API 521 SRU REACTION FURNACE WASTE HEAT BOILER EVALUATION FOR OVERPRESSURE DUE TO TUBE RUPTURE

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Abstract

American Petroleum Institute (API) Standard 521, *Pressure-relieving and Depressuring Systems* (current edition: 2014) is being revised to include information regarding Sulfur Recovery Unit (SRU) Reaction Furnace Waste Heat Boiler (WHB) tube rupture developed process side overpressure and other updates. The proposed modifications regarding the SRU Reaction Furnace WHB were first balloted in the spring of 2015. Once all of the changes are balloted and approved, a new edition of API 521 will be issued in 2019 at the earliest. The modifications to API 521 that were balloted state that the user should evaluate the system to determine if the system can relieve a rate equivalent to double the cross sectional area of a single tube in the WHB without exceeding the corrected hydrotest pressure of the reaction furnace and other low-pressure side equipment. The proposed modifications suggest that Steady State analysis be completed first. If the steady state analysis predicts that the corrected hydrotest pressure will be exceeded it is suggested that other methods such as Dynamic analysis can be completed. The proposed modifications also state that an alternative to dynamic analysis would be the application of ASME Section VIII, Division 1 UG-140 *Overpressure Protection by System Design*. The proposed modifications do not provide any real guidance on how the analysis should be done or suggested scenarios and sequences for the various analyses that should be completed. This paper focuses on the authors' understanding of how the overpressure analysis should be completed and provides a flowchart with a suggested sequence for the analysis. The bulk of this paper was originally developed and submitted to API for possible inclusion in the modifications to API 521 to provide guidance for engineers that are responsible for evaluation of tube ruptures in new and existing SRU reaction furnace WHBs. After consideration, the information was rejected, by the API 521 Task Group, from inclusion in API 521 because it was risk based direction, utilizing ASME Code Case 2211 addressing UG 140 *Overpressure Protection by System Design* and WRC Bulletin 498 *Guidance on the Application of Code Case 2211 - Overpressure Protection by Systems Design*.

This paper provides guidance for evaluating overpressure scenarios due to a WHB double ended tube failure including a suggested sequence for analysis flowchart and examples.

1.0 Introduction

API 521, *Pressure-relieving and Depressuring Systems* (current edition: 2014)[1] is being revised to include information regarding Sulfur Recovery Unit (SRU) Reaction Furnace Waste Heat Boiler (WHB) tube rupture developed process side overpressure and other updates. The proposed modifications regarding the SRU Reaction Furnace WHB were first balloted in the spring of 2015. Once all of the changes are balloted and approved, a new edition of API 521 will be issued in 2019 at the earliest. The modifications to API 521[1] that were balloted state that the user should evaluate the system to determine if the system can relieve a rate equivalent to double the cross sectional area of a single tube in the WHB without exceeding the corrected hydrotest pressure of the reaction furnace and other low-pressure side equipment. The proposed modifications suggest that Steady State analysis be completed first. If the steady state analysis predicts that the corrected hydrotest pressure will be exceeded it is suggested that other methods such as Dynamic analysis can be completed. The proposed modifications also state that an alternative to dynamic analysis would be the application of 2013 ASME BPVC *Section VIII Rules for Construction of Pressure Vessels*, Division 1 UG-140[4] "Overpressure Protection by System Design". The proposed modifications do not provide any real guidance on how the analysis should be done or a suggested sequence for the various analyses that should be completed.

Martens & Stern presented a paper at the Brimstone Sulfur Symposium – Vail in 2014 titled "*Designing to proposed API WHB tube failure document*"[2]. That paper included the results of a 2001 and 2014 SRU Waste Heat Boiler Safety Survey of WHB tube ruptures resulting in loss of containment in the SRU system and a proposed methodology for overpressure analysis of an SRU based on a WHB tube rupture where the maximum allowable stress to minimum tensile stress provides the same safety margin as ASME[4] accepts for deflagration design. The paper also addressed Quantitative Risk Analysis and Layers Of Protection Analysis (LOPA) referencing Welding Research Council (WRC) Bulletin 498 *Guidance on the Application of Code Case 2211 – Overpressure Protection by System Design*[5] and *Layers of Protection Analysis Simplified Process Risk Assessment*, Center for Chemical Process Safety[7].

Mosher & Ogg presented a paper at the Brimstone Sulfur Symposium – Vail in 2014 titled "*SRU Overpressure Scenarios Waste Heat Exchanger Failures with Different Sulfur Sealing Technologies*"[3]. That paper included detailed analysis of three SRU examples for applicable scenarios based on API 521[1] guidance for over pressure evaluation with a tube rupture equivalent to double the cross sectional area of a single tube.

This paper is a follow-up to these 2014 papers and focuses on the authors' understanding of how the overpressure analysis should be completed and provides a flowchart with a suggested sequence for the analysis. This paper was developed to provide guidance for engineers who are responsible for evaluation of tube ruptures in new and existing SRU reaction furnace WHBs.

2.0 Risk and Probability

“In this world, nothing is certain except death and taxes” is an often cited quotation from Benjamin Franklin. This quote came from a letter from Benjamin Franklin to French scientist Jean-Baptiste Leroy on November 13, 1789. The quote was actually referring to the new US Constitution and his hope that it would be durable. It can be inferred from this quote that everything else involves some level of risk. In our daily lives we make practically every decision based on our interpretation of the risk of the action. For example, many people in the US choose on a daily basis to eat red meat. There are certainly both short term and long term risks associated with this action. In the short term, there is a risk that the meat could be contaminated with bacteria causing food poisoning that can lead to illness and possibly death. However, many people in the US trust that the inspection processes throughout the food supply chain and the final food preparation is adequate to lower the risk of death to a tolerable level. Those same individuals may not be able to make the same decision in other parts of the world because the risk of illness or death is higher. In the long term, there is a risk that eating red meat can cause health issues (e.g., past research has tied red meat to increased risks of diabetes, cardiovascular disease and certain cancers). However, there is a segment of the population that continues to evaluate the risk on a daily basis and determine that the risk is low enough or perhaps that the risk is far enough in the future that consumption of red meat is acceptable. We evaluate risks everyday whether we are conscious of the action or not.

A risk is an adverse event that "may" occur. The probability of it occurring can range anywhere from just above 0 percent to just below 100 percent. (Note: It can't be exactly 100 percent, because then it would be a certainty, not a risk. And it can't be exactly 0 percent, or it wouldn't be a risk.) A risk, by its very nature, always has a negative impact (consequence). The magnitude of the impact (consequence) varies in terms of cost and impact on health, human life, environmental, or some other critical factor.

One method that engineers use to semi-quantify risk (so comparisons can be made between alternatives and to an acceptable risk level) is to complete a Layer of Protection Analysis (LOPA) based on qualifying analysis such as HAZOP. LOPA utilizes the following steps: selection of a scenario and establishing a consequence (impact) and expression of risk level, identification of initiating event Frequency (F), identification of the Independent Protection layer (IPL), estimation of the Probability of Failure on Demand (PFD), and combining these to calculate an estimated quantitative risk (R). In its simplest terms, Risk (R) = Frequency of event occurring (F) times Probability of Failure on Demand (PFD) of the layer of related protection being evaluated[7].

When looking at the risk it is important to distinguish between probability of failure of an individual item and the product of that probability resulting in a specific consequence. In evaluating process plants we typically consider risk in terms of loss of life, personnel injury, environmental consequence, and loss of production.

In the following sections of the paper (Section 3 Rationale and Section 4 Flowchart) two terms are introduced (credible and non-credible). In this context, non-credible does not mean that the event will never happen. Instead, non-credible means that the event has an annual probability of occurrence less than the acceptable risk benchmark probability established by the User and the appropriate jurisdiction, if applicable. For example, the benchmark used by some users is an annual probability that the event will occur (F) is less than 0.0001 (can be written as < $1x10^{-4}$ or < 1 in 10,000) as the maximum acceptable probability for an overpressure scenario to be considered non-credible(5).

To help put this value in perspective, the authors found references indicating the probability of failure of some commonly used items;

- The probability of failure on demand of brakes failing on a car is once in 10 years ($1x10^{-1}$) per *Layers of Protection Analysis Simplified Process Risk Assessment*(7). Another reference, *The Business of Risk(9)*, lists the probability of brake failure without warning as once in 200 driver-years ($1/200=0.5x10^{-2}$ annually). Even with this probability of failure rate, most of us drive our vehicles every day without giving the brakes much thought.

- In the *Guidelines for Process Equipment Reliability Data(10)* by the Center for Chemical Process Safety the mean Probability of Failure on Demand (PFD) to Open for a spring operated pressure relief device is 2.12×10^{-4} years and for a pilot operated pressure relief device is 4.15×10^{-3} years in a clean or mild service. API Recommended Practice (RP) 581 *Risk-Based Inspection Technology*(11) provides guidance on how to adjust the probability of failure on demand (PFD) based on service, discharge destination, and other parameters. Based on the information in API RP 581(11) a conventional spring operated pressure relief device in moderate service (most refinery applications) that discharges to the flare (closed system) would have a probability of failure on demand (PFD) to open of 5.97×10^{-4} years (once in 1,675 years). This probability of failure on demand (PFD) is 8 to 167 times less likely to occur than the car brake failure PFD described in the first example.

- The National Safety Council listed the lifetime odds of death in a motor vehicle incident at 1 in 112(13). Given a US average life span of 79 years that means in any year the odds are 1 in 8,848 (79x112) of dying in a motor vehicle incident. Which means the Risk(R) of death by motor vehicle incident is 1.13×10^{-4} years. This is the combination of probability of the event occurring (F) and the consequence of the event being death. At this rate again most of us accept these risks and either drive or ride in motor vehicles on a daily basis. The previously described user benchmark annual probability $<1 \times 10^{-4}$ is equivalent to saying that the greatest risk an employee faces is driving to and from work.

- A Class III airplane (multiple turbine engines with greater than 6,000 pounds of gross takeoff weight, i.e. Boeing 737 or MD-80) has probability of failure causing a serious or fatal injury to an occupant of < 1×10^{-7} flight hours according to US Department of Transportation Federal Aviation Administration[12]. Converting this to flight years the probability is 8.76×10^{-4}. This is the combination of probability of the failure event (F) and the consequence of serious or fatal injury. Again, many of us fly on commercial airplanes without excessive concern over safety.

In Martens & Stern[2] the results were presented for a 2014 survey of Claus Thermal Reactor Waste Heat Boiler safety history. In that survey there was a single reported loss of containment (no personnel injuries) of a low pressure-rated SRU due to a WHB tube rupture resulting in an overpressure event. The survey covered a grand total of 20,734 SRU operating years. The one loss of containment event results in the risk (R=F*PFD) of a loss of containment due to a WHB Tube rupture event of 1/20,734 = 4.8×10^{-5} annually. The value is less than the benchmark that some users use for the cutoff on defining what is a credible vs non-credible event. The rationale presented in Section 3 and shown in the Flowchart in Section 4 indicates that even though the reported event frequency is less than what some users define as the benchmark to determine credible versus non-credible, the authors believe it is prudent to add another layer of protection. That additional layer of protection for a maximum double ended tube failure scenario is verifying that the developed overpressure does not exceed the ASME Section VIII[4] criteria and accepted design method presented in NFPA 69 *Standard on Explosion Prevention Systems*[6] allowable maximum deflagration pressure methodology for deformation but not rupture.

3.0 Rationale for Sequence of Calculations for SRU Reaction Furnace WHB Tube Failure Overpressure Analysis

The basis for this analysis is derived from the American Society of Mechanical Engineers (ASME) Boiler Pressure Vessel Code (BPVC), an International Code. The 2013 ASME BPVC *Section VIII Rules for Construction of Pressure Vessels Div 1*,[4] UG-21 Design Pressure, UG-22 Loadings, and further discussed in Overpressure Protection UG-125 General requires "overpressure protection in accordance with the requirements of UG-125 through UG-138, or with overpressure protection by system design in accordance with the requirements of UG-140, or a combination of the two". UG-126 through UG-138 describes the requirements for various pressure relief devices. For an SRU Reaction Furnace WHB the following points need to be considered;

- The "Causes of Overpressure" to be evaluated include the API 521 *Pressure-relieving and Depressuring Systems*[1] events for tube failures, including leaks and a tube failure equivalent to twice the cross sectional area of the tube, resulting in possible overpressure of the process equipment. For simplicity for the rest of this paper, this type of break will be referred to as a double ended tube failure.

- The SRU industry experience is a pressure relief device is not suitable for the process side overpressure protection due to the process conditions, including the solidification of sulfur, resulting in plugging of such devices rendering them useless.

- Therefore the application of UG-140 Overpressure Protection by System Design is necessary.

    - UG-140 Overpressure Protection by System Design includes the application of Code Cases 2211, 2211-1 and associated Welding Research Council (WRC) Bulletin 498 *Guidance on the Application of Code Case 2211 – Overpressure Protection by System Design*(5).

      WRC 498(5) states that Code Case 2211-1 grew out of recognition that over the years, attempts to implement literally the requirements of UG-125 on pressure vessels in some processing systems created situations in which the overpressure protection device was not dependable, the effectiveness was not predictable or the use of overpressure protection devices introduced other dangers due to the need for frequent maintenance or increased emissions. In effect, the literal implementation of the Code requirements did not provide the level of protection intended by the Code. This inconsistency was most pronounced in processing systems that plug the inlets or outlets of pressure relief devices with deposits in either the non-relieving or relieving mode, which is a significant concern in a typical Sulfur Recovery Unit (SRU).

    - UG-140 paragraph (b) states "If the pressure is not self-limiting, a pressure vessel may be protected from overpressure by system design or by a combination of overpressure by system design and pressure relief devices, if the following conditions are met. The rules below are not intended to allow for normal operation above the MAWP at the coincident temperature."

    - UG-140 paragraph (b) (2) states "The decision to limit the overpressure by system design is the responsibility of the user. The user shall request that the Manufacturer's data report state that overpressure protection is provided by system design per (b) if no pressure relief device compliant with UG-125 through UG-138 is to be installed. If no pressure relief device is to be installed, acceptance of the jurisdiction may be required."

The suggested first step approach to confirm Overpressure Protection by System Design is to analyze the possible double ended tube failure scenarios as a steady state event analysis. Mosher & Ogg(3) presented a discussion on this at Brimstone Sulfur Symposium – Vail 2014.

- If the process equipment overpressure is less than 116% of the process equipment corrected MAWP, the system design is considered to be appropriate for any tube failure scenario including a double ended tube failure scenario.

- If the process equipment overpressure exceeds the 116% of corrected MAWP or the corrected hydrotest pressure, further evaluation of the system design is necessary.

The use of Dynamic Analysis Simulation of the double ended tube failure scenario to confirm the developed overpressure including possible system modifications by ASME[4] and API[1] methods to reduce the severity of the overpressure; *An example system modification would be the elimination of the infinite external steam source for the 100% steam scenario by use of an additional dissimilar check valve(s) to limit the backflow of steam into the WHB from the external steam source.*

- If the dynamic analysis confirms that the process equipment overpressure (including system modifications if identified) is less than 116% of the process equipment adjusted MAWP, the system design is considered to be appropriate for any tube failure scenario including a double ended tube failure scenario.

- If the dynamic analysis confirms that the process equipment overpressure is greater than 116% of the process equipment adjusted MAWP (per ASME BPVC[4]) or the corrected hydrotest pressure (per API 521[1]) but less than the NFPA 69 *Standard on Explosion Prevention Systems*[6] allowable deflagration pressure for deformation but not rupture criteria [Martens & Stern[2] described this analysis at Brimstone Sulfur Symposium – Vail in 2014] or exceeds the allowable system deflagration pressure the use of Quantitative Risk Analysis (per ASME BPVC[4] and WRC 498[5]) may be utilized to determine if the system design provides acceptable risk for the overpressure conditions.

The use of Quantitative Risk Analysis (QRA), such as Layers of Protection Analysis (LOPA)[7], for the double ended tube failure and other tube leak scenarios may be used to confirm if the overpressure scenarios are credible (quantified risk evaluation) or non-credible and low risk as qualified using WRC 498 guidance [Martens & Stern[2]]. It is cautioned that each owner/operator must establish the necessary quantitative risk analysis criteria including values for occurrence frequency, probability of failure on demand (loss of containment) frequency, acceptable risk, and risk matrix. The authors used the example risk matrix presented in Figure 4A of WRC 498[5] (See Appendix B).

- The ASME BPVC[4] accepted guidance to industry good engineering practice for conducting a Quantitative Risk Analysis is provided in WRC 498[5]. The available US SRU industry experience for an overpressure loss of containment of the process equipment due to a WHB tube failure is reported in Martens & Stern[2]. In the authors' opinion, the reported industry experience would confirm that any overpressure loss of containment due to a WHB tube failure meets the "non-credible" scenario evaluation per the WRC 498[5] guidance provided examples. The "consequence category" of this scenario meets the "low risk" evaluation per the WRC 498[5] guidance (WRC 498 Figure 4A is an example Risk matrix, see Appendix B). However, it may be prudent to add an additional layer of protection for loss of containment due to a double ended tube failure by confirming that the tube failure scenarios developed pressure does not result in a rupture of the equipment by utilization of NFPA 69[6] deflagration maximum pressure for deformation but not rupture methodology.

- The ASME BPVC Section VIII Div 1[4] Nonmandatory Appendix H Guidance to Accommodate Loadings Produced by Deflagration, NFPA 69[6] and industry practice has been utilized to safely and successfully address deflagration design pressures in excess of MAWP and corrected hydrotest pressures. Appendix H contains this engineering duty clause statement: "The limited guidance in NFPA 69[6] requires the application of technical judgments made by knowledgeable designers experienced in the selection and design of appropriate details." This same engineering duty clause can apply to a WHB double ended tube failure with the utilization of the deflagration maximum developed pressure methodology.

    - It may be reasonable to conclude that the loss of containment of the process side of a WHB due to a double ended tube failure is a non-credible scenario and is a low risk event. However, it is also reasonable for good engineering practice to provide an additional layer of protection for a maximum double ended tube failure scenario developed overpressure by addressing the non-credible and low risk scenario evaluation as not exceeding the NFPA 69[6] allowable maximum pressure for a deflagration methodology for deformation but not rupture.

    - If the non-credible and low risk scenario for a double ended tube failure scenario developed pressure exceeds the NFPA 69[6] allowable maximum pressure for a deflagration for deformation but not rupture, the loss of containment for the process equipment may present a risk that would warrant the owner/operator to take measures to reduce the risk to personnel and facilities by (for example) evaluating operating procedures, administrative procedures, limiting personnel access, and similar items. Increasing the design pressure of the system should also be considered.

4.0 Flowchart

Based on the rationale previously described and the authors' experiences, a suggested sequence of analysis Flowchart was developed to show the various steps and potential recycle loops that need to be considered when evaluating an SRU reaction furnace WHB tube leak/rupture.

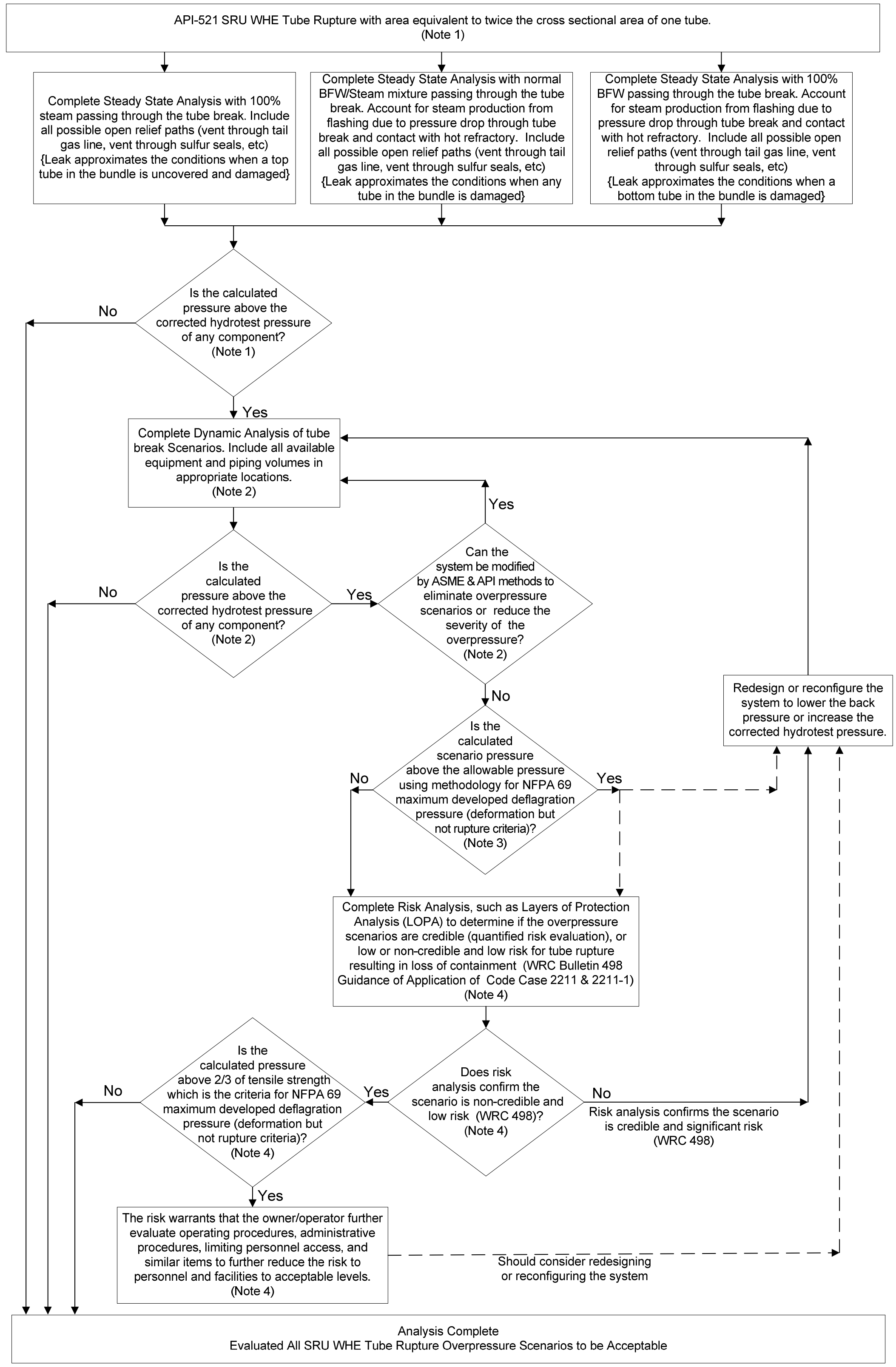

Figure 1. Sequence of Analysis Flowchart

Notes:

1. Evaluate three double ended tube failure scenarios for process equipment overpressure using steady state analysis procedures [Reference Mosher & Ogg[3]];

   a. If developed overpressure does not exceed the Maximum Allowable Working Pressure (MAWP) (ASME Section VIII Div 1[4]- UG-21, 22) of the limiting piece of equipment (including piping) within the overall system corrected for the scenario temperature to design temperature or the corrected hydrotest pressure (API 521 Pressure-relieving and Depressuring Systems[1]- 4.2.2) the system design is acceptable.

   b. If developed overpressure exceeds the MAWP (ASME[4]) corrected for the scenario temperature to design temperature or the corrected hydrotest test pressure (API 521[1]) the system design is not acceptable.

      i. Proceed to next step, the use of dynamic analysis simulation to confirm the three scenarios maximum developed pressure.

2. Evaluate same three double ended tube failure scenarios for process over pressure using dynamic analysis simulation [Reference Mosher & Ogg[3] and Crockett, Moore., & Jacobs[8]].

   a. If developed overpressure does not exceed the corrected MAWP (ASME[4]) or the corrected hydrotest pressure (API 521[1] – 4.2.2) the system design is acceptable.

   b. If developed overpressure exceeds the MAWP (ASME[4]) corrected for the scenario temperature to design temperature or the corrected hydrotest pressure the system design is not acceptable.

      i. Modify the system per ASME[4] and API[1]) methods to reduce the overpressure.

   c. Examples of possible minor/limited modifications to equipment and system controls:

      i. ASME[4];

         Rigorous analysis procedures to verify actual equipment MAWP (i.e., ASME Section VIII Div 1[4] - UG-21, 22 and API 521[1] - 4.2.2 corrected hydrotest limitations), minor revisions to equipment to increase the MAWP and hydrotest limitations.

      ii. API[1];

         Change the flow system conditions such as adding a check valve after the non-return valve (two dissimilar check valves in series) to reduce the steam flow that could return to the boiler from the connected steam system [Reference Mosher & Ogg[3]]

d. Re-evaluate the three double ended failure scenarios;

i. If developed overpressure does not exceed the corrected MAWP or corrected hydrotest pressure the system design is acceptable.

ii. If developed overpressure exceeds the corrected MAWP or corrected hydrotest the system design is not acceptable.

iii. Proceed to next step.

3. The use of ASME Section VIII Div 1[4] UG-140 and WRC 498 *Guidance on the Application of Code Case 2211-Overpressure Protection by System Design*[5] methodology to determine the credibility and risk associated with the maximum developed pressure the system must withstand is a reasonable and accepted engineering approach. The comparison of the scenario developed pressure to the NFPA 69 *Standard on Explosion Prevention Systems*[6] maximum allowable pressure for deflagration, based on deformation but not rupture, will provide guidance to determine if the use of the WRC 498[5] Quantitative Risk Analysis (QRA) methodology would be reasonable and appropriate [Martens & Stern[2]].

a. This NFPA methodology develops a system maximum pressure allowable for a scenario which is expected to result in equipment deformation damage but not rupture. Typically the maximum calculated pressure results in a stress equal to 2/3 of the material minimum specified tensile stress. This methodology is applicable only to ductile materials.

b. Evaluate the three double ended tube failure scenarios developed pressures to the NFPA methodology maximum allowable pressure:

i. If the scenarios developed overpressure does not exceed the NFPA maximum allowable pressure, the system design may be acceptable per WRC 498[5], if the QRA determined the scenario to be non-credible and low risk. Note that the terms "low risk" as used here is not the R (Risk (R) = Frequency of event occurring (F) times Probability of Failure on Demand (PFD)) but is an evaluation of the event probability and consequence as described in WRC-498[5]. WRC 498[5] guidance indicates that an event risk evaluation (see WRC 498 Figure 4A for an example Risk matrix, see Appendix B) of Moderate Risk or High risk should require a more conservative acceptable R value.

ii. If the scenarios developed overpressure does exceed the NFPA maximum allowable pressure, the QRA risk assessment for the scenario would be expected to be credible and not low risk.

iii. Proceed to the next step to either:

1. Conduct a Quantitative Risk Analysis to evaluate scenarios and establish credibility and risk levels.

2. Redesign the system.

4. The use of Quantitative Risk Analysis (QRA), such as LOPA [Reference Martens & Stern(2) and *Layers of Protection Analysis Simplified Process Risk Assessment*(7)], for the double ended tube failure is to confirm if the overpressure scenarios are credible, or non-credible, and is or is not low risk evaluation [Reference WRC 498(5) and Martens & Stern (2)]. It must be noted that the user is responsible to conduct the QRA and establish the acceptance criteria for the analysis. WRC 498(5) provides methodology and guidance examples to evaluate the credibility and risk level of a scenario. WRC 498(5) provides the guidance that the code case considers a Risk ((R) = Frequency of event occurring (F) times Probability of Failure on Demand (PFD)), based on actual industry experience, of less than 0.0001 (1 in 10,000 years of operation) as a non-credible scenario and a low risk evaluation is determined if the failure experience does not include multiple fatalities or major long term environmental impact. Martens & Stern(2) provided current US SRU industry loss of containment (process side of WHB) and fatality and injury data. This data reports a tube failure of 1 occurrence of loss of containment attributed to entering feed water after loss of boiler water level and associated tube failure in 20,734 accumulated operational years. No associated fatalities or injuries occurred. The reported industry experience confirms that a WHB tube failure resulting in loss of containment is a "non-credible" scenario and a "low risk" evaluation. The use of the criteria that any tube failure developed pressure does not exceed the maximum allowable pressure calculated by the NFPA 69(6) methodology provides an additional layer of protection for loss of containment due to a tube failure and further enhances the safety of the system design.

    a. If risk analysis confirms the double ended tube failure is non-credible and low risk and meets the uses risk acceptance criteria [Reference WRC 498(5)] and the developed overpressure does not exceed the NFPA 69(6) maximum developed deflagration pressure (deformation but not rupture criteria) the design is acceptable.

    b. If risk analysis confirms the developed overpressure exceeds the NFPA 69(6) maximum developed deflagration pressure (deformation but not rupture criteria) the authors recommend the double ended tube failure resulting in rupture scenario should not be considered as non-credible or low risk [Reference WRC 498(5)] and the system design is not acceptable *unless the owner/operator further evaluates the operating procedures, administrative controls/procedures, limiting personnel access and similar items to significantly reduce the risk to personnel and facilities such that the system now meets their QRA acceptable risk criteria.*

    c. If the final risk analysis confirms the double ended tube failure is a credible scenario and remains a significant risk [Reference WRC 498(5)] the system design is not acceptable, and the design must be modified.

5.0 Examples of How to Apply the Flowchart

The following examples are the authors suggested methodology for using the sequence of analysis Flowchart for an SRU evaluation for overpressure, due to WHB tube rupture criteria for a double ended tube failure resulting in loss of process side containment. These examples are provided for guidance for use of the Flowchart and are intended to illustrate the process but are not intended to be applicable for all situations.

The SRU unit utilized for all these examples is taken from the Mosher and Ogg(3) reference Plant B analysis having basic design information of (additional plant information is provided in the paper):

- Capacity of 155 LTPD of sulfur. When ammonia combustion is accounted for the true plant capacity is 174 ELTPD with air only operation and 265 ELTPD with enrichment up to 39% oxygen

- WHB with Two pass design with separate steam drum generating 600 psig saturated steam

- Tubes – 3 inch schedule 80 pipe

- Reaction furnace and WHB process side MAWP 75 psig (hydrotest pressure 97.5 psig)

- First Condenser MAWP 55 psig (71.5 psig hydrotest pressure)

Example 1

This is an example of the simplest evaluation;

Referencing the Flowchart, the first step for the evaluation of the plant is a classic steady state evaluation using the three scenarios listed and referring to Flowchart Note 1. The resulting pressure for each of the scenarios is compared to the respective equipment and piping MAWP and Corrected Hydrotest Pressure (see Flowchart Note 1) and the first decision diamond is evaluated per the criteria of;

- If the calculated developed back pressures do not exceed either the code MAWP, or the corrected hydrotest pressure, the evaluation answer is NO and the analysis has "Evaluated All SRU WHB Tube Rupture Overpressure Scenarios to be Acceptable" and the evaluation is complete.

- If the calculated developed back pressures do exceed the code MAWP, or the corrected hydrotest pressure, the evaluation answer is YES and the analysis is not complete and additional evaluation is necessary.

In Reference 3, Mosher and Ogg calculated a steady state backpressure of 117 psig at the 1st Condenser. Suppose instead that the calculated backpressure had been say; 68 psig. This pressure is less than the corrected hydrotest pressure of 71.5 psig, so the evaluation decision diamond answer is NO as the analysis has "Evaluated All SRU WHB Tube Rupture Overpressure Scenarios to be Acceptable" and the evaluation would be completed. Figure 2 below shows the path taken through the Flowchart.

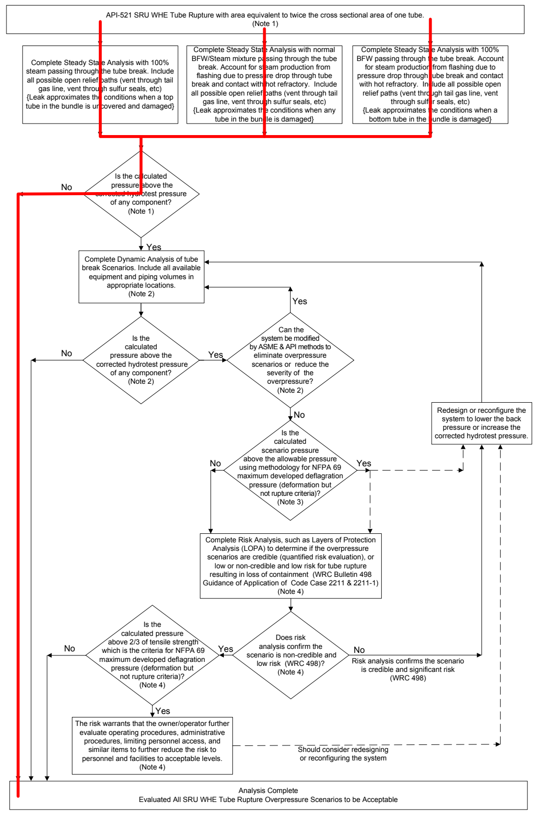

Figure 2. Path through the Flowchart for Example 1.

<u>Example 2</u>

The Mosher and Ogg(3) reference determined that the steady state maximum calculated 100% steam scenario pressure of 123 psig is the maximum pressure scenario result based on infinite steam availability.

The Figure 8 from Mosher and Ogg(3) reference indicates the Steady State 100% steam calculated developed back pressure of 123 psig shown as the top blue line (assuming infinite steam availability), did exceed the code MAWP and the corrected hydrotest pressure and the first Flowchart evaluation decision diamond answer is YES, therefore additional evaluation is necessary.

Note the low yellow line is a dynamic analysis result of a ~ 30 psig pressure based on only the steam available in the steam drum which will be discussed later in this example.

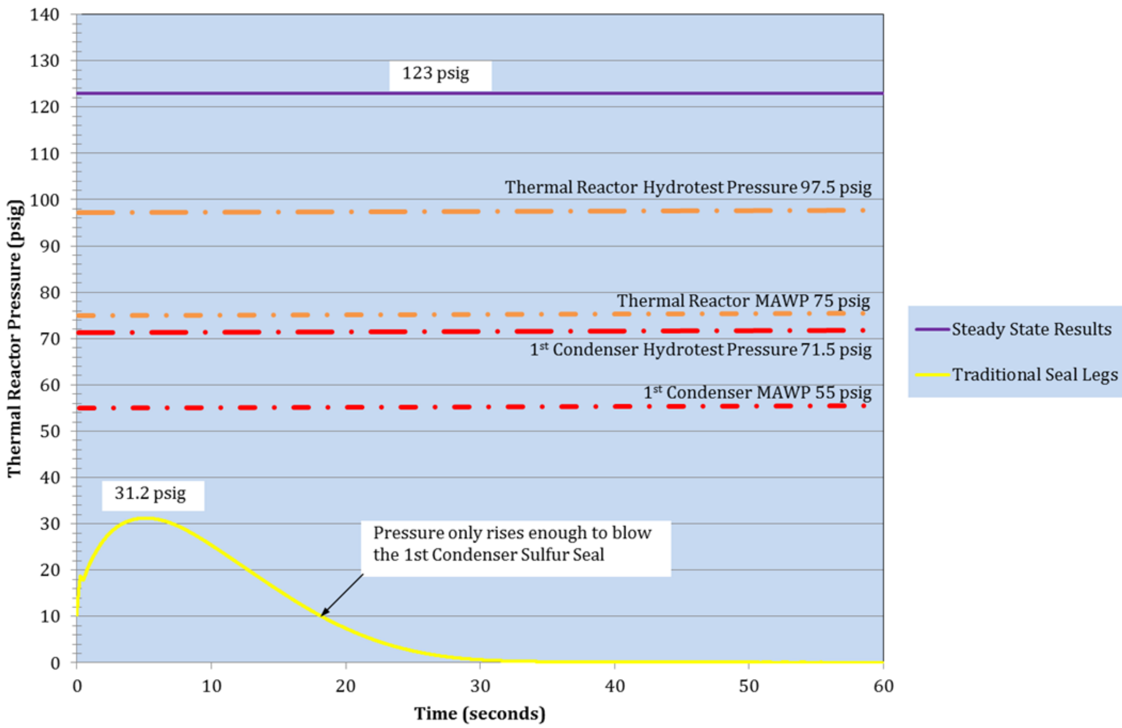

Figure 8 Plant B – 174 ELTPD Scenario 1 All Steam – Steady State vs Dynamic Results

The authors consider the use of dynamic analysis methodology (see Flowchart Note 2) of the unit using the same three tube failure scenarios to be an appropriate next step as indicted in the evaluation Flowchart. The dynamic analysis methodology is presented in Mosher and Ogg[3] reference. The yellow line in Figure 8 above indicates the dynamic analysis calculated maximum developed back pressures, the 100% steam scenario, did not exceed ~ 30 psig, however this analysis considered only the steam volume in the steam drum as the WHB steam non-return check valve was assumed to be fully closed and no steam entering the steam drum from the plant steam system. With this assumption the scenario maximum pressure is ~ 30 psig.

However, API Standard 521[1] indicates that the single non-return check valve (whether it is inspected or not inspected) is to be considered to remain fully open and has the same flow resistance in the reverse flow direction as in the forward flow direction. Mosher and Ogg[3] reference completed an additional dynamic simulation for steam entering the steam drum from the plant steam system for a single non-return check valve and the results reported in Figure 13, below. The dynamic analysis for the 100% Steam scenario, assuming an infinite steam supply, with the failed steam non-return check valve with no resistance, developed a maximum back pressure of ~120 psig as shown by the yellow line in Figure 13 from Mosher and Ogg[3] reference, which is essentially the same as the steady state 100% Steam scenario shown by the purple line. The green line indicates the dynamic simulation developed back pressure of ~ 110 psig using the API 521[1] check valve reverse flow resistant criteria. The lower blue line is addressed later.

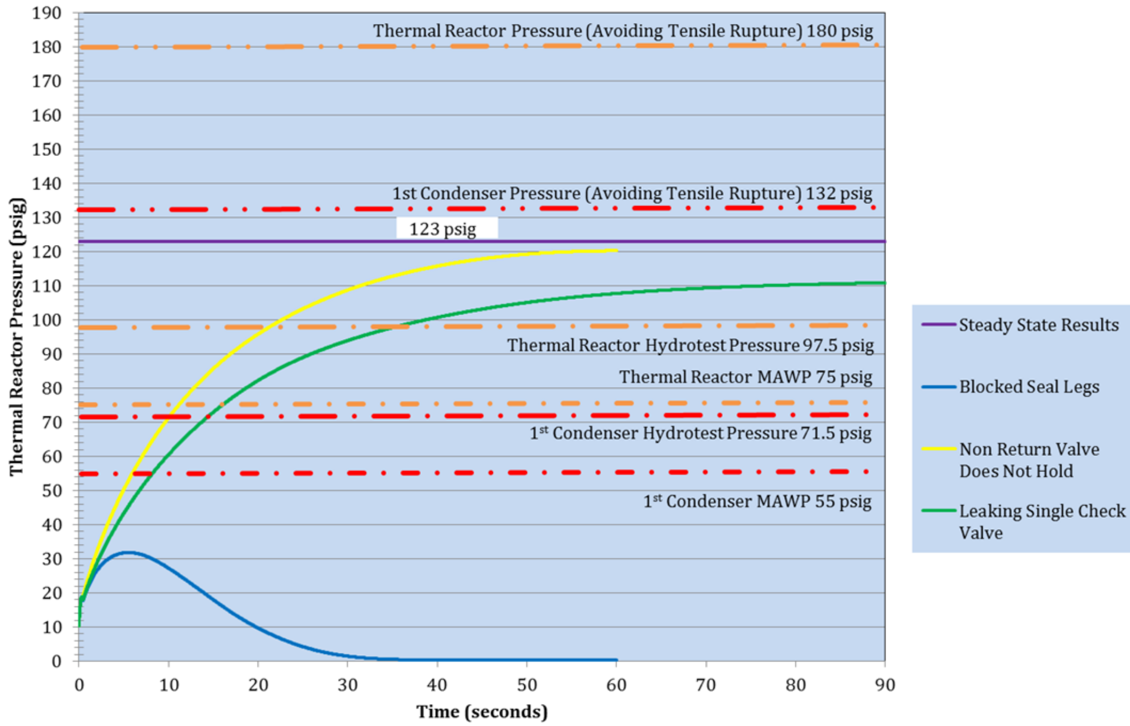

Figure 13 Plant B - 174 ELTPD Scenario 1 All Steam - Leaking Single Check Valve per API Standard 521

Entering the decision diamond (see Flowchart Note 2) the calculated developed back pressure for the non-return check valve failed open does exceed the code MAWP or the corrected hydrotest pressure, the evaluation decision diamond answer is YES and the next decision step is either modify the design by use of ASME and API industry consensus documents or proceed down the Flowchart.

For this example the choice made is to modify the design by the addition of a dissimilar second check in the steam line from the WHB steam drum.

API Standard 521(1) provides guidance for leak rates of two check valves in series resulting in significant reduction in reverse flow compared to one non-return valve failing full open. The flow rate, using the API Standard 521(1) guidance back flow leakage rate, is based on assuming the smallest check valve has completely failed and the larger check valve has severe leakage. Severe leakage can be modeled by treating the check valve as an orifice that is sized to pass 10% of the normal forward flow. For this example it is assumed that the leaking check valve back flow rate is 10% of the normal forward rate, which reduces the 100% steam scenario calculated back pressure from ~ 110 psig (green line on Figure 13 above) to ~ 30 psig, which is essentially the same as the low blue line in Figure 13. (In the Mosher and Ogg(3) reference Figure 13 the blue line in Figure 13 was for a different set of circumstances but the two results would basically overlap). Note the low yellow line in Figure 8 is the dynamic analysis result of a ~ 30 psig pressure based on only the steam available in the steam drum. For this example, by using two dissimilar check valves in series the dynamic analysis results are roughly the same as assuming the only steam available is from the steam drum.

Also it is assumed, for the purpose of this example, that all three scenarios calculated maximum pressure are less than the individual equipment MAWP of 55 psig or the corrected hydrotest pressures.

As the calculated developed back pressures do not exceed the code MAWP or the corrected hydrotest pressure, the evaluation decision diamond answer is NO as the analysis has "Evaluated All SRU WHB Tube Rupture Overpressure Scenarios to be Acceptable" and the evaluation would be completed. Figure 3 below shows the path taken through the Flowchart.

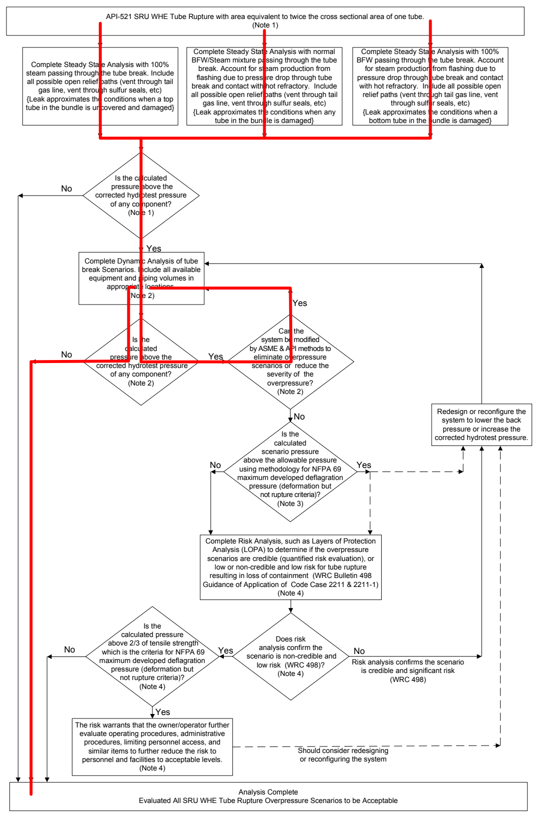

Figure 3. Path through the Flowchart for Example 2.

Example 3

This example uses Example 2 input and is an example of the use of Quantitative Risk Analysis such as LOPA, and includes the NFPA 69[6] Deflagration based maximum allowable pressure methodology. Examples of possible "simple" LOPA analysis for over pressure scenarios for loss of containment risk due to WHB tube failures from Martens & Stern[2] are provided for reference in Appendix A.

For this example it is assumed that the owner has elected, based on their experience, not to accept the API 521[1] suggested approach that the addition of a second non-similar check valve could reduce back flow (therefore no reduction in reverse steam flow rate from the header to the steam drum for the 100% steam scenario).

The 100% steam scenario with failed check valve, evaluated by dynamic analysis and static analysis, maximum built up back pressure of ~110 psig exceeds the MAWP and corrected hydrostatic test pressure as indicated in Figure 13 from Mosher and Ogg[3] reference.

For this example the 100% steam is assumed to result in the maximum pressure scenario. Note that any of the three scenarios may develop the maximum pressure for a specific plant evaluation. The NFPA 69[6] evaluation decision diamond step results in a NO which leads to a Quantitative Risk Analysis such as LOPA (see Flowchart Note 4). Note that for a YES result it would lead to either further modification to the design or to also conducting a Quantitative Risk Analysis such as LOPA (see Flowchart Note 3). For this example the owner/operator does not select redesign or modification and proceeds with Quantitative Risk analysis utilizing LOPA.

Flowchart Note 3 includes comparing the maximum built up back pressure to the NFPA 69[6] maximum allowable pressure based on deflagration methodology for a deformation but not rupture which is a 2/3 tensile design basis for avoiding tensile rupture. This methodology is accepted by the ASME BPVC[4] as providing an acceptable risk for a loss of containment failure for a deflagration maximum pressure scenario based on specific design requirements in the code, although this methodology utilizes a lower safety factor. Note the top line in Figure 13 indicates the Thermal Reactor Pressure (Avoiding Tensile Rupture) of 180 psig and a lower line indicating 132 psig for the 1st Condenser.

In Martens & Stern[2] the results were presented for a 2014 survey of Claus Thermal Reactor Waste Heat Boiler safety history for overpressure due to tube failures. In that survey there was a single reported loss of containment (no personnel injuries) of a low pressure-rated SRU due to a tube rupture overpressure event. The survey covered a grand total of 20,734 SRU operating years. The one loss of containment event, results in the risk (R) of a loss of containment due to a tube rupture event frequency of 1/20,734 = 4.8×10^{-5} annually.

This reported SRU industry experience would indicate that per WRC 498[5] guidance the typical industry utilized acceptable Risk Criteria (R) of < 1×10^{-4} would qualify a WHB tube rupture event resulting in loss of containment as an acceptable R based on a non-credible scenario and low risk evaluation as no associated injuries have been reported and that an additional Quantitative Risk Evaluation may not be warranted. However Martens & Stern[2] propose it is reasonable and good engineering practice that an additional layer of protection be provided even though the tube failure resulting in a loss of containment event may be considered to be an acceptable risk. It is proposed in Martens & Stern[2] that the use of NFPA 69[6] deflagration maximum pressure methodology, based on deformation but not rupture design, provides a reduced risk for a loss of containment failure and therefore this provides an additional layer of protection for a calculated maximum pressure that exceeds the MAWP or the corrected hydrotest pressure but does not exceed the NFPA 69[6] allowable pressure (see Flowchart Notes 3 and 4).

The use of Quantitative Risk evaluation and LOPA are discussed in Martens & Stern[2] and above. The Owner/Operator is responsible for establishing the appropriate Risk criteria and other LOPA input values for the evaluation. The ASME BPVC[4] recognizes the use of WRC 498[5] which provides guidance for Overpressure Protection By System Design including the use of Quantitative Risk analysis and Layers of Protection Analysis Simplified Process Risk Assessment[7] reference provides guidance for LOPA analysis. Applying the NFPA methodology, Figure 13 above would indicate that the developed back pressures for all three scenarios would not exceed the maximum pressure at the 1st Condenser based on the NFPA 69[6] deformation but not rupture methodology criteria.

For this example the Owner/Operator Quantitative Risk and LOPA analysis, for a SRU WHB loss of containment due to tube rupture, determines the scenarios to be non-credible and a low Risk utilizing WRC 498 guidance as the maximum developed back pressure does not exceed the NFPA 69[6] methodology calculated maximum pressure. The first decision diamond step addressing non-credible and low risk is YES (see Flowchart Note 4) and the following decision diamond step answer is NO as the analysis has "Evaluated All SRU WHB Tube Rupture Overpressure Scenarios to be Acceptable" and the evaluation would be completed. Figure 4 below shows the path taken through the Flowchart.

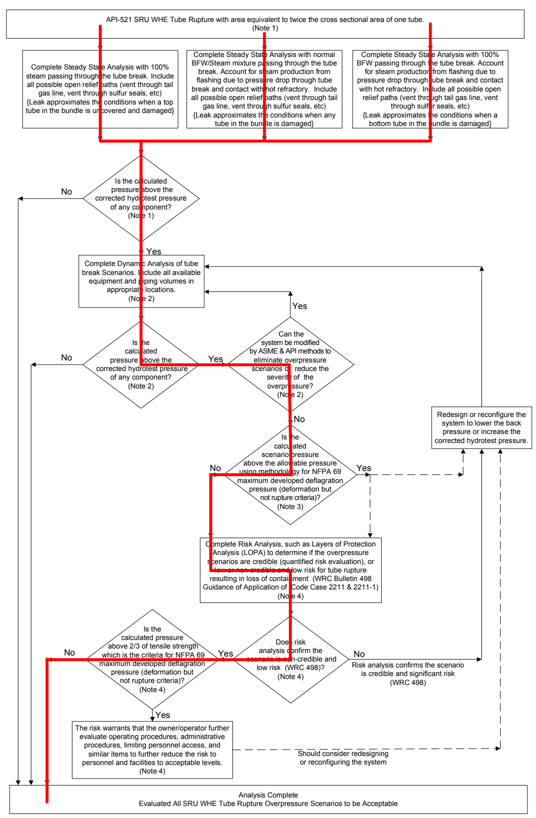

Figure 4. Path through the Flowchart for Example 3.

Example 4

This example is based on Example 2 however the Owner/Operator selects to utilize the Steady State analysis developed maximum pressures and not conduct a Dynamic Analysis but proceed directly to Quantitative Risk and LOPA analysis.

This Example becomes the same as Example 3, including analysis results, except for the use of the Steady State analysis calculated maximum pressures only. Figure 5 below shows the path taken through the Flowchart.

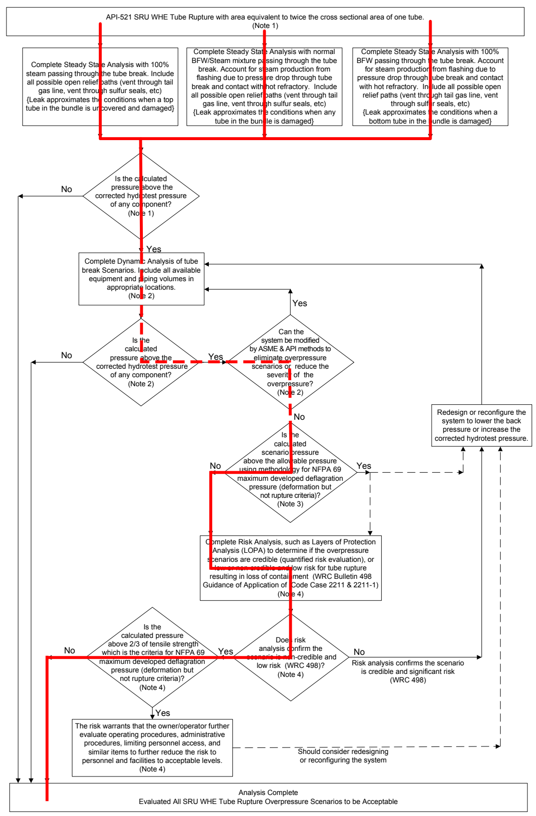

Figure 5. Path through the Flowchart for Example 4.

Example 5

This example is the same as Example 3 or Example 4 except the last decision diamond results in a YES answer as any one or more of the following assumptions apply;

- The Owner/Operator determines that their acceptable Risk (R) criteria is < $1x10^{-5}$ (instead of < $1x10^{-4}$) which would not allow the SRU WHB tube rupture resulting in loss of containment to be considered as non-credible.

- The Steady State and Dynamic Simulation calculated maximum pressures exceed the MAWP, corrected hydrotest pressure and NFPA methodology maximum pressure criteria resulting in an unacceptable Risk condition.

- The Owner/Operator does not accept the NFPA 69[(6)] methodology maximum pressure as suitable to provide a low risk situation and will use the MAWP and corrected hydrotest pressure criteria which are exceeded resulting in an unacceptable risk condition.

This would result in the decision diamond leading to the lowest Process/Information symbol stating “The risk warrants that the owner/operator further evaluate operating procedures, administrative procedures, limiting personnel access, and similar items to further reduce the risk to personnel and facilities to acceptable levels”.

The output from this symbol states “Should consider redesigning or reconfiguring the system”. However the Owner/Operator has the final responsibility for the evaluations and use of the Flowchart and may evaluate all the conditions and attributes, such as the use of a complex LOPA with additional layers of protection, taking into account their specific experience and conditions to establish an acceptable risk meeting the Owner/Operator established Risk Criteria (see Flowchart Note 4). Figure 6 below shows the path taken through the Flowchart.

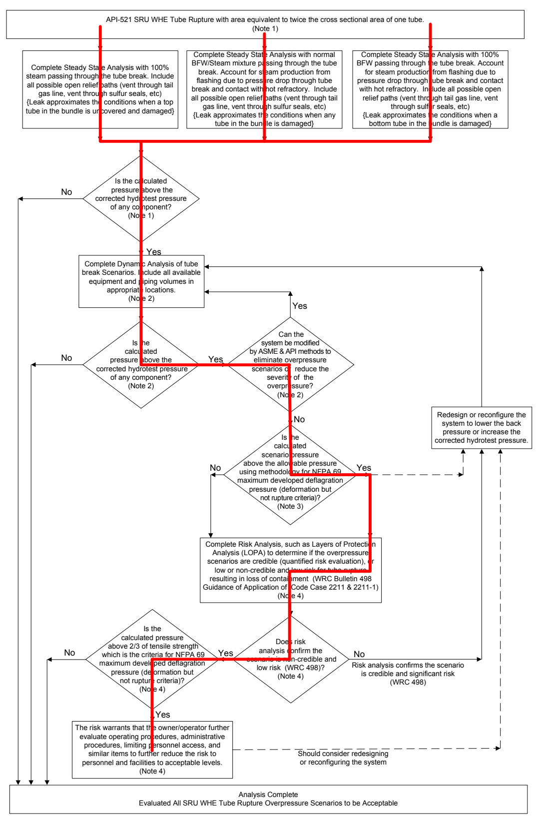

Figure 6. Path through the Flowchart for Example 5.

6.0 Conclusions

The following conclusions can be drawn from the results of this paper and from what the authors experienced while preparing this paper;

- API Standard 521[1], is being revised to include information regarding Sulfur Recovery Unit (SRU) Reaction Furnace Waste Heat Boiler (WHB) tube ruptures and other updates. The modifications to API 521[1] that were balloted in the spring of 2015 state that the user should evaluate the system to determine if the system can relieve a rate equivalent to double the cross sectional area of a single tube in the WHB without exceeding the corrected hydrotest pressure of the reaction furnace and other low-pressure side equipment. The proposed modifications do not provide any real guidance on how the analysis should be done or a suggested sequence for the various analyses that should be completed.

- No concise guideline on how to approach the overpressure evaluation process for an SRU WHB tube rupture scenario currently exists in the public domain. This paper was written to help fill that void.

- Each Owner/Operator must establish their own process for evaluating overpressure from an SRU WHB tube rupture scenario. This paper was written to express the author's opinion regarding their suggested sequence of the evaluation and process steps.

- Each Owner/Operator must determine what they consider an acceptable risk taking into account their specific experience and conditions.

- Even if the results of the Quantitative Risk Analysis evaluation, for an SRU WHB loss of containment due to tube rupture, determines the scenarios to be non-credible (the event has an annual probability of occurrence less than the Owner/Operator acceptable risk benchmark probability) and a low Risk, it is reasonable for good engineering practice to provide an additional layer of protection. That additional layer of protection is to evaluate the overpressure scenario and confirm that the maximum pressure does not exceed the NFPA 69[6] allowable maximum deflagration pressure methodology for deformation but not rupture.

7.0 Recommendations

It is expected that the final API 521 revision (probably in 2019) will include all or some of the proposed WHB tube rupture event language which will task the SRU owner/operator to evaluate the overpressure of the low pressure process side. The authors recommend that the SRU owner(s)/operator(s) fully engage and participate in the balloting of the proposed WHB tube failure provisions to provide suitable industry experience and guidance to the document.

It is the authors' experience, as given in this paper, that the proposed WHB tube failure evaluation is a necessary, lengthy, and somewhat difficult engineering process. The authors recommend that SRU owner(s)/operator(s) initiate the evaluation of possible overpressure before the API expected 2019 revision is issued both to support input to API 521 ballot comments and to determine what possible impact on their respective SRU may result from compliance with the final API 521 update.

8.0 Acknowledgements

The authors would like to acknowledge and thank Brimstone STS Limited for providing the forum for the 2014 SRU WHB Tube Rupture Panel Discussion and for allowing this paper to be presented. The goal of the panel discussion and this paper was to inform and assist the SRU industry to anticipate the inclusion of the proposed SRU WHB provisions in the next revision of API 521.

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(6) NFPA 69, *Standard on Explosion Prevention Systems*, National Fire Protection Association, 2014 Edition.

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(8) Crockett S., Moore A., & Jacobs G., "*SRU WHB Tube Rupture Modeling Insights Learned @ BP Cherry Point*", Brimstone Sulfur Symposium - Vail, September 2014.

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Appendix A

The following table is from Martens & Stern[2].

TABLE A
LOPA example for WHB tube failure scenarios including design leak criteria, pressure design, F,PDF and R estimated values (see notes for table)

Scenario	Leak rate qualification by steady state or dynamic simulation calculations	Max developed (1) pressure basis criteria for design based on ASME 55 PSI MAWP and NFPA 69 using ductile strain hardening materials such as SA 516-70	Occurrence frequency **(F)** (2) (7)	Risk of loss of containment due to rquipment rupture occurrence frequency **(PDF)** (3) (5) (6)	LOPA acceptable risk criteria **(R)** (4) (7) Reference one Appendix E page 245 "one scenario" rate of $1x10^{-4}$ to $1x10^{-6}$ Indicated a General industry at $1x10^{-5}$ **Calculated risk Values**
BP/Lamar paper Reference [7]	Leak equivalent to a 1 square inch orifice	ASME API 521 MAWP or Hydro test pressure corrected for temperature ~3.5 SF **(55 or ~= 72 psi)**	Most often, perhaps one every 5 operating years Frequency rate **$2x10^{-1}$**	No loss of containment/rupture no equipment deformation rupture frequency rate **$1x10^{-6}$**	**$(2x10^{-1})*(1x10^{-6}) = 2x10^{-7}$**
Alternative, no public papers	Leak equivalent to 20% of a tube cross section hole orifice	ASME API 521 MAWP or Hydro test pressure corrected for temperature ~3.5 SF **(55 or ~= 72 psi)**	sometimes, perhaps one every 10 operating years Frequency rate **$1x10^{-1}$**	No loss of containment/rupture no equipment deformation rupture frequency rate **$1x10^{-6}$**	**$(1x10^{-1})*(1x10^{-6}) = 1x10^{-7}$**
Alternate, no public papers	Leak equivalent to Severed tube, single end	ASME/NFPA 69 ASME 55 MAWP NFPA deflagration with deformation and avoiding Tensile/rupture with 1.5 Safety Factor **(130 psi)**	Low frequency, perhaps one every 100 to 500 operating years Frequency rate **$1x10^{-2}$**	No loss of containment/rupture expect equipment deformation rupture frequency rate **$1x10^{-4}$** (estimated data)	**$(1x10^{-2})*(1x10^{-4}) = 1x10^{-6}$**
API 521 std	Severed Tube, double end	ASME/NFPA 69 ASME 55 MAWP NFPA deflagration with deformation and avoiding Tensile/rupture with 1.5 Safety Factor **(130 psi)**	Seldom, perhaps one every 1000 to 5000 operating years Frequency rate **$1x10^{-3}$**	No loss of containment/rupture expect equipment deformation rupture frequency rate **$1x10^{-4}$** (estimated data)	**$(1x10^{-3})*(1x10^{-4}) = 1x10^{-7}$**
API 521 std	Severed Tube, double end	Based on ABPG data for all SRU reporting for design (low) pressure (<15 psi) and higher design pressure units	**See note 7**	No loss of containment/rupture expect equipment deformation rupture frequency rate **$1x10^{-4}$** (estimated data)	Based on survey data of ~20,734 operating years 1 loss of containment in a low design pressure unit none in a high design pressure unit **Survey Risk factor $4.8x10^{-5}$**

(1) Maximum developed process side pressure to be based on criteria of ASME MAWP of 55 PSI, and use of NFPA 69 deflagration based methodology resulting in no expected equipment permanent deformation with expectation of return to service after inspection. NFPA 69 methodology utilizing 1.5 Safety Factors (SF) from rupture pressure with resulting expected equipment deformation with expectation of not being able to return to service immediately and

possibility requiring repair or replacement after inspection. The 1.5 SF from rupture design basis is taken from ASME BPVC provisions for deflagration design and NFPA 69 deflagration design basis without rupture (loss of containment). The authors consider this basis to be reasonable as there is considerable use of this methodology for deflagration design and the SRU industry experience is the NFPA deformation without rupture design provides an acceptable risk and Life Safety design basis.

(2) Occurrence frequency is authors' estimation based on industry data and SRU industry experience, however each user must assign a frequency based on their experience.

(3) It is the author's opinion that the risk of damage due to single or double ended tube failure in an SRU WHB is of a lesser or same magnitude as the risk of deflagration in an SRU unit as described in NFPA 69. It is the authors' experience that deflagrations and tube leaks occur in the SRU industry without equipment rupture and injuries or fatalities occurring in equipment that has a design pressure of at least 50 psi MAWP. The industry public domain reported experience does not indicate equipment rupture occurring from deflagration events or for tube failures. There are some urban legends and none documented loss of containment due to deflagration and tube failure however these are old reports that are related to low pressure designs and lack of adequate safety systems and operating procedures. The current implemented SRU industry practice for safety systems and operating procedures have been shown to provide adequate safety to avoid the worst case scenarios and the SRU industry safety record related to deflagration or tube failure is excellent.

(4) CCPS publication "LAYERS OF PROTECTION ANALYSIS" (LOPA), authored by AIChE copyright 2001, provides methodology that may be used to quantify and evaluate risk. LOPA may be utilized as an extension of HAZOP studies when the HAZOP scenarios are difficult to satisfactorily evaluate. LOPA methodology provides a rational, objective, risk based approach for evaluating the risk for loss of containment. The acceptable risk criteria is discussed in this publication and additional guidance is provided in ASME Code Case 2211-1999, this case has been annulled and is now incorporated in Section VIII Div 1 UG-140, based on WRC 498, however each user must establish an acceptable risk value based on their experience.

(5) NFPA 69 Chapter 4 General Requirements Paragraph 4.2.1 Life Safety Subparagraph 4.2.1.2 states "Deflagration prevention and control for unoccupied enclosures shall prevent rupture of the enclosure". Typically a HAZOP considers a injury or fatality as a consequence of a pressure vessel rupture. Chapter 13 Deflagration Control by Pressure Containment provides guidance for addressing the maximum pressure a containment system may be subjected to without rupture and providing an acceptable Life Safety consideration design. The use of the NFPA deflagration design methodology based on deformation without rupture methodology for establishing the allowable pressure buildup up due to a double ended tube rupture scenario per API 521 is suggested for inclusion in the API 521consensus if the double tube end failure continues to be considered as a scenario for SRU WHB tube failures.

(6) Reference to CCPS publication "LAYERS OF PROTECTION ANALYSIS" (LOPA) authored by AIChE copyright 2001 Table 5.1 page 71, for ~ 3.5 Safety Factor Pressure Vessel failure rate @ $1x10^{-6}$, for a 1.5 Safety Factor vessel failure rate is estimated to be $1x10^{-4}$ (a factor of 100 times greater failure probability than a standard PV failure rate). No data appears to be published for the ASME/NFPA consensus standards acceptable deflagration design criteria for maintaining life safety using a 1.5 Safety Factor for rupture.

(7) The ABPG SRU industry survey data presented in this paper confirms 20,734 SRU operational years with one reported loss of containment in a low design pressure SRU (~15 psi) due to reentrance of boiler feed water after a loss of water level had occurred. Note that the other two loss of containment incidents were not included in the calculations related to overpressure failure scenarios. The incident was not reported as directly related to a double ended tube failure or a tube leakage. No personnel injuries were reported. The data would indicate a frequency of occurrence of 1/20,734 = **$4.8x10^{-5}$** event per operating year has been achieved based on currently available data for all SRU reporting which confirms a WRC 498 not credible scenario rating requirement of $1x10^{-4}$. The survey includes low pressure design units (<15 psi). Low pressure units would be expected to have a significantly greater PFD factor than SRU units designed per ASME/NFPA deflagration methodology.

Appendix B

The following tables are a recreation of tables from WRC 498[5].

Probability Category	A	L	M	M	H	H	H
	B	L	L	M	M	H	H
	C	L	L	L	M	M	H
	D	L	L	L	L	M	M
	E	L	L	L	L	L	M
	F	L	L	L	L	L	L
		VI	V	IV	III	II	I
	Consequence Category						

Fig. 4A – Example of a Risk matix, H = High Risk,
M = Moderate Risk, L = Low Risk

Category	Description	Annual Probability Range
A	Very Likely	≥0.1 (1 in 10)
B	Possible	≥0.01 (1 in 100) but < 0.1
C	Unlikely	≥0.001 (1 in 1,000) but < 0.01
D	Highly Unlikely	≥0.0001 (1 in 10,000) but < 0.001
E	Not Credible	≥0.00001 (1 in 100,000) but < 0.0001
F	Practically Impossible	<0.00001 (1 in 100,000)

Fig. 4B – Example of Probability Categories

Category	Description	Examples
I	Catastrophic	Multiple fatalities; major long term environmental impact
II	Major	Fatality; major short term environmental impact
III	Serious	Major Injuries; significant environmental impact
IV	Significant	Serious Injuries; short term environmental impact
V	Minor	First Aid Injuries only; minimal environmental impact
VI	None	No significant consequence

Fig. 4C – Example of S/H/E Consequence Categories

Category	Description	Examples
I	Catastrophic	≥$10,000,000
II	Major	≥$1,000,000 but <$10,000,000
III	Serious	≥$100,000 but <$1,000,000
IV	Significant	≥$10,000 but <$100,000
V	Minor	≥$1,000 but <$10,000
VI	None	<$1,000

Fig. 4D – Example of Economic Consequence Categories