Project: SIL analysis of a HIPPS system

*The main learning objective of this group project is to acquire knowledge and skills in how safety-integrity level (SIL) requirements are derived for a safety-instrumented function (SIF) and how the SIL requirement may impact the design, reliability analysis, and follow-up in operational phase. The study case is a high integrity pressure protection system (HIPPS), a system that is used at several land based and offshore (including subsea) processing facilities to compensate for inherently safe process design of pipelines and vessels. The primary focus is on reliability related issues for hardware, and requirements to software/configuration of logic are given limited focus. The project applies theory covered in chapters 5, 7, and 8, but some additional reading is necessary to understand the study case. The additional reading material to solve the tasks is provided. Notify Mary Ann Lundteigen (the lecturer) if something is missing!*

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# Practical information

## Learning objectives

The learning objectives of this project are:

* Be able to identify key information and supplement as needed when exposed to a new type of system
* Be able to create some selected technical documents covered in the course
* Get practical experience in performing SIL related analyses
* Get experience in planning, organizing, and writing technical reports
* Get experience in organizing work with several people involved
* Get experience in creating presentations that are suitable for conveying messages in a clear and visualized way

## Deadlines and deliverables

Due data is **April 21st.**

The deliverables are:

1. Report that answers to all the tasks of the group project

The report shall:

* + Have a front page with name of the group members
  + Font 11, 1.1 line separation.
  + Be organized so that the answer of each task is easy to retrieve.
  + Self-contained answers, with a short introduction, presentation of answers including explanations, assumptions, illustrations, and tables.
  + Include table of content, list of figures and list of tables
  + Draw your own illustrations, except for pictures. All figures and tables must be named and referenced in the text.
  + Have a bibliography covering all articles, reports, and other material and webpages that have been used. The list of references to follow guidelines provided in Chapter 4. Each reference shall preferably have a dynamic link to the bibliography.
  + Have an attachment that explains how the group organized their work: the group’s project plan w/milestones, hours spent on each task, and allocation of responsibilities within the group.

The report can be in Norwegian or English.

# Description of the study case

## What is a HIPPS system?

The term HIPPS in an abbreviation for **high-integrity pressure protection system**. In subsea oil and gas development projects are marginal fields with high wellhead pressure and long distance to existing infrastructure. If pipelines from such fields to their host platforms are designed for full wellhead shut-in pressure, the development will often not be profitable. By rating the pipelines closer to the flowing pressure, it might be possible to make the field developments profitable. This design will require a protection system that allows rapid closure of the inflow to the pipeline system upon an unwanted pressure increase. The naming of this type of safety-instrumented secondary pressure protection system is HIPPS and it must be fully independent of other safety-instrumented systems. It is able to automatically detect a shut down well stream in situations where the pressure in the pipeline is increasing above the allowable operating pressure. The HIPPS comprises pressure transmitters, a logic unit, and valves. Unlike many other SIS-systems, like process shutdown (PSD) and emergency shutdown (ESD) systems, each HIPPS system performs only one specific HIPPS function. If more than one HIPPS function is needed at a facility, they are implemented as separate HIPPS system with no dependency or communication between them.   
  
A HIPPS system often comprises the following:

* Pressure transmitters that convert pipeline pressure to electric (analogue 4-20 mA) signals.
* Logic solver that reads the electrical signals, performs threshold comparison, and acts (based on the selected voting) when a certain number of pressure transmitter signals exceed the set level. In this context, acting means to open or close solid state switches that controls the power supply to the solenoid valves.
* Electrically (solenoid) operated directional control valves, sometimes referred to as solenoid valves or just DCVs. In the following, we refer to these valves as DCVs.
* Pilot operated DCVs, where the pilot signal may be hydraulic or pneumatic pressure.
* Shutdown valves including valve actuator, often referred to as HIPPS valves.
* Non-safety related functions that provide monitoring, test facilities, communications, and power supply.

Some of the components are shown in Fig. 1. A gate valve is often chosen as HIPPS valve if fast response time is needed. Typical time requirement for HIPPS valves are in the range of 2 seconds to 30 seconds, depending on the process safety time, i.e., the time available to act before the safety is compromised. The HIPPS valves are designed fail-safe – usually towards the closed position, which means that the valve will close upon foreseeable fault situations like power loss. The HIPPS valve can be pneumatic, hydraulic, or all-electric. In the provided example, we assume hydraulically operated HIPPS valves with solenoid valves and DCV, and the combination is referred to as called electro-hydraulic activation. To open a HIPPS with fail-safe position “closed”, the valve is kept open by pressurizing a chamber with hydraulic fluids inside valve actuator. One or more springs are decompressed at the same time, assisting the valve to close when the chamber is depressurized. The HIPPS valve at Kristin is relying on ambient (subsea) pressure to ensure the fail-safe operation, due to the very high pressure conditions. The spring is only providing a marginal assistance in this case.  
  
The pressure transmitters often use 4-20 mA current signal transmission instead of fieldbus or industrial ethernet. The logic solver compares the received value to a predefined set point (e.g., 17 mA, or 6mA if inverted). The set point is selected so that the HIPPS valves closes fast enough to avoid that the maximum allowable pipeline pressure is exceeded. If the signal is below 4 mA or above 20mA, the logic solver will raise an alarm. An alarm may also be raised by the logic solver if the transmitter readings differ over time.  
  
Chart, box and whisker chart

Description automatically generated

Fig. 1. An example of a principle arrangement HIPPS system

The logic solver can be of type solid state circuits using electronic components or programmable logic controllers (PLC) where all functions are implemented into software. In either case, the logic solver closes the gate valve by switching off the power to a solenoid valve which in turn will switch the position of the pilot operated DCV so that the actuator is depressurized.

* DCV routes hydraulic fluid to the HIPPS valve actuator, causing the HIPPS valve to open.
* If the logic solver switches the power "off", the DCV loses the pilot signal and switches so that the HIPPS valve actuator is depressurized.

It may be remarked that the DCV function is realized by two pilot operated DCV valves, each operating at different hydraulic pressure level. However, for simplicity, we assume only one DCV here.

The HIPPS system often has a SIL 3 requirement resulting in the need for having two HIPPS valves in series in the pipeline rather than one*.*

## Literature to use

**General references about requirements to and the use of HIPPS:**

* Designing offshore pipeline safety systems utilizing flow and pressure in Multi design pressure pipeline systems (for pipeline from Gjøa floating facility) by Hausken et al. (2009)
* A brochure that have some useful illustrations by Emerson (2016)
* A webpage that gives an overview of HIPPS from webpage EIT (Accessed 19.12.2022)
* Article from Yokogawa company on HIPPS written by Ramsay-Connell (2006)
* SINTEF report by Hokstad et al. (2001) about use of HIPPS systems (in Norwegian)
* Overview of HIPPS applications by A. Summers (2011), well known SIS expert in the USA
* Petroleum Safety Authority facility regulations §34 w/ guideline accessible from <https://www.ptil.no/en/regulations/all-acts/the-facilities-regulations3/V/34/>
* NORSOK P-002 section 7.4.3 Accessible from standard.no where standards can be read online via this page: <https://i.ntnu.no/wiki/-/wiki/Norsk/Standarder>
* API 17O accessible via <https://www.ntnu.no/blogger/ub-teknologi/en/2017/03/03/standards-and-patents-at-the-university-library/>
* Paper on HIPPS and acceptance criteria:<https://doi.org/10.4043/7828-MS>
* Paper on HIPPS Concepts for a Subsea Field Scenario: <https://doi.org/10.4043/7830-MS>
* Paper on some HIPPS challenges: <https://doi.org/10.4043/27278-MS>
* Paper on the application of HIPPS: <https://aiche.onlinelibrary.wiley.com/doi/10.1002/prs.11608>
* On the use of HIPPS (overview of various types of reports) from Petroleum Safety Authority:<https://www.ptil.no/sok-hele-nettstedet/?q=HIPPS>
* Teknisk ukeblad artikkel fra 2004 utvidelsen på Mongstad: <https://www.tu.no/artikler/dobler-kapasiteten/264398/>
* IOGP guideline on HIPPS systems (IOGP, 2021) (uploaded on BB or downloaded for free at <https://www.iogp.org/bookstore/product/iogp-report-443-high-integrity-protection-systems-recommended-practice/>)

**HIPPS case study: Kristin subsea overpressure protection**

In most of the group project tasks, we are using subsea HIPPS system for Kristin facility as the case study. The following literature is provided:

* Article in Offshore Magazine about Kristin subsea HIPPS by Bak et al. (2007): (the illustrations are no longer visible, but the presentation below contains most of the same ones
* Presentation given at the conference where this paper was presented (uploaded at BB) by Sirevaag et al. (2007). Most likely prepared in relation with Offshore Magazine article.
* Video that explains about subsea HIPPS made by DNV: <https://www.youtube.com/watch?v=8dcwOm7TzZQ&t=212s>

**About topside initiated ESD isolation of subsea well:**

* Appendix A.13 in Guideline 070 by Offshore Norway on the application of IEC 61508 and IEC 61511 for the petroleum industry (GL 070, 2020)

**How to look into IEC, ISO, and NORSOK standards using NTNU subscription:**

* Go to standard.no via this link: <https://i.ntnu.no/wiki/-/wiki/Norsk/Standarder> (with VPN if working from home). You can download all standards, but there is a code that will make it necessary to reload again after a day or two.
* NB: When inside standard.no: After about 10 minutes (when you see that the pdf symbols changes to “handlevognsymbol”, you have to re-enter again to standard.no via <https://i.ntnu.no/wiki/-/wiki/Norsk/Standarder> (and then the pdf symbols will reappear)

## Data dossier for reliability analysis

Data for the analysis is based on PDS data handbook (2022). The data are not open source, but a sample is shown here:

|  |  |
| --- | --- |
| A picture containing background pattern  Description automatically generated | Sample pages: <https://www.sintefbok.no/book/index/1298/reliability_data_for_safety_equipment_selected_pagespdf> |

Data to use for the reliability analysis derived from the PDS data handbook:

|  |  |  |
| --- | --- | --- |
| **Component** | **Value** | **Source** |
| Subsea pressure transmitter | DC =65%  MRT & MTTR: 10 x24 hours (10 days) | PDS data handbook (2021):   * Failure rates, DC: Subsea sensors, p. 158 * β: General process transmitters (p.29)   Other data: Assumptions made for the purpose of the analysis. |
| Subsea HIPPS controller | \*  DC=95%  MRT & MTTR: 10 x24 hours (10 days) | PDS data handbook (2021).  Used for failure rates for general programmable safety logic (p.91-92. For each controller: Added failure rates for 1AI+CPU+1DO.  Other data: Assumptions made for the purpose of the analysis. |
| Solenoid/pilot valve and DCV | \*  DC=5% | PDS data handbook (2021). General data for solenoid valves (p.120) |
| HIPPS valve | DC=5%  MRT & MTTR: 30 x24 hours (30 days) | PDS data handbook (2021)– used failure rates and β for general HIPPS valves (p.114)  Other data: Assumptions made for the purpose of the analysis. |
| Functional test interval | τ=8760 hours (1 year) | Assumptions made for the purpose of the analysis. |

# Group project tasks

The group tasks have been organized with some headings to ease the navigation. Each group shall carry out **all** tasks.

## Understanding why and where HIPPS systems are used

1. From the provided list of literature: Give 2-3 examples of application areas for HIPPS systems, beyond the study case of Kristin offshore facility.
2. What are the requirements to HIPPS systems in NORSOK P-002?   
   *Remark: In this standard, HIPPS is called “Safety instrumented secondary pressure protection system” (and PSV is called PRV – pressure relief valve)*
3. With basis in PSA facility regulation §34: whymust the HIPPS system be independent of the PSD system (even if the PSD system also carries out overpressure protection)?

## Tasks related to the case study Kristin subsea HIPPS

### Understanding Kristin HIPPS study case

1. Explain why HIPPS system was introduced to the Kristin subsea pipeline
2. Identify the equipment under control (EUC) for overpressure protection
3. Explain in brief the role of the other systems seen in documentation for the Kristin study case:
   1. Well tree (Xmas tree) with PMV and PWV
   2. The surface-controlled sub surface safety (SCSSV), also called downhole safety valve (DHSV)
   3. The choke valve
   4. Subsea isolation valve (SSIV)
   5. Riser pressure safety valve (PSV) (topside)

If need for more explanation, look into NORSOK S-001 and also “google” with keywords “subsea production system” + the component you would like to know more about

1. Develop a P&ID like illustration identifying the local (subsea) PSD function closing PMV and PWV, the topside ESD closing the same valves plus DHSV, the HIPPS system and the local (subsea) PCS controlling the choke valve. Remember to add correct symbols for sensors, logic, and actuated devices, including signal transfer and loop numbers.
2. Discuss briefly which of the systems in tasks 6 and 7 are relevant for stopping and mitigating the escalation of hazardous events like:
   1. fire at the topside receiving facility,
   2. hydrate plug upstream the SSIV (and downstream the HIPPS system)
3. Provide/describe:
   1. Examples of demands (for activation of HIPPS)
   2. Examples of causes (events, circumstances) leading to these demands
   3. Safe state of the equipment under control (EUC)
   4. Safe state of HIPPS components (individually for each of the HIPPS components)
   5. Dangerous failure modes of each of the HIPPS components   
      (Hint: First you need to identify component functions and then their failure modes before deciding if they are dangerous or not)
   6. Which of the dangerous failure modes that are dangerous detected (DD) and which ones that are dangerous undetected (DU)

### Assigning SIL requirement to Kristin HIPPS system

1. Determine the following parameters characterizing the risk reduction to be provided by the HIPPS system:
   1. The required the risk reduction factor (RRF)
   2. The corresponding probability of failure on demand (PFD) requirement
   3. The corresponding SIL requirement

To solve these tasks, make use of the following assumptions:

* + Acceptance criterion for over-pressuring the pipeline is 1E-5/year
  + Demand frequency of 25/years
  + PFD of subsea PCS function (actuation of choke valve) is 1E-1.
  + PFD of subsea PSD function (actuation of PMV and PWV) is 7E-3

1. What would the PFD requirement for HIPPS be if we also could credit the riser PSV (assuming a PFD of PSV equal to 5E-2)?
2. A popular and commonly used approach in the process industry is to derive SIL requirements using a layers of protection analysis (LOPA). Illustrate and briefly explain how the analysis in task 8 and 9 can be transferred into a LOPA table ~~How could the allocation made in task 8 and 9 be transferred into a LOPA table~~?
3. Why is it reasonable to not to credit the riser PSV when determining the required PFD of the HIPPS system?

In the following, we assume that a SIL 3 requirement has been decided upon.

### Perform an FMECA for a specific HIPPS components

1. Construct a functional block diagram and a system decomposition diagram of the HIPPS system. Elaborate on how the two different diagrams provide supplementary information to each other.
2. Perform a failure, modes, effects, and criticality analysis (FMECA) of one HIPPS valve, focusing only on the HIPPS on/off valve and associated solenoid valve, and directional control valves as shown in Fig. 1. In the FMECA table:
   * + Identify if the failure is safe (S), dangerous detected (DD), and dangerous undetected (DU)
     + Comment on whether the failure causes are random hardware or systematic and give a brief explanation of how you in general have distinguished between those two.

*Remark: It may be necessary to search on the internet or YouTube for more information about the involved components and their way of operating. It may be difficult to identify the exact components used for subsea, so for simplicity we may assume that the components are similar to what is used on land, and that they are encapsulated in a housing that has 1 bar (atmospheric) pressure.*

*It is not necessary to include frequencies of the failures, but assumptions can be made about the severity.*

### Assess implications of SIL requirement for HIPPS subsystems’ architecture/voting

1. What is the meaning of the parameter safe failure fraction (SFF) and what type of characteristic does it describe about the way a component behave upon failures?
2. Determine the architectural constraints of each subsystem of the HIPPS, i.e., the minimum hardware fault tolerance requirements, with basis in the SIL requirements. Include how you derive at the results, including the assumption and rationale made about type A/B classification and how the SFF was calculated for components in each of the three subsystems.

*NB: Due to other reliability data than was used in the Kristin HIPPS study, the SFF becomes different and could lead to a different architecture than originally used.*

1. Give 2-3 examples of how the SIL requirement (SIL 3) will impact the realization of software/configuration of logic for the HIPPS system, by looking into IEC 61511 (part 1) and as needed IEC 61511 (part 2) for guidance. IEC 61511 is used as a reference here, as this standard focuses on implementation of logic for process industry that builds upon configuration tools with pre-made libraries for safety logic.
2. Develop a reliability block diagram (RBD) that implements the architecture following the architectural constraints and add as necessary the functional blocks for CCFs. For the calculation that follows later, we *exclude* the contribution from the solenoid valve and the DCV. Therefore: Make one RBD with the solenoid valves and DCVs included and one RBD without these (only the latter RBD is used for the calculations of reliability).

### Assess to what extent SIL requirement for HIPPS is met based on calculations

1. Explain the purpose of a data dossier, and describe the type of data provided from the following three examples of such sources:
   1. PDS reliability data for safety equipment: <https://www.sintefbok.no/book/index/1298/reliability_data_for_safety_equipment_selected_pagespdf>
   2. OREDA data <https://www.oreda.com/>
   3. EXIDA data handbooks <https://www.exida.com/books/safety-equipment-reliability-handbook-4th-edition>
2. In relation to formulas for calculating the PFD, explain the meaning of the following parameters:
   1. Functional test interval: What is the purpose of such a test and why must it be carried out regularly?
   2. What are the main distinction between a DU and a DD failure in the way it is revealed?
   3. What is the difference between parameters MRT and MTTR?
   4. What is the meaning of diagnostic coverage (DC)?
   5. What is the meaning of the CCF parameter β and how can it be used to distinguish independent from dependent (CCF) failure rates for a single component?
   6. What is the meaning of the CMooN factor introduced in the PDS method and applied together with the CCF parameter β?
3. Calculate the PFD of the HIPPS SIF with reliability data provided in section 2.3 when applying:
   1. Simplified PFD formulas (with only DU failure rates and standard beta factor model)
   2. PDS method (with only DU failures and CMooN factor)
   3. IEC 61508 formulas with DU failure rates, DD failure rates, repair rates (MTRT, MTTR), and CCFs.

*Remark: For all calculations: Include formulas that you have used into the report along with how the calculations were done. The excel sheet used in lecture 6 (with chapter 7 failure classification and reliability analysis) may be used to verify the results.*

1. Compare the results from task 22 and comment on whether the results (PFDs) are within the SIL requirement. If one or more of the results are outside the SIL requirement, discuss what to do in order for the HIPPS function to meet the SIL requirement, with each of the two strategies:
   1. Redesign of the subsystems
   2. Change the functional test interval, including how much.
2. With basis in the results from task 22, discuss:
   1. Importance of including DD failure rates when calculating PFD for this particular (Kristin HIPPS) case study
   2. Impact of CCFs to the PFD compared to independent failures
   3. Impact of using standard beta factor model compared also incorporating CMooN

In the following analyses for the operational phase, use the PDS method, i.e., simplified formulas with DU failures only but incorporating the CMooN-factor for CCFs.

### Follow-up of SIL in the operational phase

1. Assume that the same type of HIPPS valves are used for similar subsea pipelines by the same operator. For a total of 10 HIPPS valves, it is experienced 5 DU failures in a period of 3 years.
   1. Calculate the new updated failure rate, using Bayesian approach. Assume that a conservative estimate of the initial failure rate is 50% higher than the failure rate from the data dossier.
   2. Recalculate the PFD using the simplified formulas
   3. Decide if the SIL requirement continues to be met or not
   4. If the PFD deviates from the SIL requirement. How much must the functional test interval be adjusted to meet the SIL requirement?

*Remark: Make sure to document how you arrived at the results.*

1. Assume that 4 more DU failures have been experienced for the HIPPS valves in the next observation period of 3 years, following after the first period that was considered above.
   1. Using the Bayesian update: What is the new experienced failure rate using the previously calculated failure rate as the prior knowledge and using the same assumption for % for the conservative failure rate as was done for the first 3-year period.
   2. Is it necessary to adjust the functional test interval again?
   3. How many failures can be experienced in the next period to be able to revert to original test interval of 8760 hours

*Remark: Make sure to document how you arrived at the results.*

1. ~~Discuss the pros and cons of the following strategies for reducing the PFD in case the PFD is not meeting the SIL requirement:~~
   1. ~~More frequent functional testing~~
   2. ~~Redesign of the HIPPS~~

*Remark: Make sure to document how you arrived at the results.*

1. Why are such reassessments of PFD important throughout the operational phase?

## Reflecting some more general aspects of the case study

These last three tasks focus on the group members reflections/opinions to more high level questions, and “brainstorming” together in the group can be a suitable approach:

1. Are SIL requirements leading to more reliable systems?
2. What may contribute to uncertainty in the calculations of PFD?
3. Higher SIL requirement often leads to requirements about higher hardware fault tolerance. However, does a high level of hardware fault tolerance always lead to higher level of safety?

# How to make a bibliography

The following information may be useful (per now in Norwegian). The information below is from: <https://www.itk.ntnu.no/ansatte/lundteigen_ma/tips>

|  |
| --- |
| I rapporten din skal du ha en referanseliste over litteratur du har benyttet. Her er det flere alternativer:   * Bruke innebygget funksjon i Word eller LaTeX * Bruke eget (open source eller tilgjengelig via NTNU) program, eks: Endnote (m/Word), Jabref (hvis LaTeX)   Velg en style/stilart/mal - eksempelvis Harvard, Numbered, APA, eller andre. Her kan du velge mellom en mal som enten gir referanser i form av forfattere + år eller nummerering. Om du velger en style/mal med nummerering, så påse at nummereringen skjer etter den rekkefølgen artiklene er referert første gang i rapporten (som gir en mer naturlig progresjon) heller enn at de nummereres alfabetisk etter forfatternavn.  Innenfor malen får du flere alternative felt få fylle inn for de enkelte referansene og det er ofte oppgitt en hel del standardtyper for hvordan referansene oppgis. Det anbefales å bruke så få standarder som mulig, og jeg velger selv som oftest kun å bruke:   * Journal article. Brukes for tidsskriftsartikler. Felter som typisk skal være med er:   + Forfatter(e): Alle, i den rekkefølgen de er oppgitt   + Tittel på artikkelen   + Utgivelsesår   + Tittel på journalen   + Sidenummer (for artikkelen)   + Volume number (et slags nummer på utgivelsen)   + Issue number (også en del av utgivelsesnummeret. Ikke alltid oppgitt)   + DOI (som er en permanent lenke til artikkelen) * Part of Book (alt: Book section). Brukes i forbindelse med konferanseartikler og boka kalles da ofte en conference proceedings (proceedings= en form for protokoll). Har to typer forfattere. Forfattere av artikkelen og Editors (redaktørene som har sydd boka sammen). Felter som typisk skal være med er:   + Forfatter(e): Forfattere av konferanseartikkelen! Alle forfattere skal oppgis, i den rekkefølgen de er listet   + Tittel på artikkelen   + Utgivelsesår: For selve boka. Det hender at boka utgis i kalenderåret etter konferansen, avhengig av når på året konferansen ble avholdt)   + Navn på konferansen med årstall og sted   + Navn på boka (conference proceedings) som artikkelen er publisert i   + Editors: Redaktørene oppgis i den rekkefølgen de er oppgitt.   + Sidenummer   + Utgiver/forlag (publisher) der boka er utgitt   + Hvilket land og by boka er blitt publisert fra (dersom dette er oppgitt)   + DOI (som er en permanent kilde til boka), alternativt en URL. * Book (for bøker og standarder)   + Forfatter(e): Alle, i den rekkefølgen de er oppgitt. Hvis boka er en internasjonal standard, så kan koden for standarden legges inn som forfatter (eks: IEC 61508). Hvis boka er en rapport utgitt av en organisasjon (eks: SINTEF) så kan navnet på organisasjonen legges inn som forfatter.   + Tittel på boka/rapporten/standarden   + Utgivelsesår   + Utgiver/forlag (publisher)   + Hvilket land og by boka er blitt publisert fra (dersom dette er oppgitt)   + Sidenummer (dersom man viser til noe i en stor bok, kan sidehenvisning til hvor i boka legges til)   + DOI (som er en permanent kilde til boka), alternativt en URL.   For nettsider forsøker jeg å benytte en av de ovennevnte, men må da tilpasse at nettsidens URL kommer med, samt når du besøkte siden.  En god bok å se på når det gjelder å registrere referanser riktig er [denne boka](https://onlinelibrary.wiley.com/doi/book/10.1002/9781118776353). Her vet jeg forfatteren har lagt mye arbeid i akkurat dette. |

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