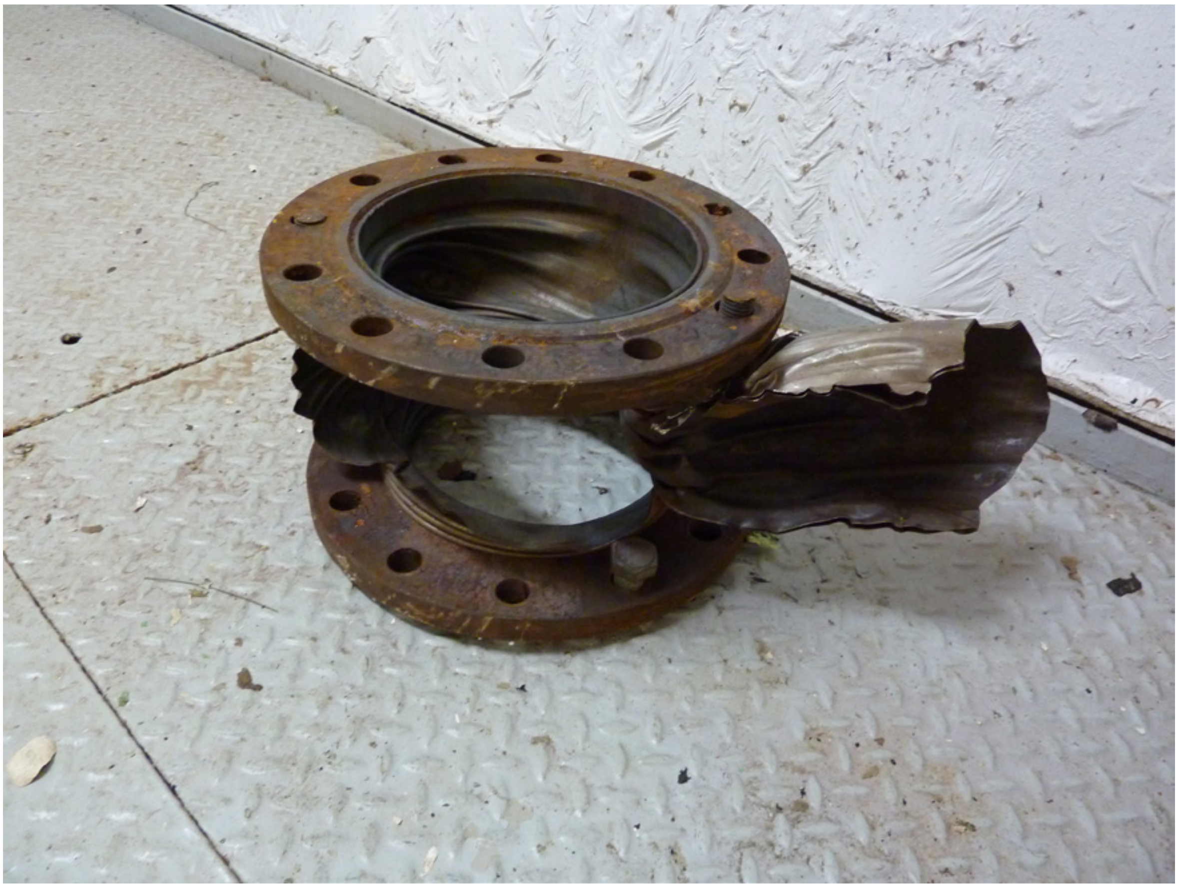
3.3.4 Expansion joint

Expansion joints are installed in steam piping to allow for thermal expansion of the piping. In actual practice, expansion joints are also sometimes used when two lengths of piping from different newly constructed sections do not connect up precisely. Figure 9 shows a new expansion joint. Figure 10 shows the ruptured expansion joint. Figure 11 shows steam piping encased in insulating material.

The expansion joint was made of two layers of stainless steel and designed for a maximum working pressure of 11 bar. During inspection, the expansion joint is subjected to a test pressure of 1.5 times the design pressure: 16.5 bar. For certification[14], the manufacturer conducted a number of tests with the same type of expansion joint.

▲ *Figure 9: New steam system expansion joint (source: Dutch Safety Board).*

14 An expansion joint from the series was subjected to various tests in order to obtain a prototype certificate for the series. The expansion joints were not subjected to all tests individually.



▲ *Figure 10: The ruptured expansion joint after removal (source: Dutch Safety Board).*

▲ *Figure 11: Steam piping encased in insulating material (source: Dutch Safety Board).*

3.3.5 Inspection of the steam system

The steam system is periodically tested and inspected as part of the *Harmonized System of Survey and Certification* (HSSC)[15]. Inspection is carried out by a classification society; for the passenger vessel concerned, this was Lloyd's Register.

Among other things, these inspections involve testing all the safety systems, including the safety valves and the alarms, and random inspections of parts of a steam pipe. Expansion joints are considered a part of a steam pipe.

The classification society carried out the most recent inspection of the steam system for the HSSC on 18 December 2023. The owner acted on all the recommendations made following this inspection to the satisfaction of the classification society.

3.4 Crew composition

The nautical department on the vessel consisted of 60 crew members. Command of the vessel lay with the captain. Below him was the staff captain, who was responsible, among other things, for dealing with emergency situations from the control centre on the bridge (*Command Emergency Operations*).[16]
The technical department on the vessel consisted of 84 crew members, led by the chief engineer. Below him was the staff engineer officer – who was responsible, among other things, for dealing with emergency situations in the engine room (*Command Emergency Operations Engineering*)[17] – and several engineer officers. Table 2 shows the roster of watches. The watch on duty from 00.00 hours to 06.00 hours was responsible for the steam system. The watch on duty from 12.00 hours to 18.00 hours was responsible for the sewage processing system. The watch on duty from 18.00 hours to 24.00 hours was responsible for the potable water system. The other technical staff were not part of the watches.

As a result of this setup, responsibility for the part of the steam system leading to the steam heaters rested with two separate watch teams. The officer in charge of the watch responsible for the potable water system had been part of this watch for only a month and had not been responsible for the steam heaters before.

15 HSSC is part of the safety legislation and certification of seagoing vessels as laid down by the International Maritime Organization.
16 Because the staff captain is responsible for dealing with emergency situations, the captain can then continue to concentrate on safe navigation of the vessel in such situations.
17 Because the staff engineer officer is responsible for dealing with emergency situations in the engine room, the chief engineer can then continue to concentrate on the operation of the vessel's propulsion system in such situations.

▼ *Table 2: Composition of engine room watches.*

	Time	Composition of the watch	Additional responsibility
1	Day watch	Chief engineer	
2		Staff engineer officer	
3		Environment officer	
4	00.00–06.00	Second engineer officer	Boilers
5		Third engineer officer	Boilers
6		Motorman	
7	06.00–12.00	First engineer officer	
8		Third engineer officer	
9		Motorman	
10	12.00–18.00	Second engineer officer	Sewage processing
11		Third engineer officer	Sewage processing
12		Motorman	
13	18.00–24.00	Second engineer officer	Potable water
14		Third engineer officer	Potable water
15		Motorman	

3.5 Procedures and training

3.5.1 Procedure

For maintenance of the technical installations (including repairs), the crew of the passenger vessel follow a *Lock Out Tag Out* (LOTO) procedure. This is a safety procedure that ensures that the power supply to machinery or equipment is switched off during maintenance or repair work. This process is intended to protect employees from the unexpected release of energy and the dangers posed by machinery that is running. Energy sources are isolated and secured with locks that are labelled (tags) with the name of the person who secured them. A LOTO tag is only removed after all the work has been completed.

The owner has procedures for work on hazardous stored energy systems.[18] Working on these types of systems requires a Permit to Work (PTW[19]). In order to apply for and be granted a PTW, it is necessary (among other things) to carry out a Risk Assessment (RA[20]). A standard RA is available for working on steam systems. This focuses mainly on replacing gaskets, valves, or piping in the steam system.

3.5.2 Training

The owner's familiarisation procedures[21] stipulate that all engineer officers must undertake technical familiarisation before they are allowed to act as a watch officer. This includes becoming familiar with the layout of the main steam system.

The owner also makes use of an e-learning programme to train the engineer officers on board. The e-learning programme includes the use of LOTO, PTW, and RA. It also covers the steam system, with the focus being on maintenance of the system and not on the underlying technical principles. Among other things, the e-learning programme deals with the dangers of opening up systems that are under pressure and at high temperature.

---

18 *Hazardous stored energy systems*: energy sources such as electrical, mechanical, hydraulic, pneumatic, chemical, thermal (including steam), or other sources in machines and equipment that can be dangerous for employees.

19 Permit to Work is a system that specifies exactly which activities must be carried out and when, and which components are safe. A responsible person must assess the work and check safety at each stage. The people who carry out the work sign the permit to indicate that they understand the risks and the necessary precautionary measures.

20 The RA is intended to identify all the hazards associated with the conditions at the work site. It ensures that any additional precautionary measures are implemented before anyone may be exposed to expected and unexpected hazards.

21 Familiarisation means that the crew familiarise themselves with the safety aspects of the specific vessel, for example its layout and equipment. They must also be familiar with relevant work procedures and safety equipment.

4 ANALYSIS

4.1 Introduction

The two crew members lost their lives because hot steam was released into the room where they were working after an expansion joint in the main steam pipe ruptured. We discuss the repair of the steam heater in Section 4.2, before moving on to the rupture of the expansion joint in the forward sewage room in Section 4.3. Lastly, in Section 4.4, we analyse the attention paid to steam systems in training and instruction.

4.2 Repair of the steam heater

We mentioned in Section 2.1 that one of the steam heaters underwent repair on 17 March 2024, as it was leaking. Before the heater was removed for repair, a valve in the inlet pipe to this steam heater that was slightly open, was fully closed.

The risk analysis that was available for work to the steam system focused mainly on replacing gaskets, valves or pipes in the steam system. This risk analysis described the precautionary measures to be taken prior to starting the work, such as ensuring the release of all steam pressure. The risk analysis did not cover the dangers involved in isolating parts of the steam system, such as the risk of condensation or the risk of steam hammer.

An isolation plan is required for all work that entails a risk of release of dangerous energy. This isolation plan must be drawn up by the responsible crew member, who must also see to it that it is complied with.

The LOTO form for isolating the steam heater specified the following procedure:
- Close the two steam inlet valves.
- Close the small drive steam valve (steam to steam traps).
- Close the steam trap valves.
- Open the heater condensate outlet.
- Open the potable water inlet and outlet valves.

When the valve was closed and the steam heater was removed, nobody realised that this resulted in the isolation of part of the steam system. As a result, no Permit to Work was issued and no additional risk analysis was performed. This was potentially due to the fact that the steam inlet pipe to the steam heaters was ‘not in use’ most of the year (see Section 3.3.2).

The heater was removed on 17 March for repair and reinstalled on 21 March. Although this signified the completion of the work, the LOTO tag remained in place, so the valve remained closed. We have been unable to find out why the LOTO tag remained in place. Prior to the occurrence on 22 March, the steam pipe with the expansion joint had been isolated for six days.

Interim conclusion
In preparation of the repair of one of the steam heaters, a crew member closed a valve in the steam inlet pipe to the steam heaters. The crew involved knew that the valve was slightly open in order to keep the pipe warm. However, they did not know that the purpose of keeping the pipe warm was to prevent condensation. As a consequence, they were unaware of the fact that closing the valve isolated part of the steam system, thereby increasing the risk of steam hammer.

4.3 Rupture of the expansion joint

As noted in Section 3.3.4, the expansion joint was designed for a maximum working pressure of 11 bar and the test pressure was set at 16,5 bar. The average pressure in the steam system on board was 8 bar. The expansion joint did not therefore rupture because it was unable to withstand the working pressure in the system. In this section, we discuss two scenarios that can explain the rupture of the expansion joint, namely material fatigue and steam hammer.

4.3.1 Material fatigue

In order to determine whether material fatigue had occurred, material testing was carried out on the edges of the rupture of the expansion joint by Element Material Technology (see Appendix C for the full report in English). In its report, Element Material Technology concludes that material fatigue had not been an issue:

> 'The metal had the expected appearance of thin plate material of this type. There were no faults or weak spots in the material.
>
> The bellows failed due to rupturing of the metal. Two ruptures ran circumferentially and were combined with one longitudinal rupture. Wherever the bellows had ruptured, it was evident that the metal had first stretched before breaking. This indicates that the metal failed due to excessive force, and not, for example, due to rust or ruptures caused by repeated stress (fatigue).
>
> The conclusion is that the bellows failed because of overloading of the metal. It appears that the internal pressure became too high, causing the metal to rupture. The way the metal ruptured, especially longitudinally, indicates that the pressure increased suddenly or very quickly.'

Interim conclusion
Based on the investigation and the conclusions of Element Material Technology, it can be established that there were no signs of material fatigue and that the material did not exhibit any inherent defects or imperfections.

4.3.2 Steam hammer

On 17 March 2024, prior to the repair of one of the potable water steam heaters, a crew member fully closed a valve in the steam inlet pipe to this heater that was slightly open (see Section 4.2).

Because the steam traps in which the condensate is separated from the steam were closed, the condensate was able to build up in the pipe. We have been unable to find out why the steam traps of the steam heaters for the galleys were closed. They were not closed to facilitate the repair to the steam heaters in the days leading up to the occurrence. According to the planned maintenance system, no maintenance or repair of the steam system took place in the months prior.

If condensate builds up, it can flow back against the direction of the steam. The steam then re-heats this water, turning it back into steam. As a result, the volume suddenly increases significantly, causing dangerous peaks in pressure ('steam hammer', as explained in Section 3.3.3). This can cause loud bangs in the system, The noises (bangs) heard by the crew members in the potable water room are consistent with this phenomenon. The investigation by Element Material Technology supports the theory that there were pressure peaks in the pipe. 'The rupture, particularly in the longitudinal direction, suggests a rapid or sudden build-up of pressure. A slower pressure build-up would normally lead to far more local deformation ('necking') rather than rupturing.' The rupture of the expansion joint can therefore be explained by the presence of steam hammer.

The steam heaters were only used when no cooling water from the engines was available. This was the case on only a few days a year, for example when the vessel was connected to shore power (electrical). The design did not take into account that the steam heaters would not be used. There was no valve at the beginning of the branch to port. As a result, a long stretch of pipe could only be closed at the steam heaters themselves. A habit had formed on board of keeping two valves slightly open. This was not only to keep the system warm, but also to counter the build-up of condensate. Consequently, while the steam heaters were not in use, they were not fully closed either.

Although the steam system was designed to be used in its totality, the branch to port was hardly ever used in practice. The system was not adapted with the installation of a valve to take this into account. Instead, a practical solution was adopted of leaving two valves slightly open. Because a valve could be closed by mistake, this method raised the risk of steam hammer.

Interim conclusion
When the valve in the steam inlet pipe to the steam heaters was fully closed, the pipe with the expansion joint became a dead end. This caused the steam present in the pipe to cool down to condensate. As the steam traps were also closed, the condensate built up in the dead end. A build-up of condensate can lead to steam hammer. The bangs that were heard and the type of rupture in the expansion joint also point to the steam hammer that occurred. The resulting pressure waves caused the expansion joint to rupture.

The system had been designed to be in use, but it was not. In order to keep the system at the right temperature and prevent the build-up of condensate and hence steam hammer, a number of valves were left slightly open. This method raised the risk of steam hammer.

4.4 Steam systems in training and instruction

The legally required safety training sessions do not include scenarios involving a major steam leak. They do include scenarios for firefighting, abandoning ship, survival at sea, and first aid. The emergency scenarios practised on board were in line with the legal requirements. The crew had not therefore received safety training for a major steam leak.

Only a few vessels still use steam for propulsion. The training programmes for engineer officers do still deal with steam systems as auxiliary systems but those programmes focus on the efficient use of steam systems and how to start and shut down the system safely. The legally required[22] training programmes do not specifically cover the dangers of working with steam systems, such as steam hammer.

The owner's internal crew training and procedures comply with the legal requirements. There is a procedure for starting and stopping the steam system. It was not necessary to shut down the steam system (or part of it) during the repair prior to the occurrence, meaning that that procedure was not followed.

In the steam inlet pipe to the steam system, two valves to the steam heaters had been left slightly open in order to keep the pipe warm. Although the engine room crew members knew this, they did not know that the reason for this was preventing condensate from forming in the pipe, which could lead to steam hammer. No explicit attention was paid to the possibility of condensation in the steam system (other than when starting the steam system) and the topic was not covered by internal training and instruction.

22 *Standards of training, certification and Watchkeeping* - STCW

Interim conclusion
The crew did not receive any training or instruction regarding the causes, dangers, and prevention of steam hammer in steam systems. There is no legal requirement to cover this topic in the curriculum of navigational training and instruction.

The risk of condensation and steam hammer was not acknowledged on board, except during the procedure to start the steam system. Because it was not known that these risks were also present in other situations, the crew had received no training or instruction for this.

5 ACTION TAKEN BY THE OWNER AFTER THE OCCURRENCE

This chapter provides a brief summary of the action taken by the owner after the occurrence.

Action already completed

1. Redesign of the steam piping in the forward sewage room of the Nieuw Amsterdam and the Eurodam. The expansion joint has been replaced by a U-bend (approved by the classification society).
2. In all the vessels in the fleet, the steam piping has been inspected to identify any previously unknown expansion joints. It has also been verified that all expansion joints have been included in the planned maintenance system.
3. An Engine Room Safety Management working group has been set up at the head office in Seattle.

Action currently being taken

4. Replacement of mechanical steam traps by electronically controlled steam traps in the steam system.
5. The inspections referred to under point 2 revealed the presence of deformed expansion joints within the fleet. These are being replaced and where necessary the steam piping is being aligned.
6. Updating the risk assessments for the engine room, including checking emergency exit locations and emergency warning systems.
7. Standardisation of watertight door warning systems within the HAL fleet.
8. An investigation into the possibility of installing a location tagging system for the engine room, with location trackers for engine room personnel.

Action currently being investigated

9. Installation of temperature and moisture sensors in the rooms where the steam system is located.
10. The options for dealing with the existing overpressure in the engine room.

The owner is also evaluating the existing emergency scenarios and exercises and making changes where necessary. A programme is also underway to ensure that in future the new build team will verify that all expansion joints that are installed are actually shown on the drawings and are included in the planned maintenance system.

6 CONCLUSIONS

On 22 March 2024, two crew members of the Dutch passenger vessel the Nieuw Amsterdam lost their lives after an expansion joint in a steam pipe ruptured and filled the room they were in with steam within 86 seconds. The release of the mixture of water and steam at a temperature of more than 100 degrees Celsius created conditions in the room that prevented the two crew members from reaching the watertight doors and the emergency exit, so that they were unable to survive.

Rupture of the expansion joint due to steam hammer
Due to steam hammer in the steam system, the steam pipe ruptured in a weak spot: the expansion joint. The rupture in the expansion joint was large enough to fill up the forward sewage room rapidly and entirely with steam.

Maintenance prior to the occurrence
The steam hammer occurred because a valve that was normally left slightly open had been fully closed. This was done on 17 March 2024, ahead of the repair of one of the heaters in the steam system. The crew involved knew that the valve was normally slightly open in order to keep the pipe warm, but they did not know that the act of closing the valve turned the pipe with the expansion joint into a dead end where condensate could build up. If condensate builds up, it can flow back against the direction of the steam. The steam then re-heats this water, turning it back into steam. As a result, the volume suddenly increases significantly, causing dangerous peaks in pressure (steam hammer). None of the crew members were aware of the danger of the build-up of condensate in this part of the steam piping.

Steam heaters not in use, but not fully closed either
During normal operation, the steam heaters were not in use (except for a few days a year). However, this did not mean that all steam heater valves were fully closed. The necessity of keeping the valves slightly open was not covered in the work procedures on board. Consequently, the risk of the build-up of condensate as a result of closing the steam inlet pipe fully was not covered in the Lock Out Tag Out procedure, nor in the risk analysis for steam system maintenance.

Steam hammer not covered by training or instruction
The crew did not receive any training or instruction regarding the causes, dangers, and prevention of steam hammer. The owner's internal training and instruction regarding the steam system procedures are in line with international legislation and regulations. The legislation and regulations do not mention the risk of steam hammer in a steam system.

In both the internal training and instruction and the procedures on board, the risk of the build-up of condensate and hence the risk of steam hammer was assumed only to be present during the procedure to start the steam system (or parts of it).

Design versus use of the steam system

The design of the steam system did not account for the possibility that part of the system was not in use. In practice, this meant that the valves in the branch to port were not fully closed in order to prevent the build-up of condensate. Because a valve could be closed by mistake, this method raised the risk of steam hammer.

7 RECOMMENDATIONS

Prevent structural workarounds in steam systems

During normal operation of the steam system on board the Nieuw Amsterdam, a structural workaround was necessary (a valve was kept slightly open) to prevent condensate build-up in the system. Although a workaround is sometimes unavoidable in practice, its prolonged use should be avoided.

Recommendation to Holland America Line (HAL)
To promote the elimination of structural workarounds in steam systems on HAL vessels, we recommend the following to the HAL:

1. Check all your existing ships to determine whether structural workarounds are being used in the steam system during normal ship operations. If a structural workaround is found, the system or procedure should be modified so that the crew no longer needs to use the workaround.

Recommendation to NMT-IRO[23]
To prevent steam systems that require the structural use of a workaround from being installed in new ships, we recommend the following to NMT-IRO:

2. Draw your members' attention to the need to avoid installing steam systems in new ships that require the structural use of a workaround during normal ship operation.

Recommendation to the Royal Association of Netherlands Shipowners (KVNR)
To ensure that other shipping companies can also learn from this incident, we recommend the following to the KVNR:

3. Draw attention to the need to avoid the use of structural workarounds in steam systems among your members and international contacts.

Improve crew awareness of the risks of condensate build-up and steam hammer in steam systems.

The crew aboard the Nieuw Amsterdam had limited knowledge of the risks of condensate build-up and steam hammer in steam systems. These risks were not addressed in procedures and training. Crew training also pays little attention to these risks.

23 NMT-IRO is a trade association for the maritime manufacturing and offshore energy industry in the Netherlands.

Recommendation to Holland America Line (HAL)
To increase crew knowledge and awareness of the risks of condensate build-up and steam hammer in steam systems on HAL ships, we recommend the following to HAL:

4. Amend your procedures and training regarding working with steam systems so that crews are better aware of the risks of condensate build-up and steam hammer.

Recommendation to the Minister of Infrastructure and Water Management (I&W)
To incorporate the risks of condensate build-up and steam hammer in steam systems into seafarer training, we recommend the following to the Minister of Infrastructure and Water Management:

5. Submit a proposal to the International Maritime Organization to amend the Standards of Training, Certification and Watchkeeping for Seafarers (STCW) so that the risks of condensate build-up and steam hammer in steam systems are addressed in crew training. In anticipation of an amendment to the STCW, bring these risks and this case to the attention of maritime schools in the Netherlands, so that they can already address them in their education.

APPENDIX A

Vessel Data Nieuw Amsterdam

Vessel Data	Nieuw Amsterdam
Call Sign	PBWQ
IMO Number	9378450
Flagstate	Netherlands
Type of vessel	Passenger ship
Year of Construction	2010
Shipyard	Fincantieri (Italy)
Length	285 m
Beam	32 m
Draught	8.2 m
Gross Tonnage (GT)	86.273 ton
Passengers	2106
Crew	1735
Main Engines	6 x diesel-electric MaK M 43 C
Propulsion	Azipod thrusters
Maximum Power	64.000 kW
Ships certificates	All valid

APPENDIX B

Responses to the draft report

The draft report (without recommendations) was submitted to the various parties involved.
These parties were requested to check the report for factual inaccuracies and inconsistencies. The following parties responded to the draft report:

- Holland America Line
- NMT-IRO
- Ministry of Infrastructure and Water Management

The responses received were dealt with in the following manner:

- Whenever the Safety Board has decided to adopt responses, these are incorporated into the final version of the report.
- Whenever the Safety Board has decided not to adopt responses, an explanation
- for that decision is given.

The responses and the Safety Board's explanation are included in a table on the Safety Board's website (https://onderzoeksraad.nl/en/).

APPENDIX C

Report Element Material Technology

Element Materials Technology
[redacted]
info.amsterdam@element.com
element.com
[redacted]

REPORT

ANALYSIS OF A FAILED STAINLESS STEEL EXPANSION JOINT

Client	: De Onderzoeksraad Voor Veiligheid
Client's reference	: ---
Element Project	: ERO042123P
Report no	: ERO042123 Rev. 0
Investigation period	: April 24 - May 24, 2024
Report date	: June 06, 2024
Revision date	:
Investigator/Author	: [redacted]
Classification	: ---
Distribution	: De Onderzoeksraad Voor Veiligheid [redacted] (pdf) Element, file (pdf)

1 Introduction and background information

An expansion joint from a vessel has failed during service.

The following information was submitted by De Onderzoeksraad Voor Veiligheid (''Onderzoeksraad''):
The expansion joint was part of a steam conduit. The saturated steam had a working pressure of 7 to 8 bar. As far as could be determined the working pressure at the time of failure was 7.6-7.8 bar.
The materials of the expansion joint were not specified.

For the investigation the failed expansion joint has been submitted to Element Materials Technology Rotterdam B.V. ("Element", location Amsterdam).

Element was requested to determine the nature, and if possible, the cause of failure of the expansion joint.

2 Experimental details

The failed expansion joint was first examined visually in the as received condition. The complementary fracture surfaces were subsequently examined in more detail by stereomicroscopy. Selected fracture surface segments were examined by Scanning Electron Microscopy (SEM) to determine the fracture mechanism. The chemical composition of the failed material was analysed by an Energy Dispersive X-ray (EDX) microanalysis probe of the SEM. Cross section samples were cut from the failed expansion joint to examine the material in relation to the fracture by optical microscopy.

3 Results and discussion

3.1 Visual and stereomicroscopic examination

The expansion joint consisted of a metal bellows in between two flange rings. The metal flange rings had an outer diameter of 340 mm, an inner diameter of 220 mm and a thickness of 20 mm. A type plate on the flange confirmed the production company as "steelflex" and the expansion joint as type "AFX 3F".
The bellow section, in the as received/failed condition, had a length of ~15 cm. The bellows was double walled with both plates having a thickness of ~0.5 mm. The bellows appeared to have a total of 15 convolutions, due to the deformation and fracture in the bellows they were difficult to identify. The expansion joint in the as received condition is presented in figure 1.

The expansion joint appeared to have failed due to overlapping circumferential cracks and an axial crack in both bellows, accompanied by significant material deformation leading to a blown-out lip further referred to as "fracture". To form the blown-out lip, the fracture most likely started in the axial section to progress in to circumferential cracks to form the complete lip.
As far as still could be determined, the internal diameter of the bellows had been 20 cm, the external diameter 24 cm, and the number of convolutions has been 15. The original width ("wavelength") of the convolutions (and thereby also the original distance between the flanges), could not be determined with any accuracy.
Both the internal and external bellows showed (non-overlapping) axial welds. The formed cracks however clearly did not relate to these longitudinal welds.

The fracture itself showed the following dimensions and details:
The fracture had a width of 115 mm across 9 convolutions with 3 unfractured convolutions on each side. The fracture length was roughly 230 mm along the circumference of the bellows. An overview of the fracture is presented in figure 2.
On the fractured side of the bellows the fractured convolutions were expanded ("blown up"), while the same convolutions were compressed on the opposite side of the bellows. Similarly, the unfractured convolutions were compressed adjacent to the fracture and expanded on the opposite side, see figure 3. The plate material

of the bellows showed some corrosion products, however, these appeared superficial and unrelated to the fracture.
In both the external and the internal bellows plate the fracture followed the exact same fracture path. The fracture path is illustrated in figure 4 for the fracture across the width of the bellows (axial crack direction). The fracture along the side of the convolutions of the bellows (two circumferential cracks) is illustrated in figure 5.

Due to the thin nature of the plate materials used for the bellows, little characteristics of the crack surfaces could be distinguished by visual and stereomicroscopic examination. Additionally, some corrosion appeared to have occurred on the fracture surfaces further obscuring fracture characteristics. Details of the fracture surfaces in the axial direction of the bellows are presented in figure 6. Here corrosion indeed obscured the details of the fracture. The circumferential fracture surfaces appeared slightly less corroded, see figure 7. Some plastic deformation of the material, most likely a form of necking, appeared to be visible.

3.2 Scanning Electron Microscopy (SEM)

Sections were cut from the fractured bellows material to enable an examination of the crack surfaces by Scanning electron microscopy. Sections were cut from both circumferential cracks (inner and outer bellows sections) as well as a section taken from the axial crack section in the bellows.
In all examined crack surfaces, both from the internal and external bellows, only a dimple morphology was observed. The dimple morphology is characteristic for a ductile cracking mechanism. Representative images of the fracture surfaces with dimple morphology are presented in figures 8 to 12. Some corrosion products were present on the fracture surfaces, as was also determined visually.
All examined crack surfaces only revealed evidence of ductile failure, no evidence was found for stress corrosion cracking or fatigue cracking. The corrosion of the crack surfaces was superficial and thus appeared to have occurred after cracking (secondary damage).

3.3 Energy Dispersive X-ray microanalysis (EDX)

To confirm the alloy type that was applied for the bellows clean samples were analysed for chemical composition. Due to the limited thickness of the material the analysis was performed in the SEM equipped with an Energy Dispersive X-ray microanalysis (EDX) probe. The analysis was performed at relatively low magnification to cover a larger surface area and at an accelerating voltage of 20 kV. An analysis was performed for both the inside and outside bellows plate. The results of the analysis are presented in table 1.

Table 1. Chemical composition (mass %) as determined with EDX* analysis.

sample / element	C	Si	Mn	Cr	Ni	Ti	Fe
Plate outside	little	0.7	1.9	18	9.0	0.6	70
Plate inside	little	0.7	1.7	18	9.3	0.6	70

* Remark: EDX (EDS, energy dispersive X-ray microanalysis) is a semi quantitative analysing method. Depending on the accelerating voltage, in principle all elements, except those lighter than boron, can be detected. The detection limit depends on the measured element, the composition of the surrounding matrix and the used accelerating voltage. In general, it can be said that the detection limit is approx. 0.1 mass% to 0.5 mass%. The accuracy of the results also depends on element and matrix and is approx. a few tenths of a weight percent up to a few weight percent (absolute value). EDX analysis is performed on relatively small surfaces. This implies that local variations in the chemical composition may influence the results. The carbon content cannot be determined with sufficient accuracy. The carbon content therefore is estimated, judged by experience based on the relative size of the carbon peak in the spectrum. The carbon content is reported in terms of "much" or "little". In the calculation of the percentages of the other elements (a total of 100% is assumed) the carbon content is <u>not</u> included. When a large quantity of carbon is present this therefore will influence the calculated results for the other elements significantly. Thus, in EDX analysis of substances consisting mainly of carbon (e.g. polymers), the estimated carbon content is reported in [m%] with an uncertainty of +/- 10%.

Based on the compositional analysis by EDX it is concluded that the failed bellows plate materials of the expansion joint are stainless steel type AISI 321 or an equivalent such as alloy X6CrNiTi18-10 (1.4541) in standard EN 10088-2.

3.4 Microscopic examination

Cross section samples were cut over the fracture surfaces of the axial and circumferential cracks in the internal and external bellows. The samples of the internal and external bellows plates were sampled at roughly corresponding positions. The cross-sectional samples were subsequently prepared for examination by optical microscopy. To reveal the microstructures the samples were electrolytically etched in 10% oxalic acid solution (following standard ASTM E407, no. 13).

The general microstructures of the bellows plates were similar for both the internal and external bellows. The plates had an austenitic microstructure with a deformation texture and TiN particles. The texture is the result of the plate and bellow forming process. The texture was most pronounced in the sample taken over the axial cracks in the bellows. Representative images of the general microstructure are presented in figure 13.

At the fracture surfaces plastic deformation was clearly visible in the material. In all instances a ductile type fracture was observed in the microstructures; a predominantly shear type fracture was observed in the cross-sectional samples. Apart from the deformation there were no deviations from the general microstructures at the fractures. Representative images of the cross-sectional samples at the fracture are presented in figures 14 and 15. No material degradation or defects were observed in the examined cross-sectional samples.

4 Overall discussion

The bellows of the expansion joint were a double walled construction and both walls were made out of stainless steel of type AISI 321 (or an equivalent alloy). The microstructures of the material followed expectations for thin plate material of this alloy type. The material did not show any inherent defects or imperfections.

The bellows showed plastic deformation in that the convolutions of the bellows were either compressed or completely expanded (blown up). The bellows failed by cracking of the material. Two cracks ran circumferential and were combined with one axial crack, thereby forming a lip ("fracture"). The fracture ran through both walls of the expanded sections in the bellows and the fracture path was identical for both the internal and external bellows wall.
At all positions the examined crack surfaces of both the bellows showed evidence of plastic deformation (dimples) that had resulted in shear, thus pointing to failure by ductile overloading. No evidence was found for stress corrosion cracking or fatigue cracking, and the observed (superficial) corrosion of the crack surfaces had occurred after cracking (secondary damage).

It is concluded that the materials of the bellows in the expansion joint failed due to a fully ductile overload of the material. It appears that a too high internal pressure has led to the occurred ductile failure. The ductile failure apparently has started with axial cracking, almost instantaneously progressing in two circumferential cracks, together making a blown-out lip. Material stresses due to internal pressure are highest in the circumferential direction thereby promoting an initial axial rupture.

The predominantly shear type fracture, especially in the axial direction, suggests a rapid or sudden pressure build-up. A slower pressure build-up would normally lead to much more local deformation (necking) at the fracture surface, instead of the shear type fracture.

5 Conclusions

The materials of the bellows in the expansion joint failed due to a fully ductile overload of the material.

The ductile failure was caused by a high internal pressure build-up in the expansion joint.

Amsterdam, June 06, 2024

Author: [redacted]
Consultant failure analysis
[redacted]

Authorised: [redacted]
Group leader failure analysis NL

p.p. [redacted]
Sr. Consultant failure analysis
[redacted]

Figure 1. The failed expansion joint as received by Element Materials Technology, Amsterdam.

Figure 2. Overview of the fracture in the bellows with visibly expanded and compressed convolutions, the fractured double plate segment is still connected to the bellows.

Figure 3. The unfractured side of the bellows with expanded convolutions adjacent to the central compressed convolutions. The central convolutions are obscured by the expanded convolutions on each side.

Figure 4. The fracture across the width of the bellows illustrating the exact same fracture path through both bellows plates.

Figure 5. The fracture across along the side or circumference of the bellows illustrating the exact same fracture path through both bellows plates.

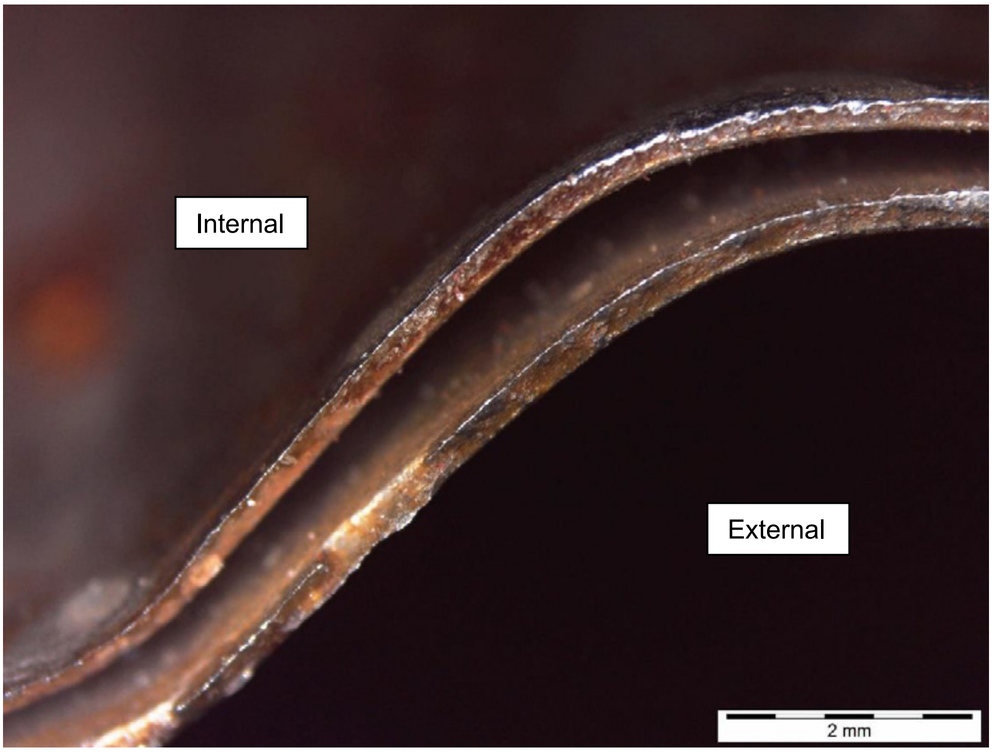


Figure 6. The fracture surfaces of the bellows plates in the fracture across the width (see figure 4 for reference). Mostly corroded fracture surface, no visible details.

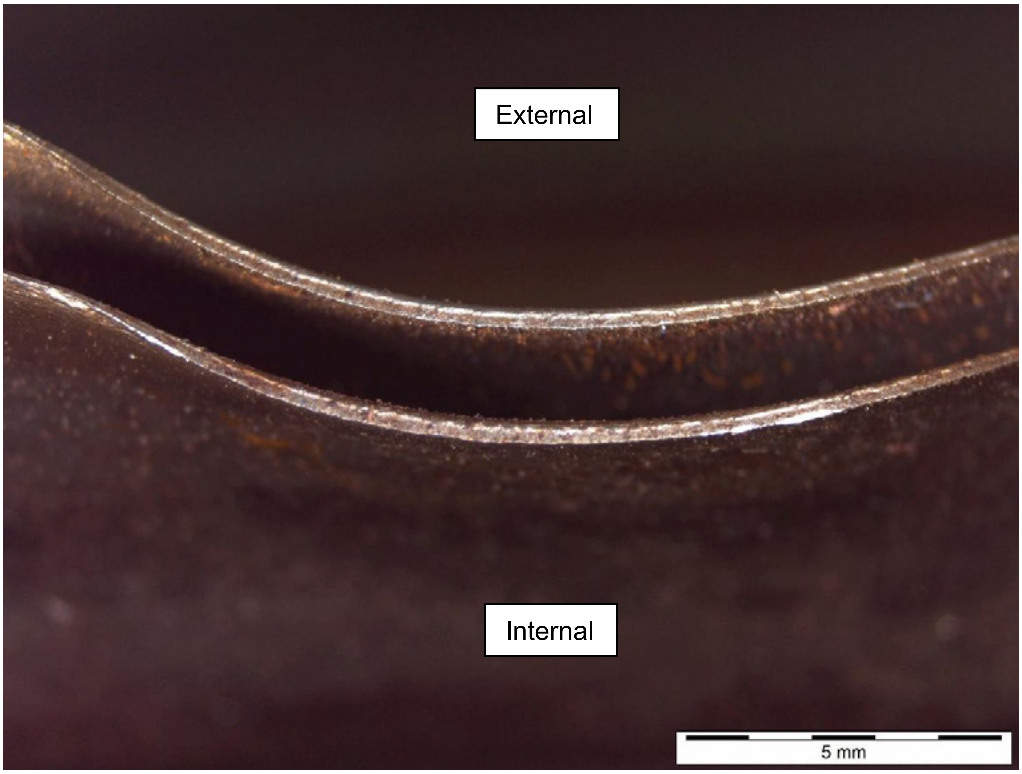


Figure 7. Detail of the fracture surfaces along the circumference, some plastic deformation appeared to be visible.

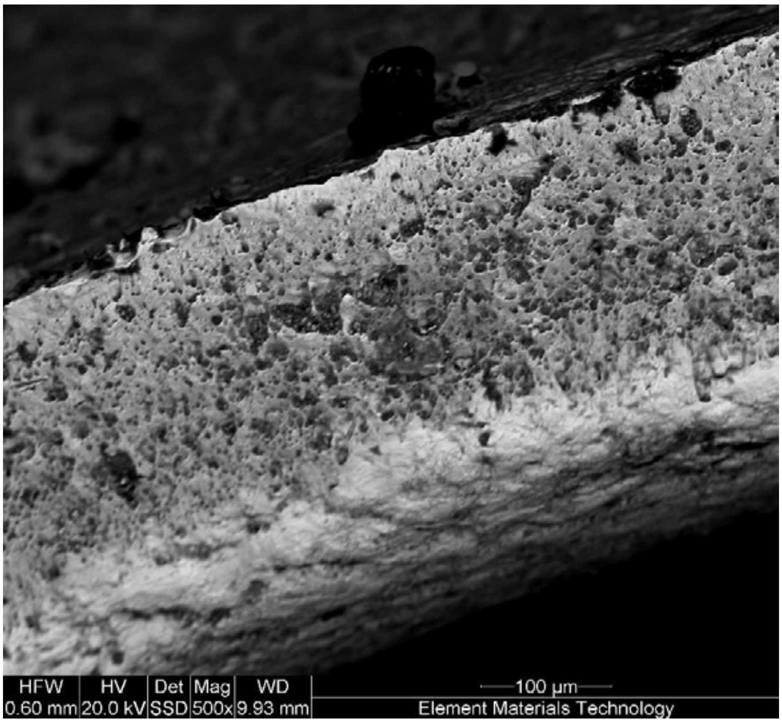


Figure 8. Typical fracture surface in bellows plate: dimple morphology and slightly corroded fracture surface.

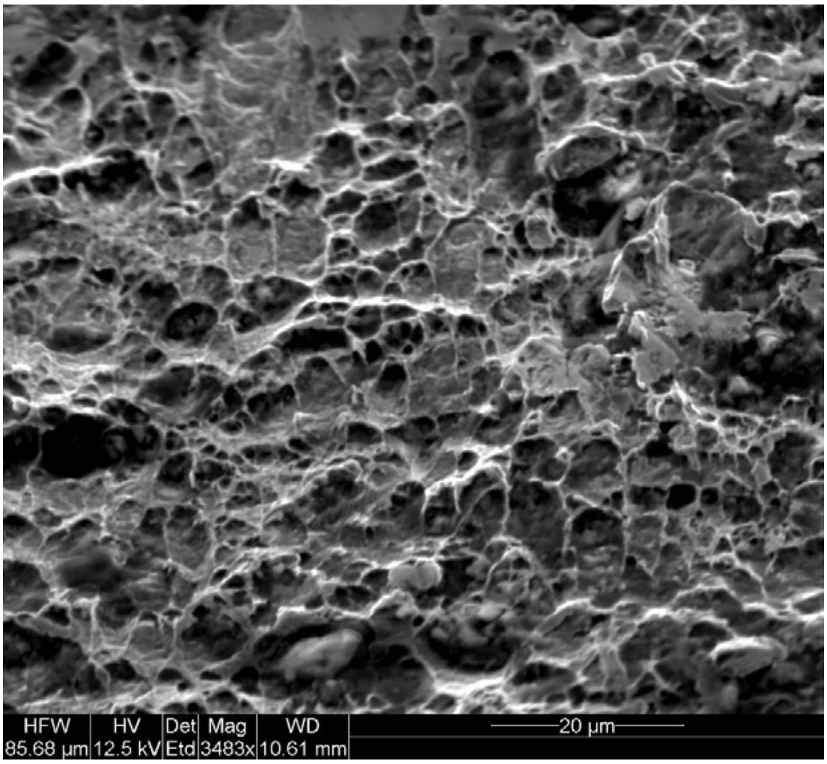


Figure 9. Internal bellow plate width section: dimple morphology indicative of ductile fracture.

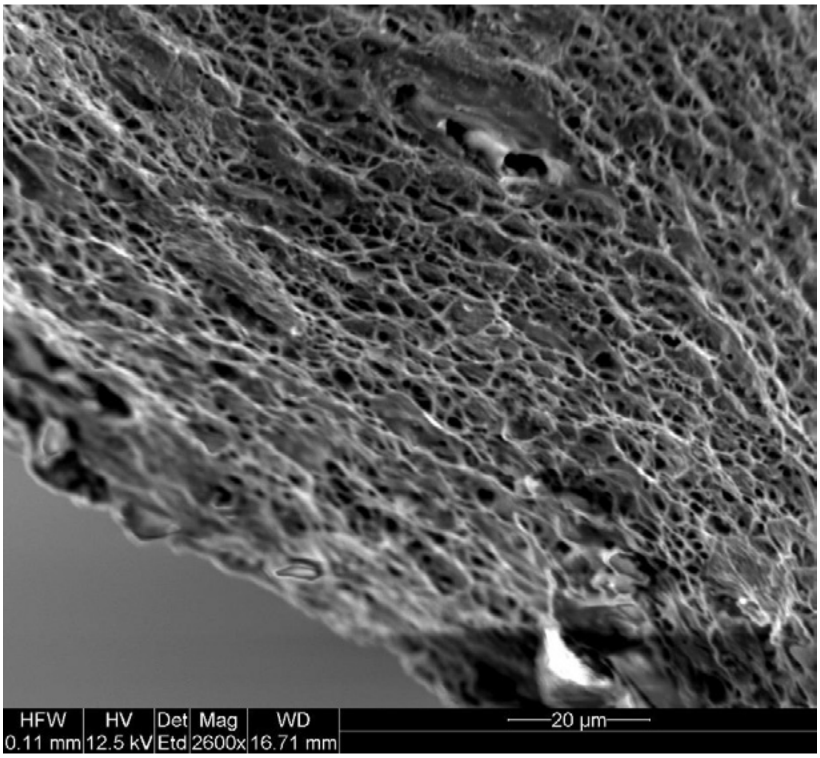


Figure 10. External bellow plate width section: dimple morphology indicative of ductile fracture

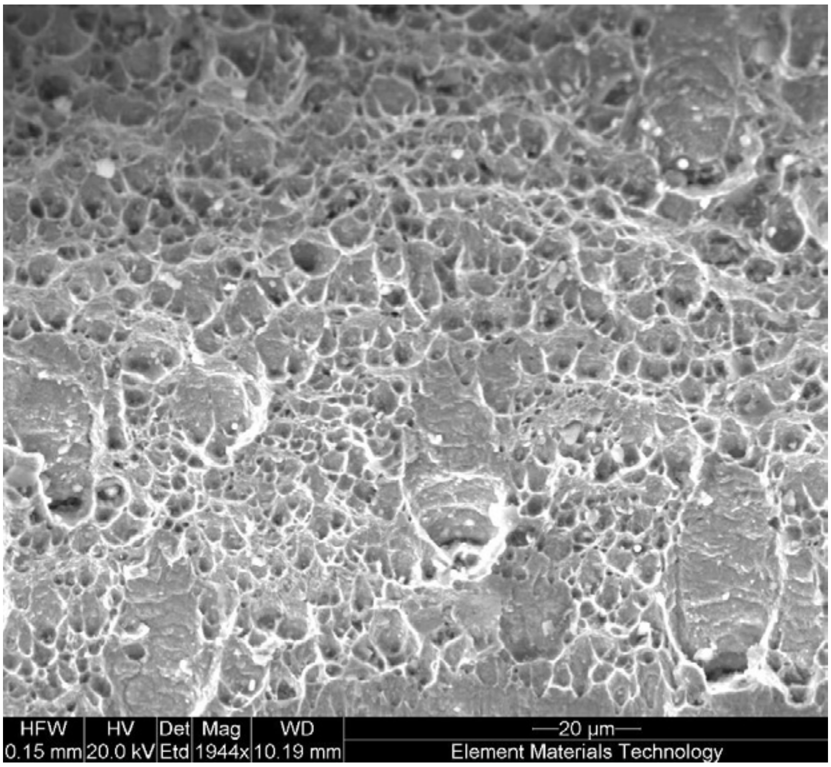


Figure 11. Internal bellow plate circumferential section: dimple morphology indicative of ductile fracture.

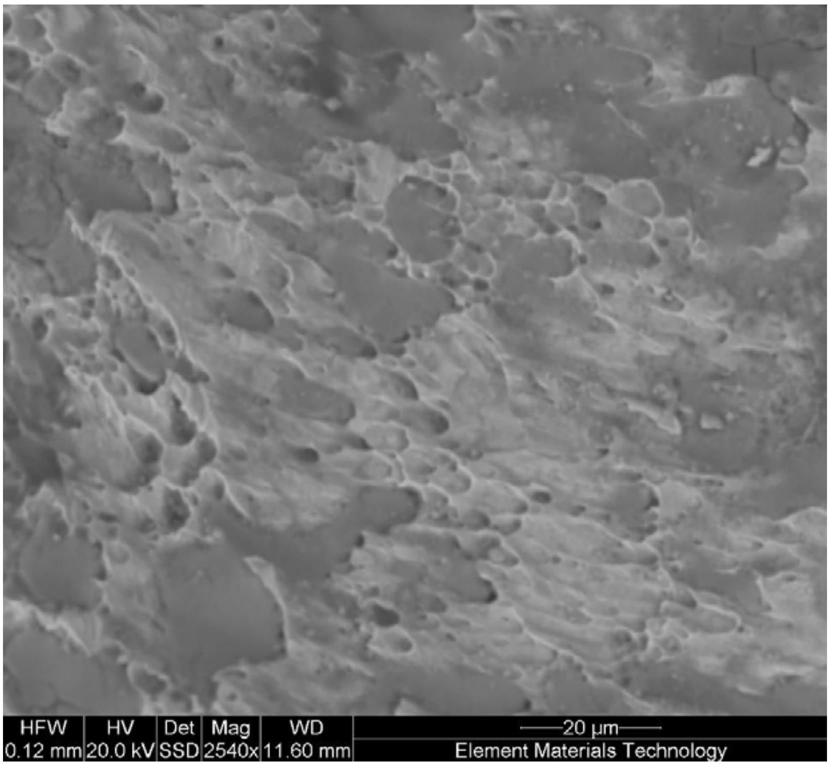


Figure 12. External bellow plate circumferential section: dimple morphology indicative of ductile fracture and some corrosion products present in the fracture surface.

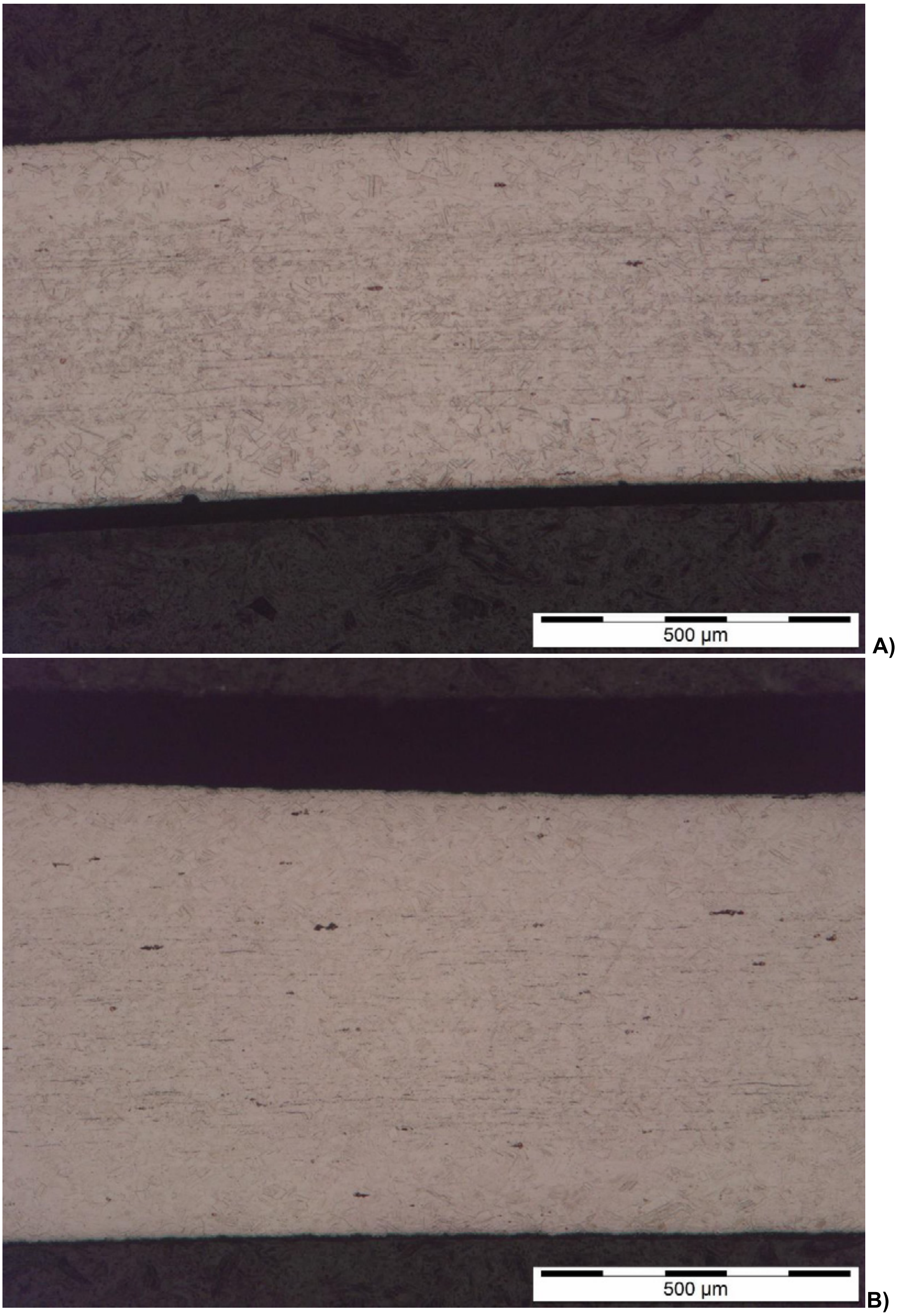
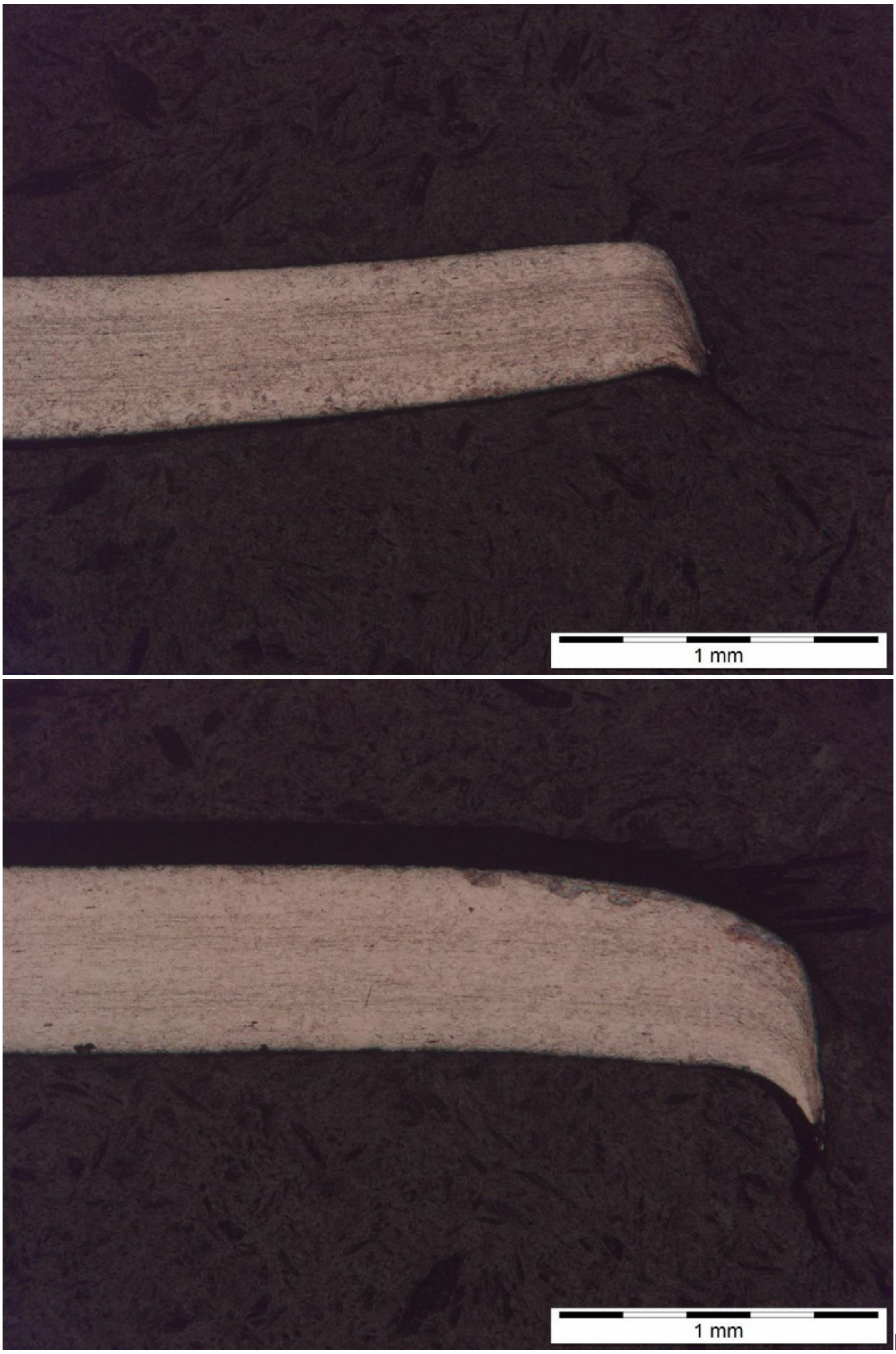
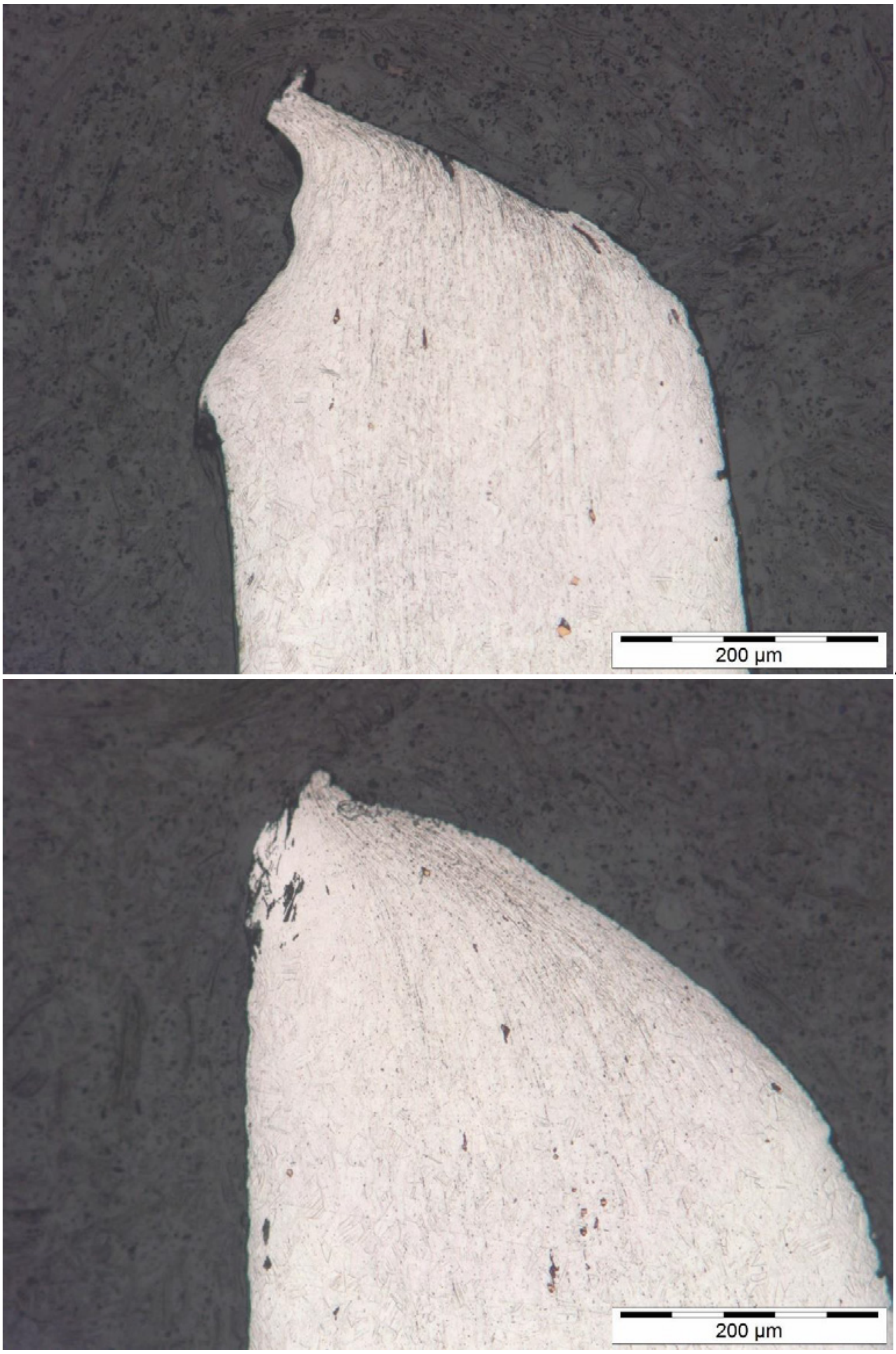


Figure 13. The general microstructures of the bellows plates, A) Internal and B) external: austenitic microstructure with deformation texture and TiN particles. (Oxalic acid etch, magn ~100x)



A) B)

Figure 14. Fractures in cross section along the width of the bellows plates, A) Internal and B) external: plastic deformation visible at the fracture, shear type ductile fracture. (Oxalic acid etch, magn ~50x)



A)
B)

Figure 15. Fractures in cross section along the circumferential section of the bellows plates, A) Internal and B) external: plastic deformation visible at the fracture, predominantly shear fracture. (Oxalic acid etch, magn ~200x)

DUTCH
SAFETY BOARD

Visiting address
Lange Voorhout 9
2514 EA The Hague
The Netherlands
T +31 (0)70 333 7000

Postal address
PO Box 95404
2509 CK The Hague
The Netherlands

www.safetyboard.nl