PETROLEUMSTILSYNET

Investigation report

Report	
Report title Report following the investigation of a turbine breakdown with subsequent fire at Tjeldbergodden on 2 December 2020	Activity number 001904026

Security grading		
☐ Public	☐ Restricted	☐ Strictly confidential
☐ Not publicly available	☐ Confidential	

Involved	
Team T-L	Approved by/date Espen Landro/23 June 2021
Members of the investigation team Bjørnar André Haug, Knut Ivar Hjellestad, Damir Mihajlovic, Eivind Sande, Arnt H Steinbakk	Investigation leader Jorun Bjørvik

Contents

1 Summary

A fire broke out on 2 December 2020 in the compressor house in the methanol factory at the Tjeldbergodden plant (TBO) operated by Equinor.

In addition to equipment for pressure increase of synthesis gas (H_2, CO_2 and CO), a two-stage steam turbine generator (TG) with associated auxiliary systems is installed in the compressor house.

An attempted process shutdown (PSD) of the steam TG caused the machine to overspeed and then break down. As a result of the breakdown, components from the turbine shaft and a flexible coupling on the shaft were flung about with great force. Objects struck included piping for the turbine's lube oil system, which in turn caused a lube oil leak. The oil ignited and started a fire. This did not spread to other systems in the compressor house.

When PSD is initiated, the generator disconnects from the power network and the turbine is isolated from the steam network. The direct cause of the turbine breakdown was that isolation from the steam network at the medium pressure (MP) level failed to function as intended after initiating PSD. Steam backflow from the MP level increased turbine rotation, causing turbine blades to come loose from the rotor. The latter then became wedged and stopped abruptly, causing the shaft to break between turbine and gear.

The actual consequences of the incident were a fire lasting around an hour and a spill of about 1 000 litres of lube oil.

No physical personal injuries were sustained as a result of the incident.

Owing to the incident, production from the methanol factory was down for about 12 weeks. The facility came back on line in week 7 without the damaged turbine.

Where potential consequences are concerned, the investigation team takes the view that the incident could have caused serious personal injuries or death. When PSD is initiated, the plant operators must physically check unloading of the TG. Had they or other personnel been in the compressor house when the breakdown occurred, they could have been struck by flying components. Some of the latter were also hurled with great force through the walls of the compressor house and could have hit people outside the building.

Flying components also hit the synthesis gas plant. Had this caused a synthesis gas leak, the outcome could have been an explosion and/or a large fire.

The direct cause of the incident was the failure of the closure function in a valve which formed part of the turbine's protection against overspeed and breakdown. According to the maintenance system, the criticality of this valve was assessed as "low" in terms of HSE consequences. That will affect how the valve is followed up. Criticality assessments provide, for example, guidance in preparing maintenance programmes and setting requirements for function testing, prioritisation of maintenance, who becomes involved in the event of impairments, assessing the need for measures to compensate for impairments, and following up integrity. A systematic review of the plant had failed to identify this deficiency in the criticality assessment.

Four nonconformities have been identified by the investigation, related to:

- identifying safety functions and barrier follow-up
- follow-up of the system
- documentation
- safe distance from the fire scene.

Two improvement points have also been identified in relation to:

- unclear how the Tjeldbergodden fire appliance was used
- unclear performance standard for personnel check (POB) in the plant.

2 Background information and descriptions

2.1 Description of plant and organisation

Equinor's industrial plant at TBO comprises a gas receiving terminal, a methanol factory and an air separation factory. Operational from 1997, it receives gas from the Heidrun field for conversion into methanol through a process involving reforming, synthesis and distillation. Surplus heat from this production is used to provide steam as an energy source in various parts for the plant as well as for electricity output via a steam TG.

TBO's organisational structure accords with Equinor's model for its land plants – in other words, a plant manager with associated sub-units as shown in figure 1 below. Some of these sub-units report in operational terms to the plant manager but administratively to other superiors. This is shown in the figure by dotted lines and is intended in part to ensure the necessary independence of the relevant sub-units from the plant manager.

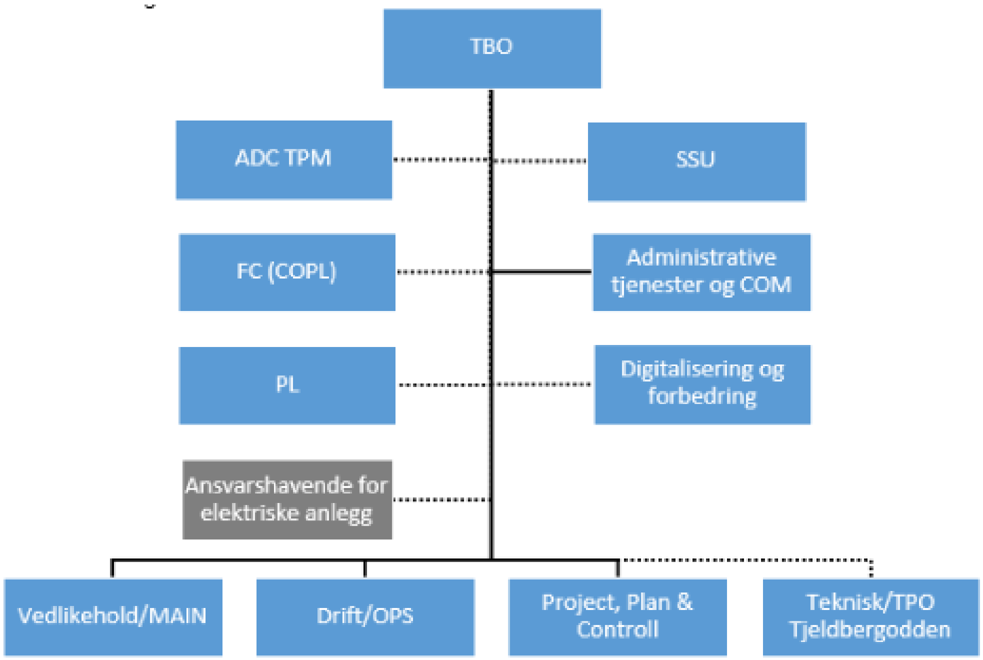

Figure 1 Organisation chart for TBO (source: Equinor).

2.2 Position before the incident

The plant was operating normally on the day of the incident. Because of the Covid-19 position, a certain number of employees were working at home.

One of the ongoing activities at the plant on this day involved adjusting the control parameters for a two-stage steam TG – the machine which broke down during the incident. The background for this job was challenges related to maintaining stable pressure in the steam network. This was a planned activity, and additional personnel were present in the central control room (CCR) to deal with possible operating disruptions.

Temporary repairs had been carried out in October-November 2020 on a valve intended to prevent backflow from the steam network to the turbine's MP stage. Failure of this valve's closure function was the direct cause of the incident.

2.3 Area of TBO where the incident occurred

The incident occurred in the compressor house, which forms part of the methanol plant. Circled in red on the image below, this building contains equipment for compressing synthesis gas as well as a steam TG with associated auxiliary systems. Synthesis gas is a mix of hydrogen, carbon monoxide and carbon dioxide (H_2, CO and CO_2).

Figure 1 The TBO plant (source: Equinor).

2.4 Abbreviations

CCR	Central control room
CM	Corrective maintenance
DSHA	Defined situations of hazards and accidents
ESD	Emergency shutdown
Hazop	Hazard and operability analysis
HP	High pressure
LP	Low pressure
MP	Medium pressure
NSO	Norwegian Industrial Safety and Security Organisation
OSC	On-scene commander
PM	Preventive maintenance
PS	Performance standard
PSA	Petroleum Safety Authority Norway
PSD	Process shutdown
TBO	Tjeldbergodden
TG	Turbine generator
Timp	Technical integrity management programme
TTS	Condition monitoring of technical safety
WO	Work order

3 The PSA's investigation

The PSA was notified by Equinor of the incident at TBO at 14.58 on 2 December 2020. A meeting took place on 3 December where Equinor representatives provided a short briefing, and the PSA decided on the same day to investigate the incident. The police decided to launch an inquiry, and requested the PSA's support.

3.1 Mandate for the investigation team

The mandate for the PSA's investigation was as follows.

a. Clarify the incident's scope and course of events (with the aid of a systematic review which typically describes time lines and incidents).
b. Assess the actual and potential consequences
    1. harm caused to people, material assets and the environment
    2. the potential of the incident to harm people, material assets and the environment.
c. Assess direct and underlying causes.
d. Identify nonconformities and improvement points related to the regulations (and internal requirements).
e. Discuss and describe possible uncertainties/unclear points.
f. Assess the player's own investigation report (may become available after the PSA's own report).
g. Prepare a report and a covering letter (possibly with proposals for the use of reactions) in accordance with the template.
h. Recommend – and normally contribute to – further follow-up.
i. Support the police on request in its inquiry into the incident.
j. Contribute brief information to the Norwegian Industrial Safety and Security Organisation (NSO) about findings from the investigation which are relevant to it. The timing will be agreed during the course of the investigation.

3.2 Investigation team

The investigation team was established and some members went to TBO on 7 December 2020 to support the police during interrogations and to conduct its own interviews and inspection of the damage site. The Covid-19 position meant that part of the team participated in interrogations, interviews and meetings via Teams.

Composition of the investigation team.

Name	Position	Discipline
Bjørnar André Haug	Principal engineer	Process integrity
Knut Ivar Hjellestad	Principal engineer	Occupational health and safety
Damir Mihajlovic	Principal engineer	HSE management
Eivind Sande	Principal engineer	Process integrity
Arnt Heikki Steinbakk	Principal engineer	Logistics and emergency preparedness
Jorun Bjørvik	Principal engineer/ investigation leader	Process integrity

Steinbakk took part in selected interviews related to the emergency preparedness aspects of the incident.

3.3 Methodology

The investigation was conducted through interviews with personnel in the TBO operations organisation, verifications and inspection at the plant, and a review of governing documents, the maintenance system (SAP) for the equipment concerned and other documentation relevant to the incident.

In support of the police inquiry, the PSA team met investigators led by the Møre og Romsdal police district at the plant on 7 December 2020. Tactical and technical personnel as well as officers from the National Criminal Investigation Service (Kripos) took part in work at TBO. The PSA team participated in on-site inspections and interrogations with the police, and put its own questions in understanding both with the police and those being interrogated.

Part of the PSA team was at the plant until 9 December. The team took part in some interrogations via Teams after its stay at TBO.

As part of its investigation, the team also conducted its own interviews via Teams with personnel in the operations organisation.

Before Equinor launched its internal investigation of the incident, work began on a root-cause analysis of technical personnel at TBO and the PSA team has received preliminary results from this. It has also received information on vendor calculations related to the quantities of steam required to create the rotation which occurred during the incident.

Part of the PSA team participated in the opening of low pressure (LP) control valves at the plant on 8 March 2021. During that inspection, a review was also conducted of the original vendor documentation which is available only in paper format.

A meeting with the NSO was conducted on 24 March 2021.

4 Description of equipment involved and the activity

4.1 Description of equipment involved

4.1.1 General system description of the steam turbine

Surplus heat from the methanol production process is used to produce steam, which is utilised in turn as an energy source in various parts of the plant as well as for electricity generation via a steam TG.

TBO has steam at three different pressure levels: high (HP), medium (MP) and low (LP).

Electricity is generated via a two-stage steam turbine driving an electric generator. Steam extraction is at the MP level. See the diagram below.

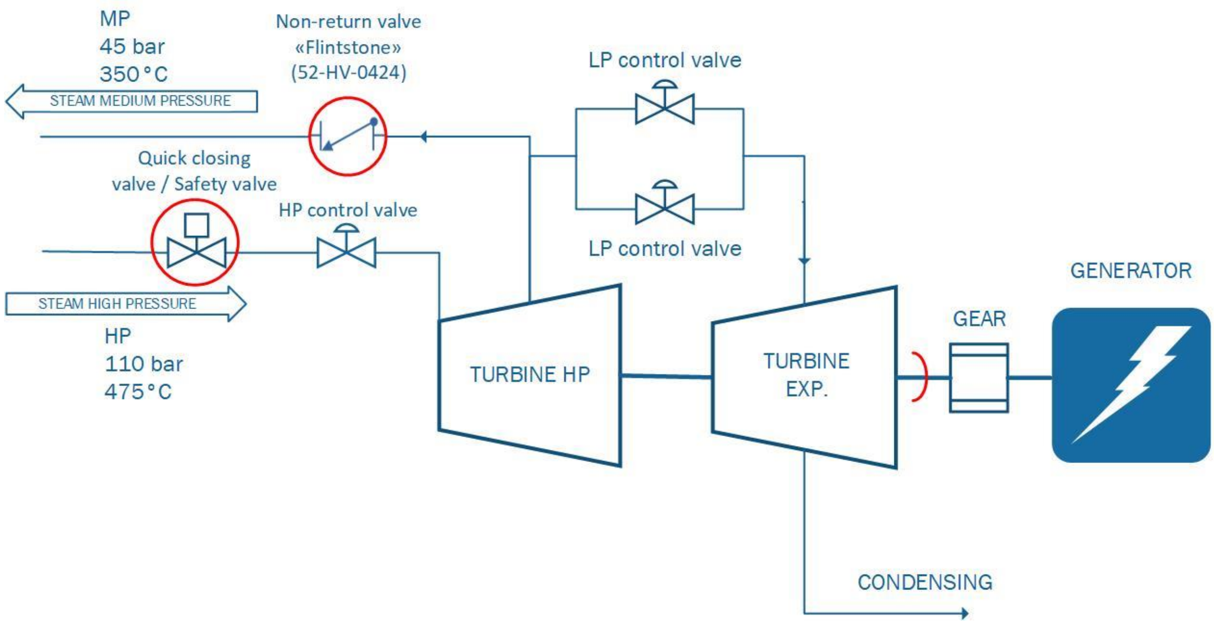

Figure 2 Simplified diagram of the TG.

HP steam at 110 barg and 475°C is routed into the HP part of the turbine. Its quantity is regulated by a volume-regulated control valve at the intake. The pressure is reduced to about 45 barg with an associated temperature of 350 °C at the outlet of the turbine's first stage. Steam is extracted at the MP level, and largely comprises the energy source for the process. The remaining steam is sent to the turbine's LP stage via pressure-regulated control valves.

If the steam turbine is shut down, steam from the HP network can be routed directly to the MP network via a reduction station.

The steam turbine and generator are operated via a dedicated control panel. In the event of a PSD, valves in the steam system close to prevent continued supply to the machine while the generator is disconnected from the power grid.

Valves circled in figure 3 are those intended to isolate the turbine from the steam network in the event of a PSD. The HP steam intake has a quick closing safety valve, while an actuator-controlled non-return valve at the MP level, nicknamed the "Flintstone", is intended to prevent steam backflow.

The HP and LP control valves will also close in a PSD. The intake control valves at the LP stage incorporate two holes related to cooling the machine when running down the plant and warming the machine before a cold start.

Vendor calculations carried out after the incident have shown that the quantity of flow through these holes, combined with steam which will leak past the shaft seal between where MP steam is extracted and the LP part of the machine, will be sufficient to increase turbine rotation if the generator is disconnected from the power grid. That also applies when the LP control valves are closed.

The total moment of inertia of the rotating mass, referenced to the turbine side of the gear, is 616 kgm^2. See the table below. This breaks down between turbine rotor, gear and generator rotor as shown figure 4. The investigation has used the system's moment of inertia to assess how much power was applied to the TG to produce the observed rise in revolutions. Based on data acquired from the generator protection system (report from Siemens Energy), for example, it took only 3.5 seconds for revolutions to increase from 5 000 to 5 250 rpm. The average power applied to accelerating the rotating mass in this time interval can then be calculated as 2.5 MW.

When the TG is shut down, it will be automatically disconnected from the power grid and will then rotate with no load. If steam supply does not cease completely, the TG can then quickly overspeed.

Sum of the moment of inertia for the rotating mass with all values referenced to the turbine side of the gear.

	Specified moment of inertia (kgm^2)	Conversion factor, gear	Rounded off and converted to turbine side of gear
Steam turbine rotor	285		285
Gear shaft high speed with flexible connection	10.24		10
Gear shaft low speed	779.35	$(121/38)^2=10.14$	77
Generator rotor	2 472	$(121/38)^2=10.14$	244
Total			**616**

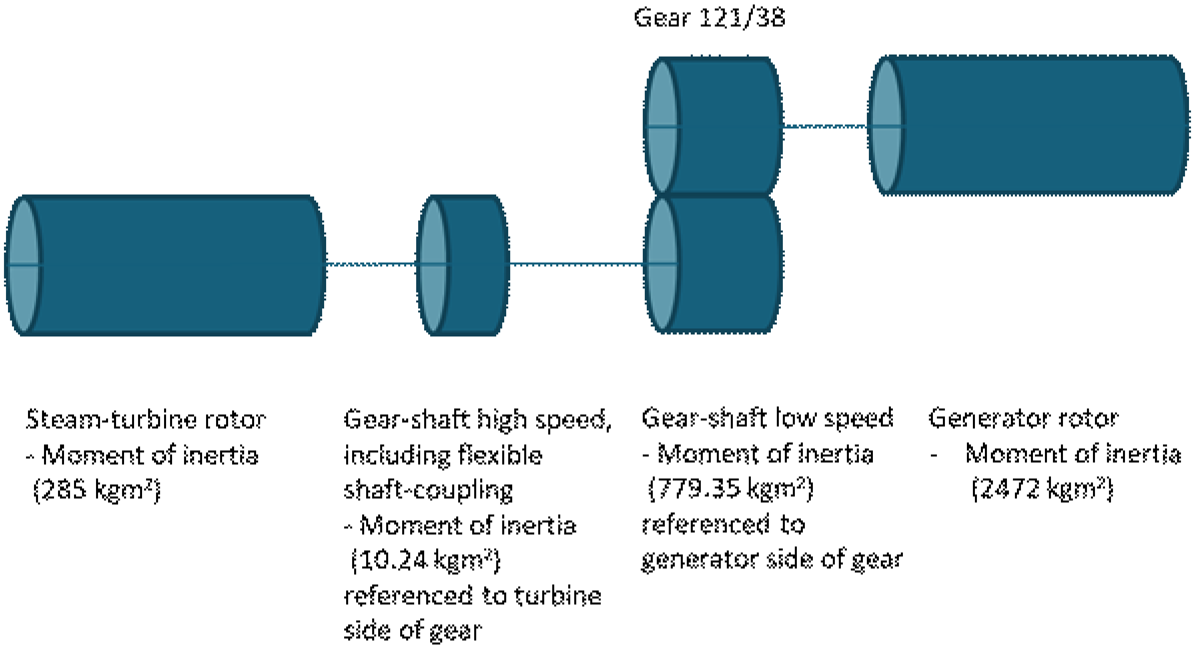

Figure 3 Overview of moment of inertia for the various machine components.

More details of the overspeed protection system are provided in the next section.

4.1.2 System for overspeed protection

In normal operation, admission to the turbine is regulated by an electronic governor. This provides set points for opening both the HP and LP control valves on the basis of a predefined logic process. Measurements of the turbine's rpm and pressures measured in the MP (PIT0423) and HP (PIT1029) steam networks respectively provide input signals to the governor.

The steam turbine and generator are constantly monitored on a number of parameters which will initiate PSD, such as rpm and vibration. PSD can also be initiated manually in the CCR and locally at the machine.

In addition comes a mechanical overspeed protection which comprises an eccentric bolt attached to the rotor shaft by a spring. At high rpm, centrifugal force will move the bolt outwards to connect with an arm for bleeding off the oil pressure which keeps the quick closing and HP/LP control valves open. The bolt is marked as 1 in figure 5 below. This arm can also be operated manually for local PSD of the turbine.

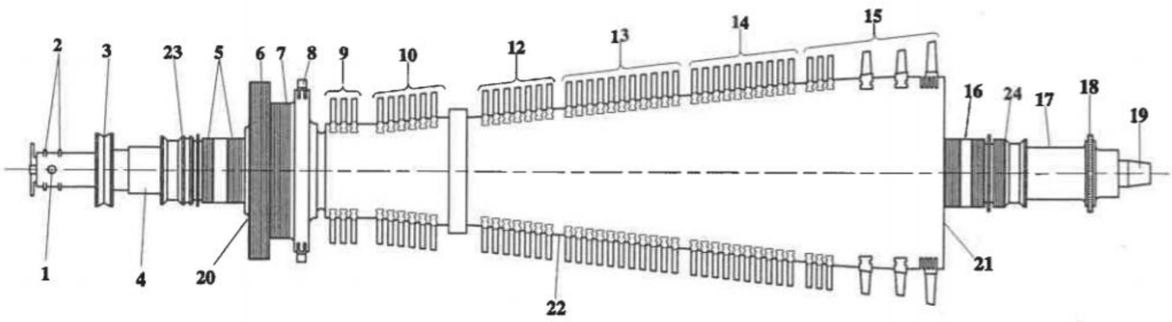

Figure 4 Simplified drawing of the steam turbine rotor (source: vendor documentation).

Regardless of how a PSD is initiated, the quick closing and Flintstone valves are the barriers intended to prevent steam admission to the system.

The quick closing valve is a shut-off type kept open during normal operation by oil pressure against a compressed spring. In a PSD, the pressure will be rapidly bled off in a trip oil circuit and the valve will close immediately. A test system allows movement of the valve stem to be checked even when the plant is operating.

In the event of a PSD, the Flintstone valve will also receive a closure signal. Two functions close this valve. One involves passive closure as a non-return valve if upstream pressure falls in relation to downstream pressure. In that case, steam backflow will close the valve. The other is an auxiliary function comprising a spring-loaded actuator arm which keeps the valve closed. This arm is controlled by a pneumatic solenoid valve governed in turn by an electromagnet. When the latter loses its supplied voltage of 24V, the solenoid valve will change position and cause the air holding the arm in position to bleed off through it. The actuator arm will close the Flintstone valve with the aid of the spring force. Figure 6 provides a simplified diagram

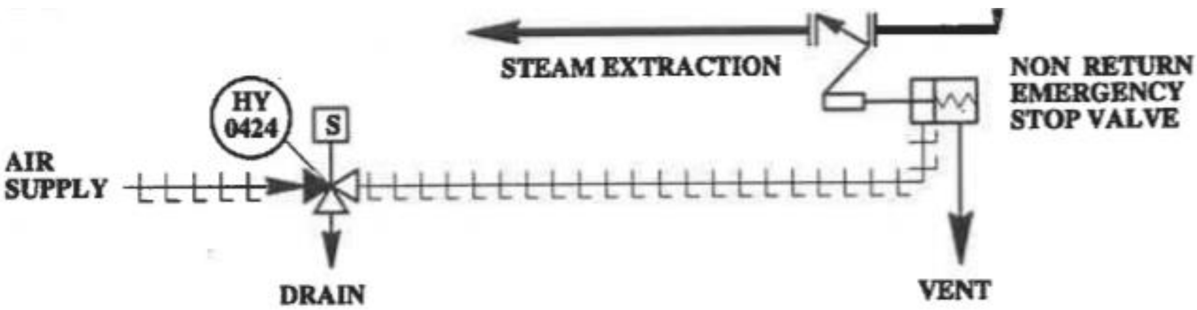

Figure 5 Flintstone valve (source: vendor documentation).

The passive non-return valve function can be tested by moving an arm mounted on a weight. This is attached directly to the same shaft in the valve as the damper. The design of the arm is the reason why the valve is locally nicknamed a Flintstone.

4.1.3 Flintstone valve condition before the incident

Actuator movement was noticed in October during a logging tour of the plant. The Flintstone valve's solenoid had probably been damaged by a sandblasting job in the vicinity. A temporary repair was made with a non-original piston seal and some new O rings while the plant was in operation.

The valve was entered in SAP as "serious ill". It was assumed that the impairment could cause unintentional closure but not that it could fail in the event of a closure signal. The Flintstone valve functioned as intended in connection with a shut-down in November, when a repair (tightening) was made to the pack box to avoid external steam leaks.

Figure 6 The Flintstone valve after the incident (source: Kripos).

4.1.4 Generator

The steam turbine drives a synchronous generator connected in normal operation to the TBO power grid via a flexible connection and a speed-reduction gearbox with a conversion ratio of 38/121. When the generator is connected to the grid, rpm is determined by the grid frequency of 50 Hz. The four-pole generator operates at 1 500 rpm when connected to the grid. This gives a synchronous 4 776 rpm on the turbine side.

Maximum continuous output of the TG is 30 MW.

4.1.5 Ongoing activity to adjust governor parameters

In the run-up to the incident, work was under way to adjust the control parameters for the Woodward governor regulating steam admission to the TG. This job was an attempt to reduce fluctuations observed from time to time in the plant's MP steam network. These had been challenging for operating the rest of the process. The work involved disconnecting the governor from cascade control and then tuning the parameters iteratively by taking small jumps in order to observe the response.

This activity had been planned for a long time, and preconditions were established. These included dedicated execution personnel and extra staffing in the CCR to handle possible operational disruptions. It was anticipated that the job could lead to fluctuations in the steam network along the way but, if these became too large, the plan was to shut down the TG by initiating a PSD.

A procedure had been prepared for the work, and a toolbox talk was carried out.

4.2 Maintenance and classification

Maintenance jobs are registered in SAP, either manually or by being generated automatically as periodic jobs. If a maintenance job – either preventive (PM) or corrective (CM) – is required, the first step will be to establish a notification. If this calls for immediate action, it forms the basis for generating a work order (WO). Depending on the equipment classification, all WOs are given a deadline – shorter if safety-critical equipment is involved or longer if the equipment is not considered critical.

Registered notifications are assessed in approval and priority (AP) meetings, which are normally chaired by the operations engineer. If a notification or WO for safety-critical equipment is nearing its deadline, extending the latter is considered in AP meetings.

The TG and the Flintstone valve are entered in Equinor's SAP maintenance system with dedicated PM programmes, while the quick closing valve forms part of a package follow-up together with the actual TG. The relevant equipment is registered in SAP under system 52, which includes the steam system.

Recommendations from the manufacturer for following up the TG package describe two types of service – minor and major – which should be performed every third year or after a certain number of operating hours, depending on which comes first. The company has opted to do a service every other year. In cooperation with the manufacturer, minor services were performed on the TG in 2007 and 2010 and major ones in 2002 and 2016. Others were performed on Equinor's own account. The quick closing valve falls within the manufacturer's scope, and is swapped with a reserve which has been maintained between services.

Reportedly, most of the components were replaced in the 2016 service and the service interval has now been increased from two to four years. A major service planned in 2020 was postponed until 2021 because of Covid-19. However, a minor service was done on the TG in 2020, which included replacing the HP control valve. WOs for servicing are tied to the TG's tag number, which makes it difficult to trace the equipment history of individual components included in this package.

The Flintstone valve is not included in the manufacturer's service, and is followed up by Equinor's operating personnel. It is entered in SAP with a two-year maintenance interval. Increasing this to three years was under assessment.

Equipment inspection and function testing are also included in the PM programme, and function tests were reported to be normally carried out after repairs and modifications. However, the PM programmes for the quick closing and Flintstone valves do not include testing of closing time.

Safety-critical equipment is followed up more closely than other components, in part through the technical integrity management programme (Timp). The most recent Timp review of system 52 took place in November 2020. Equipment classified with low HSE criticality is not covered by Timp and receives longer deadlines for correcting faults. This highlights the importance of correct equipment and system classification for the HSE consequences of potential function faults. It was also reported that the classification is not reviewed unless somebody takes action. The classification has remained unchanged since the equipment was entered in SAP, and it was not possible to trace the assessments which underpinned the TG's classification.

The Flintstone and quick closing valves are both classified in SAP with low criticality for HSE consequences.

4.3 Follow-up of barrier condition

Various activities, such as Timp, technical condition safety (TTS) and a hazard and operability analysis (Hazop), are pursued to identify the status of safety systems and expose possible deficiencies in existing designs.

Timp is a methodology for identifying deviations from current standards/ requirements and impairments in the physical condition of identified safety functions at the plant. Condition assessments are conducted for the individual barrier elements (performance standards – PS) and for the plant as a whole. Timp is conducted quarterly, with activities pursued over a week in a specified sequence using input from contributors to the evaluation process (people with discipline, system or PS responsibility), and results in a rating for the system on a scale from A to F. Once all the input has been assembled, action meetings are held if the PS is ranked as D or lower. A D ranking means the system has faults or deficiencies which could result over time in the failure of individual safety functions, reduced reliability, or uncertainty about the real condition because of a lack of maintenance or documentation. Whether several impairments might influence each other is also assessed.

TTS is an independent review of barrier condition at the plant. Led by personnel from outside the organisation, it is typically implemented every five years. The most recent TTS verification of the methanol factory was conducted in 2016 and covered assessments related to the following barrier elements:

- containment
- ESD
- PSD
- blowdown/flaring.

A TTS review covers predefined checkpoints. The checklists used are largely based on requirements in Equinor's TR2237 document for the individual barrier element. No deficiencies in the TG were identified by the TTS review in 2016 for the above-mentioned barrier elements.

A Hazop is typically conducted in the event of modifications or operational changes. Doing one otherwise is not established practice.

The TG was also included when a Hazop was conducted for the synthesis gas plant in 2000. In that case, the analysis largely involved a review of operational conditions rather than design solutions. Code words used in the review reflected that. No design findings were made for the TG on that occasion.

4.4 Governing documentation

This section includes a brief description of two governing documents referred to in the present report.

TR2237 (performance standards for safety systems and barriers - onshore) describes PSs for safety functions and barriers at Equinor's land plants. Each plant may have an annex to this document which describes its specific features. Where TBO is concerned, this document is entitled TR1099 (safety systems and fire and explosion strategy, Tjeldbergodden). No specific requirements related to the steam facility are described in either TR2237 or TR1099.

OM202.201.01 (mapping functions and classifying function impairments) is a work process which describes requirements and guidelines for mapping functions, identifying potential function failures and their effect, and classifying the consequences of the function failures. Intended for use in all relevant service-live phases, the process refers to TR2237 with plant-specific annexes as the basis for mapping barrier functions.

4.5 Organisation

TBO forms part of Equinor's MMP OPL[1] business unit, and has the organisational designation MMP OPL TBO.

The technical department (TPO) is also part of MMP OPL, organised as a separate sub-unit with the designation MMP OPL TPO. At TBO, therefore, the TPO department does not report up the line to the plant manager, but to the head of TPO in the MMP OPL unit. This ensures that it is independent of the plant manager and gives it the authority to shut down the plant independently of the latter.

TBO's overall organisation is presented in figure 8.

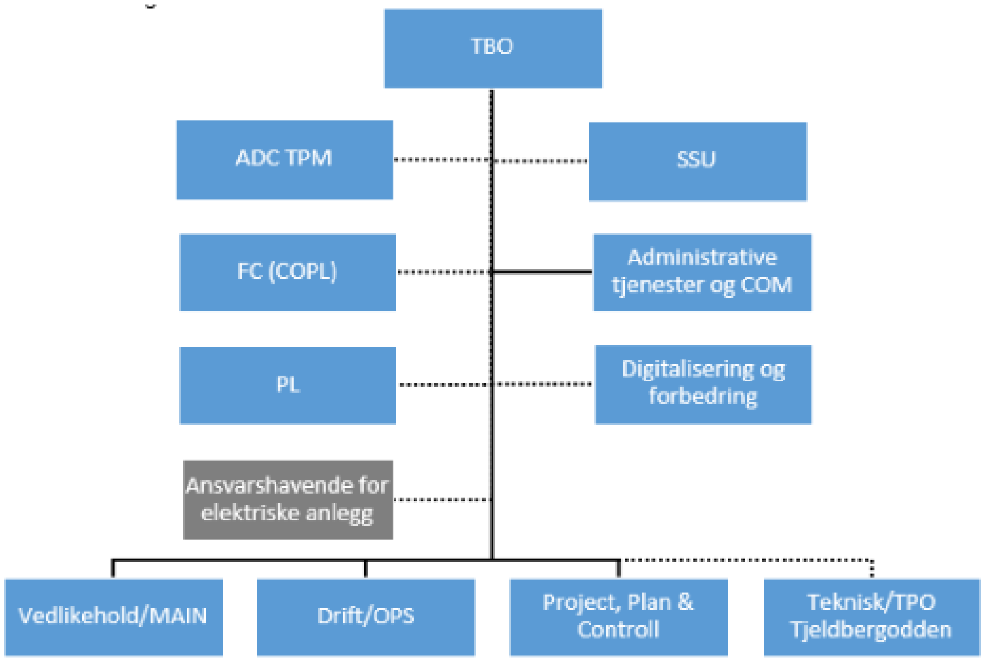

Figure 7 Overall organisation chart for TBO (source: Equinor).

A solid line means that the role reports both up the line and in terms of assignments, while a dotted line means reporting up a different line. Line reporting for technical/TPO at TBO is to the manager of MMP OPL TPO.

4.5.1 Maintenance unit

The maintenance unit (Main) is the client for maintenance assignments. It evaluates, plans, facilitates and executes PM/CM and has technical responsibility for allocated disciplines. Discipline responsibility is assigned to responsible personnel in Main. Their duties include evaluating technical integrity and service life as well as providing

---

[1] MMP OPL = marketing, midstream and processing, onshore plants.

input to Timp assessments and preparing and executing inspection and maintenance programmes.

4.5.2 Operations unit

The operations unit (OPS) is responsible for safe, reliable and efficient operation. It has operational system responsibility for allocated systems, including the system 52 which incorporates equipment involved in the incident. System responsibility is assigned to responsible personnel in OPS. Their duties include following up day-to-day operation, supporting the TPO in correcting TTS findings and providing input to Timp evaluations.

4.5.3 Technical

The technical unit (TPO) is function-based and responsible for assignments related technical integrity and to provide support for the OPS and Main. That includes classification of equipment and implementing Timp verifications. The TPO is also responsible for analyses and in-depth studies of technical findings and challenges, incidents and improvement proposals. In addition, it initiates and coordinates TTS verifications at TBO and deals with TTS findings.

5 Course of events

A couple of months before the incident, actuator movement was observed on the Flintstone valve during a logging tour of the plant. Owing to uncertainty over the choice of solenoid type, it was decided to make a temporary repair while the plant was operational. This was expected to prevent unintentional closure of the valve, and the safety function was considered to remain intact. A notification was established for final repair. During a system shutdown a couple of weeks later, a new temporary repair was carried out with the same valve. This involved tightening the pack box to avoid external steam leaks.

On the day of the incident, work was under way to adjust the governor parameters in the TG control system. This activity began that morning. While it was under way, a PSD of the TG had to be initiated because of an unexpected response from the control system. However, the machine failed to stop. The generator was disconnected from the power grid as expected in a PSD, but turbine rpm increased. This ultimately resulted in uncontrolled overspeed of the machine with consequent breakdown. One result of this breakdown was that components from the turbine shaft and a flexible coupling on the shaft were flung about with great force. Objects struck included piping for the turbine’s lube oil system, which broke. That caused a lube oil leak, which ignited.

The table below lists activities ahead of the incident which could have been significant for its occurrence, as well as the course of the event itself.

In addition to information from the control system as specified in the table, reports about the incident were also made to the CCR by operators out in the plant

Time	Event	Comment
Jan 2020	Notification established for Flintstone valve because of pack box leak	
Oct 2020	Sandblasting under way	Pack box leak resulted in heating under lagging
18 Oct 20	Notification established to replace solenoid on Flintstone valve	Possible air leak found on logging tour of plant. Priority set for notification, resulting in six-month deadline for correction
19 Oct 20	Temporary repair of Flintstone valve solenoid	Non-original piston seal and some new O rings. Notification for permanent correction maintained
20 Oct 20	AP meeting – changes priority for solenoid correction from low to medium	This changed the deadline for correction from six months to 45 days, at 2 December 2020
26 Oct 20	Escalating steam leak via pack box on Flintstone valve reported	
7 Nov 20	TG trip	Shutdown functioned normally
8 Nov 20	WO for repair of pack box leak established	
11 Nov 20	WO completed in SAP for repair of Flintstone valve pack box leak	
2 Dec 20 Timing of events on day of incident		
08.30	Calibration of control parameters for TG starts (toolbox talk)	Preconditions for CCR staffing fulfilled
14.29.30	TG disconnected from cascade	Control valve for steam admission opens more and more, soon fully open, LP valves start opening further
14.30.59	HP/MP trip from PCDA	Decision to initiate PSD to "rescue" MP deliveries to steam network
14.31.12	PSD initiated in CCR	
14.31.13	Generator disconnected from the grid (rpm stable until then)	
14.31.16	High-level (HH) alarm for rpm at	This alarm is intended to mean TG

Time	Event	Comment
	5 250 rpm (alarm limit set at 10 per cent above nominal rpm)	shutdown and alarm in the CCR
14.31.37	Rpm about 6 330 and instrument measuring rpm cannot show higher value even if rpm continues rising	Maximum rpm not known
14.36.54	Vibration alarms kick in	Breakdown occurs
14.38.13	First fire and gas (F&G) detection	
14.38.34	Process shutdown of synthesis gas compressor initiated from CCR	
14.38.59	Blowdown	
14.39.44	Deluge initiated	
14.40.05	Fire pump activated	
14.46.08	ESD activated	
Abt 14.52	Lube oil supply halted	Fire reduced
Abt 15.00	Fire water monitor started to cool building	
15.24	POB check	
15.40	Fire extinguished	

6 Potential of the incident

6.1 Actual consequences

The actual consequences of the turbine breakdown were that turbine components came loose and caused damage to equipment and the building. Objects struck by components included piping for the turbine's lube oil system. The leaking lube oil ignited and caused a fire which lasted around an hour, but which did not spread to other systems in the compressor house. About 1 000 litres of lube oil are estimated to have leaked out.

No physical injuries were sustained as a result of the incident.

The incident meant that production from the methanol factory was down for about 12 weeks, with associated financial consequences. The plant came back on line in week 7 without the damaged turbine.

6.2 Potential consequences

In the event of a PSD, plant operators are supposed to make a physical check of the TG. Had they or other personnel been in the compressor house when the breakdown occurred, they could have been struck by flying components. The latter were also hurled with great force through the walls of the compressor house and could have hit people outside the building.

Flying components also hit the synthesis gas plant located in the same building. Had this caused a synthesis gas leak, the outcome could have been an explosion and/or a large fire.

On that basis, the PSA team's assessment is that the incident had a major accident potential and could have caused serious personal injury or death as well as substantial financial loss.

7 Direct and underlying causes

7.1 Direct cause

The direct cause of the turbine breakdown with subsequent fire was that isolation from the steam network at the MP level failed to function as intended during a PSD.

When a PSD is initiated, the generator is disconnected from the power grid and the turbine is isolated from the steam network. Steam backflow from the MP level increased turbine rotation, which caused turbine blades to come loose from the rotor. The latter then became wedged and stopped abruptly, causing the shaft to break between turbine and gear.

7.2 Underlying causes/discussions

The investigation has identified several elements which have or could have been significant for the incident occurring. These are described in the following sub-sections.

As described in the report, failure of the closure function in a valve is the direct cause of the incident. This valve was part of the steam turbine's protection against overspeed and breakdown. The maintenance system assessed the valve's criticality as low in terms of HSE consequences.

The classification of equipment components determines how they are followed up in operating conditions. That applies to such aspects as preparing a maintenance programme and requirements for function testing, prioritisation of their maintenance, who is involved in the event of impairment, assessing the need for compensatory measures should impairment occur, and follow-up of technical integrity. Only equipment classified as safety-critical is covered by the Timp process.

If components with a safety function are incorrectly classified, the result could be that impaired barrier functions are not identified and dealt with.

7.2.1 Information used as a basis for classification

The threat of overspeed and breakdown is one of the main risks in operating steam turbines and, as described in section 4.1.2, the machine is protected against this. Safety functions related to overspeed protection are described in the original user manual from the manufacturer. This designates the quick closing and Flintstone valves as ESD components, and recommends that they are function-tested – including testing the non-return function by moving the arm. Performance requirements related to closure time are set for the quick closing valve. The manufacturer's recommendations do not appear to have been implemented when the equipment was classified and entered in SAP.

Equinor's OM202.201.01 procedure on mapping functions and classifying function impairments describes the assessments to be made, in part to ensure follow-up of barrier function performance requirements in the operating phase. This procedure refers to TR2237, as well as to plant-specific annexes to that document, for identifying barrier functions. Barrier functions related to the steam system and the TG are not reflected in TR2237 or TR1099. A precondition for correct classification is that the input used for this includes information on identified safety functions.

Equipment classification at TBO has largely remained unchanged since the components were entered in the system, and the assessments which underpinned the current classification are not accessible.

7.2.2 Failure to handle an impaired barrier function

The Flintstone valve was categorised in SAP as "serious ill". As described above, the valve has two independent closure functions. Temporary repairs were made to both of these in October and November 2020. Section 4.1.2 describes the machine's overspeed protection. The mechanical protection closes the quick closing and the HP/LP control valves by bleeding off the oil pressure keeping them open. Calculations have shown that the volume of flow through the holes in the LP control valves is sufficient to speed up turbine rotation if the generator is disconnected.

The failure to identify barrier function and classification meant that impairment of the Flintstone valve was not treated as a barrier impairment during start-up after the shutdown in November. Nor was any assessment made of the need for measures in connection with this start-up.

7.2.3 Maintenance

Both the quick closing and Flintstone valves are entered in SAP with dedicated PM programmes. As described above, they are not classified as safety-critical and their safety functions are not described.

The maintenance requirement also covers testing of the equipment, but performance requirements for closure time/leaks were neither assessed nor implemented for the quick closing or Flintstone valves in the maintenance programme. No routines were established for testing the mechanical non-return function for the Flintstone valve. Post-repair function tests could not be documented.

Long-standing challenges with the Flintstone valve's actuator and pack box have been revealed by the PSA team's review of SAP. An overview taken from this system shows a total of nine CM jobs related to these components since 2000. The latest WO established for repairing the Flintstone valve's actuator is dated 18 October 2020 and had a deadline for execution of 2 December 2020. This job was not done by the deadline, nor was any assessment made of a possible deadline extension. Extending deadlines is handled in the AP meeting if the equipment is safety-critical.

7.2.4 Failure of system reviews to identify design weaknesses

The activities described in section 4.3 to monitor barrier functions have failed to identify that the quick closing and Flintstone valves have a barrier function and that they are thereby incorrectly classified in the maintenance programme.

TTS verifications and Hazop are the primary activities intended to identify deficiencies in existing design and follow-up. Based on the documentation for TTS verifications carried out, it appears that the methodology and checklists used for these have largely been developed on the basis of the requirements in TR2237. Requirements for barrier functions related to the steam system and the TG are not reflected in either TR2237 or TR1099. Nor are references provided to industrial standards or other requirements for steam turbines in connection with reviews. This means that specific requirements related to the steam system and the TG will not be covered by a TTS verification as this is performed.

7.2.5 Technical documentation

As part of its investigation, the PSA team has requested documentation related to the preconditions for and functionality of components involved in the incident. Much of the documentation for this plant exists only as paper copies of the original vendor documentation.

No data sheets have been available for the quick closing and Flintstone valves.

The original vendor documentation contains information related to functionality and recommendations for following up such components as the quick closing and Flintstone valves. These details are not reflected in the data on the system used today for follow-up and operation.

Earlier challenges related to steam backflow from the MP level are described in the procedure for normal running down of the TG. However, the PSA team was informed that this was little used since the TG is normally shut down via the PSD function.

The difficulty of accessing safety-function descriptions could contribute to the data being insufficiently known to those responsible for following up the system.

8 Emergency preparedness

The regulations require licensees and others participating in petroleum activities on the NCS and on land to maintain an effective emergency preparedness at all times to handle hazards and accidents which could cause loss of human life, personal injury, environmental pollution or substantial damage to material assets.

In addition, the responsible party must establish barriers which reduce the probability that faults and/or hazards or accidents develop, and limit possible harm and inconveniences.

TBO's emergency response organisation, including its own first and second lines, was notified of the incident immediately, and initiated a number of measures continuously in line with the plant's response plan. That included notifying the local civil emergency agencies such as the police, the Heim and Aure fire and rescue services and the emergency medical communication centre/ambulances.

The PSA team's overall impression is that the response organisation and established measures functioned by and large as planned, but that certain aspects have a potential for change and improvement. These will be covered in more detail below.

This report breaks the response into four main phases, covering alarm, notification and mobilisation, combating and handling the incident – including rescue and evacuation – and finally normalisation.

TBO's emergency response plan (WR-1884) describes how predefined dimensioning incidents will be handled in the various phases which normally succeed each other in time. Response duties and description of roles and teams are defined through analyses as well as through roles defined in a standard response organisation based on internal company standards and designations and on enterprises required to maintain a health and safety system.

8.1 Alarm phase

The incident was detected and notified to the CCR around 14.40 by personnel out in the plant, who first heard a very loud noise and felt vibrations in the ground and then observed a fire in the compressor house. Several detectors also activated alarms related to fire detection. The CCR then sounded the alarm in accordance with specified procedures, and initiated ESD. This included shutdown of all energy supply to the compressor house, activation of the stationary deluge system, and blowdown.

An evacuation alarm was also sounded by sirens, with loudspeaker/public address announcements that fire had broken out in the relevant area. Personnel present were asked to evacuate through two door at each end of the factory. From there, they could return to the administration building either on foot or by internal bus transport.

8.2 Notification and mobilisation

TBO's own response organisation was immediately notified, with both first and second lines mobilised. Equinor's third line at Forus was also notified of the incident. The PSA was notified by phone at 14.58.

In normal working hours, the emergency health and safety team is established with the organisation discharging its various functions. At other times, this is based on the operations shift and on-duty functions.

The response leadership based its efforts on the defined situations of hazards and accidents (DSHAs) which cover fire and explosion in the factory area and in the compressor house, and evacuation of personnel from the plant.

External civil emergency agencies were then notified one after another, and reported back with estimated arrival times. The fire and rescue service responded with fire appliances and crews from both Heim and Aure, and five ambulances from the local area were at one point assembled ready for action in front of the administration building. The Aure district sheriff's office also sent a patrol car and two officers. Immediately on arrival, the leaders of the emergency services contacted the response leadership to be briefed on the incident and to offer their assistance.

Personnel considered by the response leadership to be necessary for fighting the fire were kept at the plant to assist the response effort.

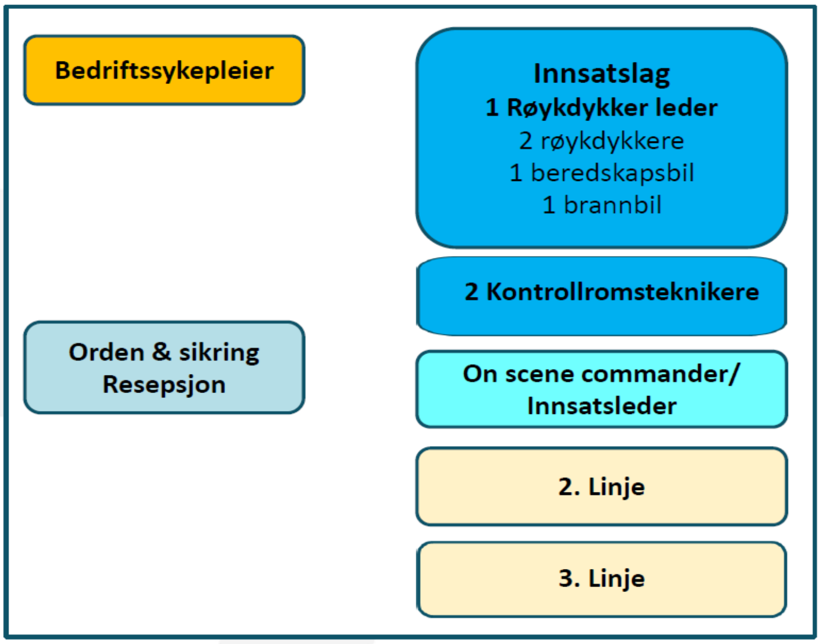

Figure 8. Minimum staffing for response teams and the CCR in an emergency (source: Equinor).
Key: Company nurse; Response team, 1 smoke diving leader, 2 smoke divers, 1 response vehicle, 1 fire appliance; 2 control room technicians; Order and security, Reception; 2nd line; 3rd line.

8.3 Combating – rescue and evacuation

The on-scene commander (OSC) arrived at the fire scene soon after the alarm was sounded, and decided that personnel in the response team had to maintain a good and safe distance (about 150 metres) from the compressor house, which was now alight with visible flames through the ceiling. He also decided to wait in taking action towards the building until the fire had been moderated by the stationary deluge systems, and then possibly continue extinguishing work in collaboration with the fire brigade when it arrived with appliances for spraying water and perhaps laying foam.

After the police and fire brigade arrived, it was clarified that TBO's OSC would continue to lead efforts at the fire scene.

When establishing the assembly/muster point out in the field, ambiguities meant that the response team failed to receive clear instructions on where they should assemble, and the response vehicle with rescue equipment was also initially parked in a less convenient position than the one considered optimal with hindsight.

The OSC was in regular radio contact throughout with the second-line response leader. With the aid of CCTV, the CCR could see the compressor house from the outside but had no direct internal view of the fire scene.

Weather conditions were favourable during the incident, with a wind speed of 0.2-1.4 metres/second and a temperature of about 4 °C according to YR.no.

Two stationary water monitors positioned about 30 metres from the compressor house had to be activated manually by the response team after its arrival at the fire scene. It cannot be ruled out that an escalation of fire/explosion could have occurred after the team arrived, and that further consideration should therefore be given to the question of a safe distance.

TBO has its own fire appliance with water monitors. It is somewhat unclear whether and how possible use was made of this in fighting the fire.

Security personnel are responsible for counting personnel, based on reporting from the individuals present and from supervisors out in the factory area. According to the log, this was under control about 15.25. Some 40 people were evacuated from the plant. TBO's performance requirements can be understood to require an overview of personnel within 15 minutes in the factory (E.YK-4) and within 45 minutes for the whole plant.

Once the fire looked like being under control, around 15.40, the OSC decided that people could enter the building to check if the flames were extinguished. Before then, the CCR also confirmed that pressurised systems, including the synthesis gas and CO_2 level, were under control. Two smoke divers from the response team then entered the compressor house at ground level, but discovered about 40 centimetres of water and oil on the floor and decided to withdraw until this liquid had been pumped out. The roof structure also appeared to have suffered considerable damage from the fire and fragments thrown off in the turbine breakdown, which contributed to the decision to withdraw response personnel from the building for safety's sake.

A vehicle equipped with pumping/suction equipment was then requisitioned from the SAR company to remove oil spillage and polluted water from the compressor house. This unit arrived around 18.30 and began work immediately. No acute spills were registered over and above the liquid observed and collected inside the compressor house in addition to the actual fire.
Plans were made to replace TBO's own response personnel out in the field during the afternoon, and fresh people were ready to take over at about 16.45.

8.4 Comments on combating the incident

The conditions mentioned in this section could indicate a need for more training and drills directed particularly at positioning response personnel during an incident of this kind and at the use of response equipment – including TBO's own fire appliance.

8.5 Normalisation

The main purpose of the normalisation phase is to restore the plant with associated personnel resources to a safe and normal condition.

Nobody was physically injured in the incident, but several were affected by it – partly because it was not possible to shut down the TG from the CCR. The actual fire scene also became a powerful experience for the responding personnel. Everyone involved took part immediately after the incident in post-mortems and debriefings, and – along with other people who wanted this – were offered follow-up by health personnel.

After the blaze had been extinguished, the fire scene was secured and cordoned off to permit further follow-up and investigation of the incident. This was also ordered by the police.

External emergency services started leaving TBO at about 16.30, since the incident was under control. The Aure fire and rescue service and one ambulance stayed a little longer through the afternoon before departing in agreement with the police and the response leadership.

The PSA team has not assessed the contribution of the civil emergency services and their collaboration with TBO, since this falls outside the mandate for its investigation. TBO's own response personnel were available through the evening, and the final log entry was made at 19.04.

The PSA team has not gone into further detail on measures taken by the company during the normalisation process, but has secured confirmation that personnel involved have received the follow-up prescribed by the company's internal rules and routines. Furthermore, evaluations of the emergency response during the incident have been conducted with personnel involved.

Methanol production resumed during week 7.

9 Regulations

The technical and operational regulations specify requirements on the design of land plants which also contain steam facilities. These requirements are almost entirely risk-based and functional, and do not set explicit design standards for steam plants.

10 Observations

The PSA's observations fall generally into two categories.

- Nonconformities: this category embraces observations where the PSA has identified breaches of the regulations.
- Improvement points: these relate to observations where deficiencies are seen, but insufficient information is available to establish a breach of the regulations.

10.1 Nonconformities

10.1.1 Failure to identify safety functions and to follow up technical integrity and barrier function

Nonconformities

Failure to identify and follow up valves with a barrier function. Inadequate measures to compensate for impaired barrier function.

Grounds

The classification of equipment components determines how they are followed up in operating conditions. That applies to such aspects as preparing a maintenance programme and requirements for function testing, prioritisation of their maintenance, who is involved in the event of impairment, assessing the need for compensatory measures should impairment occur, and follow-up.

The following conditions were identified by the investigation in relation to following up valves with a barrier function.

- The quick closing and Flintstone valves serve as barriers for overspeed protection of the steam turbine by halting steam supply to the turbine in a PSD. A review of the maintenance system shows that these valves were classified with low criticality. Their barrier function was not described.
- Maintenance of components is intended to ensure that they are capable of performing their function. Maintenance also covers testing and follow-up of performance requirements. The latter were not established for either Flintstone or quick closing valves because of their classification. No routines were established for testing the Flintstone's mechanical non-return function.
- The Flintstone is the only barrier to steam backflow at the MP level. Two functions are available to close the valve. Temporary repairs were made to both of these, and the valve was categorised in SAP as "serious ill". The barrier functions are not reflected in SAP and no assessments were made with regard to the need for compensatory measures as a consequence of the temporary repairs and possible barrier impairment.
- The latest WO established for repairing the Flintstone valve's actuator is dated 18 October 2020 and had a deadline for execution of 2 December 2020. This

job was not done by the deadline, nor was any assessment made of a possible deadline extension.

Requirements
Section 5 of the management regulations on barriers
Section 58 of the technical and operational regulations on maintenance
Section 58 of the technical and operational regulations on classification

10.1.2 Follow-up of the system

Nonconformity
Inadequate follow-of the system to identify technical and operational weaknesses.

Grounds
Routines have been established for reviewing the various TBO systems in order to follow up their technical condition and possible barrier impairment. The review largely covers follow-up of defined barrier functions.

The checkpoints used to detect deficiencies in the plant are insufficiently tailored to identify weaknesses in systems other than those identified in TR2237. That applies to auxiliary systems which could have a serious incident potential.

Requirement
Section 21 of the management regulations on follow-up

10.1.3 Documentation

Nonconformity
Operating documentation for equipment components related to the steam TG were lacking or difficult to access.

Grounds
The original vendor documentation contains information related to functionality and recommendations for following up such components as the quick closing and Flintstone valves. These details are not reflected in the data found in the system used today for follow-up and operation.

No data sheets have been available for the quick closing and Flintstone valves.

Requirement
Section 40, litera c of the technical and operational regulations on start-up and operation of onshore facilities

10.1.4 Safe distance from the fire scene not established

Nonconformity
Barriers to reduce opportunities for faults, hazards and accidents occurring and developing are deficient in that no minimum safe distance has been established for response personnel on arrival at the relevant fire scene.

Grounds
The safe distance to be used by response forces when responding at the relevant fire scene were neither established nor known, including what represents a safe distance when threatened by an explosion or the uncontrolled ejection/hurling of fragments from a fire and explosion in the compressor house.

Requirements
Section 5, litera b and c of the management regulations on barriers
Section 66 of the technical and operational regulations on emergency preparedness plans

10.2 Improvement points

10.2.1 Unclear how the Tjeldbergodden fire appliance was used

Improvement point
TBO has its own fire appliance with water and foam spraying equipment. It is unclear whether and how this was used during the response at the fire scene.

Grounds
Based on interviews, feedback and the document review, including logs after the incident, it is somewhat unclear whether and how TBO's own fire appliance was used during extinguishing work and in fighting the fire.

Requirements
Section 64 of the technical and operational regulations on establishment of emergency preparedness
Section 66 of the technical and operational regulations on emergency preparedness plans

10.2.2 Unclear performance standard for personnel check (POB) in the plant

Nonconformity
The performance requirement for counting personnel (POB) in the plant (factory area) in the event of such an incident, after the alarm is sounded and evacuation announced, can be interpreted to be 15 minutes (E.YK-4). The log shows that this took significantly longer than is considered to be the performance requirements for this part of the TBO complex.

Grounds
The emergency preparedness plan for TBO, with associated appendix E, sets the performance requirements at 15 minutes for establishing the status of people in the factory (E.YK-4). According to the log, it took about 45 minutes during the incident for the response leadership to obtain a full overview of personnel evacuated from the factory area, over and above those participating in the response.

Requirement
Section 66 of the technical and operational regulations on emergency preparedness plans

11 Barriers which functioned

Barriers intended to detect overspeed of the machine functioned as intended during the incident. A review of the control-system log shows that functions for shutting down steam supply were initiated. Fire detection functioned as intended.

CCR operators took manual actions related to PSD and blowdown in the area and initiated deluge.

12 Discussion of uncertainties

12.1 Reason why the solenoid failed

The closure function on the Flintstone valve failed during the incident. Technical investigations of the solenoid are still under way. The reason for the failure has therefore not been established when this report is published.

13 Assessment of the player's investigation report

Equinor has conducted its own investigation of the incident at TBO. The report is detailed and its conclusions related to the causes of the incident largely coincide with those drawn by the PSA team.

Equinor's report has identified a number of lessons learnt, including the following:

1. increase and maintain expertise on steam turbines
2. establish adequate PM for critical valves
3. evaluate measures to prevent fragments scattered by breakdowns causing escalation
4. safeguarding similar equipment at other plants.

Where point 3 is concerned, challenges are described in relation to lack of distance/ physical separation between the TG and the synthesis gas compressor. This is significant both with regard to hot surfaces on the TG as a possible ignition source and because fragments scattered by breakdowns can cause escalation.

With regard to point 4, Equinor has investigated other plants it operates with similar steam turbines and found that several of them have also assigned low criticality to shutdown valves.

In the section on emergency response, the company refers only to the PS of 45 minutes for a personnel overview (POB) of the whole of TBO (E.YK-2) and not to the performance requirements which can be interpreted to apply to the POB in the plant/factory area (E.YK-4), which specifies 15 minutes.

14 Other comments

Information on incidents related to overspeed and breakdown of steam turbines is provided in technical articles. Common causes of such breakdowns relate to such aspects as the design and robustness of solutions for isolation from the steam network as well as follow-up related to inadequate testing and maintenance of these valves. Where two-stage steam turbines are concerned, challenges related to isolation from the MP stage are also described. Measures described for improving the robustness of this function include two non-return valves in series or double solenoids.

15 Appendices

Appendix A: List of documents