FMEA and PFD Evaluation of Ball Valve

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Table of content

1. Purpose and scope

General two options exist when doing safety integrity level assessment for hardware product like valves.

Option 1: Hardware assessment according to IEC 61508

Option 1 is a hardware assessment according to the relevant functional safety standard like IEC 61508. The hardware assessment consists of a FMEA to determine the fault behavior and the failure rates of the devices, which are then used to calculate the Safe Failure Fraction (SFF), and the average Probability of Failure on Demand (PFD_{AVG}).

Option 2: Hardware assessment with proven-in-use consideration according to IEC 61508 / IEC 61511.

Option 2 is an assessment according to relevant functional safety standard like IEC 61508. The hardware assessment consists of a FMEA to determine the fault behavior and the failure rates of the devices, which are then used to calculate the Safe Failure Fraction (SFF), and the average Probability of Failure on Demand (PFD_{AVG}). In addition this option consists of an assessment of the proven-in-use documentation of the device.

This assessment shall be done according to option 2.

This document shall include the FMEA of Valve, and assess whether the device meet the average Probability of Failure on Demand (PFD_{AVG}) requirements and the architectural constraints for SIL 2 sub-systems according to IEC 61508 / IEC 61511.

2. Referenced documents

2.1. Codes & standards

- **IEC 61508 edition 2.0** – Functional safety of electrical/electric/programmable electronic safety-related systems;
- **IEC 61511 first edition 2003-03 –** Functional safety – Safety instrumented systems for the process industry sector;
- **API Q1 9th edition**– Specification for quality management system requirements for manufacturing organizations for the petroleum and natural gas industry.

2.2. Documents used as proven-in-use evidences

- After-sales service records
- Delivery records of 2011, 2012 and 2013
- Statistics of field-feed-back tracking; sold and return devices

3. Product Description

4. Failure modes, effects, and analysis

4.1. Description of the failure categories

Three Safety Instrumented Functions (SIF) are defined in Safety Requirement Specification for Valve:

a) Valve to open on demand;
b) Valve to close (full stroke) on demand;
c) Valve to close (tight shutoff).

SIF a is considered to have same failure categories with SIF b. The failure categories for SIF c shall be separately defined.

Failure categories	SIF a&b	SIF c
Fail-safe state	Valve to open or close	Valve to close (tight shutoff)
Fail dangerous	Valve does not respond to a demand from the process to open or close	Valve does not respond to a demand from the process to tightly shutoff.
Fail no effect	Failure of a component that is part of the safety function but that has no effect on the safety functions	Failure of a component that is part of the safety function but that has no effect on the safety functions
Not considered	Not considered means that this failure mode was not considered. When calculating the SFF this failure mode is divided into 50% safe failure and 50% dangerous failures.	Not considered means that this failure mode was not considered. When calculating the SFF this failure mode is divided into 50% safe failure and 50% dangerous failures.
Not part	Failures of a component which is not part of the safety function but part of the product and is listed for completeness. When calculating the SFF this failure mode is not taken into account. It is also not part of the total failure rate.	Failures of a component which is not part of the safety function but part of the product and is listed for completeness. When calculating the SFF this failure mode is not taken into account. It is also not part of the total failure rate.

Table 1. Failure categories of FMEAs for valve

4.2. Methodology – FMEA, failure rates

4.2.1. FMEA

A Failure modes and effects analysis (FMEA) is a systematic way to identify and evaluate the effects of different component failure modes, to determine what could eliminate or reduce the change of failure, and to document the system in consideration.

4.2.2. Failure rates

The failure rate used in this FEMA are collected from the statistics of field experiences. The user of these numbers is responsible for determining their applicability to any particular environment. Some industrial plan sites have high levels of stress. Under those conditions the failure rate data is adjusted to a higher value to account for the specific conditions of the plant.

4.2.3. Assumptions

The following assumptions have been made during the FMEA:

- 0 Failure rates are constant, wear out mechanisms are not included.
- 0 Propagation of failures is not relevant.
- 0 The repair time after a safe failure is 8 hours.
- 0 All modules are operated in the low demand mode of operation.
- 0 External power supply failure rates are not included.
- 0 5% of the valves delivered in 2011 is assumed to have not been put in use, and 10% for 2012, 15% for 2013.
- 0 Due to the failures are usually reported during commissioning or beginning stage, the valves with complaint are considered delivered in the same year of complaint reported.
- 0 Due to lacking of accurate records regarding to when the valves are put in use and when the failures happen, the successive working hours are calculated by using average method, ie. a valve delivered in 2013 is considered has 4380 successive working hours (0.5 year), and 13140 hours (1.5 year)for a valve delivered in 2012, 21900 hours for 2011.

4.2.4. Abbreviation

DOP	Delayed operation, including fail to respond and any other circumstances of failing to open or close
ELP	External leakage
PST	Partial stroke test
LCP	Valve leakage in closed position

4.3. Summary of sales and after-sales data

Year	**2014**		
Delivered Number	817		
Complained Number	6		
Failure category	**Dangerous**	**Safe**	**No effect**
SIF a & b	0	4	2
SIF c	2	2	2
Year	**2015**		
Delivered Number	877		
Complained Number	34		
Failure category	**Dangerous**	**Safe**	**No effect**
SIF a & b	9	2	23
SIF c	9	2	23
Year	**2016**		
Delivered Number	227		
Complained Number	67		
Failure category	**Dangerous**	**Safe**	**No effect**
SIF a & b	0	2	65
SIF c	2	0	65

Table 2. Data summary

NOTE

Due to lacking of effective method to monitor the working performance of the product supplied for foreign projects, all the data above stated is collected from domestic sales and after-sales records.

4.4. FMEA Table

Refer to Appendix A.

5. Result of assessment

5.1. Methodology – Markov process

According to the assumptions stated in 4.2.3, the total successive working hours T=5.1168E07 hours. And the λ and SFF are as listed in following table.

	λ_{safe} (per 10^9 hour)	$\lambda_{dangerous}$(per 10^9 hour)
SIF a&b	293	329
SIF c	146	475

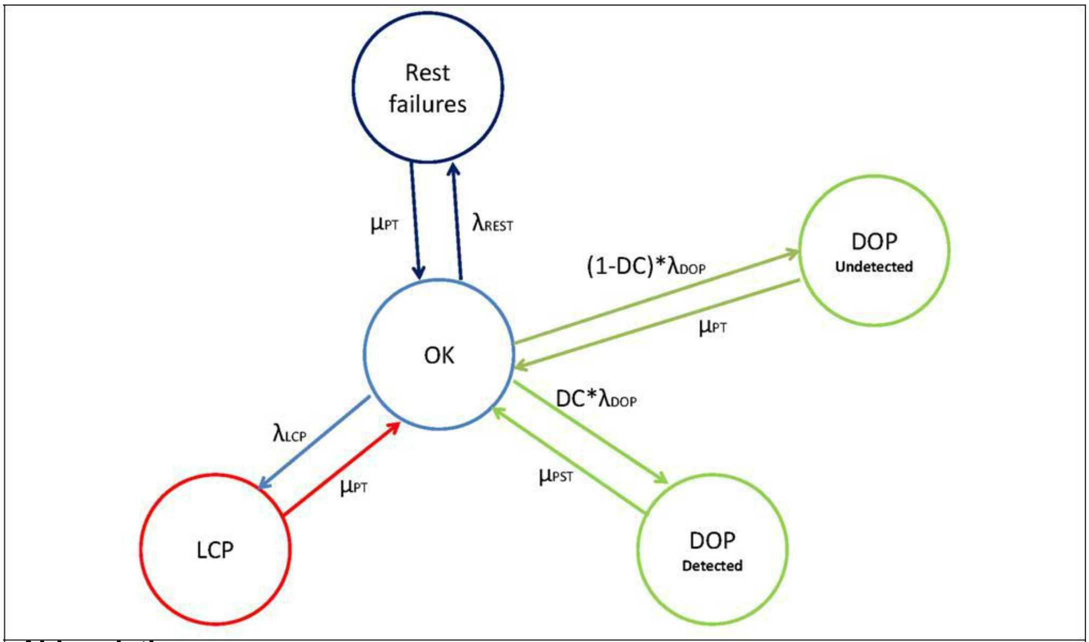
Table 3. λ_{safe} and $\lambda_{dangerous}$ for each SIF

The PFDAVG calculations for three SIFs are done in one Markov model, the λ data are re-summarized as following table.

λ_{DOP}	λ_{LCP}	λ_{REST}
1.76E-07 per hour	7.82E-08 per hour	1.84E-06 per hour

Table 4. Reorganization of λ values

The Markov model is showed in following figure.



Abbreviations:

λ_{DOP} Failure rate of delayed operation (including not responding etc.)
λ_{LCP} Failure rate of leakage in closed position
PT Repair rate of proof test

μ_{PST}	Repair rate of partial stroke test
DC	Diagnostic Coverage (45.2%)

Figure 3: Markov model for valve

NOTE

1) For SIF a&b, $\lambda_{dangerous}$ is equivalent to λ_{DOP}, while λ_{safe} equals to the sum of λ_{LCP} and λ_{REST}. For SIF c, $\lambda_{dangerous}$ is equivalent to the sum of λ_{DOP} and λ_{LCP}, λ_{safe} equals to λ_{REST}.
2) The Diagnostic Coverage data used in this document is quoted from Volume 3 of *Safety Equipment Reliability Handbook*, 3rd edition, exida. The diagnostic only applies to those failure related to the full stroke, failure related to the tight shutoff will not be detected by the partial stroking of the valve.
3) The failures are considered independent from each other, the states with two or more failures occurring at same time period are not taken in into account.
4) The proof test is assumed to be perfect. And except the failures detected during partial stroke test (PST), all other failures will be detected and restored during proof test.

The PDF_{AVG} (average unavailability) was calculated based on equations as follow.

$$PFD_{AVG}(T) = \frac{1}{T}\sum_{k=1}^{n} q_k MCT_k(T)$$

Where $q_k = 1$ if the system is unavailable in state k, and $q_k = 0$ otherwise; MCT is the Mean Cumulated times spent in the states. Refer to IEC 61508-6 for details.

5.2. PFD_{AVG} Calculations for SIF a & b

5.2.1. PFD_{AVG} calculations (without PST function)

The PFDAVG was calculated for three different proof test intervals using the Markov model without taking the PST into account. The PFDAVG values for three proof test intervals (1 year, 2 years and 5 years) are displayed in following table.

	TI=1 year, MTTR=24 hr	TI=2 year, MTTR=24 hr	TI=5 year, MTTR=24 hr
PFD_{AVG}	0.007825537602	0.007818795991	0.008813905087

5.2.2. PFD_{AVG} calculations (with PST function)

The PFDAVG with PST taken into account was calculated by using the multi-phase Markov model. The partial stroke tests are singular points along the time, and the system will start again from a new beginning state when the PST is performed. The new beginning state will be calculated from the previous state before PST by using a linking matrix [L].

The PFDAVG values for three proof test intervals - TI (1 year, 2 years and 5 years) with two different PST intervals - PSTI (3 months and 6 months) are displayed in following table. (DC=45.2%, refer to 5.1).

	TI=1 year, MTTR=24 hr	**TI=2 year, MTTR=24 hr**
PSTI=3 months	PFDAVG = 0.0008615831273	PFDAVG = 0.001614029029
PSTI=6 months	PFDAVG = 0.0009515547176	PFDAVG = 0.001702524390

5.3. PFD_{AVG} Calculations for SIF c

5.3.1. PFD_{AVG} calculations (without PST function)

Different from SIF a & b, the occurrence of either LCP or DOP will be regarded as dangerous failure of SIF c. The calculation was done based on the same Markov model stated in Figure 1.

	TI=1 year, MTTR=24 hr	**TI=2 year, MTTR=24 hr**	**TI=5 year, MTTR=24 hr**
PFDAVG	0.008059109870	0.008071594209	0.009842307347

5.3.2. PFD_{AVG} calculations (with PST function)

The PFDAVG with PST taken into account was calculated by using the multi-phase Markov model. The partial stroke tests are singular points along the time, and the system will start again from a new beginning state when the PST is performed. The new beginning state will be calculated from the previous state before PST by using a linking matrix [L].

The PFDAVG values for three proof test intervals - TI (1 year, 2 years and 5 years) with two different PST intervals - PSTI (3 months and 6 months) are displayed in following table. (DC=45.2%, refer to 5.1).

	TI=1 year, MTTR=24 hr	**TI=2 year, MTTR=24 hr**
PSTI=3 months	PFDAVG = 0.001486710499	PFDAVG = 0.002850611022
PSTI=6 months	PFDAVG = 0.001576668885	PFDAVG = 0.002939083193

6. Conclusion

The calculated PFD_{AVG} values are within the allowed range for SIL 2 according to Table 2 of IEC 61508-1 which is as follow.

Safety integrity level (SIL)	Average probability of a dangerous failure on demand of the safety function (PFD_{AVG})
4	$\geq 10^{-5}$ to $< 10^{-4}$
3	$\geq 10^{-4}$ to $< 10^{-3}$
2	$\geq 10^{-3}$ to $< 10^{-2}$
1	$\geq 10^{-2}$ to $< 10^{-1}$

Table 5. Table 2 of IEC 61508-1

Appendix A: FMEA of valve

FMEA of Valve								
N°	Component	Function	Failure mode	Cause	Effect	Detection Mode	Failure category for SIF a&b	Failure category for SIF c
1	Body	Contain the process pressure	Fracture	Material Defection	ELP	Undetectable during PST	No effect	No effect
			Distortion	Material Defection, Overpressure	DOP	Detectable during PST	Dangerous	Dangerous
			Explosion	Material Defection, Overpressure, Corrosion, Erosion	No function can be implemented any more	Undetectable during PST	Dangerous	Dangerous
2	Ball	Shut off the medium	Fracture	Material Defection, Overpressure	LCP	Undetectable during PST	No effect	Dangerous
			Distortion 1	Material Defection, Overpressure	DOP	Detectable during PST	Dangerous	Dangerous
			Distortion 2	Material Defection, Overpressure	LCP	Undetectable during PST	No effect	Dangerous
			Erosion 1	Pollution	LCP	Undetectable during PST	No effect	Dangerous
			Erosion 2	Pollution	DOP	Detectable during PST	Dangerous	Dangerous
3	Sealing ring	Provide sealing between seat and body	Break	Material Defection	LCP	Undetectable during PST	No effect	Dangerous
4	Seat	Shut off the medium	Fracture	Material Defection, Overpressure	LCP	Undetectable during PST	No effect	Dangerous
			Distortion 1	Material Defection, Overpressure	DOP	Detectable during PST	Dangerous	Dangerous
			Distortion 2	Material Defection, Overpressure	LCP	Undetectable during PST	No effect	Dangerous
			Erosion 1	Pollution	LCP	Undetectable during PST	No effect	Dangerous
			Erosion 2	Pollution	DOP	Detectable during PST	Dangerous	Dangerous

5	Spring	Provide sealing force between ball and seat	Distortion or Break	Material Defection	LCP	Undetectable during PST	No effect	Dangerous
6	Thrust washer	Decrease the friction	Break	Material Defection	DOP	Detectable during PST	Dangerous	Dangerous
7	Bearing	Decrease the friction	Break	Material Defection	DOP	Detectable during PST	Dangerous	Dangerous
8	Grease fitting	Grease injection for emergency	Choked	Pollution	LCP under fire	Undetectable during PST	No effect	Dangerous
10	Stem	Drive the ball to required position	Break	Material Defection	DOP	Detectable during PST	Dangerous	Dangerous
11	Screw	Fasten the stem sealing devices	Break	Material Defection	ELP	Undetectable during PST	No part	No part
12	Mounting plate	Mounting the actuator	Distortion	Excessive actuator output	DOP	Detectable during PST	Dangerous	Dangerous
13	Packing	Seal the stem	Wear off	Material Defection, Over-duty use	ELP	Undetectable during PST	No effect	No effect
			Distortion	Incorrect installation	DOP	Detectable during PST	Dangerous	Dangerous
14	Bolt/Nut	Fasten the body and bonnet	Fracture	Material Defection	ELP	Undetectable during PST	No effect	No effect
			Simultaneously break	Corrosion, Design Defection	No function can be implemented any more	Undetectable during PST	Dangerous	Dangerous
15	Gasket	Seal the body/bonnet	Break	Corrosion	ELP	Undetectable during PST	No effect	No effect
16	Bleeding & Drain	Bleed the body	Plugged	Pollution	Can't bleed	Undetectable during PST	No part	No part
17	Trunnion	Support the ball	Distortion	Material Defection, Over-pressure	DOP	Detectable during PST	Dangerous	Dangerous

Appendix B: Calculation example of multiphase Markovian equations (MTTR=24 hour; TI=2 year; PSTI=3 month)

>
$p := \frac{3 \cdot 720}{2} + 24$

$$1104$$

$T := (817 \cdot 0.95 - 6) \cdot 21900 + (877 \cdot 0.9 - 34) \cdot 13140 + (227 \cdot 0.85 - 67) \cdot 4380$

$$2.734258800\ 10^{7}$$

1-3months

$$A := add\left([1, 0, 0, 0, 0] \begin{bmatrix} 1 - \frac{94}{T} - \frac{4}{T} - \frac{0.452 \cdot 9}{T} - \frac{0.548 \cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452 \cdot 9}{T} & \frac{0.548 \cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1 - \frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{k}, k = 1..2160 \right)$$

$$[2151.03985597549, 8.00130090465542, 0.340480889544950, 0.198570605645084, 0.419812936933905]$$

$$a := [1, 0, 0, 0, 0] \begin{bmatrix} 1 - \frac{94}{T} - \frac{4}{T} - \frac{0.452 \cdot 9}{T} - \frac{0.548 \cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452 \cdot 9}{T} & \frac{0.548 \cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1 - \frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{2160}$$

$$[0.991762041096043, 0.00739500301976258, 0.000314680979550635, 0.000140292954066077, 0.000388001647901444]$$

$$B := add\left([0.991762041096043,\ 0.00739500301976258,\ 0.000314680979550635,\ 0,\ 0.000388001647901444] \begin{bmatrix} 1-\frac{94}{T}-\frac{4}{T}-\frac{0.452\cdot 9}{T}-\frac{0.548\cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452\cdot 9}{T} & \frac{0.548\cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1-\frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{k},\ k=1..2160 \right)$$

$$[2133.31967804118,\ 23.9085930393119,\ 1.01738693779867,\ 0.196934789156246,\ 1.25443809467921]$$

$$b := [0.991762041096043,\ 0.00739500301976258,\ 0.000314680979550635,\ 0,\ 0.000388001647901444] \begin{bmatrix} 1-\frac{94}{T}-\frac{4}{T}-\frac{0.452\cdot 9}{T}-\frac{0.548\cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452\cdot 9}{T} & \frac{0.548\cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1-\frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{2160}$$

$$[0.983591946158989,\ 0.0147290863085537,\ 0.000626769630123875,\ 0.000139137226475966,\ 0.000772806954172809]$$

7-9 months

$$C := add\left([0.983591946158989,\ 0.0147290863085537,\ 0.000626769630123875,\ 0,\ 0.000772806954172809]\begin{bmatrix} 1-\frac{94}{T}-\frac{4}{T}-\frac{0.452\cdot 9}{T}-\frac{0.548\cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452\cdot 9}{T} & \frac{0.548\cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1-\frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{k},\ k=1..2160\right)$$

$$[2115.74547820448,\ 39.6848415550897,\ 1.68871666184503,\ 0.195312448456418,\ 2.08218764467480]$$

$$c := [0.983591946158989,\ 0.0147290863085537,\ 0.000626769630123875,\ 0,\ 0.000772806954172809]\begin{bmatrix} 1-\frac{94}{T}-\frac{4}{T}-\frac{0.452\cdot 9}{T}-\frac{0.548\cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452\cdot 9}{T} & \frac{0.548\cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1-\frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{2160}$$

$$[0.975489156128268,\ 0.0220027517206136,\ 0.000936287307219301,\ 0.000137991019722247,\ 0.00115444225014509]$$

10-12 months

$$E := add\left([0.975489156128268,\ 0.0220027517206136,\ 0.000936287307219301,\ 0,\ 0.00115444225014509] \cdot \begin{bmatrix} 1-\frac{94}{T}-\frac{4}{T}-\frac{0.452\cdot 9}{T}-\frac{0.548\cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452\cdot 9}{T} & \frac{0.548\cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1-\frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{k},\ k=1..2160 \right)$$

$$[2098.31605390380,\ 55.3311259839361,\ 2.35451599921369,\ 0.193703472532602,\ 2.90311822789478]$$

$$c := [0.975489156128268,\ 0.0220027517206136,\ 0.000936287307219301,\ 0,\ 0.00115444225014509] \cdot \begin{bmatrix} 1-\frac{94}{T}-\frac{4}{T}-\frac{0.452\cdot 9}{T}-\frac{0.548\cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452\cdot 9}{T} & \frac{0.548\cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1-\frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{2160}$$

$$[0.967453116548828,\ 0.0292164969759278,\ 0.00124325519041077,\ 0.000136854255372660,\ 0.00153293365023285]$$

13-15 months

$$F := add\left([0.967453116548828,\ 0.0292164969759278,\ 0.00124325519041077,\ 0,\ 0.00153293365023285] \cdot \begin{bmatrix} 1-\frac{94}{T}-\frac{4}{T}-\frac{0.452\cdot 9}{T}-\frac{0.548\cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452\cdot 9}{T} & \frac{0.548\cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1-\frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{k},\ k = 1 .. 2160 \right)$$

$$[2081.03021248422,\ 70.8485169646579,\ 3.01483050900285,\ 0.192107751286326,\ 3.71728601870718]$$

$$F := [0.967453116548828,\ 0.0292164969759278,\ 0.00124325519041077,\ 0,\ 0.00153293365023285] \cdot \begin{bmatrix} 1-\frac{94}{T}-\frac{4}{T}-\frac{0.452\cdot 9}{T}-\frac{0.548\cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452\cdot 9}{T} & \frac{0.548\cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1-\frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{2160}$$

$$[0.959483277533194,\ 0.0363708156942851,\ 0.00154769428479567,\ 0.000135726855641068,\ 0.00190830705372118]$$

16-18 months

$$G := add\left([0.959483277533194,\ 0.0363708156942851,\ 0.00154769428479567,\ 0,\ 0.00190830705372118] \begin{bmatrix} 1-\frac{94}{T}-\frac{4}{T}-\frac{0.452\cdot 9}{T}-\frac{0.548\cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452\cdot 9}{T} & \frac{0.548\cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1-\frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{k},\ k=1..2160 \right)$$

$$[2063.88677111589,\ 86.2380763161839,\ 3.66970537499665,\ 0.190525175526097,\ 4.52474672871794]$$

$$g := [0.959483277533194,\ 0.0363708156942851,\ 0.00154769428479567,\ 0,\ 0.00190830705372118] \begin{bmatrix} 1-\frac{94}{T}-\frac{4}{T}-\frac{0.452\cdot 9}{T}-\frac{0.548\cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452\cdot 9}{T} & \frac{0.548\cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1-\frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{2160}$$

$$[0.951579093723842,\ 0.0434661974290548,\ 0.00184962542243227,\ 0.000134608743382134,\ 0.00228058814653794]$$

19-21 months

$$H := add\left([0.951579093723842,\ 0.0434661974290548,\ 0.00184962542243227,\ 0,\ 0.00228058814653794] \begin{bmatrix} 1-\frac{94}{T}-\frac{4}{T}-\frac{0.452\cdot 9}{T}-\frac{0.548\cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452\cdot 9}{T} & \frac{0.548\cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1-\frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{k},\ k=1..2160 \right)$$

$$[2046.88455671302,\ 101.500857110222,\ 4.31918540875717,\ 0.188955636959945,\ 5.32555561058307]$$

$$h := [0.951579093723842,\ 0.0434661974290548,\ 0.00184962542243227,\ 0,\ 0.00228058814653794] \begin{bmatrix} 1-\frac{94}{T}-\frac{4}{T}-\frac{0.452\cdot 9}{T}-\frac{0.548\cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452\cdot 9}{T} & \frac{0.548\cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1-\frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{2160}$$

$$[0.943740024255880,\ 0.0505031277006855,\ 0.00214906926376519,\ 0.000133499842086038,\ 0.00264980240301135]$$

22-24 months

$$J := add\left([0.943740024255880,\ 0.0505031277006855,\ 0.00214906926376519,\ 0,\ 0.00264980240301135] \cdot \begin{bmatrix} 1 - \frac{94}{T} - \frac{4}{T} - \frac{0.452 \cdot 9}{T} - \frac{0.548 \cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452 \cdot 9}{T} & \frac{0.548 \cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1 - \frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{k},\ k = 1\, ..\, 2160 \right)$$

[2030.02240585367, 116.637903743319, 4.96331505269061, 0.187399028187997, 6.11976746178946]

$$j := [0.943740024255880,\ 0.0505031277006855,\ 0.00214906926376519,\ 0,\ 0.00264980240301135] \cdot \begin{bmatrix} 1 - \frac{94}{T} - \frac{4}{T} - \frac{0.452 \cdot 9}{T} - \frac{0.548 \cdot 9}{T} & \frac{94}{T} & \frac{4}{T} & \frac{0.452 \cdot 9}{T} & \frac{0.548 \cdot 9}{T} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{1}{p} & 0 & 0 & 1 - \frac{1}{p} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{2160}$$

[0.935965532720041, 0.0574820880299285, 0.00244604629903917, 0.000132400075873249, 0.00301597508761318]

Preliminary calculation

$$\frac{\left(\frac{(A + B + C + E + F + G + H + J)}{2160} \right)}{8}$$

[0.967606771544661, 0.0290596768297093, 0.00123658199269963, 0.0000893234321614997, 0.00152470559745257]

PFDavg calculation for SIF a&b

$0.0000893234321614997 + 0.00152470559745257$

0.007818795991

PFDavg calculation for SIF c

$0.0000893234321614997 + 0.00152470559745257 + 0.00123658199269963$

0.008071594209