Crediting check valves as IPLs? Testing protocol to better understand check valve reliability

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Abstract

Conventional process safety wisdom assumes that check valves are not reliable safeguards. Experience indicates that check valves are prone to failure and that they may fail undetected. Therefore, the conservative assumption is that check valves may be listed in process hazard analyses as safeguards, but they are rarely considered to meet the standards required of an independent protection layer (IPL). Independent protection layers must be effective, independent, and auditable. Although independence is readily achievable by check valves, confirming and routinely auditing effectiveness is rarely pursued. And maintenance practices for check valves are often insufficient. Little data is available from operating companies regarding failure and leakage rates for different check valve types in various service applications or at various stages of service life. This paper examines a testing protocol that was put in place in 2014 for the purpose of testing check valves in order to apply layer of protection analysis (LOPA) credit to these valves for reverse flow scenarios. In order to understand check valve performance expectations, leakage allowances for new check valves are reviewed. Industry guidance and standards regarding consideration of check valves as safeguards or IPLs are also discussed. The analysis of new valve standards and the assessment of process safety requirements are the basis for establishing the pass/fail thresholds for the tests. The goal of sharing this information is that the discussion will stimulate others to consider the opportunity and the need to set-up similar testing and to begin gathering and sharing a larger body of data on check valve performance in various applications. Accumulation of check valve performance data and sharing of that data should lead to better understanding of check valve performance by type, size, age, and service. Better performance may be achieved where maintenance is improved and where learnings are applied to selection and design. In instances where requirements are met and credit is due, check valves may be credited in PHA and LOPA.1

KEYWORDS

check valve, safeguards, independent protection layer (IPL), process hazard analysis (PHA), layer of protection analysis (LOPA)

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1 | INTRODUCTION

Check valves are a curious equipment component in process plants and operations. Check valves are by their very nature a safeguard. They prevent flow in the wrong direction. However, standard practice during process hazard analysis is to assume that the check valve will fail and to give no credit to the safeguard. This long-standing practice seems prudent given experience with serious incidents involving check valve failure.

However, does the assumption of check valve failure become a self-fulfilling prophecy? Does the assumption of failure become an enabler of failure? Does failure to recognize actual failure modes and frequencies prevent improvement in check valve performance and reliability?

In most applications, check valves are not causes of hazard scenarios, they are preventative safeguards.

As per Baldas/Carithers: Check valves are almost exclusively used as safeguards, rather than as active design features.... It is not typical that the failure of a check valve is the cause of a [Layer of Protection Analysis,] LOPA[,] scenario; the cause of the reverse flow comes from some other failure [or initiating event (IE)]. A check valve is typically a failure to protect, not a cause.¹

CCPS Guidelines for Initiating Events and Independent Protection Layers in Layer of Protection Analysis (CCPS IE/IPL), 2015,² generally supports that characterization. In Section 4.3.3 and Appendix D, a distinction is made between check valves operating in low demand mode versus high demand mode.² Check valves operating in high demand mode, such as internal to equipment, tend to be design features and may be initiating events. Whereas check valves operating in low demand mode are generally operating as a safeguard.

Note: API 521 lists check valves as “causes” for over-pressure scenarios; however, the discussion regarding reverse flow scenarios is much the same.³

As such, we list check valves as safeguards in process hazard reviews, but check valves rarely meet the standards required for considering the check valve as an independent protection layer (IPL). Check valves are recognized for having the potential to fail, to fail undetected (ie, latent failure), and to fail suddenly or catastrophically. Check valves are also recognized to operate in severe service because moving parts are present in the flow stream. However, lack of testing and inspection data remain a primary obstacle to being able to better assess and quantify the actual performance, failure modes, and failure frequencies for check valves.

Although inspection, maintenance, and testing (IMT) are considered essential to assure the performance and reliability of any piece of mechanical equipment, check valves generally do not receive the same attention as other equipment and components.⁴ The lack of routine inspection and/or maintenance may in part explain why check valves are considered unreliable.

This paper advocates changing the paradigm. Critical check valves need to not only be inspected but also tested for leakage rates in order to assure their reliability. Where defects are found, check valves should be repaired and returned to acceptable condition. That means that the installation configuration must allow for future inspection, maintenance, and testing. Maintenance work must be planned, scheduled, and completed. History on the performance of check valves in various applications, for various types and sizes, and at various stages of their service life will allow for better design and selection of check valves for the particular application. Assuring proper function of check valves may allow for more robust process safety design by sharing the burden of protection across more disparate safeguarding devices and independent protective layers. Understanding the actual performance of check valves allows for attributing appropriate credit, where it is due, and also allows resources to focus attention on hazards that have a larger actual gap between target risk levels and current assessed risk.

While testing check valves is necessary to allow for potential crediting of check valves as independent protection layers (IPLs), inspection programs must also be in place to identify insipient failures. Inspections reveal conditions that are precursors to failures such as mechanical damage, fouling, debris, and looseness that are not yet manifested as leakage. The particular application, hazards, and consequences must be thoroughly understood in order to consider PHA and/or LOPA credit for individual or redundant check valve installations.

This paper discusses an example testing protocol that was written and implemented for several new check valves that were installed in an oil and gas processing plant in 2014. In preparation for that testing, standards that define maximum allowable leakage rates for new valves were reviewed. Guidance from industry publications on considering check valves as safeguards or IPLs was also reviewed. The analysis of valve standards and the assessment of process safety requirements were the basis for establishing the pass/fail thresholds. Key take-aways and experiences from the preparation and testing are summarized.

2 | HISTORY

Early publications of process safety hazard analysis methodology including CCPS LOPA (2001)⁵ and CCPS Guidelines for Hazard Evaluation Procedures, Table 7.4, (2008, 1992)⁶ cautioned practitioners that check valves should not be credited as safeguards or IPLs. With the publication of later references, such as CCPS IE/IPL in 2015, guidance has changed to allow for the usage of check valves as IPLs.² From CCPS IE/IPL:

Section 1.3 ... At the time of CCPS LOPA (2001), check valves were not generally considered to be valid IPLs due to a lack of data supporting their reliability. Since that time, understanding of check valve reliability has improved, assisted by more data that substantiates their reliability. (Refer to Appendix D for Example Reliability Data Conversion for Check Valves for more information.) Based on this data, check valves have been included as IPLs in this book.²
Section 1.7... Appendix D ... Check valve design has improved over the years, and data exist that indicate that check valves can be effective IPLs when properly specified and maintained.2

Section 5.2.2.3 ... check valves can be considered to be IPLs when properly specified, designed, installed, and maintained.2

Note: The data referenced in Appendix D2 is based on 1987 data. However, the Probability of Failure on Demand (PFD) analysis and generic IPL credit guidance came later.

Little has changed since the initial publication of PHA and LOPA guidance with respect to opinions, assumptions, and maintenance practices regarding check valve reliability. As such, practices and assumptions in the process safety arena have remained essentially the same as well.

In spite of regulation, such as OSHA PSM 1910.119(j) Mechanical integrity, (1992),7 and industry guidance, CCPS Guidelines for Risk Based Process Safety, 4.3.3 Element—Asset Integrity and Reliability (CCPS RBPS), (2007),8 that stipulate inspection, maintenance, and testing requirements to ensure equipment integrity and fitness-for-service, many check valves remain untagged equipment items indicating that the check valve will not be included in integrity management programs and no history will be tracked as to the condition of the valve. All check valves may not require testing, but inspection, failure, and repair history should be tracked, at a minimum, for all safeguards. Guidance in API 5709 May 2017 addendum also requires that critical check valves “shall” be included in inspection or testing programs.4

While some operators have migrated to include critical check valves in basic inspection and maintenance programs, very few operating companies test their check valves. Therefore, very few operating companies credit their check valves as IPLs. While many standards exist for quantifying leakage rates for new check valves provided by manufacturers, little to no quantitative data is available on check valve leakage with respect to type, size, age, or service after check valves are placed in service. Lack of performance data rather than specific data indicating unacceptable leakage rates is a primary reason for lack of movement towards potentially crediting check valves as IPLs. This situation applies not only to older check valves that may not be well configured for testing, but also to newer check valve installations.

3 | PHA OR LOPA CREDIT—WHEN TO CREDIT AND HOW MUCH

When considering giving a check valve or check valves qualitative (order of magnitude) credit as a PHA safeguard or semi-quantitative LOPA credit as an independent protection layer for a hazard scenario, there are several options for crediting that depend on the equipment and process configuration.

Check valves that meet IPL criteria may be considered for crediting as IPLs when in the following configurations:

1. Single check valve—credited as stand-alone IPL  
2. Dual check valves in series—credited as single IPL  
3. Combination IPL comprised of upstream PSV or PSV setting and downstream check valve(s)

Inspection and testing protocol including threshold leakage rates must be defined depending on which of the above configurations is applicable. When establishing threshold leakage acceptance rates, it is important to consider the amount of leakage that is deemed tolerable within the particular process system in question. Process equipment rating and capacity, reactivity hazards, relief device capacity (where applicable), upstream rotating equipment impacts, and other factors for a given scenario must be considered. As with all IPLs, each check valve IPL must prevent the consequence of concern.

It is important to note that option 3 references a single IPL that is comprised of a specific PSV or PSV setting and a specific check valve or check valves in series. Inspection, maintenance, and testing of all components are required to credit the single IPL. These components may not be used separately as independently credited IPLs. Likewise, in option 2, two check valves may be credited as a single IPL and both check valves require independent inspection, maintenance, and testing.

3.1 | Crediting check valves, single or dual check valves, as an IPL

Several reference documents address potentially crediting check valves as safeguards and/or IPLs. CCPS IE/IPL2 Section 5.2.2.3 and Table 5.3.2 address crediting a single maintained check valve as an IPL. CCPS IE/IPL distinguishes check valves operating in low demand mode as IPLs whereas check valves operating in high demand mode, such as integral to equipment, are considered initiating events. However, the calculated probability of failure is the same.

Note: In CCPS IE/IPL, the probability of failure evaluation for a single check valve in either mode, high demand as initiating event or low demand as IPL, is based on the same data set. The probability of failure on demand (PFD) calculated for a single check valve IPL is the same as the initiating event frequency (IEF) for a high demand check valve, 0.1. CCPS IE/IPL also calculates IEF for dual check valves in the high demand mode of 0.01. The data set used for the probability of failure calculation is based on Reliability Data Book for Components in Swedish Nuclear Power Plants, RKS/SKI 85-25, p 79 (Bento et al. 1987). Calculations are shown in Appendix D of CCPS IE/IPL.

CCPS IE/IPL2 highlights the fact that some check valve leakage may be expected. Therefore, the user must define tolerable leakage rates and assure through inspection and leakage testing that the check valve can be expected to perform as anticipated and protect against the scenario. As per CCPS IE/IPL, the
check valve should be operating in clean, nonfouling, noncorrosive service.

An IPL with calculated PFD for dual check valves is not explicitly discussed in CCPS IE/IPL\textsuperscript{2} Section 5.2.2.3. CCPS IE/IPL\textsuperscript{2} cautions the users to consider design, operability, and function of two check valves in series to assure that both respond appropriately and independently. CCPS IE/IPL\textsuperscript{2} also reminds the user to consider common cause failures. Manufacturers indicate that failures associated with multiple check valves in series may be more likely in the forward flow direction due to failure to meet the required cracking pressure. This type of failure does not impact the reverse flow protective function.

Although, CCPS IE/IPL\textsuperscript{2} does not show a separate dual check valve IPL category, it is assumed that the PFD for a dual check valve IPL will be similar (0.01) to the initiating event frequency (IEF) for dual check valves in high demand mode. Crediting dual check valves with this PFD assumes that the check valves are individually inspected and tested and are unlikely to experience common cause failures.

Crediting of check valves that meet IPL criteria is also discussed by Baldas and Carithers.\textsuperscript{1} They calculated check valve IPL credit for multiple valves in series based on a single check valve PFD = 0.1, or Risk Reduction Factor (RRF) = 10. Using this assumption and an assumption for common cause failure rates of 1 in 10, Baldas and Carithers calculated a PFD for dual check valves in series of 0.0181 (RRF = 55) which rounds to approximately two orders of magnitude. They further showed via the same calculation that more check valves in series would not yield a substantially lower combined probability of failure on demand; therefore, no more than two orders of magnitude credit should be attributed to check valves in series, even if more than two check valves, that are maintained, are present in series.\textsuperscript{1} This conclusion is also supported in API 521 (2014)\textsuperscript{3} Section 4.4.9.3.3. “a) Because of potential common mode failures the user is cautioned against taking a larger credit for more than two check valves in series that are inspected and maintained.”

It is notable that CCPS IE/IPL\textsuperscript{2} and API 521(2014)\textsuperscript{3} differ on guidance regarding single check valve performance and probability of failure on demand (PFD). Although API 521 (2014)\textsuperscript{3} only addresses check valve(s) working together with PSV(s) to comprise the IPL and does not explicitly address mathematical PFD for check valves, inherent unreliability is implied in this standard. API 521 (2014)\textsuperscript{3} assumes that a single check valve, regardless of service, history, or testing, is not sufficient to be credited for even partially restricting flow to the PSV. In other words, this guidance assumes a single check valve should receive no credit for being in place, therefore, PFD = 1 (RRF = 1). API 521 (2014)\textsuperscript{3} dictates guidance that all single check valves should be assumed to completely fail and not reduce reverse flow to the PSV. This conclusion is fundamentally different from the position supported by data and PFD calculations in CCPS IE/IPL\textsuperscript{2} Appendix D. Additional data should be gathered that is specific to check valve type, size, age, and service in order to better define the PFD for a given check valve.

Although CCPS IE/IPL\textsuperscript{2} provides a basis for crediting either single or, by extension of IE discussion, dual check valves when IPL requirements and other special considerations are satisfied, few companies have moved toward applying credit to check valves as IPLs. In “Check Valves as Safeguards: Friend or Foe in Process Hazard Analysis,” Modi,\textsuperscript{10} Table 9.1 provides a sampling of credit given to check valves by operating companies of various size and sector. Based on this overview, very few companies attribute any credit to a single check valve as a safeguard in PHA analyses. A number of companies attribute a single order of magnitude credit to dual check valve safeguards in PHA assessments. But LOPA credit is rarely attributed even to dual check valves.

As with any IPL, check valves considered for crediting as an IPL must meet all required criteria, including assuring (a) effectiveness, (b) independence, and (c) auditability. The decision to credit either a single check valve or dual check valves in series as a safeguard or as an IPL is based on individual company protocol. This protocol should be based on historical experience, understanding of check valve failure modes, reliability and performance, understanding of hazard scenarios involved, and company risk tolerance. The lack of credit taken for check valves represents a conservative approach. However, this conservative approach is also attributable to lack of progress in understanding check valve performance, failure modes, and failure frequencies in various process services.

Refer to Table 1 for a summary of check valve probability of failure guidance based on several references discussed above. This table summarizes potential PHA or LOPA credit that may be given when check valves are maintained, inspected, and tested and considered with regard to special considerations stipulated in the guidance documents. Table 1 also shows discrepancies between guidance documents.

### 3.2 Crediting check valve(s) and upstream PSV(s) as an IPL

CCPS IE/IPL\textsuperscript{2} not only references the possibility of crediting check valves as IPLs, it also addresses the possibility of crediting a PSV in conjunction with a check valve in Sections 3.2.1 and 5.2.2.2.2 as per configuration 3 above. API 521\textsuperscript{3} also references configuration 3. However, CCPS IE/IPL\textsuperscript{2} and API 521\textsuperscript{3} differ regarding guidance as to whether the combination PSV/check valve IPL may be credited with only a single check valve in place that limits reverse flow to the PSV. API 521 (2014)\textsuperscript{3} does not allow for crediting a single check valve with reducing flow to the PSV. API 521 (2014)\textsuperscript{3} directs the user to assume “complete” check valve failure when a single check valve is in place, even if maintained and inspected. CCPS IE/IPL\textsuperscript{2} references a single check valve in scenarios involving an IPL comprised of a PSV and a check valve.

Note: Regardless of these discrepancies in guidance, it is important to recognize that the guidance provided in API 521\textsuperscript{3} only applies to configuration 3 above. Configurations 1 and 2 are not related to relief scenarios.
| Device | Safeguard | OM | PFD   | RRF   | IEF   | RRF* | Reference                                                                 |
|--------|-----------|----|-------|-------|-------|------|---------------------------------------------------------------------------|
| Single check valve (low demand mode)**  | 1 OM      | OM | 0.1   | 10    |       |      | CCPS Guidelines for initiating events and independent protective layers in layer of protection analysis, Chap 5, 5.2.2.3, Table 5.32 based on Appendix D² |
| Dual check valves (low demand mode)    | Not Addressed | Not Addressed | Not Addressed |       |       |      | CCPS IE/IPL², Not addressed                                               |
| Single check valve (low demand mode)   | 1 OM      | OM | 0.1   | 10    |       |      | Baldas/Carithers¹, assumed value                                          |
| Dual check valves (low demand mode)    | 2 OM      | OM | 0.01  | 100   |       |      | Baldas/Carithers¹, calculated, assumption: no common cause failures       |
| Dual check valves (low demand mode)    | ~ 2 OM    | OM | 0.0181| 55    |       |      | Baldas/Carithers¹, calculated, assumption: common cause failures          |
| Three check valves (low demand mode)   | 2 OM      | OM | 0.0107| 55    |       |      | Baldas/Carithers¹, calculated, assumption: common cause failures          |
| Single check valve (low demand mode)**  | 0 OM      | OM | 1     | 1     |       |      | API 521, 2014, 6th Ed.³ Implied based on assumption that single check valve will always fail |
| Single check valve (high demand mode)  | NA        | NA | 0.1   | 10    |       |      | CCPS IE/IPL², Chap 4, 4.3.3, Table 4.11 based on Appendix D²              |
| Double check valve (high demand mode)  | NA        | NA | 0.01  | 100   |       |      | CCPS IE/IPL², Chap 4, 4.3.3, Table 4.12 based on Appendix D²              |

Note: All values assume that appropriate inspection and testing is conducted and that special considerations have been reviewed for the scenario and for the application of the generic probability of failure value given. **See text for discussion of discrepancies.
## Table 2: Industry valve standards—maximum allowable seat leakage rate references

| Standard | Valve types included within scope | Valve maximum allowable seat leakage rate by size (in diameter)—Table or section where defined | Check valve maximum allowable seat leakage rate by size (in diameter)—Table or section where defined |
|----------|-----------------------------------|-------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| API 598 (2016) Valve Inspection and Testing<sup>12</sup> | Gate; Globe; Plug; Ball; Butterfly; Check | API 598 (2016): Table 5—Maximum allowable leakage rates for closure tests, page 9<sup>12</sup> | API 598 (2016): Table 5—Maximum allowable leakage rates for closure tests, page 9<sup>12</sup> |
| ISO 5208: 2015 Industrial valves—Pressure testing of metallic valves<sup>13</sup> | Gate; Globe; Plug; Ball (Floating; Trunion Mounted); Diaphragm; Butterfly (Concentric; Eccentric); Check | ISO 5208: 2015: Table 4—Maximum allowable closure test leakage rate, page 11<sup>13</sup> defined as Rate A, AA, B, C, CC, D, E, EE, F, G from most stringent to least stringent requirements. Corresponding API 598 limits are referenced: Rate A for DN ≤ 50 and soft seated Rate CC, using liquid test, and Rate AA, using gas test. Also see Supporting Information S1 | ISO 5208: 2015: Table 4—Maximum allowable closure test leakage rate, page 11<sup>13</sup> Corresponding API 598 limits for check valves are referenced: Rate E, using liquid test, and Rate EE, using gas test. Also see Supporting Information S1 |
| MSS SP-61-2013 Pressure Testing of Valves<sup>14</sup> | Gate; Globe; Plug; Ball; Butterfly; Check | MSS SP-61-2013: Table 4—Units of Leakage per NPS/DN, page 4. Also see Supporting Information S2 | MSS SP-61-2013: As per Section 5.7.2, allows four (4) times leakage rate shown in MSS SP-61-2013 Table 4—Units of Leakage per NPS/DN, page 3, for check valves.<sup>14</sup> |
| API 6D (2014) Specification for Pipeline and Piping Valves<sup>15</sup> | Gate; Plug; Ball; Check | API 6D (2014): Regarding seat testing for valves (other than check valves), maximum allowable leakage rate is given as: ISO 5208 Rate D for liquid test per Section 9.4.3 ISO 5208 Rate D for gas test per Section H.4.3.2<sup>15</sup> | API 6D (2014): Regarding seat testing for check valves, maximum allowable leakage rate is given as: ISO 5208 Rate G for liquid test per Section 94.3<sup>15</sup> ISO 5208 Rate EE for gas test per Section H.4.3.2<sup>15</sup> These limits are consistent with API 598. |
| ANSI/FCI 70-2-2013 Control Valves Seat Leakage<sup>19</sup> | Control | ANSI/FCI 70-2-2013: Table 1, page 2, and Table 2, page 3<sup>19</sup> | Not applicable |
# Table 3: Valve Seat Leakage Allowance by Standard, 12-15 Liquid Test

| Nom Pipe Diam (inches) | Soft Seat | Soft Seat | Soft Seat | Soft Seat | Soft Seat | Soft Seat | Soft Seat |
|------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|                        | ml/min    | ml/min    | ml/min    | ml/min    | ml/min    | ml/min    | ml/min    |
| 1                      | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      |
| 2                      | 0.00      | 0.00      | 0.33      | 0.33      | 0.03      | 0.03      | 0.03      |
| 3                      | 0.38      | 0.50      | 2.00      | 2.00      | 0.50      | 0.50      | 0.50      |
| 4                      | 0.50      | 0.67      | 2.67      | 2.67      | 0.67      | 0.67      | 0.67      |
| 5                      | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 6                      | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 7                      | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 8                      | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 9                      | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 10                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 11                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 12                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 13                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 14                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 15                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 16                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 17                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 18                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 19                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 20                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 21                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 22                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 23                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 24                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 25                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 26                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 27                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 28                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 29                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 30                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 31                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 32                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 33                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 34                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 35                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 36                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 37                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 38                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 39                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 40                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 41                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 42                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 43                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 44                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 45                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 46                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 47                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |
| 48                     | 0.75      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      | 0.80      |

Note: Also see Supporting Information S3 for expanded tables showing all ISO 5208 leakage rate categories.
### Table 4: Valve seat leakage allowance by standard gas test

| Nom Pipe Diam | API 598 | API 598 Check | MSS SP-61 | MSS SP-61 Check | ISO 5208 Rate A | ISO 5208 Rate AA | ISO 5208 Rate C | ISO 5208 Rate D | ISO 5208 Rate E | ISO 5208 Rate EE | ISO 5208 Rate G |
|---------------|--------|--------------|-----------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| DN inches     | SCFH   | SCFH         | SCFH     | SCFH            | SCFH           | SCFH           | SCFH           | SCFH           | SCFH           | SCFH           | SCFH           |
| 1             | 0.00   | 1.50         | 0.10     | 0.40            | 0.000          | 0.0006         | 0.01           | 0.10           | 0.95           | 1.49           | 19.05          |
| 2             | 0.00   | 3.00         | 0.20     | 0.80            | 0.000          | 0.0011         | 0.02           | 0.19           | 1.91           | 2.98           | 38.10          |
| 3             | 0.00   | 4.50         | 0.30     | 1.20            | 0.000          | 0.0018         | 0.03           | 0.30           | 3.05           | 4.78           | 60.96          |
| 4             | 0.00   | 6.00         | 0.40     | 1.60            | 0.000          | 0.0023         | 0.04           | 0.38           | 3.81           | 5.97           | 76.20          |
| 6             | 0.00   | 9.00         | 0.60     | 2.40            | 0.000          | 0.0034         | 0.06           | 0.57           | 5.72           | 8.95           | 114.30         |
| 8             | 0.00   | 12.00        | 0.80     | 3.20            | 0.000          | 0.0046         | 0.08           | 0.76           | 7.62           | 11.94          | 152.40         |
| 10            | 0.00   | 15.00        | 1.00     | 4.00            | 0.000          | 0.0057         | 0.10           | 0.95           | 9.53           | 14.92          | 190.50         |
| 12            | 0.00   | 18.00        | 1.20     | 4.80            | 0.000          | 0.0069         | 0.11           | 1.14           | 11.43          | 17.91          | 228.60         |
| 16            | 0.00   | 24.00        | 1.60     | 6.40            | 0.000          | 0.0091         | 0.15           | 1.52           | 15.24          | 23.88          | 304.80         |
| 20            | 0.00   | 30.00        | 2.00     | 8.00            | 0.000          | 0.0114         | 0.19           | 1.91           | 19.05          | 29.85          | 381.00         |
| 24            | 0.00   | 36.00        | 2.40     | 9.60            | 0.000          | 0.0137         | 0.23           | 2.29           | 22.86          | 35.81          | 457.20         |
| 36            | 0.00   | 54.00        | 3.60     | 14.40           | 0.000          | 0.0206         | 0.34           | 3.43           | 34.29          | 53.72          | 685.80         |
| 48            | 0.00   | 72.00        | 4.80     | 19.20           | 0.000          | 0.0274         | 0.46           | 4.57           | 45.72          | 71.63          | 914.40         |

Note: Also see Supporting Information S4 for expanded tables showing all ISO 5208 leakage rate categories.

- (RS) = Resilient Seat = Soft Seat
- (Std) = Manufacturer Standard Specification (no special request)
- (Chk) = Check Valve
- (Blk) = Block Valve

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**Units for above =>**

- SCFH per nom pipe diam inch
- SCFH per nom pipe diam inch
- No visually detectable leakage per DN
- cu mm per sec per DN

**Mfr Y (RS)**

- MSS SP-61 (RS)
- MSS SP-61 Chk
- SP-61 Blk
- API 6D Blk
- API 6D Chk
- API 598 Chk

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**Mfr Y (cryo)**

- MSS SP-61 (RS)
- MSS SP-61 Chk
- SP-61 Blk
- API 6D Blk
- API 6D Chk
- API 598 Chk

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**Mfr X (RS)**

- MSS SP-61 (RS)
- MSS SP-61 Chk
- SP-61 Blk
- API 6D Blk
- API 6D Chk
- API 598 Chk

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**Mfr X**

- MSS SP-61 (RS)
- MSS SP-61 Chk
- SP-61 Blk
- API 6D Blk
- API 6D Chk
- API 598 Chk
As per CCPS IE/IPL, when a PSV or PSV setting is used in combination with a check valve or check valves as an IPL, the probability of failure on demand (PFD) attributed to the combination PSV(s) and check valve(s) IPL should be equal to the PFD of the component having the greatest probability of failure. CCPS IE/IPL references the single check valve PFD of 0.1, provided in Table 5.32, as the overall PFD for the single check valve/PSV combination IPL as an example. While check valve PFD is discussed directly or indirectly in CCPS IE/IPL and API 521, frequency of inspection and testing of check valves is not defined. Frequency of inspection and testing is left to the user to define. As with other IPLs, inspection and testing frequency must support and validate the reliability of the component. Shut-down requirements for testing of check valves must also be considered and planned in conjunction with defining inspection and test frequency.

4 | NEW CHECK VALVE SEAT LEAKAGE REQUIREMENTS—INDUSTRY STANDARDS

In order to understand the potential performance capability for check valves in operational service, we must first understand the performance expectations for new check valves. Standards have been established that define valve performance requirements including seat leakage rate allowances. In the United States, block valves and check valves are generally tested by manufacturers to one of the following standards or to an internal manufacturer standard that meets or exceeds these standards: API 598, ISO 5208, MSS SP-61, or API 6D. EN-12266-1 is an equivalent European standard which superseded BS 6755-1. The standard chosen depends primarily on the valve materials of construction, location jurisdiction, industrial sector, or customer requirements. The standards referenced stipulate not only maximum allowable leakage rate criteria, but also testing requirements and procedures, including test pressure and duration by valve type.

Metal-to-metal seated valves of all types, including check valves, are expected to have some leakage. Resilient seated valves, also called soft seat valves, have more stringent leakage standards, usually indicated as zero leakage or no visual leakage. Most of these industry standards allow for higher seat leakage rates through metal seated check valves as compared to other types of metal seated block valves. However, some manufacturers design check valves to leakage standards comparable to other valve types. Other valve manufacturers may conform to the check valve standards but exceed the minimum requirements.

Table 2 summarizes information from several valve standards. Table 2 shows which valve types are addressed by each standard and references tables within those documents that stipulate maximum allowable seat leakage rates. Recent updates to major standards have resulted in some convergence of leakage limits. Table 3 and Table 4 show maximum allowable valve seat leakage rates for various valve sizes as defined by API 598, MSS SP-61, API 6D, and ISO 5208 using consistent units of measure. Table 3 and Table 4 reference tests conducted using liquid and gas, respectively. Manufacturer performance standards for two example manufacturers are also shown. Values shown in Table 3
and Table 4 are approximate as calculated by author. Refer to Supporting Informations S3 and S4, for expanded tables that show seat leakage rates for all ISO 5208 performance levels. Figures 1 and 2 provide simplified overview graphics of allowable seat leakage rates using liquid and gas test media, respectively.

Leakage rates for various types of block valves, including gate, ball, plug, globe, and butterfly, as well as check valves, are included in the standards referenced above. A separate standard, ANSI/FCI 70-2 Control Valve Seat Leakage, specifically addresses control valves. This standard is a useful point of comparison as control valves operated as basic process control systems (BPCS) may also be considered for credit as IPLs, as per CCPS IE/IPL 5.2.2.1, Safety Control Loop (Normal Operating Control) Table 5.12, if they meet IPL criteria.

Note: CCPS IE/IPL Section 5.2.2.3, Check Valves as IPLs, references API 598 (2009b), MSS SP-61(2009), and ANSI/FCI 70-2 as applicable standards that address check valve leakage rates. Specific leakage rate classes from ANSI/FCI 70-2, Class I through Class VI are replicated in Check Valves as IPLs section of CCPS IE/IPL 5.2.2.3. This reference is misplaced with respect to check valves, as ANSI/FCI 70-2 is specific to control valve leakage. Manufacturers of check valves surveyed confirmed that they refer to API 598, ISO 5208, API 6D, or appropriate MSS standard for requirements on allowable leakage rates and testing protocol. Some manufacturers institute more stringent corporate leakage standards.

As noted, all mechanical valves are prone to leak, regardless of valve type or style. Zero leakage rates are only achieved where resilient or soft seats are included in the valve design. Valves designed for zero leakage rates using soft seats include various categories of valves, including check valves. However, temperature and materials compatibility issues as well as wear and maintenance requirements must be considered when soft seating materials are specified.

5 | IN-SERVICE CHECK VALVE SEAT LEAKAGE ASSUMPTIONS

API 521 (2014) is considered the definitive reference regarding sizing and capacity of relief equipment. API 521 (2014) provides guidance on assumptions for check valve leakage rates that dictate PSV relief capacity requirements for reverse flow scenarios. Many users reference this guidance with respect to check valves given the lack of in-service leakage rate data that is available in industry from other sources. Section 4.4.9.3.1 of API 521 (2014) discusses several scenarios for reverse flow conditions, including complete check valve failure, severe leakage, and normal leakage.

5.1 | Complete check valve failure

As per API 521 (2014), complete check valve failure is considered to be “potential for gross reverse flow because the check valve does not function at all (e.g. it is stuck wide open or the internals are gone).”
"Complete check valve failure is assumed for all check valves in series that are not inspected and maintained and for a single check valve regardless if it is inspected and maintained."³

Note: Discrepancies between API 521 (2014)³ and CCPS IE/IPL² guidance on check valve PFD were previously discussed in this article, Sections 3.1 and 3.2.

The assumption of complete failure means that the normal operation of the check valve has no limiting effect on the reverse flow rate. API 521 (2014) provides three options for estimating reverse flow through a completely failed check valve.³

1. Assume no flow resistance in reverse direction.³
2. Assume the same flow resistance in reverse through the check valve as in the forward flow direction.³
3. Assume the failed check valve has an orifice equal to the check valve flow area without internals.³

CCPS IE/IPL 5.2.2.2.2 Case 2² speaks to this "complete failure" scenario. However, since the check valve is uninvolved in a protective capacity in this scenario, the IPL is comprised of only the PSV, not a combination of the check valve and PSV.

Note: If assumption 2 or 3 above is used for sizing the PSV, in the event of removal or modification of the check valve, the PSV capacity would have to be revalidated through the MoC process.

5.2 | Severe check valve leakage

As per API 521 (2014),³ severe check valve failure is considered to be "potential for significant reverse flow because of check valve seat damage or obstruction." API 521 (2014)³ advises that it is the responsibility of the user to determine the appropriate method for estimating reverse flow, but offers the following guidance. "Where no specific experience or company guidelines exist," API 521 (2014)³ directs the user to assume complete failure of the smallest check valve and to assume severe failure of all other check valves in series.

Two alternatives are provided in API 521 (2014)³ for assuming reverse flow rate for check valves having severe leakage. The following assumed reverse flow rate may be used for sizing relief devices upstream of inspected and maintained check valves.³

1. Assume that the check valve orifice diameter is 10% of the check valve nominal diameter (1% of nominal flow area) and calculate reverse flow.³ (See API 521 (2014)³ for properties and parameters assumptions. (Note: API 521 (2008)¹¹ references the same flowrate calculation assumption without parameter details provided.)
2. Treat check valve as an orifice sized to pass 10% of normal forward flow. Back calculate orifice size. Then calculate reverse flow.³ (See API 521 (2014)³ for properties and parameter assumptions.)

These leakage rate assumptions for severe check valve failure provided in API 521 (2014)³ are considered conservative and often form the basis of PSV design calculations where leakage rates are not known or quantitatively tested.

CCPS IE/IPL² Section 5.2.2.2.2 Case 1, PSV with check valve IPL, references similar language that is taken from API 521 (2008).¹¹ (Note: A single check valve is referenced in Case 1 as described in CCPS IE/IPL.²)

From CCPS IE/IPL² one may estimate the reverse flow through series check valves as the flow through a single orifice with a diameter equal to one-tenth of the largest check valve’s nominal diameter. A lower value may be used if a condition-monitoring system for the check valves ... is installed to monitor the condition to ensure that the leakage rate is below the capacity of the low-pressure side relief device.²

This reference to API 521 (2008)¹¹ guidance alludes to "severe" leakage in the beginning of the statement and "normal" leakage as the "lower value." In practice, most users assume the severe leakage rate as described above in CCPS IE/IPL² and API 521 (2008),¹¹ or as described in API 521 (2014),³ assumption 1 or 2, because leakage rates are rarely, if ever, tested directly.

Note: In CCPS IE/IPL² Section 5.2.2.2.2 Case 1, the following statement is made: "If the ANSI/API 521 (2008) [or 2014] guidance is followed, the PRV sizing basis would be reduced to handle just the flow from a slight reverse leak through the check valve.²"

The word slight in this sentence is misplaced as this assumption for leakage represents the "severe" failure case having "significant" leakage rates. Leakage rates discussed later in this paper in conjunction with testing protocol also support the position that this reverse flowrate assumption represents "severe" rather than "slight" or "normal" leakage of the check valve.

In order to utilize this guidance and credit the entire IPL, both the relief valve(s) and the check valves, must be maintained via company preventative maintenance (PM), inspection, and repair programs. It is important to note that this guidance is provided and is often used in lieu of known quantitatively tested check valve leakage rates, which explains the "conservative" assumptions that are used in API 521 (2014),³ (2008)¹¹ for assumed leakage rates. While "severe" leakage assumptions may be considered conservative based on the magnitude of reverse flow allowed by the calculation, data is not available that supports the notion that the failure mode described by the API 521 (2014)³ "severe" failure is more likely to occur than "complete" failure as described by full loss of internal parts. From this standpoint, using the API 521 (2014)³ "severe" failure assumption to calculate reverse flow rate may not be prudent without 
seat leakage testing data and/or failure modes and failure frequency data to support that approach.

5.3 | Normal check valve leakage

As per API 521 (2014), normal check valve failure is considered to be "potential for minor reverse flow due to normal check valve wear." API 521 (2014) advises that normal check valve leakage may be assumed when two or more check valves are in series that are inspected and maintained and demonstrate reliability. API 521 (2014) does not allow for assumption of normal leakage rates through a single valve, even if inspected and maintained. (Note: Guidance changed in API 521 (2014), as API 521 (2008) did acknowledge the ability of a single inspected and maintained check valve to limit reverse flow.)

API 521 (2014) does not provide the user with assumptions for normal leakage rates. For normal leakage, the user is advised that if a pressure relief device is involved in the IPL, the relief device loads and sizing including the check valve reverse flow leakage rates must be determined by the user. API 521 (2008) alluded to methods for establishing actual leakage rates such as through condition-monitoring using pressure indicators but did not reference specific assumptions or "normal" leakage values.

Having reliable, repeatable check valve leakage data along with historical failure modes and failure frequency data associated with the check valve type, size, age, and service is essential for users planning to assume normal leakage rates. Establishing normal leakage rate data is essential for application of either combination PSV/check valve IPLs or standalone check valve IPLs. Normal leakage should be evaluated and considered relative to new check valve leakage standards.

5.4 | Alternative characterization of seat leakage

An alternative characterization to the three check valve leakage conditions described in API 521 would be complete failure; degraded condition; and like-new condition. Like-new condition implies that maximum allowable seat leakage rates given by industry standards, such as API 598, ISO 5208, or MSS-SP-61 are met. Degraded condition encompasses leakage rates ranging from like-new to complete failure. Leakage rates characterized by API 521 as severe would fall into the upper range of degraded performance. Leakage rates characterized by API 521 as normal would fall within the lower range of degraded performance or meet like-new requirements, depending on interpretation of normal and expectations of check valves.

6 | TESTING DESIGN CONSIDERATION (GENERAL)

In order to implement a quantitative leak testing program for check valves, the process and mechanical configuration should be considered in the design phase of new projects and modifications to existing installations.

7 | THIS TEST—PURPOSE AND DESCRIPTION OF CONFIGURATION

7.1 | Purpose

The check valve configuration and the testing procedure described here were put in place in 2014. The reason for testing the check
valves was to apply layer of protection analysis (LOPA) credit to these valves for reverse flow scenarios. An added benefit of testing the check valves was to better understand their performance and reliability and to quantitatively assess their performance over time through leakage testing.

7.2 Description of configuration

Five check valves, two different types, were installed and tested in two different process locations. One location involved testing a single axial flow check valve in a higher pressure service downstream of a gas compressor (See Figure 3). This check valve was in series with an existing wafer check valve on the discharge of the compressor setting. Procedures were envisioned to test the existing check valve using process pressure. Testing of both the new and existing check valves would allow for crediting as dual check valves rather than a single check valve. Testing procedures for the existing check valve are not included in the scope of this discussion. The other location involved two sets of dual check valves, an axial flow check valve in series with a wafer check, on two parallel process trains in lower pressure gas service (See Figure 4).

The check valves being tested were purchased and installed in the same year. The testing procedure was implemented at the time of installation and commissioning to serve as baseline performance testing. Follow-up testing was planned at intervals consistent with the company LOPA protocol based on the credit that was intended for these check valves. Testing would occur during planned and scheduled shut-down opportunities, either full or partial plant outages.

The testing procedure involved connecting an external pressure source to the system, nitrogen bottles, and supplying pressure at prescribed levels to the downstream side of the check valves. The nitrogen bottles were fitted with a regulator to supply the appropriate pressure. The nitrogen skid and connected equipment was protected by a PSV skid designed to protect the equipment involved in this procedure. The check valve piping assembly was fitted with ports to allow for pressuring the downstream side of the valve and relieving the upstream side of the valve through the return line. Pressure transmitters were available on both the downstream and upstream side of the check valve(s). The pressure transmitters were reconfigured during the testing period to allow for gathering of data at very short time intervals. The leakage could be measured one of two ways: (a) Using a rotometer in the outlet flow path from the upstream side of the check valve to an atmospheric vent location or (b) Closing the outlet path and monitoring the pressure transmitter on the upstream side of the check valve for pressure build-up within the closed upstream chamber using gas laws to calculate the leakage rate associated with the pressure build-up. Plan a would be used initially. And Plan b would be used in the event that the rotometer method was unsuccessful or not definitive. The check valve configuration was in an enclosed module, but the nitrogen bottle source and the return line discharge from the rotometer were both outdoors. Refer to Figure 3 for a simplified depiction of the testing configuration for Test 1: single axial check valve, higher pressure gas service downstream of compressor.

The testing protocol for dual valves vs the single valve was similar. The primary difference was that having two valves added complexity and steps to the configuration and procedure. Additionally, in this particular configuration, isolation of the location was attempted via double block and bleed rather than using blinds. Because of the number of testing points involved and a desire to minimize cost of additional pressure transmitters (PTs), a tubing manifold and valving was designed, built, and installed that would allow for usage of certain pressure transmitters in more than one testing configuration. However, achieving a successful leak test of this manifold proved difficult. Successful leak tests were also required of double block and bleed valving to the process. Refer to Figure 4 for a simplified depiction of
the testing configuration for Test 2: dual check valves (axial and wafer checks), lower pressure gas service.

8 | DEFINING MAXIMUM ALLOWABLE SEAT LEAKAGE THRESHOLDS

So what level of leakage is the threshold for “acceptable?” In order to answer this question, the hazard scenario including consequence severity must be understood. The engineer should recognize the concept of process safety time with respect to progression towards the hazardous event. In selecting the threshold for allowable leakage also called maximum allowable leakage rate (MALR), the engineer or other personnel who set up the testing procedure should look at several different points of reference for expected and/or acceptable leakage.

In the sample test procedure described here, Test 1, the following thresholds were identified in the procedure as points of reference. Rates shown in Table 5 are based on standards for new check valve allowable seat leakage, rotometer size selected, physical constraints of the equipment included in the test configuration, API 521 (2014) guidance for “severe” check valve failure, and normal as well as expected maximum forward flowrates. A pass/fail limit was selected based on review of these rates.

Review of this range of rates highlights a key point. The leakage rates associated with API 521 (2014) “severe leakage” guidance - also referenced in CCPS IE/IPL Section 5.2.2.2.2 Case 1—are four to five orders of magnitude larger than the acceptable leakage rates for new check valves prescribed by numerous standards for seat leakage. The check valve has failed from a reliability standpoint long before the API 521 (2014) “severe” failure leakage rates are approached. This situation is implied given that the failure mode is described as “severe” with leakage defined as “significant" in API 521 (2014). The reference to “slight” leakage in CCPS IE/IPL Section 5.2.2.2.2 Case 1 is in error. Leakage rates within the vicinity of these “severe” failure values may be unlikely in many check valve configurations as the leakage may be either far below these values (i.e., “normal" leakage potentially represented by values much closer to new valve leakage) or above these values (i.e., complete failure). In order to experience “severe” leakage, failure modes would likely involve significant debris or a foreign object preventing closure or may be caused by freeze up such as from Joule-Thompson flashing. These failures modes could result in fixing the check valve element at a location off but somewhat near the seat.

The specific technical origin of these API 521 (2014) leakage rate assumptions for “severe” failure is not clear. Current API 521 committee members are only aware that the values were adopted from a member company participating on the committee. It is possible that due to lack of leakage rate data, very high leakage rate assumptions were chosen using an abundance of caution. No data is known that supports the assumption that check valves commonly fail in a manner that results in these high leakage rates. Also, no data is provided that supports the assumption that “severe” failure is more likely than “complete” failure.

Since little to no data is available for typical “normal” check valve leakage rates, establishing an appropriate initial limit is challenging. However, as was made clear by defining the various thresholds, a limit well below the “severe” leakage rate referenced in API 521 (2014) and at or near new valve allowable leakage rates is an appropriate limit to assure that the check valve is performing its function as
intended. Impacts to upstream equipment including pressure build-up in lower rated low volume equipment and reverse flow impacts to rotating equipment should be considered when selecting the pass/fail threshold or MALR.

The MALR for Test 2 was defined based on similar considerations as with Test 1 configuration.

9 | TEST METHOD AND PROCEDURE

Preparation for and conducting the testing procedure involved several steps. Below is a description of the primary steps involved in the test procedure for testing dual check valves.

1 Process hazard analysis (PHA for testing configuration)
   a Safeguards and IPLs were considered that remained in place for the entire system as well as safeguards and IPLs specific to the testing equipment.
      i A PSV skid was designed and installed for use as an IPL for the equipment installed for the testing.
   b Alarm setpoints were adjusted on pressure transmitters (PTs) including on the upstream chamber to indicate build-up of pressure through leakage.
   c Board operators were engaged in monitoring potential pressure build-up.

   2 Energy isolation and safe-out: Performed as per standard energy control procedures.

   3 Equipment installed for the test:
      a Nitrogen bottle skid
      b Regulators, from nitrogen bottle skid
      c Pressure gauges at nitrogen bottle skid (scaled for each testing procedure)
      d Hose, 5000 psig, inspected and tested. Installed with appropriate safety devices and signage.
         i Connecting supply side:
            1 N2 skid and PSV skid
            2 PSV skid and check valve downstream tap
         ii Connecting return (vent) side
            1 Check valve upstream tap to rotometer (or alternatively, use SS tubing)
            2 Rotometer to atmospheric vent point
   e PSV skid, sized and with setpoint specific to each test configuration
   f PTs/PITs on existing process piping (PITs preferred for onsite pressure display.)
      i Reset appropriate alarm setpoints for the testing procedure
      ii Broadcast of data reset from once every 5 minutes to once per second for this testing procedure
   g Meter, rotometer sized at or above anticipated leakage rate and MALR

| Description of Flow Rates and Leakage Thresholds Considered: Test 1 | Rate | Units |
|---------------------------------------------------------------|------|-------|
| Maximum Process Flow Rate (forward flow), ≈ 18 MMSCFD       | 750,000 | SCFH |
| Normal Process Flow Rate (forward flow), 8.5 MMSCFD          | 354,165 | SCFH |
| Calculated Reverse Flow Rate based on API 521 (2014), Severe Leakage Assumption, Method 1) 10% orifice | 185,120 | SCFH |
| Calculated Reverse Flow Rate based on API 521 (2014), Severe Leakage Assumption, Method 2 | Not Calculated | SCFH |
| Arbitrary limit considered, 10% of normal forward flow rate | 35,416 | SCFH |
| Testing Limitation: Choked flow condition during test         | 4,050 | SCFH |
| Arbitrary limit considered, 1% of API 521 Method 1            | 1,851 | SCFH |
| Rotometer selected for Leakage Test: Maximum measurable flow rate | 57 | SCFH |
| Maximum Allowable Leakage Rate, New Check Valve, as per API 598 and ISO 5208 | 9.0 | SCFH |
| Rotometer selected for Leakage Test: Minimum measurable flow rate | 5.9 | SCFH |
| Maximum Allowable Leakage Rate, New Check Valve, as per MSS SP-61 | 2.4 | SCFH |
4 Configuration approval and sign-off before each use. Assure engineer sign-off of current job package.
5 Verify initial positions: valve positions, blind positions, as required by procedure.
6 Pre-start-up safety review (PSSR): Verify as-installed equipment and initial valve/blind positions. Visual inspection and checklist review.
7 Perform leak testing on installed testing equipment (peripheral equipment).
8 Perform leak testing of downstream double block and bleed valves. If leakage found, safe-out equipment and roll downstream blind.
9 Perform leak testing of upstream block valve (by connecting pressure source between upstream check valve (CHK-01) and upstream block valve. If leakage found, safe-out equipment and roll upstream blind between vessel and first check valve.
10 Prepare for leak test of downstream check valve (CHK-02). Operator resets Alerts and Alarms on PTs. Flowmeter is connected to check valve upstream connection and vents to atmosphere. Pressure source is connected to check valve downstream connection.
11 Assure PTs at zero pressure reading. Note time for start of test.
12 Perform leak testing as per procedure on check valve (CHK-02). Set pressure regulator at prescribed test pressure and pressure up to test pressure on the downstream side of downstream check valve.
13 Note and record pressure reading. (PT data available for further analysis at a later date.) Also note and record pressure readings downstream and/or upstream of block valves to assure no leakage.
14 Record flowmeter flow rate data.
15 Review acceptance criteria. If below acceptable leakage rate (including below measurable rate), conclude test. If below measurable rate, may consider either using a rotometer with a smaller scale or the pressure build-up method to quantify rate.
16 Wait and take another data set after specified time interval.
17 Following conclusion of test, de-pressure the downstream and upstream side of the check valve through bleed line and rotometer vent line. (Note: The rotometer should register instantaneous flow even if no flow was detected during the check valve leak test.)
18 Disconnect testing equipment.
19 (If dual check valves being tested, repeat procedure for upstream check valve (CHK-01),)
20 Return process equipment to original setpoints and data broadcast frequencies.
21 Reverse energy isolation procedures.
22 Perform PSSR and restart process as per normal start-up procedures.

10 | ALTERNATIVE TESTING AND ASSESSMENT OPTIONS

The procedure described represents a direct testing method using an external pressure source. In addition to this testing method, other alternatives should also be considered as appropriate. In some instances, use of existing process pressure may be a viable manner for applying a pressure source for testing certain check valves particularly on parallel equipment. In this case, quantification of the leakage rate could be accomplished by one of several methods. Pressure build-up analysis using SCADA systems may be most convenient if upstream isolation is available. Acoustic monitoring equipment should also be considered as a simple alternative which allows for assessing seat leakage rates and check valve performance. Given the nature of check valve operation, some type of shut-down, whether full plant turnaround, unit outage, train outage, or parallel equipment shut-down will be required to assess check valve performance.

Although not quantitative, diagnostic, or predictive, when check valves are engaged, there may be opportunities to confirm gross closure of the check valve by operators or mechanics. Operations or maintenance personnel may have some indication of closure of check valves based audible sound and on response of equipment that cannot tolerate back spinning. Equipment that cannot tolerate reverse flow, including certain rotating equipment, may be immediately or catastrophically damaged by incidences of check valve failure and loss of containment may occur. Additionally, check valve failure on a spared centrifugal pump may be detected following start-up of a parallel pump when both discharge pressure and flowrate measured on a downstream common line are lower than expected.

11 | KEY TAKE-AWAYS AND FINDINGS FROM CHECK VALVE LEAKAGE TEST

Because the testing involved only a single instance of testing five separate new check valves, the data from the testing is not presumed to represent a wider population of in-service check valves. Because of this fact and because much of the specific data from the testing is not available for sharing, the results of the check valve testing will be discussed in general terms. Descriptions of results and findings from the testing are the recollections of the author.

1 The testing procedure worked relatively well in both instances. The testing of the single valve (higher pressure) was more easily accomplished due to the simplicity of the testing procedure. Only a single valve was being tested and isolation was accomplished with blinds rather than double block and bleed valving.
2 In the case of the single axial check valve test (higher pressure application) isolated by spectacle blinds:
   a The rotometer was used for measuring the leakage rate through the check valve.
   b Leakage rates were found to be below the scale of the rotometer, therefore less than 5.9 SCFH.
      i This rate of leakage was well within the acceptable range for new check valve allowable leakage criteria, so no further investigation or calculation of actual leakage rates was pursued.
      ii During relief of the trapped pressure from the downstream system through the rotometer following the test, the functionality of the rotometer was confirmed.
In the case of the dual check valves, one axial check valve and one wafer check valve on each train (lower pressure application) isolated by block valves:

a. Initially achieving a good leak test was challenging primarily due to the tubing manifold planned for use. Usage of the tubing manifold was abandoned in preference to direct connections (and repositioning of PTs).

b. Using valving to isolate the test section from the process also required additional steps in the leak test procedure. Leak testing of block valves was successfully accomplished. No blinds were rolled.

c. Check valve leakage rates were determined using PTs and pressure build-up calculations rather than with the rotometer.

d. Leakage rates were calculated for both the axial check valve(s) and the wafer check valve(s). Both valves passed the test. Leakage rates were below the threshold stipulated in the procedure.

e. Wafer check leakage was higher than axial check valve leakage. Both were within established limits.

As anticipated, selecting rotometers that meet the actual range of leakage was challenging. However, the rotometers selected were within the “ballpark” of leakage ranges. With more time and test data, rotometers could be effectively “dialed in” that would be in the range of the actual leakage.

Pressure build-up testing proved to be a viable and simple alternative method to determine leakage rates.

System and block valve leak tests must be conducted in advance of check valve leak testing to assure that isolation from other potential leakage points have been successfully achieved.

The testing requires either a full or partial outage to accomplish.

As with any new procedure, appropriate process hazard review of the connected equipment and procedure is required as well as pre-start-up safety review. A personnel job safety analysis (JSA) must be conducted as well.

b. API 521 (2014) does not allow for crediting a single check valve with any reduction in flow rate to the upstream PSV, even if the check valve is inspected and maintained. This assumption equates to a PFD for a single check valve of 1, or RRF = 1. No data is given to support this assessment of PFD = 1. (Note: API 521 (2008)11 did acknowledge the potential for a single check valve to limit reverse flow when the check valve was appropriately inspected and maintained.)

c. CCPS IE/IPL2 references API 521 (2008)11 language in 5.2.2.2.2 Case 1 which refers to a “series check valves,” but also references a single check valve in the Case 1 description.

The discrepancies in CCPS IE/IPL2 and API 521 (2014) regarding check valve failure likelihood should be reconciled. Check valve probability of failure on demand (PFD) by valve type, size, and service should be based on inspection, testing, maintenance, operational, and failure history data.

Check valve leakage rates should be determined based on testing and should be associated with valve type, failure mode, size, and service. Check valve leakage rates for “severe” and “normal” failure should be better defined and consistently applied.

2 Leakage rate assumption(s) cited by API 521 (2008)11 and replicated in CCPS IE/IPL2 Section 5.2.2.2.2 Case 1 represent “severe”, significant, or high rates of leakage. The check valve has failed from a reliability standpoint at a much lower rate of leakage (four to five orders of magnitude less leakage). The reference to “slight” leakage in CCPS IE/IPL2 5.2.2.2.2 Case 1 should be corrected.

Little data is currently available regarding typical or “normal” leakage rates for check valves that have been in operation. Likewise, little data is available regarding check valve failure modes and frequencies. This void was a driver for designing and performing these field tests and for writing this paper.

3 Numerical estimates for “normal” leakage rates are not offered by API 5213,11 or by CCPS IE/IPL2. API 5213,11 indicates it is the responsibility of the user to determine normal leakage rates.

4 “Severe” leakage rates as defined in API 521 (2014)3 exceed new check valve performance requirements by four to five orders of magnitude. Integrity management programs should strive to achieve performance comparable to new valve standards.

5 In spite of the high rates associated with the “severe” leakage calculation in API 521 (2014),3 the assumption that check valves fail in this manner may not be accurate or conservative. Complete failure of the check valve may be a more likely failure mode.

6 Testing of check valves that have been in service is a prerequisite to not only understanding and improving check valve performance, but also to crediting check valves as IPLs or safeguards.

7 Existing industry equipment reliability databases such as CCPS Process Equipment Reliability Database (PERD) have very little data available on check valve performance including failure modes and frequencies. PERD offers guidance for data collection in a manner

12 | KEY TAKE-AWAYS FROM REVIEW OF REFERENCE MATERIAL

As noted within this paper, several discrepancies were found in reference material. The following inconsistencies should be resolved within reference documentation in order to prevent confusion for users and practitioners.

1. Crediting a Single Check Valve as IPL and using an appropriate PFD:

a. CCPS IE/IPL2 lists a single check valve as a candidate IPL in Chapter 5 and provides a generic PFD value of 0.1 (RRF = 10) based on data and calculations provided in Appendix D. Special considerations are listed that must be satisfied. Initiating event frequencies (IEFs) are also given for check valves in high demand modes of 0.1 and 0.01 for single and dual check valves, respectively, in Chapter 4 based on the same data in Appendix D.

b. API 521 (2014)3 does not allow for crediting a single check valve with any reduction in flow rate to the upstream PSV, even if the check valve is inspected and maintained. This assumption equates to a PFD for a single check valve of 1, or RRF = 1. No data is given to support this assessment of PFD = 1. (Note: API 521 (2008)11 did acknowledge the potential for a single check valve to limit reverse flow when the check valve was appropriately inspected and maintained.)

c. CCPS IE/IPL2 references API 521 (2008)11 language in 5.2.2.2.2 Case 1 which refers to a “series check valves,” but also references a single check valve in the Case 1 description.
that supports reliability analysis. Usage of PERD and other industry resources is recommended.

13 | CONCLUSIONS

Check valves perform an important and often critical function in process equipment. Therefore, check valve performance and reliability should be a foremost concern for operating companies. Check valve performance and reliability should be managed through maintenance programs that include inspection, testing, and repair of check valves. Check valves have historically not received proper attention in inspection and maintenance programs. And testing programs to quantify leakage have rarely been instituted. This situation persists in spite of regulatory and industry stipulated requirements for maintaining asset integrity. Regulation, such as OSHA PSM, explicitly references piping and piping components, such as valves, as process equipment covered by the regulation.

More and better data on check valve failure modes, failure likelihood, and performance (i.e., leakage) can lead to better design by manufacturers, better selection for the given application by operators, better piping configuration design, and better performance of the check valves. Currently, discrepancies exist in some core industry reference material regarding characterization of check valve probability of failure on demand (PFD). Those discrepancies should be reconciled. (See Section 12 for descriptions of these discrepancies.)

Little data is available regarding check valve performance and failure modes by type and in given service applications. And little progress has been made on gathering more modern data on check valve performance. The author encourages operating companies to consider testing and inspection of check valves in critical service as part of their mechanical integrity program, particularly when designing and installing new installations where appropriate isolation and testing ports may be included in the piping arrangement. The author further encourages the sharing of check valve inspection and testing data more broadly, such as through the CCPS Process Equipment Reliability Database (PERD), in order to achieve industry-wide progress towards improved check valve reliability. Better practices, better data, and better understanding of performance can lead to changing expectations regarding check valve performance.

When check valves are thoroughly and routinely inspected, tested, and maintained, PHA and/or ILOPA credit for the check valve(s) as a safeguard or IPL, respectively, may be achieved. As always, operators must consider applying this credit with a thorough understanding of the check valve failure modes and their ability to prevent the hazard consequence from being realized.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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