Overpressure by Design – An Oil and Gas Perspective on Safety for Kraft Digesters

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INTRODUCTION

Overpressure protection by system design in lieu of pressure relief devices (PRDs) as a method of pressure vessel overpressure protection has been used in industry for a long time and only relatively recently has it been codified in Section VIII, Division 1, of the ASME Boiler and Pressure Vessel Code (ASME Code) [1] as paragraph UG-140. As part of the recent restructuring of the ASME Code, most of the requirements associated with UG-140 are now located in ASME Section XIII, Part 13 [2].

Refiners and chemical companies have been utilizing instrumentation as part of their overpressure protection systems in situations where a PRD is unreliable due to the fouling or plugging nature of the relieving fluid, where the required capacity (i.e., number of relief devices) is unreasonable or where PRDs introduced other dangers due to increased emissions. For example, in the manufacture of paper and other similar processes where slurries and corrosive process streams are encountered, PRDs may not be reliable.

System design has also been used in the Paper & Pulp industry in protection of Kraft digesters. Digesters utilize PRDs as part of the overpressure protection system, but they are not always sized to handle all potential overpressure scenarios. Instrumentation is often used as part of the system design to eliminate some of the overpressure scenarios to reduce the size of the PRDs. Experience shows that not all operators are applying the system design philosophy as intended by the ASME Code. Part of the reason could be due to the fact that there is significant confusion about how it is to be applied.

BACKGROUND ON OVERPRESSURE PROTECTION BY SYSTEM DESIGN

Recognizing that the industry had been applying a system design philosophy without consistent guidance, concerned industry leaders from ASME (American Society of Mechanical Engineers) and API (American Petroleum Institute) worked together to establish minimum requirements for applying system design in lieu of PRDs. These rules were initially published in 1996 as a Code Case to the ASME Code; Code Case 2211, "Pressure Vessels with Overpressure Protection by System Design". The Code Case was reaffirmed in 1999 as CC2211-1.

In the twelve (12) years between the initial publication of CC2211 and the incorporation of UG-140 into the ASME Code, a Welding Research Bulletin, WRC 498 [3] was published in 2005 with the goal of providing the industry with practical guidance on applying the Code Case and to ensure consistency across the industry in the way it was being applied.

In addition to providing guidance to owner/users on how to apply the Code Case, WRC 498 also provided several recommendations for improvements that the ASME Code should consider when eventual incorporation occurred. Firstly, WRC 498 recommended that the ASME Code allow similar allowable overpressures (accumulations) when traditional PRD overpressure protection is supplied, i.e., 10% for normal process scenarios, 16% when multiple PRDs are used and 21% for the fire case. CC2211 was originally written to ensure that overpressure by system design applications limit the pressure rise under all circumstances to the maximum allowable pressure (MAWP). When system design was eventually incorporated into the ASME Code, UG-140 allowed accumulation of pressure of 116% of the MAWP when instrumentation is used in the design of the overpressure protection system.

Secondly, WRC 498 recommended that the Code consider both the probability and the consequences (i.e., risk) when assessing the credibility of potential overpressure scenarios. This is where some of the confusion occurs, WRC 498 interpreted CC2211 to require that all potential overpressure scenarios, regardless of the overpressure (consequence), be accompanied by a credibility analysis that uses a definition of credibility as any event that occurs more frequently than 1×10^{-4} events per year (or 1 event per 10,000 years). Some users will reduce this to 1×10^{-5} (1/100,000 years) for catastrophic events. As written, then, even if the overpressure were to exceed the MAWP by only 20%, for example, high integrity instrumentation might be required to reduce the event frequency to the tolerable 1×10^{-4} events per year. A risk-based approach that includes both likelihood and consequences using a company's risk matrix might not require additional layers of protection for low consequence overpressure scenarios.

UG-140 REQUIREMENTS

The final rules on system design were incorporated into the main body of the ASME Code, Section VIII, Division 1 in 2008 as paragraph UG-140 and later moved to Section XIII, Part 13. There was a subtle but significant difference between what was included in CC2211 and what was eventually incorporated into UG-140. CC2211 was written to provide owner/operators with requirements for using system design "**in lieu of**" PRDs, either by ensuring that the MAWP of the protected equipment was high enough such that there was no possible scenario that could cause overpressure OR providing instrumentation that would reduce the probability of any overpressure event low enough to eliminate the possibility that the protected equipment could be overpressured, thereby eliminating the need for PRDs.

System design as outlined in UG-140 can be accommodated in two ways. Inherent safety, as detailed in UG-140 (a), are applications where the pressure is self-limiting and there is no way to overpressure the vessel. In this case, PRDs are not required. UG-140 (b) details the second case where the pressure rise is not self-limiting and instrumentation in lieu of or in combination with PRDs provide overpressure protection.

In all cases, there are some basic requirements owner/operators need to include when implementing system design.

1. The decision to provide a vessel with overpressure protection by system design is the responsibility of the user, not the vessel manufacturer or the design contractor.
2. The user shall request that the MFG's Data Report state that overpressure is provided by system design (if no PRD installed).
3. Jurisdictional approval may be required to implement system design philosophy.
4. A multi-disciplined, experienced team (including Operations) shall conduct a process hazard analysis using a standard methodology (e.g., HAZOP, FMECA, What-If, or equivalent) considering the "Causes of Overpressure" as given in API STD 521 [4].
5. The results of this study shall be fully documented and signed by the individual in responsible charge of the management and operation of the vessel.

UG-140(a) – System Design using Inherent Safety

Per UG-140(a), a pressure vessel can be installed without PRDs if the pressure rise is self-limiting and the vessel cannot be overpressured. A classic example of this is a vessel that has a blocked outlet that is downstream of a centrifugal pump, where the deadhead of the pump is less than the MAWP of the vessel. If there are no other overpressure scenarios, this vessel could be installed without a PRD.

Of course, an analysis has to be completed by the multi-disciplined team experienced in the methods used (i.e., HAZOP, FMECA, What-if, etc.) and that analysis shall establish that there are no credible overpressure scenarios that could possibly overpressure the vessel above its MAWP. As part of the documentation, the calculated maximum pressure and coincident temperature for each scenario must be determined and compared against the MAWP of the vessel.

UG-140(b) – System Design using Instrumentation

A pressure vessel may be protected by system design or by a combination of pressure relief devices and system design, (i.e., typically using instrumentation to eliminate scenarios thereby reducing the size of PRDs OR eliminating PRDs altogether), if the requirements of UG-140(b) are met.

In addition to the 5 basic requirements listed above, UG-140(b) includes the following:

1. In no case shall the system design using instrumentation allow normal operation to exceed the MAWP.
2. The overpressure will be readily apparent so that operators or the protective instrumentation will take corrective action.
3. The vessel is not exclusively in steam, air, or hot water service, unless these services are critical to preventing the release of fluids that may result in safety or environmental concerns, equipment damage, or operational upsets.

The analysis to be completed by the multi-disciplined team where system design with instrumentation is used is more involved than what is required in UG-140(a). As before, all credible overpressure scenarios need to be identified and examined using API 521 guidance for "Causes of Overpressure". In this case, the analysis must demonstrate that there are no credible scenarios in which the pressure exceeds 116% of the corrected MAWP.

The corrected MAWP as determined from Equation (1), accounts for the differences in allowable stresses at the overpressure scenarios' relieving temperature when compared to the design temperature and can result in a corrected MAWP that is either lower or higher than the stamped MAWP.

$$MAWP_{corrected} = MAWP \times \frac{\sigma_{scenario}}{\sigma_{design}} \quad \text{Equation (1)}$$

σ is the allowable stress

Since it is possible that the corrected MAWP can be greater than the stamped MAWP, UG-140(b) limits the overpressure limit (116% above the corrected MAWP) to the hydrotest test pressure.

In addition to the overpressure analysis discussed above, UG-140(b) requires a credibility assessment and points to the WRC 498 bulletin for guidance on performing this analysis. In this analysis, all independent redundancies must be identified, and a reliability analysis (qualitative or quantitative) must be performed on any safety critical instrumentation used to limit the system pressure.

As discussed above, WRC 498 recommended that the ASME Code consider allowing risk-based methods to be used when performing the credibility assessment. In other words, consider the consequences as well as the probability of the overpressure events when setting the acceptance criteria in the credibility assessment and allowing companies to use their own risk tolerance criteria (risk matrix). For high consequence events (catastrophic), the probability (or credibility) of the overpressure scenario may require a mitigated frequency of 1×10^{-5} (1/100,000 years). On the other hand, lower consequence events (e.g., overpressure below hydro), may require a mitigated frequency of only 1×10^{-3} (1/1000 years) for the scenario to be deemed acceptable.

And this is where some of the confusion comes from. Some users only use a probability-based approach in their credibility assessments; others will use a risk-based approach. API's philosophy as discussed in API 521, clearly allows a user's risk criteria when applying UG-140.

API APPROACH USING RISK WHEN APPLYING UG-140

System Design Where the use of PRDs is Impractical

API's basic philosophy related to instrumentation, as provided in API STD 521, is to not take credit for basic process control systems (BPCS) when sizing PRDs. Control valves that are not part of the overpressure event are often designed to react to a process upset, but when sizing a PRD, API assumes that these basic process control valves are either in manual mode or are in a latent state of failure at the time of the upset. However, paragraph 4.2.6 indicates that there will be situations where a relief device is "impractical', and credit for instrumentation becomes a necessity.

> "Fail-safe devices, automatic start-up equipment, and other conventional instrumentation should not be a substitute for properly sized PRDs as protection against single jeopardy overpressure scenarios. There can be circumstances, however, **where the use of PRDs is impractical** and reliance on instrumented safeguards is needed. Where this is the case, if permitted by local regulations, a PRD might not be required."

The author believes that a key part of the API philosophy is to understand that replacing traditional PRDs with other means of overpressure protection, including instrumentation, is to be used in rare situations. Elimination of PRDs should only be performed when their use is "impractical". Some examples from API that may pass the "impractical" hurdle include:

- High level on column to prevent overfilling
- High temperature or plugging services (PRD not suitable)
- Trips on high pressure turbines
- Explosion prevention to avoid large vents
- Prevent overpressure due to mixing errors (possible explosive conditions)
- Reduction in number and/or size of relief vents
- Eliminate releases to atmosphere
- Chemical reactor runaways

Use of Risk Criteria when Analyzing Credible Scenarios

Also discussed in API STD 521 paragraph 4.2.6, it is clear that the API philosophy allows a user's risk tolerance criteria to be used when performing the credibility assessment required by UG-140. API states that where reliance on instrumented safeguards is needed, "the design shall comply with the local regulations and the user's risk tolerance criteria". Annex E of API 521 provides additional guidance to the user on applying UG-140 and emphasizes the use of instrumentation to reduce the probability of an overpressure contingency. It further points to the (IEC61511)[5] standard and its supplement, ISA TR84-02[6], for calculation procedures that meet the UG-140 requirement to conduct a reliability or availability analysis for safety instrumented systems (SIS).

Annex E entitled "High-Integrity Protection Systems (HIPS) provides general steps in using SIS to protect against a hazard as follows:

1. Perform a Process Hazards Analysis (PHA) to identify hazards. To meet the intent of UG-140, this analysis should be conducted by a multi-disciplined team, including Operations.
2. Although IEC 61511, does not specify the type of analysis to use, Annex E suggests that a Layers of Protection Analysis (LOPA) is usually performed as a quantitative analysis to further evaluate high risk scenarios identified in the PHA.
3. Apply non-SIS protection layers first to eliminate identified hazards or reduce the associated risk.
4. Determine if additional independent layers of protection, such as a SIS, are needed to achieve the tolerable risk.
5. Define the target Safety Integrity Level (SIL) or availability value required for the SIS. With appropriate level of redundancy, the SIS (or HIPS) can be designed to achieve a level of availability equal to or greater than a mechanical relief device.

Note that when using risk-based methods, such as LOPA, the user may determine that a SIS with a high SIL is not always needed. For example, one redundant transmitter may be all that is needed to achieve the tolerable risk. Annex E indicates that "In the large majority of cases for HIPS, the result of the hazard analysis is either a SIL-2 system (requiring a minimum of 99 % availability) or a SIL-3 system (requiring a minimum of 99.9 % availability)." The user may consider it necessary for the required overpressure protection availability to be higher than that provided by a single mechanical relief device.

At this point a word of caution is warranted. There will be many low consequence (i.e., low risk) overpressure scenarios that can be designated as meeting the user's risk tolerance criteria by taking credit for basic safeguards, such as administrative procedures or basic control valves (BPCS). In some cases, the overpressure scenario can be shown to meet the user's risk criteria without any safeguards at all. Users should not be using UG-140 to eliminate PRDs in situations where use of a PRD is the practical solution. Both WRC 498, and API 521 Annex E, indicate that the use of UG-140 to eliminate PRDs should only be done in rare applications where the use of a PRD is impractical.

Inspection and Testing Requirements for SIS

The user is responsible for developing and implementing the necessary documented procedures and methods to ensure adequate reliability of the identified Safety Critical elements. Per annex E of API 521:

> "It is critical that the instrumentation associated with HIPS be tested at regular intervals. The availability analysis assumes a test interval for each piece of equipment. In order for the actual HIPS reliability to align with that predicted by the availability calculations, it is necessary that the actual testing frequency (during operation) corresponds to the assumed in the availability calculations performed during the design."

Annex E also cautions that the user needs to consider the impact of the required proof testing on the facility receiving the SIS, and whether the facility has the skills and resources to maintain the equipment. The risk reduction credited to the SIS is achieved when the system is operated and maintained per the safety requirement specification. If the operation and maintenance requirements cannot be met, an alternative SIS design should be considered.

APPLICATION TO PAPER & PULP DIGESTERS

In applying the rules of system design to the overpressure protection philosophy for Kraft digesters, the Paper & Pulp industry needs to ensure that they are following the requirements of UG-140. Each installation where UG-140 system design philosophy has been applied should be audited to make sure that the requirements of UG-140 are met. Some of the questions that should be asked include:

1. Has permission from the jurisdiction to use system design been obtained?
2. Does the installation using a system design approach pass the "impractical" hurdle? Instrumentation should not be used in lieu of a PRD, when the installation of a traditional PRD is reasonable.
3. Where inherent safety has been established (UG-140a), has a multi-disciplined team been involved in analyzing potential overpressure scenarios in accordance with API 521 and has it been established that there are no credible overpressure scenarios that could possibly overpressure the digester above it MAWP?
4. Where instrumentation is used as a replacement for PRDs or in combination with PRDs (UG-140(b)), has a multi-disciplined team been involved in analyzing potential overpressure scenarios in accordance with API 521 and has it been established that there are no credible overpressure scenarios that could possibly overpressure the digester above it MAWP by more than 116%?
5. Additionally, has a qualitative or quantitative credibility assessment been completed by qualified individuals to demonstrate that the probability (or credibility) of any overpressure event meets the corporate risk criteria?
6. Where SIS has been used as part of the system design to eliminate or reduce the size of PRDs, has a reliability (or availability) analysis been completed per IEC 61511?

7. Was the calculation of overpressure for credible scenarios compared against the “corrected” MAWP, or 116% of the corrected MAWP, as applicable?
8. Have the results of the system design studies been documented in accordance with UG-140 and signed by the individual in responsible charge of the management and operation of the vessel?
9. For safety critical equipment, have test intervals and test protocols been established so that the required reliability (or required SIL level) as determined from the reliability analysis is maintained? Does the facility receiving the SIS have the skills and resources to operate and maintain the system?

CONCLUDING THOUGHTS

Going forward, the use of certified pressure relief devices (PRDs) will continue to be the standard means of overpressure protection. In rare cases, where a PRD is impractical, the use of Safety Instrumented system design in lieu of PRDs or to reduce the size requirements for PRDs will be necessary.

In the Paper & Pulp industry, the safety of digesters will be improved when risk and instrumentation are an integral part of overpressure protection analysis. Users should follow IEC 61511 methodology to ensure their safety instrumented systems are analyzed, documented, and signed-off in accordance with UG-140, and tested and inspected at a frequency sufficient to maintain the required SIL rating.

System design using an instrumented approach will likely be more expensive than standard PRD protection, so typically these solutions will only be applied when the PRD installation is impractical or unreliable. The initial cost of the SIS as well as the testing and inspection requirements to maintain SIL rating can be expensive making routine usage of a UG-140 system design approach infrequent.

REFERENCES

[1] ASME Boiler & Pressure Vessel Code: Section VIII, *Rules for the Construction of Pressure Vessels*, American Society of Mechanical Engineers, Two Park Avenue, New York, New York 10016-5990

[2] ASME Boiler & Pressure Vessel Code: Section XIII, *Rules for Overpressure Protection*, American Society of Mechanical Engineers, Two Park Avenue, New York, New York 10016-5990

[3] J. R. Sims and W. G. Yeich, Welding Research Council, Bulletin 498, *Guidance on the Application of Code Case 2211 – Overpressure Protection by Systems Design*, January 2005.

[4] API Standard 521, *Pressure-Relieving and Depressuring Systems*, American Petroleum Institute, 7th ed., 2020.

[5] IEC 61511-1:2016, *Functional safety - Safety instrumented systems for the process industry sector - Part 1: Framework, definitions, system, hardware and application programming requirements*.

[6] ISA-TR84.00.04-2011, *Part 1 Guideline for the Implementation of ANSI/ISA-84.00.01-2004 (IEC 61511).*