Risk-Based Approach to Centrifugal Pump Seal Selection

James Fairburn, Senior Process Risk Engineer, Chevron, 1 Westferry Circus, London, E14 4HA

The American Petroleum Institute have reported that releases from pumps are the third biggest contribution to Tier 1 Process Safety Events in the US Refining Industry from 2011-2014. The American Fuel & Petrochemical Manufacturers Event Sharing Database indicates that seal leaks are the most common mode of reported pump failure. Data from the HSE Hydrocarbon release system database reveals that seal failure from a double seal is relatively less likely compared with failure from a single seal pump. However, an EPC contractor on a fixed cost project may have no incentive to specify a more costly enhanced seal arrangement, unless the facility owner provides clear guidelines when to do so. Facility owners may not have that guidance or can be unclear of the basis of the historical guidance which does exist. Alternatively, contractors may unnecessarily specify an enhanced seal arrangement, leading to non-optimised expenditure on risk control systems.

API 682 4th Edition (Pumps – Shaft Sealing Systems for Centrifugal and Rotary Pumps) was issued in May 2014 and contains a seal selection procedure in Annex A. To determine which seal arrangement to recommend, an understanding of the vapour cloud or fire risk is needed. This paper draws together API 754 Tier 1 release threshold quantities for different materials, with aspects from the risk based approach to area classification (EI15 4th Edition), in order to develop an approach to assess the vapour cloud or fire risk following seal failure and hence recommend either an Arrangement 1, 2 or 3 seal for a range of potential situations. Some common applications are re-considered by following this approach to highlight the potential impact that engineers can make to future operational process safety performance during the design phase.

Keywords: Seal Selection, API 682, Process Safety Event, API 754, Risk-Based Approach, EI15, Inherently Safer Design

Disclaimer

The statements and data in this paper are for information only. Seal selection can be made in accordance with API 682 and from vendor/end user experience.

Introduction

The selection of an appropriate seal arrangement is a multi-faceted issue. The objectives of seal selection are (per API 682 [API, 2014]):

- Reliability, i.e. continuous seal operation for 25,000 hours; and
- Emissions of volatile organic compounds, potentially leading to environmental impact and/or adverse health effects.

The potential for process leakage to atmosphere for different seal arrangements is illustrated in Table 1.

Table 1. Potential for Process Leakage to Atmosphere for Different Seal Arrangements

Single Seal	Double Seal	
Arrangement 1	**Arrangement 2**	**Arrangement 3**
Process leakage to atmosphere	Process leakage contained and controlled	Elimination of process leakage to atmosphere, due to the higher pressure barrier fluid

Cost is always a factor in equipment selection. The life cycle costs for double seals are higher than that for single seals due to the initial outlay and ongoing repairs, and hence will only be specified for specific applications.

Seal specification is usually undertaken by rotating equipment specialists, both from the vendor and end user, rarely involving process safety professionals. Process safety aspects, such as the consequences and risk of seal failure, appear to be secondary considerations, in both API 682 and also in practice. API 682 Second Edition, issued 2002, initially included the question 'will normal leakage from an Arrangement 1 (or 2) seal present an unacceptable vapour cloud or fire risk according to guidelines/requirements of the owner or local regulators?' in its Recommended Seal Selection Procedure in an informative annex. However, facility owners may not have that guidance or can be unclear of the basis of the historical guidance which does exist.

API 682 Fourth Edition incorporated a new and alternative seal arrangement selection method using material safety datasheet information. The basis for this method is unclear, although the use of eight hour time weighted average exposure limits in the seal selection logic potentially indicates adverse health effects from continuous seal emissions are the primary concern. On the other hand, in order to adequately assess the vapour cloud or fire risk, additional information would need to be considered, which is not included in the material safety datasheet.

This paper suggests that process safety aspects of centrifugal pump seal selection are as important as reliability, emissions and cost. Any of these factors could influence the selection of a higher integrity seal arrangement.

Background

API annually publishes an internal benchmarking report, based on data voluntarily reported by petroleum companies operating in the United States. The 2014 Process Safety Events Report for the U.S. Refining Industry [API, 2015], indicates that pumps are the third biggest contributor to Tier 1 Process Safety Events (T-1 PSE), as can be seen in Table 2.

Table 2. Proportion of T-1 PSE by Point of Release

Point of Release	Proportion of PSE (2011-2014)
Piping system	39%
Atmospheric tank	18%
Pump	8%

It is noted that there has been a considerable body of work addressing some points and modes of release, for example on tank overfill prevention, following the Buncefield accident. Development of, and adherence to, similar safety standards for pumps, could therefore potentially significantly reduce the number of T-1 PSE in future.

The American Fuel & Petrochemical Manufacturers (AFPM) administers an Event Sharing Database for its members. Submission to the database is voluntary and hence causal information is not available for all events. However, in the period 2011-2013, approximately 60% of T-1 and T-2 PSE, where pump was identified as the point of release, were associated with seal failures. This statistic is unsurprising, considering seals are widely regarded as an inherent weak point of the pump design and where seal failure can’t be tolerated, sealless pumps are specified.

Neither API nor AFPM data distinguish between single and double seal pumps. However, data from the HSE Hydrocarbon release system (HCR) database, summarised in Table 3, indicate that the leak frequency from single seals is higher than that from double seals.

Table 3. Seal Leak Frequencies

	Leak frequency (1996/97 – 2004/05)
Single Seal	0.0109 / pump - yr
Double Seal	0.0088 / pump - yr

Double seal leak frequencies are lower than for single seals, as expected, but not significantly so. The seal leak frequencies presented in Table 3 are for all release sizes. However, the release rate from a pump seal is variable. Analysis of the equivalent hole size vs. cumulative frequency for incidents reported in the HSE Hydrocarbon release system database was performed by the EI Area Classification Working Group, prior to the launch of Part 15: Area classifications for installations handling flammable fluids 4th Edition [EI, 2015]. Table 4 summarises the equivalent hole size distribution at various release frequency bands from pumps, which was similarly presented in a paper in Hazards 25 [IChemE, 2015].

Table 4. Equivalent Hole Sizes for a range of Release Frequencies

	Hole size (mm)		
Equipment type	**LEVEL I Greater than 1.0E-2/ release source-yr**	**LEVEL II 1.0E-2-1.0E-3/ release source-yr**	**LEVEL III 1.0E-3-1.0E-4/ release source-yr**
Single seal with throttle bush	2	5	10
Double seal	1	2	10

Table 4 indicates that for LEVEL I and LEVEL II releases, the equivalent hole size from a double seal is approximately half that of a single seal. In other words, for a given release frequency and operating conditions, the release flow rate will be greater (by approximately half an order of magnitude) for a single seal than for a double seal, which is significant. Note that LEVEL III failures are assumed to be independent of the seal arrangement.

The background information summarised in this paper indicates that the vapour cloud or fire risk is greater for a single seal pump than that from a double seal pump and that releases from pumps, in particular seal failures, contribute significantly to the number of T-1 PSE.

How can you determine if this risk is acceptable or whether specification of an enhanced seal is appropriate?

Risk-Based Approach to Seal Selection

Seals normally leak, usually at relatively low flow rates. It is therefore proposed to replace ‘normal’ with ‘foreseeable’ in the question ‘will normal leakage from an Arrangement 1 [or 2] seal present an unacceptable vapour cloud or fire risk..?’, in order to consider the process safety aspects of seal selection.

API 754 have categorised incidents with greater consequences resulting from actual losses of containment as T-1 PSE. A T-1 PSE is an unplanned or uncontrolled release of any material that results in one or more defined consequences, including a release of material greater than the material release threshold quantity in any one hour period.

A seal selection philosophy could adopt an inherently safer design (ISD) goal that failure of the specified seal arrangement cannot result in a T-1 PSE (defined by the quantity released) at a release frequency which achieves a target level of risk.

Flammable Releases

Initially, a risk-based approach to seal selection will be developed in this paper for flammable releases.

Step 1

Determine the Tier 1 material release threshold quantity for a particular substance from API 754 for either an outdoor or indoor release.

Step 2

This paper recognises that the total individual risk (IR) for a typical onshore plant worker in the UK is of the order of 1.0E-4/yr, which is an order of magnitude less than available numerical risk criteria. The EI15 risk-based approach to area classification suggests that the IR acceptability level for a fatality due to accidental ignition of secondary grade releases[1] ($IR_{ignited\ release}$) should be 10% of the total IR (i.e. 0.1 x 1.0E-4 = 1.0E-5/yr) and is defined by the following equation:

$$IR_{ignited\ release}\ (/yr) = F_{flam}\ (/release\ source - yr) * P_{ign} * P_{occ} * V * N_{range}$$

EI15 suggests the value of 10% should be used to take account other contributions to the total IR, such as:

- Process events, such as explosions, fires, toxic releases, missiles etc
- Non-process events, such as occupational risk, transportation accidents etc.

In addition, ignited events may occur from continuous and primary grade releases or from larger releases not generally considered for area classification purposes (but for example may be assessed in a QRA). However, alternative values for $IR_{ignited\ release}$ may be used, depending on corporate requirements and site specific circumstances or to reduce risk to as low as reasonably practicable.

EI15 suggests using a vulnerability value (V) of 0.01 fatalities per accidental release within the Zone 2 area, which takes into account factors such as release direction and probability of escape, also comparing well with historical data. Note that if the fluid temperature is greater than its auto ignition temperature, a probability of ignition at the Zone 2 outer boundary (P_{ign}) value of 1 should be used. Also note that the determination of the number of release sources within range of the individual (N_{range}) needs to account for all secondary grade release sources, not just pumps, and can be determined by an exact account. Alternatively, typical values for probability that the individual is within the hazardous area (P_{occ}), N_{range}, P_{ign} are provided in EI15, although use of these values would need to be validated, taking into account site specific conditions.

Calculate the frequency of a flammable atmosphere at the Zone 2 boundary (F_{flam}) from the above equation. This enables the release frequency (LEVEL) to be determined. Usually the frequency of release only needs to be determined once for a facility (or distinct plant areas) and may already have been done so, if EI15 has been used for area classification.

Step 3

The consequence of the release depends on the equivalent hole size, which can be determined for a single seal from the release frequency (see Table 4).

Step 4

The consequence of the release also depends on the characteristics of the process fluid, including the hazardous nature of the fluid (e.g. flash point and boiling point, which can be obtained from the material safety datasheet), the maximum allowable pressure and temperature (which depend on the equipment operating conditions), and conditions of release.

The release rate and hence quantity released in one hour can either be determined by consequence modelling tools or via a look-up table contained in EI15 for different Fluid Categories and release pressures. Note that the Fourth Edition of EI15 includes some sensitivity analysis, in order to consider if the release flow rates are sensitive to the parameter values used in EI15.

For flammable releases, the relationship between API 754 threshold release categories and EI15 fluid categories are shown in Table 5. Note that there are some slight differences between the definitions, especially for substances with a flash point between 21˚C and 23˚C. In these circumstances, the flash point must be used directly to determine the IP petroleum class prior to determining the fluid category.

[1] A secondary grade release is unlikely to occur in normal operation and, in any event, will do so only infrequently and for short periods, for example as might occur from foreseeable equipment failure, such as a leak resulting from failure of seal on a pump.

Table 5. Relationship between API 754 Threshold Release Category and EI15 Fluid Category

API 754 Threshold Release Category	IP Petroleum Class			Fluid category		
	Class	**Description**	**Handled above flash point**	**Handled above boiling point**	**Can be released as mist**	**Handled below boiling point and cannot be released as a mist**
5[2] or 6[3]	0	Liquefied petroleum gases (LPG)	Yes	A	A	A
	I	Flash point less than 21˚C	Yes	B	C	C
7[4]	II(1)	Flash point 21–55˚C	No	N/A	C	N/A
	II(2)	Flash point 21–55˚C	Yes	B	C	C
	III(1)	Flash point 55–100˚C	No	N/A	C	N/A
	III(2)	Flash point 55–100˚C	Yes	B	C	C

Step 5

In order to determine if an Arrangement 1 seal failure could result in a T-1 PSE, the calculated quantity released in an hour from a single seal (from Step 4) can be compared to the Tier 1 material threshold quantity (from Step 1). If:

- The Tier 1 material threshold quantity is greater than the calculated release quantity, it can be concluded that an Arrangement 1 seal does not present an unacceptable vapour cloud or fire risk and an Arrangement 1 seal can be selected, unless other factors, such as reliability or emissions require an enhanced seal arrangement.
- The calculated release quantity is greater than the Tier 1 material threshold quantity, it can be concluded that an Arrangement 1 seal presents an unacceptable vapour cloud or fire risk. Repeat Steps 3, 4 and 5, using an equivalent hole size for a double seal instead.

Step 6

If an Arrangement 1 seal presents an unacceptable vapour cloud or fire risk, the calculated quantity released in an hour from a double seal can be compared to the Tier 1 material threshold quantity. If:

- The Tier 1 material threshold quantity is greater than the calculated release quantity, it can be concluded that an Arrangement 2 seal does not present an unacceptable vapour cloud or fire risk and an Arrangement 2 seal can be selected, unless other factors, such as reliability or emissions require an enhanced seal arrangement.
- The calculated release quantity is greater than the Tier 1 material threshold quantity, it can be concluded that an Arrangement 2 seal presents an unacceptable vapour cloud or fire risk, and an Arrangement 3 seal can be selected.

Toxic Releases

The risk-based approach to seal selection for flammable releases can be adapted for fluids containing toxic components. The equation for IR acceptability level for a fatality due to accidental toxic releases could be:

$$IR_{toxic\,release}\ (/yr)\ =\ F_{toxic}\ (/release\ source - yr) * P_{occ} * V * N_{range}$$

Note that in the above equation, the parameter P_{ign} has been removed, as it is not relevant for toxic releases. In the absence of historical data analysis, a vulnerability value (V) an order of magnitude greater than that for ignited releases, or 0.1 fatalities per accidental toxic release within the effect distance, is proposed as a conservative assumption. The contribution to the total IR attributable to toxic releases may need to be determined by QRA, because a single value may not be reasonable in all cases.

It is recognised that the calculated toxic release frequency will therefore be more likely to be a LEVEL 3 release, especially for a relatively high probability of occupancy or large number of toxic release sources in range. It has already been noted from Table 4 that LEVEL 3 failures are independent of seal arrangement and hence if it is found that an Arrangement 1 seal presents an unacceptable toxic vapour cloud risk, the same would apply to enhanced seal arrangements also, if this risk-

[2] Threshold Release Category 5 if Boiling Point ≤ 35˚C and Flash Point < 23˚C
[3] Threshold Release Category 6 if Boiling Point > 35˚C and Flash Point < 23˚C
[4] Threshold Release Category 7 if flash point ≥ 23˚C and ≤ 60˚C or released at a temperature at or above its Flash Point

based approach was followed. In such circumstances, an Arrangement 3 seal could be specified and further risk analysis performed to determine additional risk mitigation required, e.g. an alarm for leakage. However, only the calculated quantity of the toxic substance released should be compared with the relevant Tier 1 material threshold quantity. Hence the lower the concentration of the toxic component in the pumped fluid, the less likely a T-1 PSE will occur.

Example Calculations

Example 1: An LPG pump with a maximum allowable working pressure of 10 bar

- Pump is outdoors, in isobutane service, maximum allowable operating pressure 10 bar, process temperature 20˚C.
- Most vulnerable individual spends 100% of their time on site (i.e. 40 hours * 48 weeks) in a hazardous area with many release sources in range and with medium sources of ignition at plant boundary

Input Data

- Flash point -107˚C, boiling point -12˚C
- P_{occ} = 0.220 (i.e. 1920/8760), N_{range} = 30
- P_{ign} = 0.1

Step 1

Isobutane is a threshold release category 5 and hence the threshold quantity is 500 kg

Step 2

F_{flam} = 1.0E-5/yr) / 0.1*0.220*0.01*30 = 1.52E-3/yr, hence LEVEL 2 release frequency

Step 3

Equivalent hole size (single seal) = 5mm

Step 4

IP petroleum class 0, EI15 fluid category A

Release rate = 0.4kg/s

Step 5

0.4kg/s or 1,440 kg in an hour > 500 kg and hence an Arrangement 1 seal presents an unacceptable vapour cloud or fire risk.

Step 6

Equivalent hole size (double seal) = 2mm

Release Rate = 0.06kg/s

0.06kg/s or 216 kg in an hour < 500 kg and hence an Arrangement 2 seal does not present an unacceptable vapour cloud or fire risk and an Arrangement 2 seal can be selected, unless other factors, such as reliability or emissions require an enhanced seal arrangement.

This selection matches the result from the Seal Selection Logic presented as an alternative seal arrangement selection method using material safety datasheet information in API 682, for a Group III liquid with an SG <0.7 and flashing at temperature of pumped fluid. It is also common in the UK to specify a double seal for this application, although less common in other parts of the world.

However, an assessment of a different pump in exactly the same process conditions, but with a different exposure (Exp), e.g. for N_{range} = 1, it is possible for a different seal arrangement, e.g. Arrangement 1 seal, to be selected from the risk-based approach. Facilities may wish to avoid these inconsistencies by specifying minimum standards for certain applications and which would simplify other operational aspects such as operator knowledge, competency, spares etc.

Conversely, for a theoretical maximum allowable working pressure of 50bar, the risk-based approach would have selected an Arrangement 3 seal and the API 682 alternative seal arrangement selection method would appear non-conservative in this case.

Example 2: A produced water pump with maximum 1 wt% oil

- Pump is outdoors, maximum allowable operating pressure 5 bar, process temperature 40˚C.
- Most vulnerable individual spends 100% of their time on site in a hazardous area with many release sources in range and with controlled sources of ignition at plant boundary

Input Data

- Assume stabilised crude oil with flash point < 21˚C, boiling point >35˚C

- P_{occ} = 0.220, N_{range} = 30
- P_{ign} = 0.003

Step 1

Threshold release category 6 and hence the threshold quantity is 1,000 kg

Step 2

From the existing area classification, a LEVEL 1 release frequency has already been determined.

Step 3

Equivalent hole size (single seal) = 2mm

Step 4

Release rate = 0.06kg/s (assuming EI15 fluid category C) produced water or 6.0E-4 kg/s stabilised crude oil

Step 5

6.0E-4 kg/s or 2kg in an hour < 1,000 kg and hence an Arrangement 1 seal does not present an unacceptable vapour cloud or fire risk and may represent a lower life-cycle cost solution. However, an Arrangement 2 seal is sometimes specified for potential dirty service and hence the associated reliability concerns.

Example 3: A hydrofluoric acid pump

- Pump is outdoors, maximum allowable operating pressure 10 bar, process temperature 40°C.
- Most vulnerable individual spends an average of five hr/day in a hazardous area with multiple release sources in range.

Input Data

- P_{occ} = 0.13, N_{range} = 5

Step 1

Hydrofluoric acid is a Packing Group 1 Material (Threshold release category 5) and hence the threshold quantity is 500 kg

Step 2

A QRA has been performed which has determined that the IR for the most exposed individual in the vicinity of the plant area containing hydrofluoric acid is approximately 1.0E-4/yr and the contribution from toxic events is 20%.

Therefore, F_{toxic} = 0.2 * 1.0E-4/yr) / 0.13*0.1*5 = 3.08E-4/yr, hence LEVEL 3 release frequency

Step 3

Equivalent hole size = 10mm

Step 4

Release rate = 1.7kg/s (assuming EI15 fluid category C)

Step 5

1.7kg/s or 6,120kg in an hour > 500 kg and hence an Arrangement 1 seal presents an unacceptable vapour cloud or fire risk. An Arrangement 3 seal could be specified and further risk analysis performed to determine additional risk mitigation required.

This selection matches the result from the Seal Selection Logic presented as an alternative seal arrangement selection method using material safety datasheet information in API 682, for a Group II liquid with a 100% mass fraction of component contributing to hazard and a threshold limit value for an 8 h time weighted average of the component of 2.5 mg/m^3.

Conclusions

Many companies collect and report process safety metrics after incidents occur, in particular T-1 PSE, and their performance benchmarked against others in the same sector. Some of this data indicates an opportunity for reducing the occurrence of future pump seal failures.

T-1 PSE were defined as representing incidents with greater consequence and hence, even though a decision to utilise this definition in equipment design philosophies such as pump seal selection is arbitrary, it seems logical: It is possible to design a pump seal arrangement to avoid a T-1 PSE, hence prevent incidents with greater consequence occurring and thereby improve process safety performance. A sensitivity of the risk-based approach presented in this paper has been performed utilising the T-2 PSE definition, which tends to grossly over-specify seal arrangements compared with industry practice. Conversely, the examples presented in this paper or which can be generated following the presented approach, appear reasonable and in some cases conservative, compared with both alternative seal selection procedures and current industry practice.

Understanding the potential risks of pump seal failure require an understanding of the inherent hazards of the fluid, the operating conditions of the equipment and other site specific factors and need to be compared with established risk criteria. Alternative seal selection procedures do not appear to comprehensively consider all of these factors and where competent process safety expertise has not always been applied in the past.

This risk-based approach to seal selection promotes a consistent and repeatable selection process, which is simple to follow and 'joins the dots' from existing published good practice. It could be used as a process safety basis for seal selection or support verification of the recommended seal arrangement from the vendor.

Seal selection is a multi-faceted issue. This risk-based approach only considers the process safety aspects of the seal arrangement selection. Good engineering practice is also required, both from the vendor and the end-user, also considering reliability, environmental and health concerns, as well as cost. These aspects already appear well catered for. Getting seal selection right at the design phase can positively influence future safe, reliable and efficient operations.

It is noted that a similar risk-based approach could be developed for centrifugal compressor seal selection.

References

American Petroleum Institute, 2010, API Recommended Practice 754 First Edition, Process Safety Performance Indicators for the Refining and Petrochemical Industries

American Petroleum Institute, 2014, API Standard 682 Fourth Edition, Pumps – Shaft Sealing Systems for Centrifugal and Rotary Pumps

American Petroleum Institute, 2015, 2014 Process Safety Events Report for the U.S. Refining Industry

Energy Institute, 2015, EI15 Edition 4, Model Code of Safe Practice – Area classification for installations handling flammable fluids

Sherwen, S., 2015, EI15 4th Edition – Improvements and Application, IChemE, Hazards 25