PETROLEUMSTILSYNET

Investigation report

Report	
Report title **Investigation of hydrocarbon leak on Gudrun of 18 February 2015**	Activity number 001025017

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

Summary

Gas was detected in the M30 process module on Gudrun at 06.23 on 18 February 2015. A general alarm was automatically activated and the plant was automatically shut down and depressurised. Personnel on Gudrun and *West Epsilon* mustered pursuant to the alarm instruction.

The direct cause of the incident was a leak from a rupture in a two-inch pipe in the bypass line directly downstream of the first-stage separator. This break occurred in one of the most critical locations in a process plant.

Statoil estimated the initial leak rate at eight kilograms per second (kg/s). Condensate from the first-stage separator leaked to the open air. The total emission/discharge is estimated at 2 800 kilograms/four cubic metres of condensate, and more than one cubic metre is estimated to have been discharged to the sea.

A condensate escape represents a significantly higher explosion risk than an oil leak. The leak on Gudrun is regarded as one of the larger hydrocarbon escapes recorded on the Norwegian continental shelf (NCS) over the past decade. In slightly different circumstances, the incident had the potential to cause a major accident with loss of life, substantial damage to material assents and consequences for the marine environment.

Involved	
Main group T-1 Statoil	Approved by/date
Members of the investigation team Kristi Wiger — Process integrity Asbjørn Ueland — Process integrity Aina Eltervåg — Logistics/emergency preparedness Elisabeth Lootz — Occupational health and safety	Investigation leader Kristi Wiger — Process integrity

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Summary

The investigation conducted by the Petroleum Safety Authority Norway (PSA) has revealed a causal chain where an insufficiently robust design on Gudrun failed to be identified, where relationships between various operational problems in the process plant were not understood, and where decision-makers lacked sufficient experience and safety-critical expertise.

It is well known in Statoil and in the rest of the industry that flow-induced vibration in piping and equipment can lead to a weakening in the integrity of the facility and possible rupturing of stressed equipment components.

The investigation of the Gudrun incident has revealed inadequate follow-up by Statoil of equipment deterioration during operation. The equipment which failed on Gudrun handled hydrocarbons under high pressure and temperature, where a failure would cause a production shutdown. This equipment is meant to be designed to cope with heavy loads.

Repeated incidents occurred when running-up production on Gudrun in the months before the incident, which involved equipment failure and vibration in the relevant valve and the piping system it is connected to. These were registered by the offshore organisation and communicated to the land organisation as notifications and reports of concern. Understanding, assessment and action on these by Gudrun's production management have been limited.

Although powerful vibration with much noise and repeated functional failure had been experienced with control valves, leading to a valve failure on 25 January 2015, the production management – together with the asset integrity (AI) entity – considered that it would be prudent to continue production. This finally led to in an incident which could, under slightly different circumstances, have resulted in a major accident.

On the early morning of 18 February 2015, control room personnel on Gudrun registered strong vibration – "as if a helicopter was about to land". This ceased after about a minute without any cause being identified. Gas was detected at 06.23 in the M30 process module, and the plant was automatically shut down and depressurised. Within a few minutes, gas had spread to most of the M30 module. A general alarm sounded automatically, and personnel mustered pursuant to the alarm instruction. All personnel were accounted for in the space of 11 minutes on Gudrun and 16 on *West Epsilon*.

The photograph below shows the Gudrun facility in the foreground, with the *West Epsilon* drilling rig behind it.

Photograph 1: The Gudrun facility. (Source: www.statoil.com)

The plant was confirmed depressurised after 35 minutes and the area was free of gas within an hour. It was then established that the leak came from a rupture in a two-inch pipe in the bypass line downstream of the first-stage separator. This was temporarily repaired to prevent further leakage.

Statoil estimated the total escape of condensate to be 2 800 kilograms/four cubic metres. No oil was observed on the sea, but it was subsequently estimated that more than a cubic metre of condensate had been discharged to the sea.

The actual leak was caused by a rupture in a two-inch pipe in the bypass line for the ESD valve on the liquid outlet from the first-stage separator as a result of powerful vibration in the liquid piping system downstream of this separator. The vibration was a result of weaknesses in the 20-LV0114 control valve, which regulates the level of liquid in the separator. This four-inch control valve sits in a 10-inch pipeline and reduces pressure from 124 to 19 bar, or by about 100 bar. The specific valve was chosen following an assessment of results obtained from software developed by the valve manufacturer.

Following the start-up of Gudrun in April 2014, vibration was recorded on a number of occasions in various parts of the process plant. Irregularities were also recorded with the control valves for liquid level in the first-stage separator and the corresponding valves for the test separator. Although Statoil knows a lot about vibration and its possible consequences, knowledge about the threat of fatigue rupturing was not applied to the failure of the 20-LV0114 control valve. This was repaired and broken components replaced. No further investigations were conducted to clarify the relationship between the failure and vibration in this part of the process plant, or to determine whether a threat existed that vibration in the process plant could develop into an incident with major accident potential. After the repair, it was decided to modify the solution in the next turnaround, which was already planned for March 2015.

Operating conditions

- Nov 2014: Operating problems with the 20-LV0314 control valve for the test separator are recorded in the maintenance management system, but dealt with on the facility without any involvement by AI being documented.

- Dec 2014: A production operator contacts an inspector visiting for AI to express concerns about vibration in the 20-LV0114 control valve and the adjacent piping system. This vibration are judged to be within acceptable limits. The issue is recorded in the maintenance management system related to the pipe, not the valve.

- Dec 2014: Operating problems with the 20-LV0114 control valve prompt a request for changes to the maintenance routine for control valves. AI is briefly informed.

- Jan 2015: Operating problems are encountered with the 20-LV0114 control valve during start-up, and internal damage is identified. This is viewed as the reason for the operating problems, and damaged components are replaced. AI and the supplier, Solberg Andersen (SAAS), are brought in the next day, and plans are drawn up to monitor the valve until a more robust solution can be implemented. AI does not assess whether any connection exists between this incident, the observed vibration and other operating problems.

- Jan 2015: Plans for monitoring the valve are registered in Synergi, and the action is closed in the space of a week. AI does not set specific criteria for the follow-up and no documentation showing how the valve is to be monitored gets passed on in connection with crew changeovers.

- During this period, most of the items on the operations management’s list of challenges related to technical integrity on Gudrun concern conditions and deficiencies not closed out by the development project. This means the offshore organisation’s attention is concentrated on these conditions in addition to following up day-to-day operations. Problems associated with equipment on control valves coming loose and consequent operating disruptions and vibration in the plant are not included on this list.

Conditions in the design phase

- The wellstream on Gudrun is characterised by high pressure and temperature. Statoil has opted for a plant with two-stage separation, which involves a big pressure drop over the valve which controls the flow of liquid from the first-stage separator.

- The 20-LV0114 control valve has been chosen on the basis of decision support provided by the supplier’s software for valve selection.

- No activities or tools have been identified in the engineering process at Aibel which checks the choice made. A Hazop review was conducted before the final choice of valve.

- Statoil’s team supervising the Gudrun project has had specialist expertise on control valves. This expertise was not utilised in dimensioning the 20-LV0114 control valve.

- Statoil’s GL2212 guideline on the choice of control valves was introduced at the end of the commissioning phase, two months before Gudrun start-up. This systematises Statoil’s expertise with control valves and appears after the design of the facility has been completed. This experience and knowledge are not checked against the solution chosen for Gudrun.

Conditions related to organisation and learning

- Operating problems have been registered with three different equipment units: two control valves and the pipe downstream of the first-stage separator. Vibration in piping is not followed by the same discipline leader in AI who is responsible for operating problems in control valves. The complex causal picture is not understood.

- Technology excellence (TEX), Statoil's central technical team, is responsible for communicating the company's experience in the form of technical requirements (TRs) and guidelines (GLs). TRs do not have retroactive effect and no procedures have been identified for implementing the introduction of new GLs (including GL2212). This knowledge, which was also present in the organisation during engineering work on Gudrun, did not challenge the choice of the 20-LV0114 control valve. Nor was it utilised in connection with the operating problems encountered after the start-up of the facility.

- Systems for collating data from incidents are not suitable for the purpose. Searches conducted by the investigation team in Synergi and SAP revealed that eight incidents had occurred in Statoil over the past 10 years which showed similarities with the Gudrun event. This knowledge was first revealed by Statoil's own investigation, and had not previously been systematised for the organisation.

- The valve supplier has a repair shop in Bergen and an engineering team in Oslo. No formal system has been implemented for transferring information from the repair team to the design organisation.

1 Introduction

Gas was detected in the M30 process module on Gudrun at 06.23 on 18 February 2015. The plant was automatically shut down and depressurised, and a general alarm automatically sounded. Personnel mustered pursuant to the alarm instruction. The facility was in normal operation with drilling from the *West Epsilon* jack-up ahead of the incident. There were 26 people on Gudrun and 97 on *West Epsilon.* A gale was blowing from the south-west – a favourable wind direction, since the gas was largely blown away from the facility.

The PSA investigation team went offshore on the same day and returned on 21 February 2015. The police requested assistance for its investigation of the hydrocarbon leak and travelled out with the PSA team. An inspection of the incident area offshore was conducted. The police interviewed personnel involved offshore with support from the PSA.

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

a. *Clarify the incident's scope and course of events with an emphasis on safety, working environment and emergency preparedness aspects.*
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, with an emphasis on human, technology and organisation (HTO) and operational aspects, from a barrier perspective.*
d. *Discuss and describe possible uncertainties/unclear aspects.*
e. *Identify nonconformities and improvement points related to the regulations (and internal requirements).*
f. *Discuss barriers which have functioned (in other words, those which have helped to prevent a hazard from developing into an accident, or which have reduced the consequences of an accident).*
g. *Assess the player's own investigation report (the PSA's assessment is communicated in a meeting or by letter).*
h. *Assess the incident in the light of improvement initiatives implemented by Statoil to reduce hydrocarbon leaks.*
i. *Prepare a report and a covering letter (possibly with proposals for the use of reactions) in accordance with the template.*
j. *Recommend – and contribute to – further follow-up.*

Following the period offshore, the police have conducted interviews with support from the PSA, and the PSA has also carried out a number of interviews with personnel from operations and the development project.

Documentation has been acquired during the period spent offshore and the investigation on land. External investigations have been conducted in relation to:

- damage to the 20-LV0114 control valve (carried out by SAAS on behalf of Statoil)
- material technology investigations of the rupture (leak site) in the two-inch pipe (carried out by Statoil's material technology laboratory)
- analyses to understand flow conditions in the 20-LV0114 control valve (carried out by Sintef on behalf of the PSA).

Results from these investigations have been made available to the police, Statoil and the PSA.

An HTO approach has been applied as the methodology in the investigation process.

Investigation team	
Kristi Wiger	Process integrity (leader)
Asbjørn Ueland	Process integrity
Elisabeth Lootz	Occupational health and safety
Aina Eltervåg	Logistics and emergency preparedness
Contributions from	
Helene Bjelland	Legal and regulatory affairs
Bjarne Sandvik	Logistics and emergency preparedness (participated offshore)
Terje Andersen	Structural safety
Ole-Jacob Næss	Structural safety

2 Information about Gudrun

Gudrun came on stream on 7 April 2014, less than a year before the incident occurred.

The partners in production licence PL 025 are Statoil (operator with 75 per cent) and Engie (formerly GdF Suez Norge – 25 per cent). The Gudrun field lies in block 15/3 about 55 km north of Sleipner and is characterised as a high pressure and temperature (HPHT) reservoir. Its production facility is supported on a steel jacket, has no drilling equipment of its own and incorporates a process plant to separate oil and gas. The hydrocarbons are piped to Sleipner. The *West Epsilon* rig is used for production drilling on the field.

Gudrun was originally proven in 1975 and contains some 184 million barrels of oil equivalent. The HPHT reservoir calls for special technology. Statoil utilised its experience and technology from developing Kvitebjørn and Kristin. The plan for development and operation (PDO) was submitted in 2010. Gudrun ranks as Statoil’s first field development for 10 years and was implemented as a fast-track project. This is a way of working intended to halve the time required to develop uncomplicated fields on the NCS. Such standardisation helps to boost the pace of development and creates profitability for small discoveries which have previously been difficult to make commercial.[1]

An engineering, procurement, construction and installation contract for the facility was awarded to Aibel in 2010. The jacket was built at Verdal. Engineering and fabrication of various modules took place in Asker, Stord, Poland, Singapore and Thailand, with topside assembly in Haugesund.

The Gudrun topside was designed by Aibel’s engineering team in Asker, with further detailing at the company’s Singapore offices. The topside modules (M20 and M30) were built at Aibel’s Deeline yard in Laem Chabang, Thailand. This was the first development project where Aibel used its own Thai yard.

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1 Definition taken from TU http://www.tu.no/petroleum/2013/04/26/fast-track-er-en-megasuksess-for-statoil (in Norwegian only).

Topside fabrication began in May 2011. The living quarters were delivered by Apply Lervik at Stord. The module support frame (M10) was assembled in Haugesund, with modules delivered from Poland. The topside was completed in 2014. Roughly 7 000 people in all were involved in the project, and 100 Aibel employees took part in offshore hook-up work.

Engineering of the piping system and equipment downstream of the first-stage separator, where the rupture occurred, was done at the Aibel offices in Asker and Singapore. Layout and large pipes were designed in Aker, while piping with diameters below six inches – including the bypass line where the leak occurred – was handled in Singapore. All pipe supports were calculated and positioned by the Singapore team. The 20-LV0114 control valve was chosen by Aibel in Asker in cooperation with the Oslo branch of valve supplier SAAS.

2.1 Operating model and organisation of Gudrun

Statoil's common operations model assumes a close technical collaboration between land and offshore and between the various disciplines. Key managers in the Gudrun organisation emphasise that this is a prerequisite for Statoil's operations model.

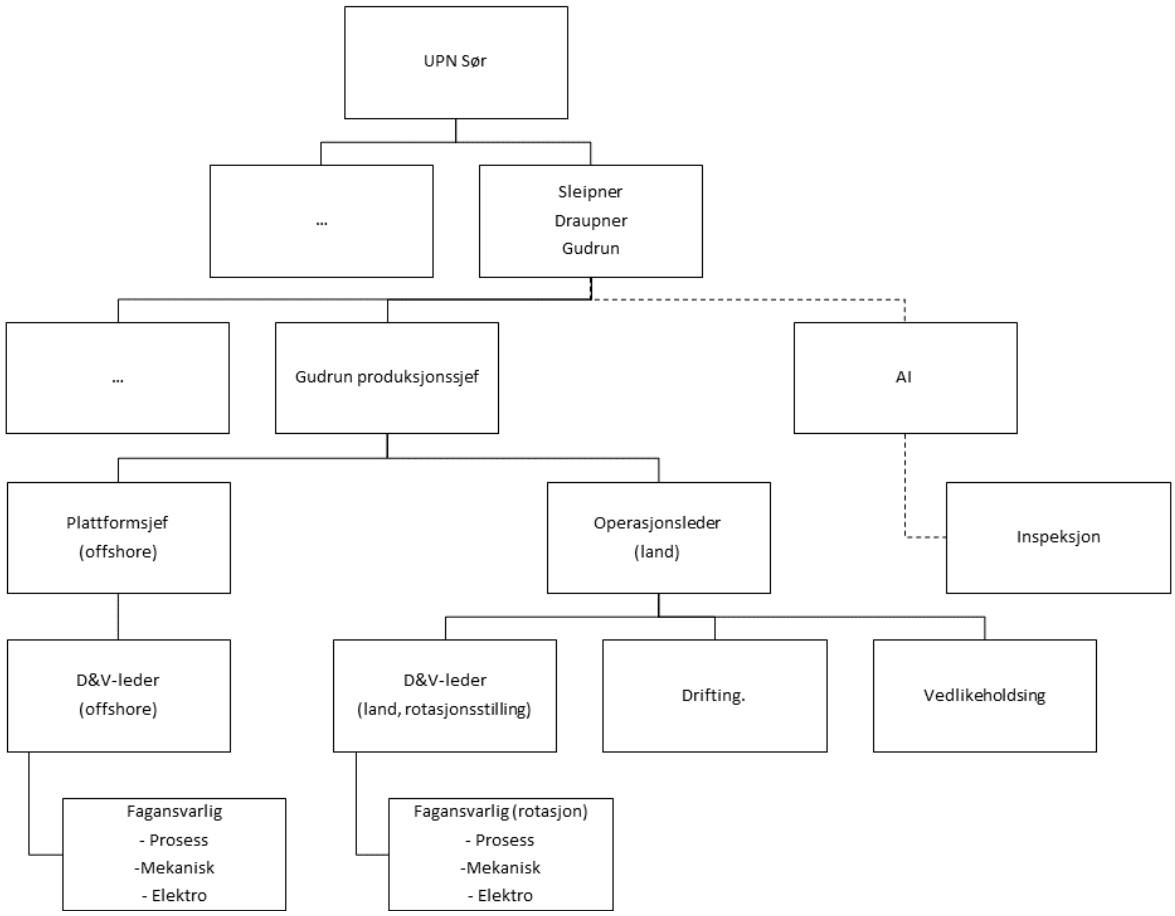

Figure 1: Section of the Gudrun organisation model (merger of organograms in OMC01-004 and OMC01-005).

Gudrun is operated in the same way as most facilities on the NCS. An offshore workforce handles day-to-day operation and simple corrective maintenance with support from the land organisation. Gudrun was planned for low staffing, and 26 people were on board when the incident occurred.

The production manager for Gudrun is responsible for “safe and efficient operation and maintenance”. AI Sleipner, Draupner and Gudrun is a support function for this business unit and has technical responsibility for the facility. Pursuant to OMC01-004-UPN *Operation – organisation, leadership and management*, it is intended to have “the principal responsibility for technical integrity from wing valve pipe, or incoming emergency shutdown valve (ESV) on the platform [...] Conduct an integrated assessment of the plant’s technical integrity based on input from all contributors/sub-managers. Based on an overall assessment of technical integrity, ensure the implementation of necessary measures [...] Provide the necessary support to the operations team and the platform to deal with operational disruptions which need expanded support.”

Some of the resources in AI are assigned to Gudrun. In addition to the AI leader Gudrun, the following technical disciplines are particularly relevant to this incident:

- instrumentation has responsibility for control valves
- mechanical has responsibility for piping
- process has responsibility for ensuring that the plant is operated in accordance with the process conditions.

The daily morning meeting at 08.30 between land and offshore is chaired by the operations department (OPS) with the AI manager Gudrun present. Relevant issues raised in the meeting will be passed on by the latter to the responsible discipline lead in AI.

OPS supports day-to-day operation of Gudrun with planning and practical organisation of work packages sent offshore. This group reports to the production manager.

Statoil’s specialist expertise is found in TEX. This entity is responsible for providing technical expertise and technological solutions to development projects, as well as technical support for the production entities. If an operations department wants TEX support, it must order this. The entity’s responsibilities include developing, maintaining and implementing Statoil’s TRs and associated GLs. TEX receives information on development projects and production entities throughout the Statoil organisation, and thereby has valuable knowledge and experience related to various types of technical equipment – including control valves and vibration. Technical experts in TEX, which has a special responsibility for transfer of safety-critical information in Statoil, are contacted by project teams and AI when support is needed.

3 Course of events

Design, construction and assembly of facilities to ready them for operation are often characterised by great complexity, involving many companies, different disciplines, a variety of suppliers and work at different locations. Information sharing and technical assessments must be pursued across a number of interfaces between players, disciplines, work at different sites and rolling shift patterns.

This description of the course of events is based on conversations and interviews with personnel in Statoil, Aibel and SAAS, as well as a review of documents.

3.1 Project phase

16 Jun 10 PDO approved by the Storting (parliament).

20 Jul 10 Aibel wins the engineering, procurement and construction (EPC) contract for the Gudrun topside. Statoil has project personnel at Aibel in Asker, and contributes relevant technical and operations expertise in the engineering phase.

Undated: 3D model reviews of piping and design were conducted when the design work was 30 and 60 per cent complete.

1 Nov 10 Aibel in Asker implements the first Hazop[2]. Control valves cannot have been a topic since their size was fixed at a later date.

8 Nov 10 Aibel in Asker issues an enquiry for delivery of control valves to three suppliers, who all have frame agreements with Statoil.

10 Nov 10 Aibel implements the second Hazop. System 20, which includes the control valves, is reviewed but a full Hazop is not conducted with it. The size of the valves is fixed at a later date.

3 Nov 10 Aibel receives tenders from the valve suppliers for the delivery which covers all the control valves.

14 Jan 11 Aibel completes a process data sheet for the 20-LV0114 valve so that the supplier (SAAS) can propose a choice. At an earlier stage, Petek[3] in Statoil has provided Aibel with production rates and profiles as a design basis. Aibel uses these data to dimension equipment and piping in the process plant.

26 Jan 11 Bid clarification meeting (BCM) with the SAAS design department at Aibel. Relevant discipline experts from Statoil's project team also attend. The meeting covers the delivery of 85 control valves. Topics include nonconformities between Statoil's own valve TRs and the SAAS bid.

Feb 11 Sizing calculation meeting between Aibel and SAAS. Dimensioning of 20-LV0114, among others, is discussed on the basis of the manufacturer's calculation programme. This programme warns of chocked flashing[4] with the note: "Flashing-induced problems of erosion and corrosion are possible for these service conditions". The issue is discussed, but terminated on the basis of comments from SAAS that the programme is conservative. To handle loads caused by flashing in the valve body, high-quality materials are chosen.

14 Apr 11 Aibel orders control valves for the first-stage and test separators.

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2 Hazop (hazard and operability study) is a structured review of a planned or existing process or operation in order to identify and evaluate problems which could represent a risk to personnel or equipment or prevent efficient operation. Conducted by a multidisciplinary work group which contributes technical expertise and experience. The Hazop method seeks to stimulate the imagination of participants in identifying potential hazards and operational challenges. Among other uses, it provides a tool for reviewing process systems in the design and operations phases.

3 Centre for petroleum technology.

4 Flashing occurs when a liquid gasifies following a pressure reduction. Condensate flowing from the first-stage separator is in a liquid phase at a pressure of 124 bar. It comprises various hydrocarbon fractions which differ in terms of vapour pressure – ie, the pressure where the liquid gasifies. The pressure drop across the valve, which is no less than 104 bar, will cause a large proportion of the condensate to reach its vapour pressure and gasify. This phase change is termed flashing.

1 Dec 11 Statoil conducts a TTS[5] for Gudrun's process plant. No findings in the report relate to the 20-LV0114 valve and the piping downstream of the separator.

Jan 12 Personnel from Statoil's AI entity join the company's team supervising the hook-up and commissioning of the platform modules.

7 Jan 12 The process module built in Thailand arrives at Aibel's Haugesund yard.

19 Apr 12 The control valves for the first-stage and test separators are ready for final inspection by Aibel at the manufacturer in France before dispatch to Haugesund.

17 Jul 13 The platform topsides are shipped from Aibel's Haugesund yard and lifted onto the jacket the following day.

19 Feb 14 Statoil issues GL2212 Valve selection manual – control valves as a supplement to TR2212 based on operating experience acquired by the company. It specifies the need to pay special attention when choosing control valves for demanding operational conditions. GL2212 cites 10 factors which characterise critical operating conditions, of which eight are relevant on Gudrun: flashing, cavitation, high noise, high pressure drop, high velocity/kinetic energy, erosion, high/low temperature and high rangeability.

Nothing has been found to confirm that the valve choices subsequently made on Gudrun have been checked against the GL.

7 Apr 14 Gudrun delivered from project to operations.

3.2 Operations phase prior to 18 February 2015

7 Apr 14 Gudrun comes on stream.

11 Nov 14 Well A-07 comes on stream. Powerful vibration is subsequently recorded periodically in the piping system downstream of the first-stage separator. The strong vibration registered with incidents reflects loosening of the positioner. This means the mechanism is not under control and the valve is chasing.

2 Nov 14 Production shut down as a result of a fault in the 20-LV0314 control valve downstream of the test separator. This is recorded in SAP as an operational disruption.

Wk 49 14 An inspector goes offshore on behalf of AI static mechanics to follow up vibration associated with the gas compressor after new wells have been phased in and total production increases. The gas compressor is not located close to the separator.

The lead process operator has personally seen that vibration can cause ruptures. He reports verbally to the inspector on his concerns about periodic powerful vibration in the piping system downstream of the first-stage separator after

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5 Technical condition safety (known as TTS from the initials of its Norwegian designation) is a Statoil tool which involves a review and assessment of the technical condition of safety systems. A TTS review is based on a checklist drawn up on the basis of TR 1055 – performance standards for safety systems and barriers, and basically does not involve an assessment of whether operations-related systems could pose a safety challenge.

production has increased. The inspector checks for low-frequency movement which could lead to fatigue, and concludes that the vibration is not critical. The job is registered in SAP with the pipe downstream of the valve as the functional location.

Work order M3 43892631 specifies further measures:

- AI must assess the integrity of the pipe on the basis of the inspection, and consider in more detail whether a follow-up inspection is required
- the pipe must be followed up by inspection in 2015, and a separate work order for this has been generated.

DNV is commissioned by the AI discipline expert for mechanics to follow up vibration related to gas compression, but is also to look at the piping system downstream of the first-stage separator. This inspection is said to have been planned for the spring of 2015, when Gudrun has reached full production.

No available information or documentation indicated that AI has considered this issue in relation to previously registered valve faults and vibration.

14 Dec 14 Production on Gudrun is shut down. Unstable production on the field because of loose positioner affects Sleipner, which experiences problems with output and water production and asks for Gudrun to be shut down.

The PSA investigation team does not know whether vibration was observed with the unstable operating conditions, which were caused in this case by loose positioners.

Mechanics on Gudrun identify problems with the 20-LV0114 control valve and correct them by tightening screws on the connecting arm between valve and positioner. Gudrun's operations and maintenance (D&V) manager writes notification M5 43899614 (in SAP): "Because of a number of incidents with control valves, the following text needs to be included in the maintenance programme for control valves: 'Check the connecting arm between valve and positioner carefully. Look for loose screws and damage'".

The incident is discussed at the morning meeting on the following day and the issue is considered for a working meeting in AI. The AI discipline lead contacts technical personnel on board for further clarifications.

24 Jan 15 Production on Gudrun is halted for a planned heavy lift.

25 Jan 15 On start-up after the heavy lift, heavy shaking, loud noise and powerful vibration are experienced in the process plant. The connecting arm between valve and positioner on the 20-LV0114 control valve has loosened and been twisted out of position. The valve is chasing between closed and open positions. This is corrected and a new attempt made to restart, but a great deal of energy is observed in the valve and production must be halted because of these problems.

The valve is opened for inspection. The work order in SAP shows that the actual repair job meets Statoil's A standard.[6] Operators on Gudrun do the job. A faulty seal ring is identified on the plug, and understood to be the cause of the problem. Worn and broken parts are replaced. A guide is installed on the valve stem to prevent twisting.

Opening of the valve, the faults found and the completed repair were documented in writing in SAP with photos and via e-mail by the responsible operators.

Production was then restarted in the early morning of 26 January 2015. No overall assessment by the platform management of the cause of the strong vibration ahead of production start-up has been documented. The OPS group and AI are first notified of the repair on the morning of 26 January 2015.

26 Jan 15 Monday morning meeting between the platform management and OPS on land. Operators on Gudrun report on the repair carried out the day before and on noise and vibration related to the valve.

The AI manager Gudrun involves relevant AI personnel in further follow-up of the 20-LV0114 control valve. No assessment can be documented by the platform management, OPS on land or AI of the possibility that vibration experienced by the plant might lead to serious incidents or major accidents. Nor does any documentation show that consideration was given to rescheduling the DNV inspection planned for the spring of 2015 as a result of the incident.

Statoil's TTS team arrives on Gudrun to verify performance standard PS 1 Containment. This standard focuses on identifying conditions which could lead to leaks in process plants, particularly in relation to flexible and mechanical connections. Furthermore, connections and piping must be designed to withstand vibration. This review was conducted from 26-30 January 2015.

The AI mechanical discipline lead, who was part of the TTS team, was informed by a worried production operator about the powerful vibration in and behaviour of the control valve observed the day before in connection with the failure. They go into the plant together to look at the piping and supports. A fault found was recorded as M2 43942335 "Piping not resting on support". It is later confirmed that this fault was rectified.

Concerns about strong vibration expressed by the production operator are not followed up further in the TTS review, which assesses a different piping segment. No evaluation is therefore made of the vibration as a condition which could undermine the integrity of the containment, nor is it included in the TTS assessments.

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[6] Pursuant to Statoil's own requirements in the *Statoil Book*, an A standard action pattern must always be followed for work operations. This is described as a "common mode of action" for the Statoil organisation. An A standard will identify the risk of the activity and requirements for the work pursuant to formal regulations and the method to be used. The work team must assess whether further assessments are needed of methods, requirements or risk. In addition to the A standard, the *Statoil Book* refers to the importance of compliance and leadership. Managers have a responsibility in an A standard as communicators, role models, trainers and advisers. A continuous risk assessment must also be conducted during the work.

27 Jan 15 Video meeting held with platform manager, discipline leads on the facility, AI mechanical and instrumentation discipline leads and SAAS (operations team in Bergen) to discuss the repair already made to the 20-LV0114 control valve and to assess whether maintaining production would be prudent.

It emerges from the summary of the meeting that the valve has failed twice at start-up after a plant blowdown. This is assumed to be the result of vibration generated by turbulent gas under the seat as a consequence of the pressure drop of about 105 bar across the valve. The vibration is assumed to be the reason why the positioner has loosened, causing the valve to chase between closed and open.

SAAS recommends reversing the valve and replacing the actuator with a more powerful type. This is to be done in March 2015 during a planned turnaround. The meeting considers it acceptable to operate the repaired valve as it stands until then. It has not been clarified whether the quality of and the work done on the 20-LV0114 valve were reviewed at the meeting. The delivery time for the actuator means that the change is not made immediately.

The instructions on close visual inspection in Synergi 1429529, measure 2, describes how the valve is to be monitored. This involves close visual inspection and a check that the clearance to the guide is unchanged, that the valve acts smoothly and that no leaks exist. The meeting concludes that the valve must be closely monitored when changes in production occur and during running-up/down.

Whether AI makes any assessment at this meeting related to vibration and the associated risk that this could pose for the process plant is not documented. Statoil opts to maintain production with the measures described in the notification. It emerged from interviews that the solution and decision has not been discussed with other managers or other technical experts in Statoil.

27 Jan 15 The AI mechanical discipline lead and the inspector tour the plant on the Tuesday evening to document possible vibration after the repair was completed and production had resumed.

28 Jan 15 The D&V manager reports that there was considerable vibration in the plant, and wants noise and vibration ahead of this incident to be documented. Synergi 1429529 is accordingly written. This contains the summary from the meeting of 27 January 2015, with actions and operational measures. The latter involve regular monitoring with close visual inspection, particularly in the event of changes to flow, running-up/down and so forth. Checks are to be made that clearance to the guide is unchanged, that the valve acts smoothly, and that no leaks exist.

1 Feb 15 The action pack in Synergi relating to operational measures for ensuring that the 20-LV0114 control valve does not fail again is closed. How the operational measures are communicated at the next crew change is not documented.

12 Feb 15 Condition monitoring of control valves on Gudrun by Statoil’s condition monitoring (TK) centre begins. The 20-LV0114 control valve for liquid level in

the first-stage separator is said to be in good condition during 12-18 February, according to Statoil’s investigation report.

3.3 The incident of 18 February 2015

Times given in seconds are based on information from CCTV footage and alarm logs.

06:21:37 CCTV footage shows powerful vibration in the process plant. Personnel in the control room compare it to the arrival of a helicopter – but no helicopter is arriving at this moment. They check the condition of large rotating machinery, but find nothing to explain the vibration – which is also noted by others on board.

06:21:51 Fuse P-82-EL55_040 for heating cables blows. Notified in the control room as a “non-critical alarm”.

06:22:48 Vibration ceases after about a minute.

06:23:17 Vibration resumes.

06:23:36 Hydrocarbon discharge visible on CCTV.

06:23:39 Alarm sounds in the control room. The gas detection system reports gas in the M30 process module, detector P-DG-M30-LG049R.

06:23:45 The next detector, P-DG-M30-LG059, sounds an alarm six seconds later. The emergency shutdown (ESD) system initiates automatic shutdown of the plant with blowdown and deluge (ESD level 2). General alarm initiated automatically.

06:23:54 The ESD system initiates shutdown of normal power supply (ESD level 1) because of deluge over lifeboat station.

06:24:38 Seventeen gas detectors have sounded alarms, 11 in the module and six on the upper mezzanine deck. A gale (40 knots) is blowing from the south-west and most of the activated detectors are north-east of the leak point.

06:26 First-line emergency response on Gudrun musters. The incident commander comprises the platform manager (on-scene commander), the D&V manager (response leader), the catering manager (evacuation leader) and an electrician (log-keeper).

06:30 First-line response on Gudrun notifies the relevant joint rescue coordination centre (JRCC).

06:34 Personnel on board (POB) check, 26 people on Gudrun confirmed OK.

06:35 Second-line emergency response (Statoil land) is notified.

06:39 POB check on *West Epsilon*, 97 people confirmed OK.

06:57 PSA emergency response duty officer notified by phone.

07:00 Plant is confirmed depressurisation.

07:20 *West Epsilon* is notified that the incident has been caused by the rupture of a pipe in the process plant. Platform personnel check for possible discharge to the sea. No discharge is observed.

08:10 Technical personnel on board report that the leak has been sealed with rubber seals and clamps. That prevents further vaporisation. Respirators are worn when doing this job.

08:25 First-line response reports that the position has been clarified. All personnel are accounted for, no discharge to sea has been observed and the leak site is temporarily sealed.

28 Feb 15 Pipe components are received by Statoil Rotvoll for investigation of the failure surface.

28 Feb 15 The 20-LV0114 and 20-LV0314 control valves as well as the shut-off valves downstream of the first-stage separator arrive at SAAS in Bergen, and 20-LV0114 is opened. The PSA and the police witness the investigation.

3.4 Findings which could be relevant for the incident of 18 February 2015

3.4.1 Foreign bodies in the separator

Screws were discovered in and removed from the 20-LV0114 valve during the repair on 24 January 2015. More screws were found in this valve when it was investigated at SAAS in Bergen on 28 January 2015. An internal inspection of the separator by Statoil after the incident established that screws and nuts came from internal components in the separator. These are assumed to have loosened as a result of vibration in the process plant.

3.4.2 Desalination mixer

In connection with the presentation of Statoil's investigation report on 19 May 2015, the PSA learnt that the desalination mixer had sustained a lot of internal damage. This device sits downstream of the 20-LV0114 control valve and ahead of the inlet to the second-stage separator. The damage was discovered when Statoil investigated whether the piping systems had suffered further harm in addition to the actual rupture. It is assumed to have also been caused by vibration in the process plant.

3.4.3 Helideck

The PSA has not investigated whether cracks found in Gudrun's helideck on 9 March 2015 could have been affected by the vibration in the process plant on 18 February 2015. Statoil's investigation report on the helideck states that no such connection had been identified.

3.5 Investigations

3.5.1 Site investigation

Statoil personnel entered the process module in the M30 area once the post-incident position had been stabilised and the plant was depressurised. Large quantities of spillage/wax were observed on the floor and on equipment/structures, even though deluge had been under way throughout the incident. Condensate remained in the separator, so that hot condensate/steam was still emerging from the rupture site as a result of the difference in height between the level in the separator and the rupture. Statoil personnel decided to seal the rupture to avoid further leakage and vaporisation. This was done using a seal and a clamp.

When the PSA and the police arrived on Gudrun in the afternoon, the damage site had been secured and the rupture sealed. The seal was only removed once the plant had been emptied of hydrocarbons several days later. The PSA therefore could not observe the actual rupture site.

The PSA made its own observations at the damage site and, as part of the police's work, its technicians conducted investigations on Gudrun in the form of photographs and diagrams at the site.

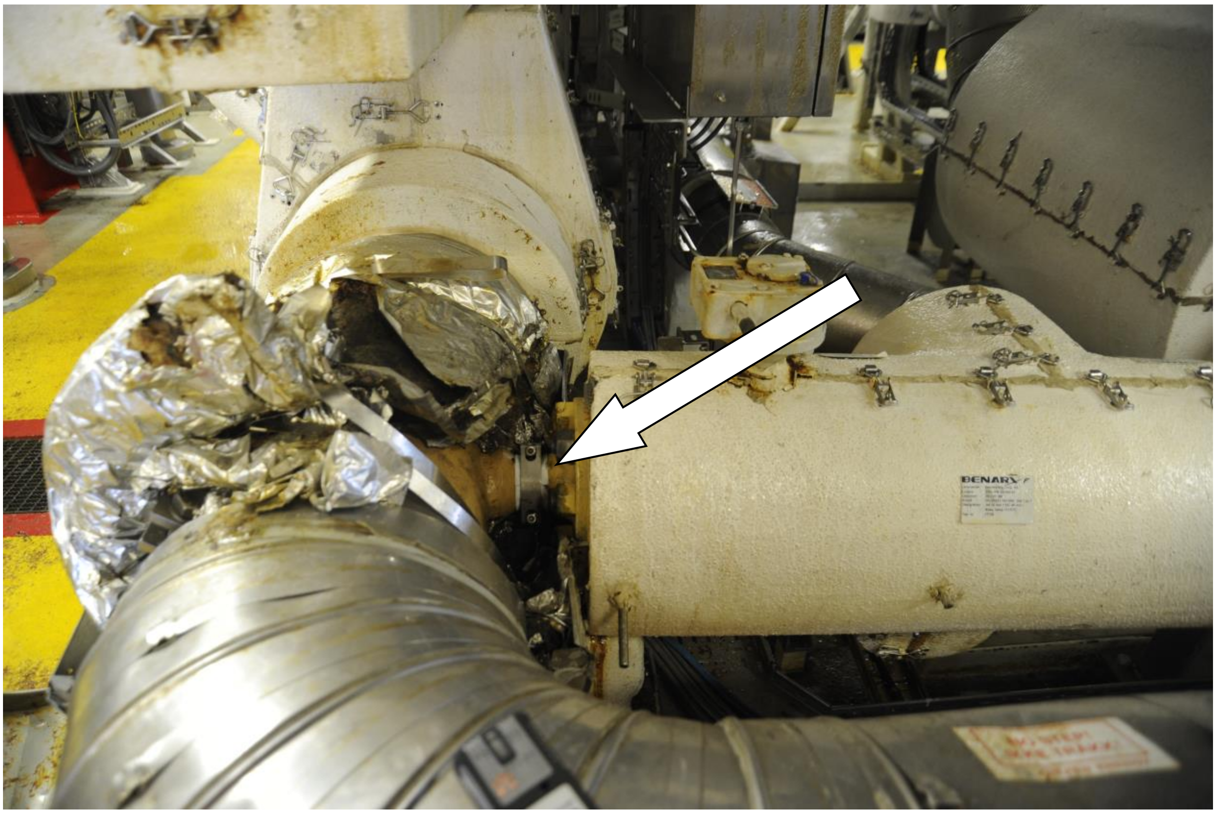

Figure 2: The damage site. The rupture site (arrowed) has been sealed with a rubber seal and clamps. Insulation was blown away as a result of the leak. (Photo: police)

3.5.2 Investigation of valves

The 20-LV0114 and 20-LV0314 control valves as well as the shut-off valves downstream of the first-phase separator arrived at SAAS in Bergen on 28 February 2015, and 20-LV0114 was opened. The PSA and the police witnessed the investigation.

Figure 3: 20-LV0114 control valve (red). The cover below right was bent upwards by the leak and was removed to give access for sealing the leak site. (Photo: police)

3.5.3 Investigation of the failure surface

Pipe components were received by Statoil Rotvoll on 28 February 2015 to investigate the failure surface. The PSA was not present during these investigations, but attended the presentation of the analysis at Statoil's premises in Stavanger.

Figure 4: The rupture (photograph from Statoil's material technology investigation).

3.5.4 Evaluation of flow conditions in the 20-LV0114 control valve

Statoil commissioned an evaluation of flow-induced vibration in the piping system around the 20-LV0114 control valve for its internal investigation. However, the PSA wanted a separate and independent analysis of operating conditions experienced by the valve ahead of the incident on 18 February 2015. This report emphasised challenges with and lack of knowledge and understanding about the physics of multiphase flow related to control valves.

Study of flow conditions in the valve
Sintef's institute for materials and chemistry was commissioned to analyse the valve and design from a flow-related perspective. The aim was to identify possible causes of the vibration experienced before the incident.

The report begins by noting that the damage to the valve was caused by vibration and that it is difficult to identify causes other than flow conditions. It describes and discusses conditions in the control valve as well as upstream and downstream of this unit. Emphasis is given to challenges with knowledge about and understanding of multiphase-flow physics related to control valves. Sintef's analysis checks the configuration against well-known design rules and best practice, and finds in part that flow speeds are high. At the time of the incident, the speed directly downstream of the valve is calculated to have been about 100 metres per second (m/s). If maximum multiphase-flow speed is calculated in accordance with the Norsok P-001 standard, it should have been 16 m/s assuming a density of 123 kg/m^3 – the estimated figure for the liquid/medium downstream of the valve. The calculated speeds apply locally out of the valve for the four-inch cross-section.

Furthermore, the report discusses which phenomena could be involved when multiphase flow is combined with a high pressure drop over the valve, as was the case on Gudrun:

> In any case, these phenomena are very complex, involving multicomponent boiling and de-gassing. On top of this the sound velocity in a multiphase system may be very low and locally vary strongly. This will allow for evolution of shock waves which are driven by the vaporization-condensation process, interacting with pressure waves travelling downstream and being reflected at downstream bends, junctions and valves. To our knowledge no method has been developed which can simulate the flow and physics taking place under such conditions. The literature on this subject is very limited.

Physical conditions such as possible cavitation, low speed of sound, forces in the valve and instabilities in multiphase flow are identified and discussed in the report. Sintef sums up:

- Downsizing valves may increase the risk of vibration
- The flow directions for worst case should be used if there is any risk for vibration (in other words, reverse the valve)
- The standard for LOF (likelihood of failure) parameter should be applied, but improvement must be considered
- Staged pressure reduction is highly recommended
- More fundamental knowledge of the physical phenomena taking place during the Gudrun event should be obtained.

The report concludes that a pressure drop of more than 100 bar over one valve will be very demanding. That valve components can cause extreme vibration is known to the industry, but knowledge of its causes is inadequate. Low speed of sound, imbalances in phase transitions and pressure fluctuations can result in phenomena and interrelationships which are not adequately understood in the industry.

In light of these phenomena, the valve appears to have been under-dimensioned. Furthermore, the report notes that the direction of flow through the valve should have been reversed in order to handle the forces arising in a better manner.

4 Actual and potential consequences of the incident

4.1 Actual consequences

Consequences:

- rupture in a two-inch pipe in the bypass line downstream of the first-phase separator
- destruction of the actuator on the 20-LV0114 control valve
- discharge to the sea estimated at one cubic metre
- emission of large quantities of hydrocarbon gas (no estimate made of volume)
- production completely shut down for 23 days.

No personnel were in the area when the incident occurred.

Powerful vibration occurred in the plant, and the actuator on the 20-LV0114 control valve was destroyed. A valve wheel was observed on the floor. This had come off valve 20-CW199.

Leakage of condensate was observed at 06.23.39 on 18 February 2015. Hot condensate, 90-100^{0}C, under high pressure, 124 bar, flowed from a rupture in a two-inch pipe in the bypass line downstream of the first-stage separator. The failure surface embraced 90 per cent of the pipe diameter, and the leak was accordingly limited by comparison with a full rupture.

Large quantities of gas were released as a result of the pressure drop, and gas was detected in much of module M30 within a minute.

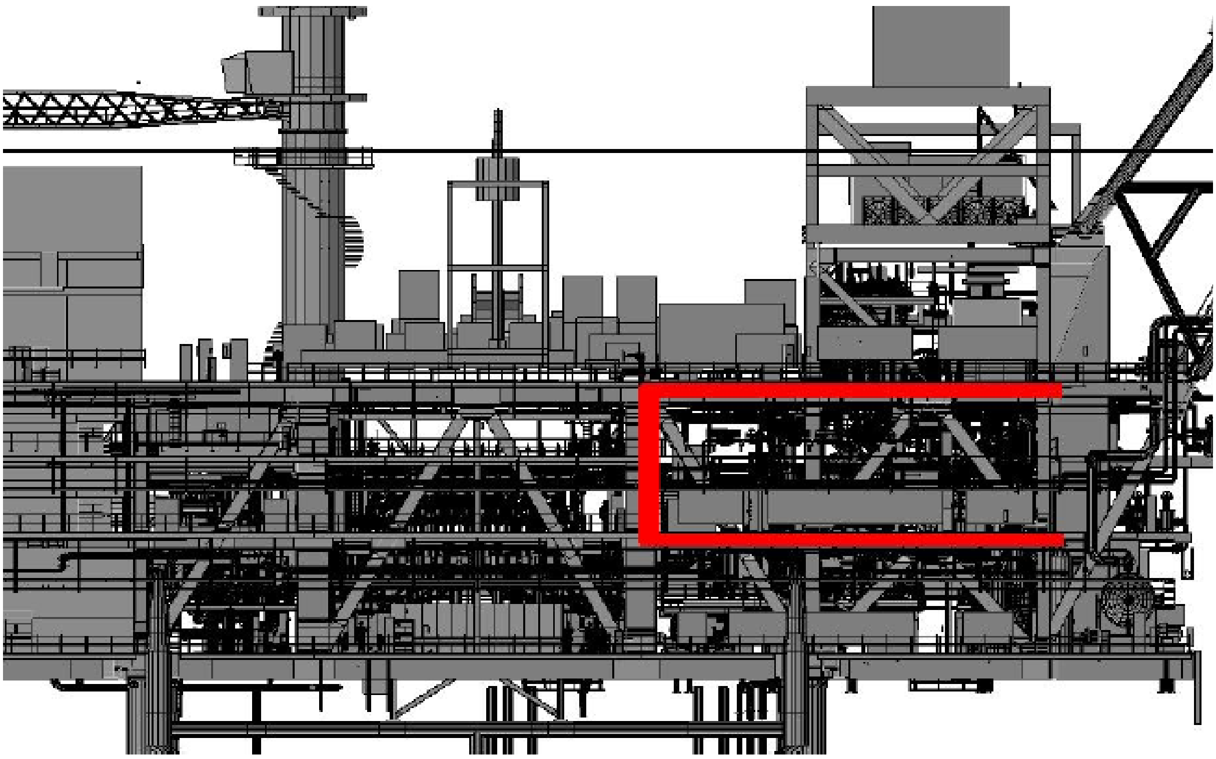

Figure 5: Layout viewed looking north. (Illustration: Aibel)

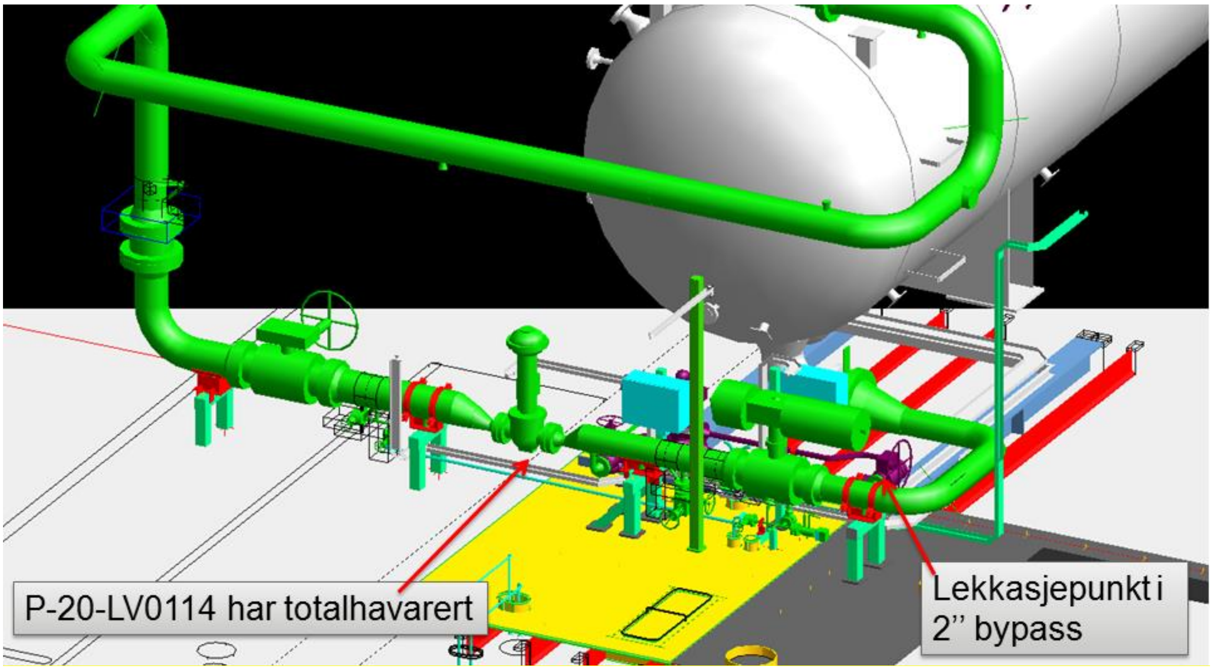

Figure 6: Piping downstream of first-stage separator. (Illustration: Aibel 3D-model)
Key: P-20-LV0114 totally destroyed   Leak site in two-inch bypass

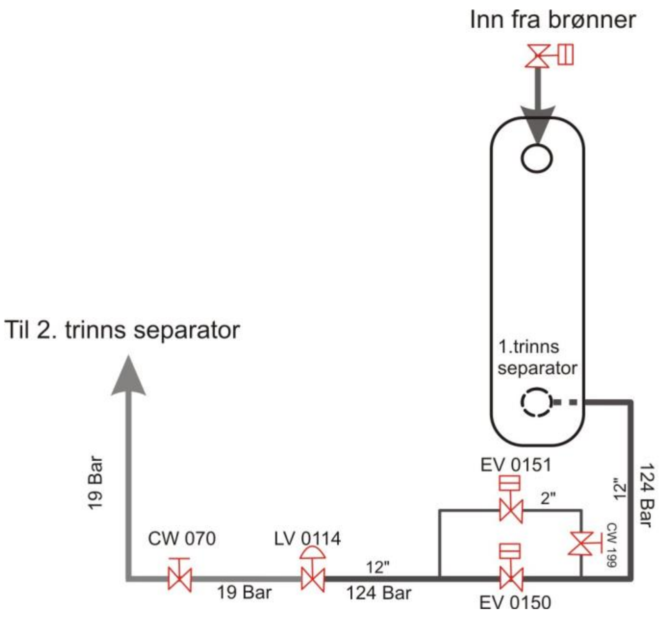

Figure 7: Diagram of liquid outflow from separator. (Illustration: police)
Key: To second-stage separator   In from wells   First-stage separator

The leak rate is calculated as a maximum of eight kg/s. The discharge lasted just under two hours, and totalled a calculated 2 800 kg/four cubic metres of condensate, making this one of the larger HC discharges registered on the NCS over the past decade. A condensate escape presents a significantly higher explosion risk than an oil leak.

The condensate contained a number of heavier viscous hydrocarbons, such as wax, and a quantity of these remained on equipment, deck and structures even after lengthy deluge. About a cubic metre of hydrocarbons are estimated to have been discharged to the sea. This is supported by the fact that the manifold for open drain collection tank 56-TB01 became overfilled.

Following the incident, production from the facility was shut down completely for 23 days. Production was then resumed via the test separator, and restarted through the main separator on 1 April 2015 with a step-by-step increase to full output over the space of two weeks.

4.2 Potential consequences

Under slightly different circumstances, the incident could have resulted in a major accident with loss of life, extensive damage to material assets and consequences for the marine environment. A condensate escape presents a significantly higher explosion risk than an oil leak. No particular actions or operating conditions which formed the direct cause of the incident were identified.

4.2.1 Timing

The timing of the incident can be regarded as arbitrary, and it could equally have occurred at a different time of day and with personnel in the vicinity. Crew working on the night shift were in the quarters module preparing for the shift change. However, they were on their way out to the plant in an attempt to establish the cause of the vibration.

4.2.2 Personnel

Had the incident occurred at a different time, personnel could have been in the vicinity who would have sought to investigate where the vibration was coming from. The gas spread rapidly and was detected over most of the process plant, module M30, in the space of one minute. No gas was detected in other modules on the facility. In high concentrations, gas can have a narcotic effect and lead to unconsciousness and death. Even the concentration where the gas detectors sounded the initial alarm (20 per cent lower explosive limit – LEL) was three times above the level which is acutely toxic. The potential for the death of personnel who were in the area would then have been present.

After the incident, Statoil has observed condensate in a drain box in the evacuation tunnel. This means that the latter could have contained some gas at one point in time, and would thereby have been unusable for evacuation. No gas was detected in the tunnel.

Figure 8: CCTV footage of the area where the leak occurred. The actual leak site is roughly at the left-hand side in the centre of the image, hidden behind the screen. Images with red clouds have been edited in Photoshop to clarify where the leak caused visible changes. The images were taken one, five and 10 seconds after the first visible observation of gas/condensate. (CCTV footage: Statoil)

4.2.3 Volume leaked

The initial leak rate during the incident, where a rupture covered about 90 per cent of the pipe diameter, is estimated to have been close to eight kg/s. Roughly four cubic metres of condensate escaped.

Had the pipe ruptured completely, the initial leak rate is estimated at 140 kg/s and all the condensate, in the order of 20-30 cubic metres, would have escaped in about four minutes.

Statoil's investigation reports notes that it was arbitrary that the rupture did not develop into a complete break, but was confined to 90 per cent of the pipe diameter.

4.2.4 Ignition

Statoil's investigation report says that damage has been registered in two places on the heating cable lying on the two-inch pipe where the leak occurred, probably caused by vibration in the piping system. It also notes that the cable was not protected as required by Statoil's technical standards.

The heating cable has earth fault protection. The damage it suffered led to an earth fault, and the earth fault relay disconnected the cable automatically. That occurred about 90 seconds before the leak, and coincides with the first video observations of vibration. This could equally well have happened when the vibration resumed, presenting some risk of a spark capable of causing ignition while gas is present.

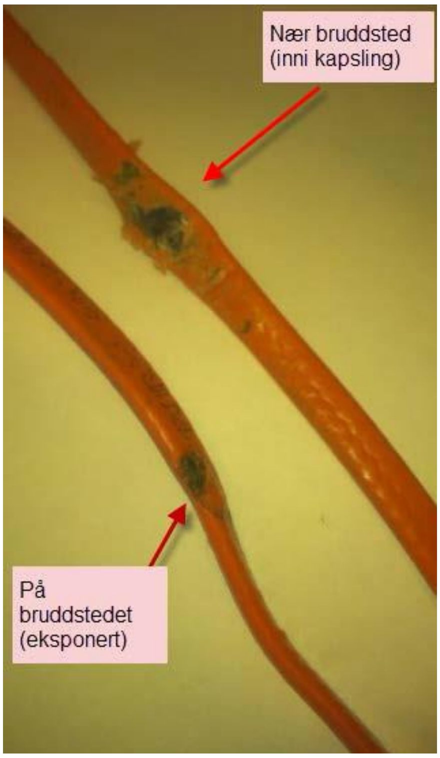

Figure 9: Damage to heating cable. (From Statoil's investigation report)
Key: Near rupture site (within insulation) At the rupture site (exposed)

Ignition source disconnection of all heating cables took place following gas detection, four seconds after the leak occurred.

Furthermore, the leak means that the insulation and the metal sheathing around it were ripped off. The potential for this producing sparks with ignition capability has not been investigated. Gas ignition with a subsequent fire would have caused extensive damage in M30, but documentation from Statoil's investigation report shows that the integrity of the main structure and fire partitions with neighbouring modules would be maintained.

Large volumes of gas are liberated quickly from a condensate leak (one litre of condensate gives some 900 litres of gas), which spread fast throughout the module. An explosion would probably have created a local explosion load in excess of the design load, but the global integrity of the partition would not be threatened. In the event of a full pipe rupture, ignition would have caused a powerful flash fire with large flame volumes which had the potential to spread to other modules. That would have exposed personnel in external areas to critical heat loads and radiant fluxes. This emerges from Statoil's investigation report.

4.2.5 Weather conditions

A gale was blowing from the south-west when the incident occurred. Most of the gas was thereby blown away from the facility. The drilling derrick plus deck equipment caused some turbulence. Other weather conditions could have created a large gas cloud with a greater potential for ignition.

5 Direct and underlying causes

5.1 Direct causes

The direct cause of the incident was a rupture in a two-inch pipe in the bypass line for the ESD valve on the liquid outlet from the first-stage separator as a result of heavy vibration in the piping system.

5.2 Underlying causes

Dimensioning and selection of the 20-LV0114 control valve downstream of the first-stage separator was never identified by Statoil as a problem or altered in the design, construction or commissioning stages.

Control valves are not generally categorised as safety-critical, but faults in them could be significant for production regularity. Problems with control valves accounted over the past five years for roughly one per cent of Statoil's total lost production on the NCS. Low production losses caused by control valve failures on other facilities could have contributed to the low priority given to following them up in this development project.

5.2.1 Insufficiently robust design

5.2.1.1 Pipeline design and control valve choice

The Gudrun wellstream is characterised by high pressure and temperature. Statoil has opted for a facility with two-stage separation, which calls for a large pressure drop over the value which controls liquid leaving the first-stage separator. Engineering and design of the Gudrun process plant was done by Aibel, with its Singapore office responsible for area design – ie, smaller pipes and detailed layout – and the Asker office handling system design – equipment, instrumentation and control valves.

Valve design was based on the first- and second-stage separators operating at 124 and 19 bar respectively. This meant the control valve had to handle a pressure drop of up to 105 bar. The pipeline carrying liquid (condensate) from the first-stage separator is 10 inches in diameter, while the chosen 20-LV0114 control valve has a diameter of four inches. This means a narrowing (coning) from 10 to four inches. Several interviewees commented that the pressure drop over the valve is so large than an alternative design should have been investigated. Several also pointed to the substantial coning as a problem in terms of normal practice for piping design.

In connection with the selection of the 20-LV0114 control valve, Aibel's project team drew up a process data sheet in January 2011 using input from Petek Statoil as the basis for the valve choice. This documentation specifies five different operating regimes – two with 124 bar separator pressure and three with 64 bar. The valve is specified to fail safe.

A bid clarification meeting (BCM) was held at Aibel on 26 January 2011 with the SAAS project department. Statoil's discipline expert for control valves in the project, whose background was from TEX, also attended. The meeting concerned the delivery of 85 control valves, including 20-LV0114 and, among other issues, reviewed the lack of conformity between Statoil's internal TRs and the SAAS bid. The investigation has not received any information which indicates that special operating conditions related to the 20-LV0114 control valve were discussed at the meeting.

Final dimensioning of valve and actuator was done in February 2011. Aibel and SAAS held a sizing calculation meeting. Dimensioning of 20-LV0114 and others was discussed on the basis of a calculation programme from the valve manufacturer. This warned of chocked flashing, with the note: “Flashing induced problems of erosion and corrosion are possible for these service conditions”. This was discussed at the meeting. Aibel challenged this issue, and was told by SAAS that the programme was “conservative”. A tailored material quality was selected for the valve body, but no changes were made to its size. Statoil technical personnel did not attend this meeting, and it has not been confirmed whether Aibel contacted relevant technical specialists in Statoil about this choice.

When a pressure drop over a control valve is as high as the one on Gudrun, a valve which spreads the drop over several stages can be selected. No such assessment has been documented for Gudrun.

Statoil’s discipline experts for piping and valves in the Gudrun design and construction phases came from TEX, and were therefore likely to be well informed about the TRs and the knowledge underpinning the development of GL2212. Whether Statoil personnel with discipline responsibility followed up this process for selecting the 20-LV0114 valve or considered the inclusion of a four-inch valve in a 10-inch line under the specified operating conditions has not been documented

5.2.1.2 Quality assurance in the project

In response to a direct question, the following activities and tools were named as possible check points which could identify valve choice related to piping downstream of the first-stage separator at the engineering stage (quality assurance of the design).

- A Hazop was conducted in the autumn of 2010 before the valve choice was made. This does not include a check point which explicitly challenges the dimensioning of the control valves. However, a Hazop can identify this type of challenge if the people involved represent a good composition of expertise and experience.

- A BCM with representatives from SAAS, Aibel and Statoil was held on 26 January 2011, but before the choice of valve had been made.

- 3D model reviews are conducted when engineering has reached certain milestones. Representatives from both operator and engineering company participate. The primary intention is to verify accessibility and that no equipment clashes are present.

- A factory acceptance test (FAT) was conduced at the French manufacturer. This verifies that the delivery complies with the specification. Owing to valve coating problems, the FAT was not approved until the third test. Statoil’s discipline expert for control valves took part in the tests. No assessment of the valve choice in relation to process conditions is made in a FAT.

- Statoil conducted a TTS verification of the Gudrun process plant in December 2011. The control valves for the first-stage and test separators had been chosen and ordered at this point. No findings in the report relate to the 20-LV0114 valve and piping downstream of the separator.

Both the Hazop and the BCM were conducted before the final valve choice was made. During interviews, it was noted that a design review could have challenged the valve choice. The investigation has verified that no design review was conducted for the procurement package containing this control valve. It has not been possible to verify whether other tools or design reviews were used which could have picked up the design choice.

The investigation has not found that the 105-bar pressure drop in the pipeline downstream of the first-stage separator, combined with the piping and operating conditions, was identified as critical or demanding by Statoil, Aibel or SAAS.

5.2.1.3 Expertise and experience with control valves

Qualified and experienced people from both Aibel and Statoil were involved in the process of choosing valves.

The process and solutions adopted for Gudrun required a control valve design which could cope with large forces. This was a challenging design involving multiphase flow and high speeds. The investigation has exposed a lack of knowledge about and understanding of the physical phenomena which can occur in control valves exposed to multiphase flow.

Representatives from Aibel say that when a facility is taken over by Statoil and brought on stream, they are not informed about operational experience and equipment problems unless guarantee issues are involved. In the Gudrun case, Aibel was told to use the process plant on Kvitebjørn as a template. This facility was built by Aibel and came on stream in 2004. The investigation has not found whether Aibel was informed that Kvitebjørn had experienced vibration problems with the corresponding control valve. On the recommendation of the supplier (SAAS), the decision was taken on Kvitebjørn to reverse the valve in order to reduce vibration. Interviews revealed that Aibel did not know about operating experience on Kvitebjørn.

Statoil’s technical requirements for control valves are found in TR2212. A lot of maintenance on such equipment prompted TEX to draw up a GL for TR2212 which was supposed to guide the choice of control valves. GL2212 was issued in February 2014, when Gudrun was at the end of its commissioning phase.

Statoil’s investigation report lists 12 facilities suffering operational problems with level control valves. Until GL2212 was issued, this experience and knowledge had not been systematised and communicated further, but seems to have been held by individuals – partly in certain operations entities and partly in TEX. GL2212 is targeted at people involved in all phases of a project, from conceptual studies to operations. The GL makes special reference to conditions which indicate that the choice of both dimensions and design for control valves calls for experience and good understanding of the specific application. Mention is made hereunder of flashing and choked flow as conditions requiring particular attention. The GL also specifies areas of operation as well as limits for pressure drop (relative inlet pressure) and flow speed. The chapter describing critical applications makes special mention of level control of oil in the separator. This states in part: “Flashing is often associated with vibration” and “Vibration problems in some of these applications are solved by flowing the fluid up through the trim". The recommended solution for the latter means reversing the valve[7], as was recommended after the incident of 25 January 2015.

The SAAS engineering department responsible for valve selection is located in Oslo, while its workshop for maintenance and repair of valves lies in Bergen. It has emerged from interviews that the workshop staff were also familiar with damage to and failure of similar control valves in use offshore. This experience and knowledge were not communicated in a systematic way to the engineering team in Oslo for use in its work.

Some of the operations personnel on Gudrun had a background from operating Kvitebjørn. The fact that similar control valves in use had been "reversed" to improve handling of the operating conditions was known both at the SAAS workshop in Bergen and within several of Statoil's operations units and its TEX expertise centre. This information was not passed on to Aibel or the SAAS engineering department in Oslo.

The investigation has revealed that information from similar facilities has not been transferred back to the project organisation.

5.2.1.4 Operator's responsibility

A presentation of Statoil development projects given to the PSA in June 2015 states that "Roles and responsibilities are communicated to all project members". Clear and detailed expertise requirements are described for many technical posts in Statoil, but no corresponding formal qualifications exist for the company's engineers in development projects.

Job descriptions for Statoil's discipline experts for piping and valves in projects give little detail on formal education or necessary experience. The investigation also saw that some people managed a project discipline other than the one they were formally qualified in. Discipline experts also appear to have long experience from various development projects, but limited operational experience – including how relevant equipment functions in practice.

Statoil had a number of discipline experts in the Gudrun project to monitor it. Job descriptions contain little detail about their specific duties and responsibilities in the project. Interviewees said that their role was to check whether design and construction for Gudrun accorded with Statoil's TRs, but that big distances between the locations where different elements were designed and built made this challenging. During interviews, however, Aibel's independent responsibility to create a robust design was emphasised by both management and discipline experts in the Gudrun project.

At no time did any of the Statoil personnel interviewed mention the operating company's responsibility. Instead, they referred to and emphasised Aibel's contractual duty to design and build Gudrun in accordance with Statoil's TRs.

5.2.1.5 Understanding of the division of responsibility between the players

Interviewees in Statoil, Aibel and SAAS have described the valve choice as "wrong" or "unfortunate", but also as "correct". SAAS specialists noted that the choice was right in terms of process data, the calculation programme and Statoil's TR. If Aibel believed that the valve

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[7] When a control valve is reversed, the direction of flow changes. The forces arising as a result of the pressure drop in the valve are then handled by the actual valve body rather than the actuator.

choice was unfortunate with regard to the production conditions, it could have gone back to SAAS and asked for a bigger or better-adapted control valve which would be more capable of handling the forces. Aibel did not contact the discipline expert for valves in Statoil's project organisation for a technical clarification. SAAS expressed an expectation that Aibel's engineering team would conduct an independent and integrated assessment of the recommended valve choice in terms of process conditions and piping design.

Statoil's discipline expert for valves in the Gudrun project did not attend the dimensioning meeting in February 2011. This person had long experience from various development projects, and claimed to have expertise which would have led to another valve choice for this piping. It emerged during interviews that the workload during the project had been high. The discipline expert had to prioritise which meetings to attend or which documents could be reviewed, and was not aware of the meeting where the control valve in question was chosen.

As far as can be established, Statoil's discipline expert for valves in the project with responsibility for quality assurance of the design did not participate in other activities where the choice of the 20-LV0114 control valve was discussed or evaluated. The investigation has not found clear criteria concerning which activities should be prioritised when following up the project.

The investigation has not been told of other Statoil personnel from TEX or the Gudrun project who participated in assessments related to the choice of the 20-LV0114 control valve.

5.2.1.6 Division of responsibility and trust across disciplines

Discipline leads and experts at the various players who had a role in and a responsibility for assessing the process plant design were interviewed by the investigation. As part of a pattern, interviewees referred to the responsibility of experts for other disciplines when asked who had a role in making design choices and assessing piping design. Discipline experts for valves in Aibel and Statoil assessed valves, and those for piping focused on pipes.

The investigation was unable to verify whether cross-disciplinary assessments were made either during detailed engineering in Aibel or subsequently for valve choices. An unfortunate design choice was never identified. A contributory factor was that no cross-disciplinary assessment was made of the combination of valve and actuator size in relation to their placement in a pipeline with a large pressure drop.

During the investigation, a number of those involved expressed the view that they had to rely on assessments and deliveries from other disciplines, departments or players concerned with the project. They themselves were responsible for their own discipline. It was asserted that the work of designing a complex facility assumes that everyone takes responsibility for their part of the job. People commented that they expected other disciplines, departments or companies to check significant conditions for achieving a secure facility.

A number of investigations into other incidents with major accident potential identify the importance of everyone involved making active use of their technical expertise and experience to ask critical questions about the choices, decisions or practice of others in order to prevent major accidents.

The significance of being able to question or challenge choices or designs by others was not adequately emphasised in the Gudrun project.

5.2.1.7 Follow-up in the construction and commissioning phases

Fabrication of the M20 and M30 modules began in the spring of 2011 in Thailand and was pursued in parallel with detail engineering in Singapore. The process module arrived at Aibel's Haugesund yard on 7 January 2012. The control valves for the first-stage and test separators were ready for Aibel's final inspection at the supplier in France during April 2012 and were dispatched to Haugesund for installation there on 17 July 2013.

In January 2012, discipline experts and other personnel from AI joined Statoil's project team following up Gudrun construction. The AI people were described in interviews as owners and responsible for the technical condition of the process plant. Their job in the commissioning phase included establishing inspection and maintenance programmes as well as procedures for plant testing. It emerged from interviews with Aibel technical personnel that the AI people were active in this phase, with many detailed questions. They reviewed the process plant on Gudrun which they were later to take over and operate.

When AI personnel in Statoil's project team were asked if they had assessed the completed design of the pipeline concerned, the investigation was told that the design was finalised and their attention had not been on questioning the delivered design. They assumed they had obtained a robust process plant. Their attention was on checking functionality, and they pointed out that discipline experts from Statoil in the project team were responsible for following up the design in an earlier phase. Attention in this follow-up phase was on checking that installations accorded with the design and specifications, rather that on the design base.

Few activities have therefore been identified which could have picked up an unfortunate design choice in the commissioning phase.

5.2.2 Follow-up during operations

Signals from the process plant, notifications and reports of concern from the offshore organisation were received during the operations phase, but were not adequately understood, assessed and handled by Statoil. Although powerful vibration had periodically occurred, with much noise and repeated functional failures in control valves and a subsequent valve failure on 25 January 2015, the platform management together with AI considered it would be prudent to maintain production.

Information obtained by the investigation indicates that AI had not conducted an overall risk assessment before 18 February 2015 related to signals from the offshore organisation on the basis of repeated operating problems with control valves and vibration this part of the process plant. Interviews revealed that the incident of 25 January 2015 had not been discussed with other management or elevated to other technical experts in Statoil (TEX) familiar with operating experience across the organisation related to both control valves and risk associated with vibration. Nor had Aibel been asked before 18 February 2015 to clarify conditions related to the design with regard to vibration.

5.2.2.1 Handling of warnings about vibration

It has been confirmed that operators contacted technical specialists from the land organisation making visits offshore on at least two occasions to report concerns about technical conditions in the plant. It might appear that the concerns expressed about these conditions were not perceived as an indication of a wider problem, but were given weight on the basis of the individual's technical background.

- An inspector sent offshore on behalf of AI was notified in week 49 about periodic powerful vibration in the piping system downstream of the first-stage separator. An immediate investigation concluded that the vibration were not critical and a work order was established to obtain a further assessment of the conditions. Provision was made to follow up the condition as part of a planned inspection of gas compression in the spring of 2015, but this was not rescheduled as a result of the notification.

- In connection with a TTS verification in January 2015, the AI discipline lead was notified of noise and powerful vibration in connection with the failed valve the day before. This was investigated and the pipe support was found to be unsatisfactory. A work order was created to follow up the lack of support, but the issue of vibration in the piping system was not brought into the TTS inspection and followed up there.

No clear criteria for excessive vibration exist. The degree of vibration linked to this pipeline varied. It is worth mentioning that the vibration was not at its greatest when personnel from the land organisation were offshore, which could have influenced their understanding of how great the vibration had actually been.

Each individual condition reported appears to have received satisfactory treatment, but no indications exist that they were assessed in relation to the other incidents recorded with the equipment in this area. Although Statoil knows a lot about vibration and the risk of hydrocarbon leaks, follow-up of the conditions suggests that this knowledge was not assessed together with observations of vibration. AI's lack of understanding of the relationship between vibration and valve failure resulted in inadequate follow-up of the reported concerns.

5.2.2.2 Follow-up of vibration downstream of the first-stage separator

The pipe section downstream of the first-stage separator periodically experienced powerful vibration owing to the operating conditions for the 20-LV0114 control valve. Outlined below, these were observed as "a lot of energy in the valve" and could contribute to the vibration.

- Big pressure drop across the one-stage valve. The entire drop occurred at one point in the valve. With a more advanced design, it would be spread over several stages. This can provide better control of the forces created as a result of the pressure drop.

- Operating conditions which cause the condensate to boil in the valve (flashing) and create unstable conditions in the valve body. Only limited attention appears to have been paid to unstable conditions in the valve body when assessing design and dimensioning choices.

- High flow rates in and around the valve. In those cases where the positioner loosened, control was lost over regulation of liquid flow from the first-stage separator. The control valve then chased between fully open and shut. The big opening could have caused flow rates through the valve to be significantly above the design level and can explain the big vibration registered in connection with the incident of 25 January 2015 and ahead of the incident on 18 February 2015.

- Low spring pressure in the actuator. When this force is higher, it permits sturdier regulation. Reducing it means that internal conditions in the valve will be under insufficient control and the valve will not be exclusively governed by the control system. It emerged from interviews that spring pressure between the repair of 25 January 2015 and the start of monitoring on 12 February 2015 had been reduced by at least 20 per cent. The spring was completely loose when the valve was investigated by the supplier after the incident.

These conditions challenge the valve individually, and can collectively help to push the valve beyond what it can handle. Vibration is a consequence of these operating conditions.

5.2.2.3 Follow-up of incidents involving control valves

Four incidents on Gudrun are documented in SAP which involve loose components and possible vibration in connection with control valves.

1. Statoil's investigation report refers to an incident with the test separator on 25 November 2014, where a loose nut was identified on the positioner for the 20-LV0314 control valve. The incident is recorded in SAP as production disruption Y3 200157133. It was left out when the PSA requested information on earlier incidents related to control valves.

2. A notification was recorded in SAP on 15 December 2014 concerning a change in the maintenance routine. The comment "because of a number of incidents with control valves" found in the notification could indicate more such incidents than those described above. The investigation has not found any record of these.

3. The incident on 25 January 2015 has been described in detail in section 3.2 above on the operations phase prior to 18 February 2015. Powerful vibration had occurred and the positioner had loosened. These conditions are also documented in Synergi. No documentation indicates that AI conducted any assessment in the follow-up meeting of 27 January 2015 of the vibration and the associated risk this could pose for the plant. Statoil chose to maintain production.

4. The incident of 18 February 2015 is described in detail in section 3.3.

Roughly the same flow occurred in the 20-LV0114 control valve on 15 December 2014 and 18 February 2015, and components were shaken loose. It is clear that the valve experienced demanding working conditions, and that measures taken offshore related only to symptoms. It has emerged that the conditions registered on 15 December 2014 were discussed in the daily morning meeting between offshore and land, and the issue was considered by working meetings in AI. The AI discipline lead contacted technical personnel on Gudrun for further clarification

The first two conditions described here were entered in SAP as a production disruption and a change in maintenance routine respectively. This means that no history related to the equipment is recorded. AI was involved in relation to the 20-LV0114 control valve on 15 December 2014. Following the incident, management personnel in Statoil made it clear that a valve which causes vibration should be monitored.

It has not been established whether AI made an overall assessment of the notifications which were relevant for operating problems with control valves and vibration in this process section. The lack of such an assessment also means that involving the TEX specialists has not been relevant. This unit contains the leading technical expertise and has the greatest familiarity with operating experience across Statoil related to these challenges.

5.2.2.4 Feedback from and condition monitoring of control valves

The way the level control valves for the test and main separators are connected to the control system means that their actual position is not shown on the control room screens, only the desired position. The valves are also equipped with positioners customised to provide follow-up of valve condition. According to Statoil's investigation report, condition monitoring was first initiated on 12 February 2015, even though the technical equipment was already installed when the facility came on stream.

This means that no exact information (trend curves) exists for the incidents where problems have been encountered with the control valves. As a result, it has not been possible to learn about them in detail.

5.2.2.5 Handover: close visual inspection of 20-LV0114 after repair of 25 January 2015

The instruction on close visual inspection in Synergi describes how the valve is to be followed up. This involves close visual inspection and checking that guide clearance does not change, that the valve operates evenly and that no leaks are present. The meeting of 27 January 2015 referred to in Synergi concludes that the valve must be closely monitored in the event of production changes as well as with running up/down. This measure was terminated in Synergi as early as 1 February 2015, and the way follow-up of the measures was communicated in connection with crew changes has not been documented.

It emerged from one of the interviews conducted offshore with relevant personnel that they did not know about the requirement for monitoring the valve.

5.2.2.6 Organisation and management involvement

It emerged during the investigation that the problem of the connecting arm between positioner and control valve coming loose had been observed a number of times before being registered in SAP as a maintenance condition. Work processes for registrations in SAP show that the management, represented by the onboard D&V manager, is involved in approving these.

Problems with control valves and associated equipment or vibration in the relevant area were registered at least three times before the valve failure on 25 January 2015. Although offshore posts are rotated, positions in OPS on land have continuity.

Those responsible for Gudrun have not understood the risk potential of and relationship between vibration and operating problems with control valves. Collaboration between the facility and the operations organisation on land is structured in the form of two 15-minute meetings each morning. The agenda for the first is HSE, deviation from plans, the day's risk picture, assistance from land and actions. Deviation from plans and assistance from land could be relevant items for the issue under discussion, but the meeting does not provide sufficient time to reflect over connections and earlier incidents. The next meeting is for coordination, setting priorities and planning notifications. This also involves determining which person in the land organisation should follow up a specific notification.

Organisation of the operations entity does not facilitate the identification of relationships between different notifications.

- The primary responsibility of the OPS team is to establish, update and be in possession of harmonised plans. Technical expertise in the team is provided by discipline leads who have been rotated from the relevant facility.

- The duties of the regularity and maintenance analysis unit include facilitating root-cause analyses and proposing improvement measures in the event of lost production. In this case, such an analysis would have identified the reason why the connecting arm for the control valve had come loose several times.
- AI is responsible for overall assessments of the facility’s technical integrity.

Since the relationship between problems with control valves and vibration has not been raised as an issue, the way this has been dealt with by the various technical departments has been inefficiently integrated.

These conditions come to light in the following parts of the course of events.
- The D&V and AI managers who attended the daily morning meetings said they were unaware of vibration related to the 20-LV0114 control valve.
- No documentation indicates that the operations management sought a review of the reason for the repeated production disruptions caused by control valve problems. The governing document for operations in Statoil’s development and production Norway business area specifies that root-cause analyses must be conducted and improvement measures proposed in the event of repeated equipment failures which cause lost production.

Management attention was focused on a number of conditions and guarantee cases related to Gudrun. It emerged from interviews that a series of challenges and deficiencies not dealt with by the development project had to be handled during the facility’s first year on stream in addition to following up day-to-day operation.

5.2.3 Learning from incidents with control valves and vibration

Statoil possesses much information and experience on both risk from vibration in a process plant and incidents involving control valves. This knowledge had not been systematised and communicated so that it was applicable in a practical way to operating the facility.

5.2.3.1 System for registering incidents and equipment failures

Nonconformities such as operating disruptions, equipment problems and incidents are registered in at least three different ways – operating and equipment problems in SAP and incidents in Synergi. This means that problems with an equipment item could be recorded in different ways, making it difficult for relevant personnel to see links between the various conditions. Vibration in piping is not followed up by the same specialist in AI as the one responsible for operating problems with control valves. The complex causal picture is not understood and therefore not subject to risk assessment.

- Operational disruptions are recorded in SAP with the code Y3. It is unclear how this registration relates to physical equipment.

- Equipment problems are recorded against the relevant item (functional location). That provides good opportunities for learning if operating problems relate to the equipment’s location in the process, but systematising this knowledge at a more overarching level is demanding. The incidents dealt with here are recorded against valves 20-LV0114 and 20-LV0314 and against pipeline 1163-12"-PR-20-004-BD200.

- Incidents are recorded in Synergi and classified by type, work process and activity. The incident of 25 January 2015 is registered as “process equipment – pressurised tanks and columns – separators”. No connection is made to the relevant valve.

Registration of incidents or equipment failure in SAP by personnel offshore provides the basis for assessing the process plant and initiating necessary measures by management and discipline leads in OPS and AI Gudrun. Reports in SAP can also provide the basis for TEX to call up historical data across the organisation. It emerged from interviews, including with technical personnel from AI Gudrun and TEX, that accessing historical data on equipment failures and incidents in SAP and Synergi was difficult. That made it challenging to apply and learn from relevant experience related to vibration and control valves.

The risk of leaks caused by vibration in process plants is known to the petroleum industry. Two of the Statoil personnel interviewed said they had personal experience of vibration leading to ruptures and hydrocarbon leaks. They both said that vibration in the process plant was a matter of great concern. One commented that the presence of vibration indicates a design error. Interviewees varied greatly in their familiarity with the risk of hydrocarbon leaks from vibration and their knowledge of challenges posed by control valves. A number of them expressed concern over vibration and the risk of hydrocarbon leaks in a process plant.

5.2.3.2 Communication and use of experience data in Statoil

The key system in Statoil for communicating experience is the TR documents and associated GLs. GL2212 is entitled *Valve selection manual - control valves*, and both its purpose and structure clearly show that this document focuses on design choices in projects or modifications. It is formulated not as a knowledge base for operating problems, but as a guide for valve replacement.

When GL2212 was issued, the Gudrun field development was Statoil’s first for 10 years and the only project where the GL might be relevant. It appeared two months before Gudrun came on stream. The GL contains information relevant for quality assurance of the choice of control valve for Gudrun. No such assessment has been documented.

Statoil has not ensured that the operating experience which forms the basis for the GL was communicated in an adequate way to the development project and to relevant operations personnel in the group. As a result, relevant information and experience available to Statoil was not utilised in the valve choice and in following up the Gudrun process plant.

According to its report, Statoil’s investigation team conducted searches in Synergi and SAP to identify information on similar incidents. These searches revealed that Statoil had experienced the following over the past 10 years:

- 20 cases with vibration involving medium or large risk
- 10 cases with control valves involving medium or large risk
- eight cases of level regulation involving medium or large risk.

Eight of these cases have similarities with the Gudrun incident. This knowledge was first identified by Statoil’s investigation. In other words, it has not been utilised in the organisation.

This demonstrates that, although Statoil has a central expertise unit which ensures the compilation of requirement documents to supplement industry standards and has an extensive system for recording incidents, it seems difficult to get this expertise utilised in the operation of individual facilities.

6 Observations

The PSA's observations fall generally into two categories.

- Nonconformities: observations where the PSA believes that regulations have been breached.
- Improvement points: observations where deficiencies are found, but insufficient information is available to establish a breach of the regulations.

The investigation has identified eight nonconformities from requirements in the regulations.

6.1 Nonconformities

6.1.1 Weaknesses in Statoil's exercise of its responsibility

Nonconformity
Statoil failed to fulfil its responsibility adequately for ensuring that a design choice was adopted which reduced the risk of serious incidents. The 20-LV0114 control valve was not suited to the loads it would be exposed to.

Grounds
Statoil delivered the production profiles which formed the basis for the calculations but did not adequately communicate experience and information which could provide relevant background input. Aibel passed these to SAAS, and the choice of the 20-LV0114 control valve was thereafter made on the basis of a recommendation from the latter as supplier.

As full production approached, strong vibration occurred periodically around the valve. This ultimately led to a rupture in a two-inch pipe upstream of the valve. Investigation of the failure surface shows a fatigue rupture resulting from substantial vibration over time. The actual rupture was caused by sudden strong vibration. The rupture was caused by the choice of an insufficiently robust control valve in relation to the pressure drop in the piping downstream of the first-stage separator and to the rate of production.

The design process is described in detail in section 5.2.1.1.

Requirements
Section 7 of the framework regulations on responsibilities pursuant to these regulations
Section 4 of the management regulations on risk reduction
Section 11 of the management regulations on basis for making decisions and decision criteria

6.1.2 Inadequate robustness in the design

Nonconformity
Functional failure of the 20-LV0114 control valve has had unacceptable consequences.

Grounds
Operating conditions for the 20-LV0114 control valve periodically caused substantial vibration. Investigation of the failure surface shows that this had gone on for some time. Inspection of the actuator by the supplier immediately after the incident revealed a loose spring. When spring force in the actuator was lost, the valve could not be controlled and hunted between closed and open positions. That caused substantial variations in flow through the valve, resulting in powerful vibration which led to a rupture in the two-inch pipe upstream

of the ESD valve. The result was that the liquid quantity in the separator could not be contained and a substantial portion of the content leaked out.

Requirement
Section 5, letter c) of the facilities regulations on design of facilities

6.1.3 Deficiencies in information management and expertise

Nonconformity
The information required to maintain the plant in an acceptable condition was not communicated and processed so that adequate measures could be taken. Important contributors to risk were not identified.

Grounds
Process operators attempted on several occasions to communicate that the 20-LV0114 control valve was dealing with large amounts of energy and that disturbingly high levels of vibration had been experienced in this part of the plant. That was conveyed to both the inspector and the mechanical discipline leads. Noise and vibration in the relevant process section were also reported in meetings with AI where operating problems related to the 20-LV0114 control valve were discussed.

Operating problems experienced with control valve positioners were not understood to be a symptom of a more fundamental problem. Work to determine why the positioner arm was coming loose has not been documented.

Notifications and operational disruptions were not dealt with and risk-assessed in such a way that adequate action was taken to prevent the incident on 18 February 2015 becoming possible.

Requirements
Section 15 of the management regulations on information
Section 14 of the management regulations on manning and competence

6.1.4 Inadequate information at shift and crew changes

Nonconformity
Inadequate information was given at crew changes about monitoring the 20-LV0114 control valve from the repair of 21 January 2015 until the planned turnaround in March 2015.

Grounds
The instruction on the scope of close visual inspection in Synergi 1429529, measure 2, is unclear about what new crew should check when conducting close visual inspection of 20-LV0114 after the repair of 25 January 2015. The measure in Synergi on making close visual inspection is recorded as completed on 1 February 2015.

The instruction on continuous monitoring until the replacement in March was not clearly conveyed at the next shift change. This is confirmed by the fact that control room personnel present at the 18 February 2015 incident were not aware of the need to monitor the valve.

Senior personnel offshore who were present at the repair on 25 January 2015 confirm that this monitoring was supposed to continue until corrective work had been carried out in the planned turnaround.

Requirement
Section 32 of the activities regulations on transfer of information at shift and crew changes

6.1.5 Weaknesses in information transfer and learning

Nonconformity
Knowledge and experience which could have prevented the incidents on Gudrun were not applied in an appropriate way.

Grounds
Knowledge available to Statoil's experts about the use of control valves under demanding operating conditions could have been utilised both in the design and in dealing with operating problems on Gudrun. The direct cause of the incident could thereby have been avoided.

Statoil knows a great deal about risk associated with vibration and the danger of fatigue. Incidents involving fatigue ruptures in small-bore pipe connections have occurred on other facilities. Attention was also paid to vibration on Gudrun, both with the compressor module and with low-frequency vibration in the separator module. However, the scale of vibration associated with the control valve was not understood and therefore neither risk-assessed nor dealt with.

While the Gudrun project was underway, Statoil's TEX expertise unit drew up a GL on the choice of control valves for demanding operational conditions. This GL2212 sums up the available expertise in the area. It was issued two months before Gudrun came on stream. The demanding operational conditions which the 20-LV0114 control valve works under on Gudrun are emphasised in this GL.

Statoil's investigation report includes Kvitebjørn in its overview of facilities which have had problems with the operation of level control valves. The group has not ensured that operational experience from this and similar facilities, which forms the basis for GL2212, has been communicated adequately to the Gudrun project and the operations organisations.

Interviews revealed that the GL documents associated with the TRs were not passed to Aibel, since they do not form part of the base requirements in the contract.

Requirements
Section 23, paragraph 3 of the management regulations on continuous improvement
Section 19 of the management regulations on collection, processing and use of data

6.1.6 Conduct of electrical installation work

Nonconformity
A heating cable was installed with inadequate protection against abnormal conditions.

Grounds
The incident log shows that the heating cable was disconnected 90 seconds before the gas leak occurred. Statoil's investigation report reveals that the heating cable on the two-inch pipe where the leak occurred was not properly installed. Both friction damage owing to inadequate protection alongside a flange and a tear in the cable near the rupture site were uncovered. The damage led to automatic disconnection owing to an earth fault.

Requirement

Section 47 of the facilities regulations on electrical installations

7 Barriers

The table below is based on Statoil's barrier definition. It presents the investigation team's assessment of the way the various barriers functioned during the incident on 18 February 2015 in relation to technical, organisational and operational elements.

Barriers	Technical elements	Organisational elements	Operational elements
PS 1 – Containment	Exposed to vibration which ultimately led to a fatigue rupture,	Area operator	Leak site sealed after the area was gas-free
PS 2 – Natural Ventilation and HVAC	Incident occurred in a naturally ventilated area, Strong wind from the south-west ensured good ventilation. The incident log shows that most of the gas detectors activated were north-west of the leak site.		
PS 3 – Gas Detection	Comparison of CCTV footage and the incident log shows rapid gas detection.		All detection was automatic.
PS 4 – Emergency Shut Down (ESD)	No failure to shut down was registered, but one ESD valve failed to confirm that it was shutting down.	Control room operator	Error message was observed on the display.
PS 5 – Open Drain	**Observation from Statoil:** The plant lacked the capacity to handle the quantity of liquid. and hydrocarbons overflowed from drain boxes in the evacuation tunnel.		
PS 6 – Ignition Source Control	Heating cable at the rupture site disconnected as a result of an earth fault. That occurred 90 seconds before the leak. Inessential ignition sources were automatically disconnected when gas was first detected. Main power was disconnected as a result of deluge at lifeboat.		Disconnection of main power complicated the response to the incident.
PS 7 – Fire Detection	n/a		
PS 8 – Emergency Depressurisation and Flare/Vent System	Functioned satisfactorily.		
PS 9 – Active Fire Protection	Deluge automatically initiated with confirmed gas detection in order to reduce explosion pressure from a possible ignition of the gas.		
PS 10 – Passive Fire Protection	n/a		
PS 11 – Emergency Power and Lighting	Functioned satisfactorily.		

PS 12 – Process Safety	Functioned satisfactorily.		
PS 13 – Alarm and Communication System for use in Emergency Situations	Functioned satisfactorily.		
PS 14 – Escape, Evacuation and Rescue (EER)	Functioned satisfactorily, but deluge was initiated by a lifeboat.	Emergency response personnel. Other personnel.	Emergency response personnel dealt with the incident. Other personnel mustered in accordance with instructions and were not directly affected by deluge. Hydrocarbons were subsequently detected in drain boxes in the evacuation tunnel. This could have led to the loss of the main safety function evacuation. See also PS 5.
PS 15 – Layout Design Principles and Explosion Barriers	n/a		
PS 16 – Offshore Cranes	n/a		
PS 16B – Drilling Hoisting System	n/a		
PS 17 – Well Integrity	*West Epsilon* The 17.5-inch section of well 15/3-A-14 had been completed. The bit was pulled up to a safe depth in the well before the incident. No contact with the actual reservoir, and well integrity was not threatened. During preparations for secure shut-in, a hose ruptured and some oily mud was spilt.		
PS 18 – Ballast Water and Position Keeping	n/a		
PS 19 – Ship Collision Barrie	n/a		
PS 20 – Structural Integrity	n/a		
PS 22 – Human Machine Interface & Alarm Management		Control room operator	Personnel in the control room thought all detectors in the module were activated. That does not accord with the incident log from the control system.

Table 1: Identified barriers related to technical, organisational and operational elements.

7.1 Barrier elements which failed

As table 1 shows, weaknesses or failures were observed with the following barrier elements.

PS 1 – Containment: Exposed to vibration which ultimately led to a fatigue rupture.
PS 5 – Open Drain: The plant lacked the capacity to handle the quantity of liquid and hydrocarbons were present in drain boxes in the evacuation tunnel.
PS 22 – Human Machine Interface & Alarm Management: Personnel in the control room thought all detectors in the module were activated. That does not accord with the incident log from the control system, which shows that more detectors were gradually activated during the first few minutes.

8 Discussion

A number of conditions emerged during the investigation which have not been discussed in depth but which could nevertheless be relevant to the incident.

8.1 Uncertainties related to shrinkage and savings

It emerged from the investigation that the facility was "shrunk" in both length and width to reduce topside weight. This shrinkage influenced the layout, but the investigation has been unable to determine whether it affected process plant design in a way which was significant for the incident.

A decision to seek savings of NOK 2 billion on the original cost estimate was also taken during the project phase. The investigation team was told that great attention was paid to costs during the project and the need for variation orders reported by Aibel was discussed. Nothing emerged from interviews which might suggest a direct connection between the pressure on costs and the choice of valve or piping dimensions. Nobody suggested that pressure on time or workload for Aibel's engineers in this project was greater than in others.

It has not been possible to verify whether contractual or other incentives prompted the choice of a four-inch control valve rather than a more robust unit.

8.2 Use of models

Design work involves extensive use of models and estimates. The work done for Gudrun used production data supplied by Petek for dimensioning the 20-LV0114 control valve. This information was used to calculate operating parameters for the control valve, and showed that the chosen valve could cope with them.

Nothing about the margins for the choice emerges from the available material. Flow coefficients (CV values), for example, are specified for maximum and minimum liquid flows under the relevant operating conditions. With unstable operating conditions, liquid flows could vary both above and below the values used for dimensioning. The documentation does not show how robust the choice is.

When such information is lacking, the threat exists that insufficiently robust solutions will be chosen. Dimensioning could then be acceptable for stable conditions, but unable to deal with variations in a prudent manner.

The Sintef study revealed that complex conditions prevail in a control valve with the process conditions which applied here. The valve manufacturer is a market leader, and the investigation has found no grounds for disputing the expertise of its research and development team. It is unclear how far this leading-edge expertise has been implemented in the calculation programme which supports the sales organisation when choosing valves.

8.3 Considerations related to tools

Both project and operations organisations have had access to tools which could have helped to identify factors relating to the 20-LV0114 control valve.

Hazop is used in part as a tool for reviewing process systems in the design and operational phases. This cross-disciplinary appraisal can be conducted with different degrees of detail. Had any of the participants raised the issues of high pressure drop and dimensioning of the control valve, this would have been recorded as an action point for follow-up even if the issue was not directly anchored to a key word.

A TTS review checks the plant against the applicable performance standards. The one conducted on Gudrun in January 2015 related to PS 1 Containment. This performance standard concentrates on identifying conditions which could lead to leaks from the process plant, particularly in relation to flexible and mechanical connections. Furthermore, connections and piping must be designed to withstand vibration. The checklist for PS 1 contains 49 points, and two of these deal with the subject of vibration. They do not deal with vibration conditions identifiable in a design phase, but only with the operations phase.

Control valves on Gudrun are fitted with FieldVue, but this condition monitoring system was not connected to Statoil’s TK centre until 12 February 2015. Information on what was happening with the 20-LV0114 and 20-LV0314 valves during incidents before that date was not available as base data when seeking to understand the incidents registered in SAP.

8.4 Repairs carried out

The repair done on 25 January 2015 was carried out on the facility, not at the SAS workshop. Personnel doing the work had long relevant experience and, according to Statoil’s expertise management programme, the competence to do the job. The repair used new parts, but the stem was retained since a new one was not available on the facility. A bench set after the completed repair – recommended in the product documentation – is not documented.

8.5 Sharing operational experience between players in the industry

Engineering companies depend on operational experience to improve the design of new facilities. Aibel is a relevant supplier of new process plants to Statoil and other operators. If companies are to utilise operational experience, both production-related and safety-critical information from facilities on stream must be fed back to the engineering teams.

This issue has been discussed and raised at industry level between the Federation of Norwegian Industries on behalf of the engineering companies and the Norwegian Oil and Gas Association representing the operators. On the basis of information from investigation reports, which shows that a large proportion of hydrocarbon leaks are caused by design errors[8], these organisations have chosen to establish a dedicated body for exchanging experience.

The investigation was told that GL documents associated with the TRs were not passed to Aibel since they do not form part of the base requirements in the contract.

When interviewed, engineering personnel at Aibel said they lacked this type of information from Statoil. If the knowledge underpinning GL2212 have been conveyed to Aibel, the design solution for the 20-LV0114 control valve is likely to have attracted greater attention.

Statoil has chosen not to pass on the contents of GL2212 actively even if it contains highly relevant information for Aibel, not only for this development project but also for future ones.

8.6 Responsibility and understanding of roles

A number of the interviewees commented that designing a complex facility presupposes that everyone takes responsibility for their part of the job. They accordingly expect “the others” to check significant conditions. This emerged clearly from the discussion on dimensioning the valve, where the choice of the four-inch size was based on the recommendation of the valve supplier’s calculation programme. Coning had to be used in the 10-inch line. Aibel said that SAAS had to assess this, while SAAS said that it bases dimensioning on the process data sheet and that the necessary adjustments between valve and piping must be done by Aibel. Furthermore, the latter noted that Statoil had not involved itself in this issue. It emerged during the interviews that the contract was described as crucial for the division of responsibility, even though the regulations place responsibility for ensuring a robust design on the developer.

The division into disciplines, such as piping, valves and process, appears to result in few people realising that they had a responsibility for checking their own technical contribution against the final design. This also accords with findings in Statoil’s own investigation report.

It emerged during the interviews that a lack of clarity prevailed about which specialists in the project, both internally in the various companies and at the interface between them, were responsible for checking that the final design of valves in the pipework was robust.[9] People repeatedly referred to other disciplines, organisational units or companies when asked who was responsible for the final design.

The incident had a major accident potential, and prompted the police to establish a case for investigation. Both the PSA and Statoil launched investigations, which gives clear signals of the seriousness of the incident. The majority of those interviewed did not regard their role as central in terms of the design security of the solution. This indicates that roles and responsibilities related to securing a robust design have not been adequately communicated, or that training related to major accident risk has been insufficient.

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8 The PSA conducted a causal analysis in 2010 as part of its annual report on trends in risk level in the petroleum activity (RNNP). This reviewed investigations into hydrocarbon leaks over an eight-year period.

9 The exceptions were those interviewed from Aibel. They emphasised that they had an independent responsibility to design and build a safe facility.

9 Review of Statoil's investigation report

Statoil's investigation report was submitted to the PSA on 19 May 2015. It contains a detailed review of the incident and the framing of recommended measures.

However, the PSA observes that conditions it regards as key underlying causes why the incident occurred have been given less coverage in the Statoil report. Conditions are not given emphasis by Statoil include risk understanding, the relationship between different operating problems in the processing plant and conditions where decision-makers lacked adequate operating experience and safety-critical expertise.

The PSA takes the view that lack of information transfer related to control valves from operations to project and to the supplier, as well as a lack of involvement by Statoil's technical experts in the selection and dimensioning of control valves, were contributory underlying causes where the choice of control valve was concerned. Statoil's investigation report identifies lack of information transfer, but does not reflect to any extent on the roles and responsibility of the Gudrun, AI Gudrun and OPS Gudrun leadership and the lack of involvement of the rest of Statoil's technical expertise.

Repeated incidents of equipment failure and vibration occurred with the relevant valve and the piping system it is connected to in the months before the incident occurred. These were registered by the offshore organisation and communicated to the land organisation as notifications and reports of concern. According to the investigation report, the TTS team was not aware of the valve failure on 25 January 2015. The PSA investigation has found that at least one member of the team knew of these circumstances.

10 Documentation used

The following documents have been available to the investigation.

1. WR1156, *Tillegg til: Beredskap på norsk sokkel – GUDRUN*
2. WR1156, *Feltspesifikk oljevernberedskapsplan for Gudrun*
3. WR2545, *Bridging document between Gudrun production platform and* West Epsilon *Jack-up-drilling rig in SDP phase*
4. Notification/report about undesirable incident from Statoil to the PSA, dated 18 February 2015
5. E-mail with overview of personnel evacuated to *West Epsilon*
6. TV_REP_POBREPORT, dated 19.29 on 18 February 2015
7. Photographs by Statoil: various images taken after the incident on 18 February 2015 before the PSA arrived on Gudrun
8. Images from CCTV on Gudrun
9. Photographs by the police on Gudrun 19 February 2015
10. Photographs by the PSA, SAAS inspection in Bergen 28 February 2015
11. Drawing of Gudrun, lower mezzanine deck: fire and gas detection
12. Overview of detector location in the M30U and M30 areas
13. Log and documentation from the emergency response room in connection with the incident of 18 February 2015
14. Presentation of inspection plan and findings condensate leak – version 2 – PSA May 2015
15. MAT-2015018 *Materialteknisk undersøkelse av 2" rørstuss fra Gudrun.* Statoil.
16. Report EV0150. Document number 52300022-02-001. Solberg Andersen

17. Report 20-LV0114. Document number 52300022-03001. Solberg Andersen.
18. Report 20-LV0314. Document number 5235564-001. Solberg Andresen.
19. Minutes of meeting 28 February 2015 on inspection and check of valves, Gudrun investigation, from Solberg Andersen
20. *Fisher control valve handbook*, downloaded 25 February 2015
21. E-mail 22 June 2015 from Aibel, ref AI-O-15-000177/OFSKASVE
22. Documentation from FieldVue – trigger profiles
23. Synergi report 1429529, (Report after incident 25 January 2015) with images
24. Overview from Statoil of notifications related to 20-LV0114
25. M2 43942335 *Rør hviler ikke på support*
26. M2 43926511 *Baseline insp. prod. rør*
27. M2 43700000 *Modifisering av personellbeskyttelse/isolasjonskapsling til strømning og prod. rør*
28. M2 43434269 *Baseline tykkelsesmåling av utestående produksjon og strømning rør*
29. M2 43940330 *Vibrasjon i ventil*
30. M2 43936995 *Feilsøking på 20-LV0114* with photo
31. M3 43353777 *NDT baseline erosjon inspeksjon*
32. M3 43892631 *INSP; NVI og vurdering vibrasjoner med vedlegg*
33. M5 43951772 *Ny Actorator til ventil*
34. M5 43899614 *Endre tekst for reguleringsventiler*
35. History: 1163-10"-PM-20-003-ED202
36. History: 1163-P-20-LV0114
37. History: 1163-2"-PM-20-040-ED202-5 No notifications registered
38. History: 1163-12"-PR-20-004-BD200
39. Print-out of history for LV0114 control valve
40. Print-out of history for pipeline from first-stage separator
41. Print-out of history for pipeline downstream of the control valve
42. Technical condition safety (TTS) verification Gudrun, TEX SST ST-14009. December 2014
43. Appendix B List of all examination activities with observations, technical condition safety (TTS) Gudrun, December 2014. TEX SSC MON-14009-02
44. Timp Gudrun barrier deteriorations 18 December 2014
45. Emergency preparedness analysis - Gudrun C123-B-S-RS-138, report no 100662-3/R1
46. Supplement to: *Beredskap på norsk sokkel - GUDRUN, Arbeidsprosesskrav*, WR1156
47. Gudrun emergency preparedness analysis 2012 C123-B-S-RS-101
48. Emergency preparedness analysis Gudrun 17 February 2015 with phone list
49. Gudrun safety strategy 2012 C123-B-S-RE-102
50. Findings concerning heating cable received 6 March 2015
51. Presentation by Statoil on project management, Vassbotn, 29 January 2014, PSA ref 2013/1544
52. Presentation by Statoil on expertise requirements 9 June 2015
53. Presentation by Statoil on Gudrun investigation report 13 May 2015
54. Flow diagram, Gudrun main process
55. P&ID Legend, C123-B-M000-PT-002-05
56. P&ID, Separation, 1st stage separator, C123-B-M000-PE-202-01, rev 04Z
57. P&ID, Separation, 2nd stage separator, C123-B-M000-PE-203-01, rev 05Z
58. P&ID, Separation, test separator, C123-B-M000-PE-204-01, rev 05Z
59. ISO drawings of relevant piping downstream of the first-stage separator

   a. C123-B-LL-320A-PM-20-003-01, PIPING ISO (AS BUILT)
   b. C123-B-LL-320A-PM-20-003-02, PIPING ISO (AS BUILT)
   c. C123-B-LL-320A-PM-20-003-03, PIPING ISO (AS BUILT)
   d. C123-B-LL-320A-PM-20-040-01, PIPING ISO (AS BUILT)
   e. C123-B-LL-320A-PR-20-004-01, PIPING ISO (AS BUILT)
   f. C123-B-LM-M30L-PM-20-004-01, STRESS SKETCH G20004
   g. C123-B-LM-M30L-PM-20-004-02, STRESS SKETCH G20004
   h. C123-B-LM-M30L-PM-20-004-03, STRESS SKETCH G20004
   i. C123-B-LM-M30L-PM-20-004-04, STRESS SKETCH G20004
   j. C123-B-LM-M30L-PM-20-004-05, STRESS SKETCH G20004
   k. C123-B-LM-M30L-PM-20-004-06, STRESS SKETCH G20004
   l. C123-B-LM-M30L-PM-20-004-07, STRESS SKETCH G20004
   m. C123-B-LM-M30L-PM-20-004-08, STRESS SKETCH G20004
60. Pipe support drawings related to piping downstream of the first-stage separator
   a. C123-B-M30L-LF-3200039-01, PS 320-0039 (AS BUILT)
   b. C123-B-M30L-LF-3200238-01, PS 320-0238 (AS BUILT)
   c. C123-B-M30L-LF-3200239-01, PS 320-0239 (AS BUILT)
   d. C123-B-M30L-LF-3200320-01, PS 320-0320 (AS BUILT)
   e. C123-B-M30L-LF-3200979-01, PS 320-0979 (AS BUILT)
   f. C123-B-M30L-LF-3200992-01, PS 320-0992 (AS BUILT)
61. C123-B-L-RE-004 *Pipe stress analysis report*
62. R-12520-TPD-*Utfør umiddelbar skadebegrensning av HMS hendelse*
63. I-12564-*Umiddelbare tiltak*
64. Matrix for responding to undesirable incidents in DPN – version 14
65. Print-out of display image for system 20 production manifold, first- and second-stage separators
66. Copy of work permit for ongoing wok in area M20D
67. Inspection reports for valve conducted by Solberg Andersen, Report EV0150
68. Inspection reports for valve conducted by Solberg Andersen, Report LV0114
69. Inspection reports for valve conducted by Solberg Andersen, Report LV0314
70. Material technology report, Statoil Rotvoll. MAT-2015018 *Materialteknisk undersøkelse av 2 inch rørstuss fra Gudrun_final per 11032015*
71. 3D model of piping system downstream of first-stage separator
72. Process datasheet – C123-B-P-DP-482 *Actuated on/off valves*
73. Process datasheet – P-20-LV0114, rev 00
74. Process datasheet – P-20-LV0114, rev 0A
75. Extract from C123-B-J108-CE-0001 *Valve and actuator size calculations*
76. Process datasheet for EV0150 and EV0151
77. VDS BMFD102J for EV0151 and CW199
78. VDS BNED103C for EV0150
79. 005861-OTH-MM-00039, Minutes of BCM for the procurement package containing 20-LV0114 control valve
80. 005861-J108-MM-00003, Minutes from kick-off meeting
81. 005861-J108-MM-00005, Minutes from follow-up meeting
82. 005861-J108-MM-00011, Minutes from follow-up meeting
83. Book 01.000 - *Project Assignment (PAS) Gudrun* DG3-DG4
84. OMC01-000 - *Development and Production Norway (DPN)*
85. OMC01-003 - *DPN Field Development – Organisation, management and control*
86. OMC01-004 - *UPN Drift – Organisasjon, ledelse og styring*
87. OMC01-005 - *UPN Sør SDG – Organisasjon, ledelse og styring*

88. Organisation chart asset integrity, Sleipner, Draupner, Gudrun and Gina Krog at March 2015 and at 1 April 2015
89. Overview of technical system and discipline leads DPN OS OMT SDG
90. Job description auto instrument engineer
91. Job description piping engineer
92. Job description leading advisor – field instrumentation
93. FR05 - *Project development* rev 2 February 2015
94. FR06 - *Drift og vedlikehold* rev 29 December 2014
95. TR2212, *Control and choke valves*, rev 4, 2014-12-01
96. GL2212, *Valve Selection Manual*, rev 1, 2014-02-19
97. Statoil mandate for investigation of leak from bypass line on oil outlet from first-stage separator, 18 February 2015
98. A 2015-4-DPN L1, Statoil investigation report with appendices. *Kondensatlekkasje på Gudrun 18.2.2015*
99. Gudrun – *Lekkasje i kondensatutløp 1. trinnseparator*, PowerPoint presentation from Aibel
100. Sintef report, *On the events causing the HC leak at Gudrun on February 18th 2015* dated 1 July 2015

11 Appendix

Overview of personnel interviewed