# Reliability Assessment for Subsea HIPPS Valves with Partial Stroke Testing

**Shengnan Wu**

**Co-authors**: L. Zhang & S. Liu
Y. Liu & A. Barros & M.A. Lundteigen

China University of Petroleum-Beijing
Norwegian University of Science and Technology

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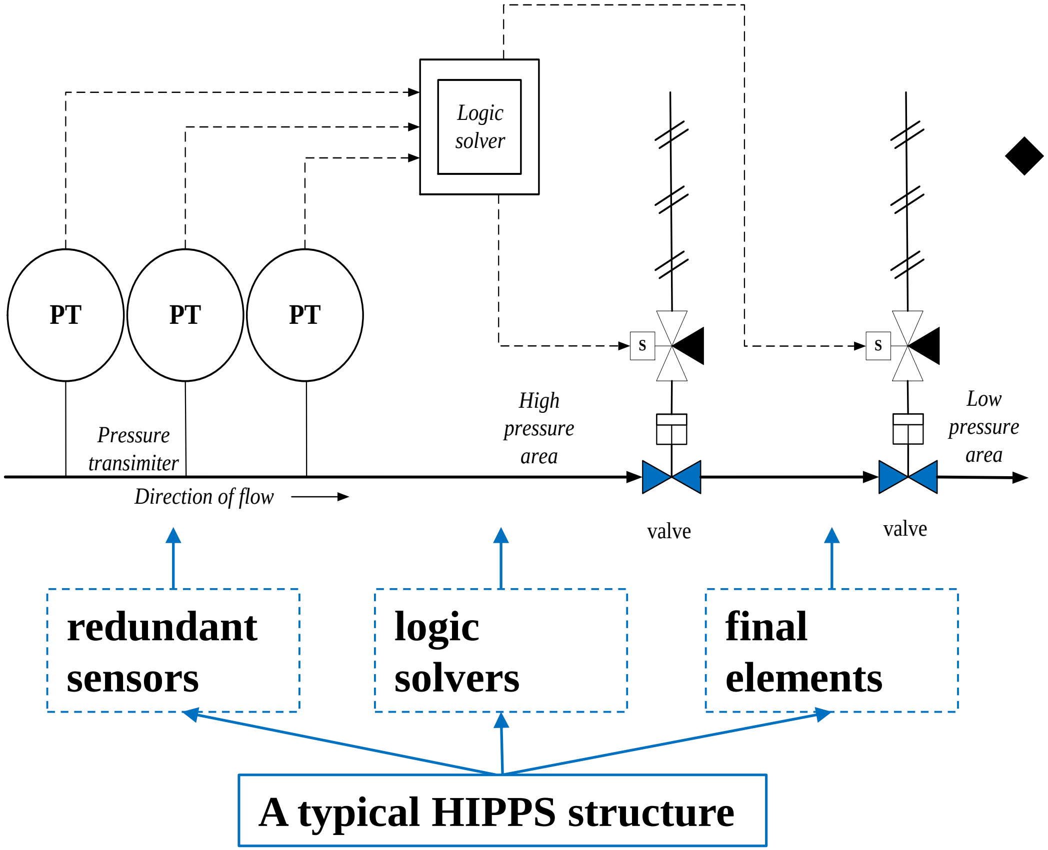
# 1. Introduction

## 1.1 Background

**What is the HIPPS?**

**high-integrity pressure protection system**




- **What kind of function can it perform?**
  - **Prevent pressure build-up**
  - **Avoid loss of containment**
  - **Prevent hazardous events**
  - **Mitigate the consequences**

# 1. Introduction

## 1.1 Background

**Requirements from standards**

- **IEC 61508**
- **IEC 61511**

**HIPPS valves as the last safety barriers are always operated in low demand mode.**

- Safety integrity level (SIL)
- Average probability of failures on demand (PFDavg)
- Regular proof testing (PT) of all SIS functions

**SILs for low-demand SISs**

| SIL | $PFD_{avg}$ |
|---|---|
| SIL4 | $10^{-5}$ to $10^{-4}$ |
| SIL3 | $10^{-4}$ to $10^{-3}$ |
| SIL2 | $10^{-3}$ to $10^{-2}$ |
| SIL1 | $10^{-2}$ to $10^{-1}$ |

# 1. Introduction

## 1.1 Background

**Why do we choose the partial stroke testing(PST)?**

- **PST**
- **Advantages**

◆ **PST of HIPPS valves , as a supplement to PT and partially operate a valve and reveal several types of dangerous failures**

- **Perform without any extra production disturbances**
- **Avoid the loss of production and reduce economic loss**
- **Reduce wear of the valve seat area and sticking seals**
- **PFDavg is reduced if without changing the PT interval**

# 1. Introduction

## 1.2 Research Status

**There have been a high number of PFDavg approaches that encounter the influence of PT and PST**

| Proposed formulation | Influence factors | Limitations | Authors |
|---|---|---|---|
| Establish generalized formulations using multi-phase Markov models | Regular partial, full proof tests and repair time | Degradation effect is not considered | Innal, Lundteigen, Liu, and Barros (2016) |
| Develop approximate generalized expressions by mathematics | Regular partial, full proof tests and CCFs | Degradation effect and postpone repair is not considered | Jin and Rausand (2014) |
| Develop generalized expressions by multi-objective genetic algorithm to optimize design and test policy of SIS | CCF, diagnostic coverage, lifecycle cost and spurious trip rate | Degradation effect is not considered and postpone repair is not considered | Torres-Echeverría, Martorell, and Thompson (2012) |

# 1. Introduction

## 1.3 Motivation

**The existing literatures focus to a large extent on the reliability assessment of SIS based on assumptions that are questionable in a subsea context, for example:**

- The failure rates are generally assumed to be constant.
- The time to repair a revealed DU-failures has been considered to be negligible.

**In order to overcome these limitation, new approximate PFDavg formulations are developed by taking into account :**

- Non-constant failure rate
- Postpone repair

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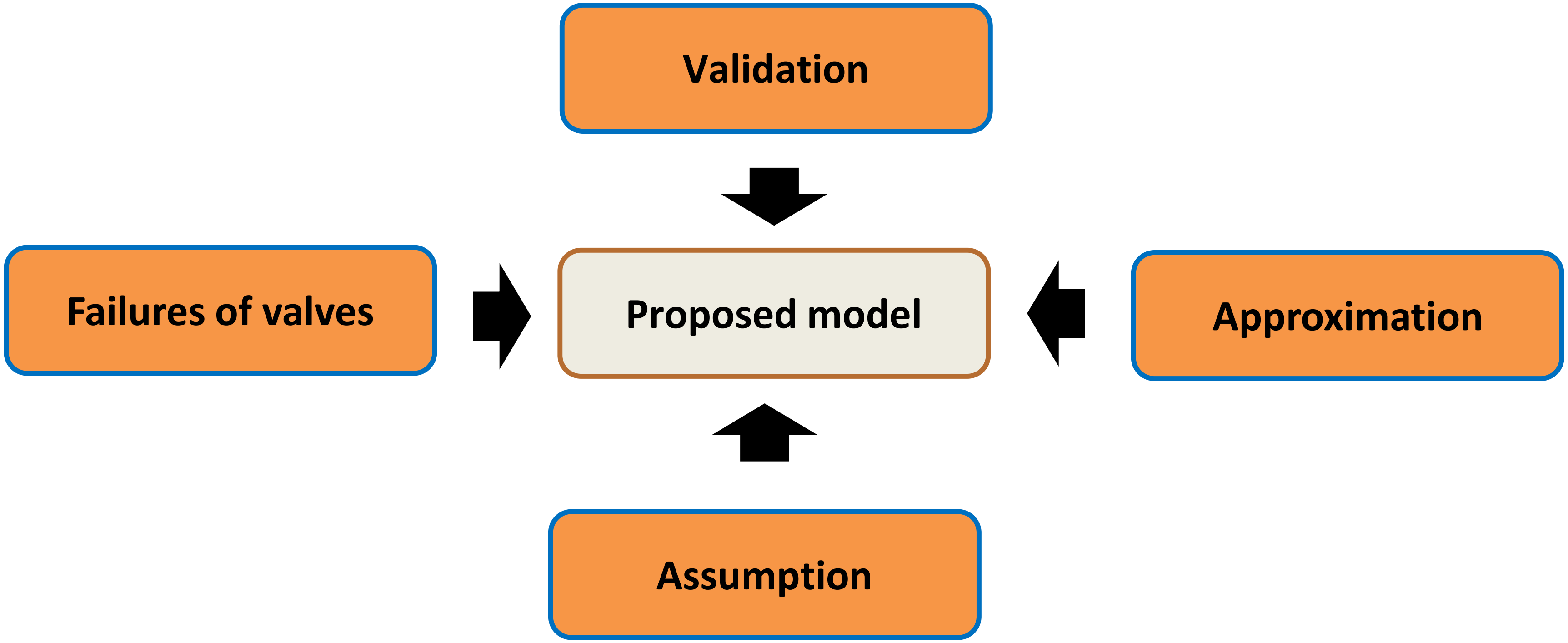
# 2. Proposed model



# 2. Proposed model

## 2.1 Failures of valves

For valves, dangerous undetected(DU) failures are considered here.

**Two types of DU failure modes of valves**

**Failures of detected by PST**
- **Fail to close due to sticking in open position**

**Remaining failures of only detected by PT**
- **Leakage in closed position**

# 2. Proposed model

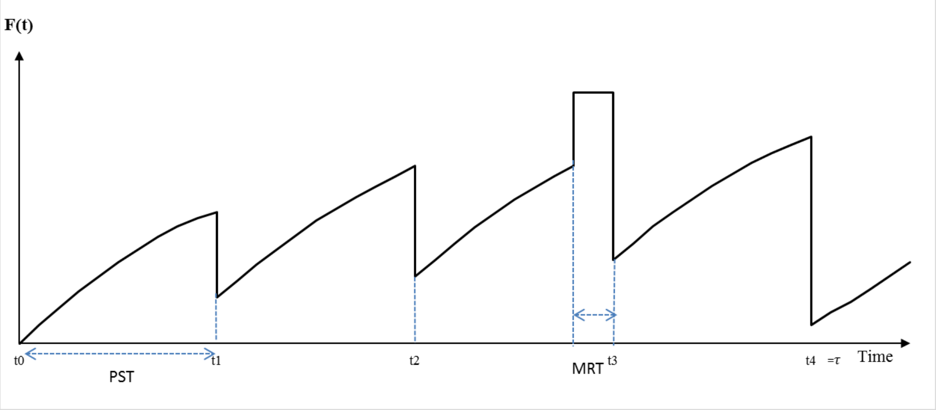
## 2.2 Assumption for PFDavg formulas

- **Failures of components assume Weibull distribution**
- **Mean repair time (MRT) is considered to be non-negligible.**
- **All components are initially in a perfect state.**
- **All PSTs are performed simultaneously for the valves.**
- **The testing time is recognized to be negligible compared with a PST interval.**
- **The effect of DD failure is not ignored**
- **Common cause failures (CCFs) have been excluded.**

# 2. Proposed model

## 2.3 Approximation formulas

**PFDavg formulas for DU failures**




**Unavailability with PST interval($\tau_i$), proof testing interval($\tau$) and MRT**

$$PFD_{avg} = PFD_{avg,PT} + PFD_{avg,PST} + PFD_{avg,MRT}$$

- $PFD_{avg,PT}$ refers to the $PFD_{avg}$ for the DU-failure detected by PT in a proof test interval.
- $PFD_{avg,PST}$ refers to the $PFD_{avg}$ for the DU-failure detected by PST in a partial test interval.
- $PFD_{avg,MRT}$ refers to the $PFD_{avg}$ for the DU-failure detected by PT in a repair.

# 2. Proposed model

## 2.3 Approximation formulas

**Non-constant failure rate function**

Weibull distribution

$$z(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1 - F(t)} = \alpha \lambda^{\alpha} t^{\alpha - 1}$$

$$\tilde{\lambda}(0,\tau) = \frac{1}{\tau}\int_0^{\tau} z(t)dt = \frac{1}{\tau}\int_0^{\tau} \alpha \lambda^{\alpha} t^{\alpha-1} dt = \lambda^{\alpha}\tau^{\alpha-1}$$

$$\tilde{\lambda}_{DU}(0,\tau) = \tilde{\lambda}_{PST}(0,\tau_{PST}) + \tilde{\lambda}_{PT}(0,\tau) = \theta_{PST} \cdot \tilde{\lambda}_{DU}(0,\tau) + (1 - \theta_{PST}) \cdot \tilde{\lambda}_{DU}(0,\tau)$$

$$\theta_{PST} = \frac{\tilde{\lambda}_{PST}(0,\tau)}{\tilde{\lambda}_{DU}(0,\tau)}$$

Partial stroke testing coverage

- λ is a scale parameters, α is a shape parameter
- $\tilde{\lambda}(0,\tau)$ is average failure rate in the proof test interval (0, τ)
- $\tilde{\lambda}_{PST}(0,\tau_{PST})$ and $\tilde{\lambda}_{PT}(0,\tau)$ are average failure rate in PST and PT interval, respectively

# 2. Proposed model

## 2.3 Approximation formulas

**Formulas for 1oo1 configuration**

Basic formulas for development

$$PFD_{avg} = \frac{1}{\tau}\int_0^{\tau} \Pr(T_{DU} \le t)dt = \frac{1}{\tau}\int_0^{\tau} 1 - e^{-\frac{z_{DU}(t)}{\alpha}t} dt$$

$$PFD_{avg,MRT} = \frac{\Pr(T_{DU} \le \tau)gMRT}{\tau}$$

| Approximation PFDavg | PT | PT +MRT | PST |
|---|---|---|---|
| The proposed formulas | $PFD_{avg} =$ $\tilde{z}_{DU}(0,\ )$ | $PFD_{avg} = \frac{\tilde{z}_{DU}(0,\tau)\cdot\tau}{\alpha+1}$ | $PFD_{avg} = \frac{\theta_{PST}\cdot\tilde{z}_{DU}(0,\tau)\cdot\tau_{PST}}{\alpha+1}$ |
| Verification α=1 | $\frac{\ }{2}$ | $\frac{\ }{2} + \lambda\cdot MRT$ | $\frac{\ \tau_{PST}\ }{2} + \frac{\ \tau_{PT}\ }{2}$ |

**These expressions are identical to the formulas in Lundteigen and Rausand (2008), Rausand (2014) and Jin and Rausand (2014) for 1oo1 systems.**

# 2. Proposed model

## 2.3 Approximation formulas

**Formulas for 1oo2 configuration**

Addition assumptions:

1. DU failures of only one HIPPS valve are discovered by a test
2. DU failures for both valves are discovered by a test

$$PFD_{avg1,MRT} = \frac{\int_0^{MRT} (1 - e^{-\frac{z_{DU}(t)}{\alpha} t}) dt}{\tau}$$

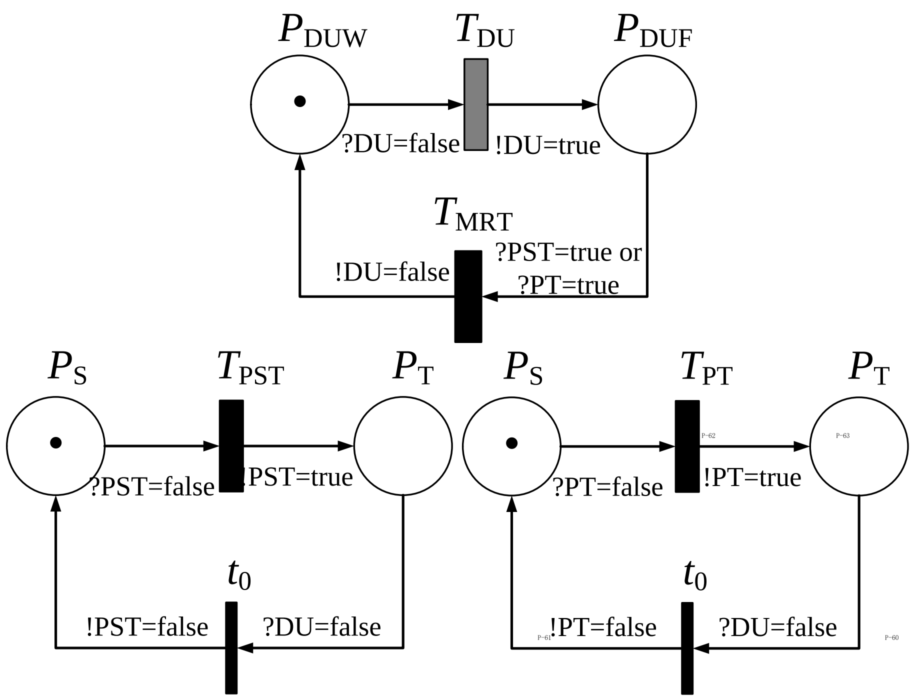
| Approximation PFDavg | PT | PT +MRT |
|---|---|---|
| The proposed formulas | $PFD_{avg} = (\%_{DU}(0,\tau)\cdot\tau)^2$ | $PFD_{avg} = \frac{(\%_{DU}(0,\tau)\cdot\tau)^2}{2\alpha+1} +$ |
| Verification α=1 | $\frac{(\lambda\tau)^3}{3}$ | $\frac{\lambda\tau}{2} + \lambda \cdot MRT$ |

**These expression are identical to the formulas in Rausand (2014).**

# 2. Proposed model

## 2.4 Validation for proposed model

**Methods: Petri nets approach**




**Petri net model for PST and PT**

**$PFD_{avg}$ for comparison between approx. formula and Petri net simulation**

| PST interval | PFDavg | |
|---|---|---|
| | Approx. formula | Petri net |
| 720h | 1.91E-04 | 1.50E-04 |
| 2190h | 2.31E-04 | 1.72E-04 |
| 2920h | 2.51E-04 | 2.33E-04 |
| 4380h | 2.92E-04 | 2.69E-04 |
| Without PST | 4.13E-04 | 3.67E-04 |

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# 3. Case study

## 3.1 Contribution from PST

**In the case study, we consider 1oo1 and 1oo2 HIPPS valves.**

**Parameters for HIPPS valves**

| Property | Parameters | Value |
|---|---|---|
| Scale parameters | $\lambda$ | $4\times10^{-4}$ |
| Shape parameters | $\alpha$ | 2 |
| PSTC | $\Theta_{PST}$ | 65% |
| PT interval | $\tau$ | 8760h |

**PFDavg of valves with PST**

| PST interval | configurations | |
|---|---|---|
| | 1oo1 | 1oo2 |
| 720h | 1.91E-04 | 5.43E-08 |
| 2190h | 2.31E-04 | 5.95E-08 |
| 2920h | 2.51E-04 | 6.48E-08 |
| 4380h | 2.92E-04 | 8.00E-08 |
| Without | | |

- $PFD_{avg}$ for 1oo1 and 1oo2 is approximately reduced by 47% and 74%, respectively with 4380h of a PST interval .
- Optimize partial testing strategies for the intervals

# 3. Case study

## 3.2 Contribution from parameters

**PFD$_{avg}$ of valves with PST at different λ and α given PST interval 2190h**

| λ | 1oo1 | 1oo2 |
|---|---|---|
| $1\times10^{-6}$ | | |
| $2\times10^{-6}$ | | |
| $4\times10^{-6}$ | | |
| $8\times10^{-6}$ | | |
| $1\times10^{-5}$ | | |

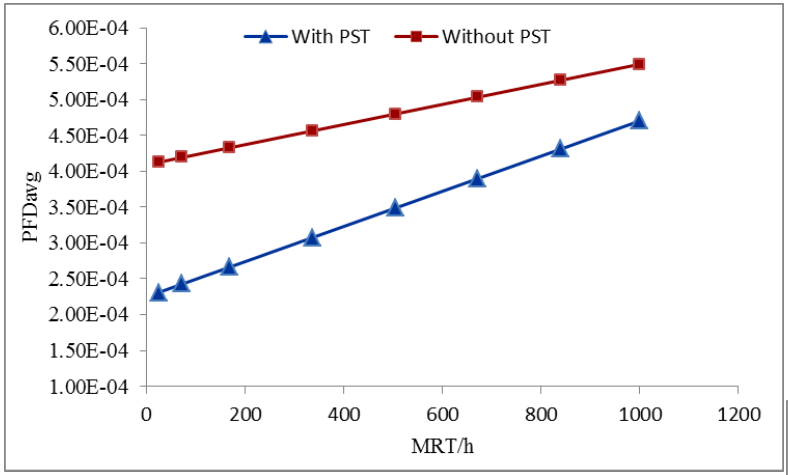
| α | 1oo1 | | 1oo2 | |
|---|---|---|---|---|
| | With PST | Without PST | With PST | Without PST |
| 1 | 1.00E-02 | 1.76E-02 | 8.23E-05 | 4.13E-04 |
| 1.5 | 1.49E-03 | 2.64E-03 | 2.12E-06 | 1.09E-05 |
| 2 | 2.31E-04 | 4.13E-04 | 5.95E-08 | 3.06E-07 |
| 2.5 | 3.70E-05 | 6.63E-05 | 1.75E-09 | 8.95E-09 |
| 3 | 6.06E-06 | 1.09E-05 | 5.33E-11 | 2.69E-10 |

- **The values of PFD$_{avg}$ decrease by performing PST compared with PT under different values of parameters.**
- **Make decision for choosing the parameters based on SILs.**

# 3. Case study

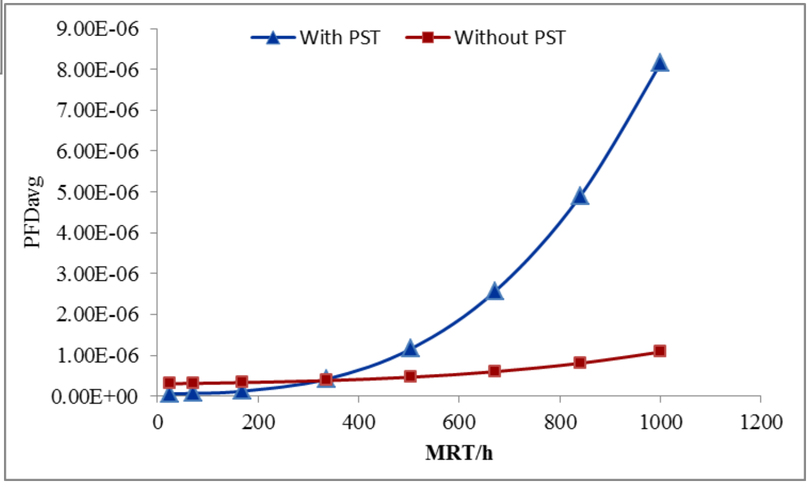
## 3.3 Contribution from non-negligible repair time

$PFD_{avg}$ with both PST and PT under different MRT for 1oo1 and 1oo2 HIPPS valves




- $PFD_{avg}$ is increasing with the growth of MRT.

- Effect over the repair time becomes large if manager do not anything for the fault channel.



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# 4. Conclusion

## 4.1 Conclusion

- **Investigate reliability of a low-demand HIPPS valves with both PT and PST.**
- **Propose a new model considering the effect  of  postpone repair associated with PST.**
- **Develop approximation formulas by introducing the non-constant failure rate and partial stroke testing coverage.**
- **Validate approximation by Petri net simulation.**
- **Provide an method to make decision for PST and MRT strategies.**

# 4. Conclusion

## 4.2 Further Research

- **Common cause failures**
- **Non-period PST intervals**
- **Effects of minor repairs after PT and PST**

**Thank you for your attention!**