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Technical Paper #2

Ammonia Refrigeration System Pressure Relief Vent Design Evaluation

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Abstract

Pressure relief device performance is affected by pressure drop in its inlet and outlet piping system. Recognized and generally accepted good engineering practice and National Regulations, Codes, Standards and Guidelines applicable to ammonia refrigeration systems require evaluation of these pressure drops and documented confirmation that they are within acceptable limits.

This paper presents a method that identifies the necessary documentation and uses a specialized software application that can evaluate any ammonia refrigeration pressure relief vent piping system, including those with common headers. The method is inexpensive, comprehensive, meets regulatory requirements and follows recognized and generally accepted good engineering practice.

Introduction

American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC), Uniform and International Mechanical Codes, and, current editions of ANSI/ASHRAE 15 and ANSI/IIAR 2 require that the pressure drop in pressure relief device inlet and outlet piping does not negatively affect the device capacity, but provide limited details regarding the associated engineering calculations.

These references are collectively referred to as Code in this paper. While differences exist among these documents and nationwide concerning local modifications and adoption, these differences do not affect the technical elements of the presented method.

In addition, OSHA's Process Safety Management of highly hazardous chemicals and EPA's Chemical Accident Prevention Provisions require that the relief system design and design basis be documented as part of a stationary source's Process Safety Information (PSI).

To assist the ammonia refrigeration community in both performing the engineering calculations and suitably documenting the design basis, a worked example is presented of a method which can be used to evaluate any ammonia refrigeration facility vent system. Figure 1 shows the example system which consists of three packaged chiller units with four (pairs of) spring loaded pressure relief valves (PRV) per chiller unit. All of the PRVs in the system feed into a common header which terminates in a water filled absorption tank.

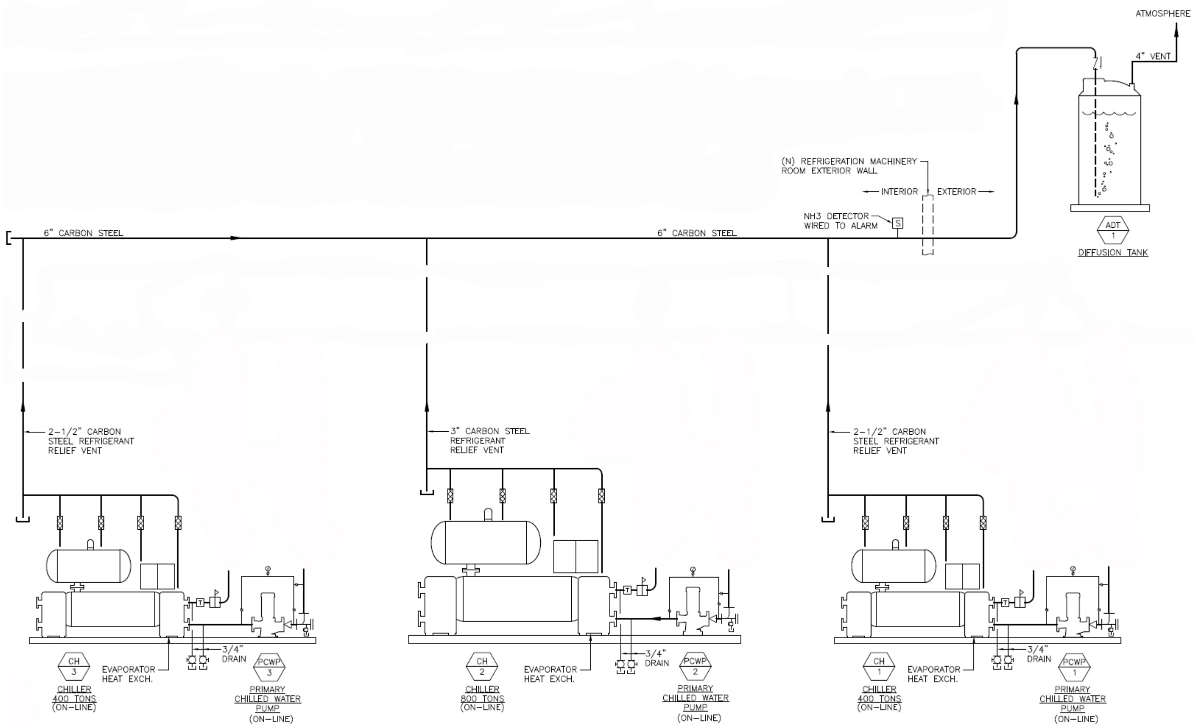

Figure 1: "Equipment Layout"

The Method

Identify required PRV set pressures and capacities.

Code requires every pressure vessel used in anhydrous ammonia refrigeration service be protected by pressure relief devices to safely relief pressure due to fire or other abnormal conditions. Determination of the required relieving capacity is found within the Code and is not repeated here. However, it is important to recognize this information is a component of the required documentation for any system and any covered facility must have access to it.

The first step of the method is to collect and if necessary verify system requirements for pressure relief and relief device capacity. Code limits relief device set pressures to no greater than the protected vessel's maximum allowable working pressure (MAWP). Table 1 shows the data for our example. The PRV set pressures are equal to the MAWP for vessels and heat exchangers and the required capacities were calculated using ANSI/IIAR 2 equations.

Protected Vessel	Set pressure (psig)	Code Required Capacity (lbair/min)
Chiller #1		
V100	300	29.49
V200	300	12.45
V300	300	27.80
V400	300	7.00
Chiller #2		
V100	300	55.30
V200	300	16.89
V300	300	35.49
V400	300	10.00
Chiller #3		
V100	300	29.49
V200	300	12.45
V300	300	27.80
V400	300	7.00

Table 1: Vessel Set Pressure and Code Required Relief Capacity

Determine accumulated pressures and rated relief capacities.

A PRV will start to open at the set pressure, which must be equal to or less than the equipment MAWP. *Code* further requires that the PRV be sufficiently sized to prevent the protected equipment pressure from exceeding the allowed *accumulated* pressure. Thus, the fluid properties and pressure drop at the PRV are based on the *accumulated* conditions in the vessel. The *accumulated* pressure (in psig) is calculated in accordance with the *Code* (ASME BPVC UG-125(c)) requirement from the set pressure (in psig) as follows:

$$\boldsymbol{P_{accumulated} = 1.1 \times P_{set}}$$

Equation 1

It is also important to differentiate between *required* and *rated* relief capacity. The required relief capacity is the flow rate required by Code to protect the equipment against overpressure. PRVs are produced in specific sizes and each relief valve has a full open flow called the rated relief capacity. PRVs are chosen to have rated relief capacity in excess but as close as practical to the required relief capacity. Both required and rated relief capacity are based on the accumulated relieving pressure.

Table 2 below summarizes data for the selected PRV and inlet 3-way valve for each protected vessel. It is important to note the *rated* relief capacity is expressed on a pound per minute of air basis.

Vessel	PRV			3-Way Valve
	Size	Paccumulated (psig)	Rated Capacity (lbair/min)	Cv
Chiller #3				
V100	¾" x 1"	330	42.0	10.4
V200	¾" x 1"	330	20.2	10.4
V300	¾" x 1"	330	42.0	10.4
V400	¾" x 1"	330	20.2	10.4
Chiller #3				
V100	¾" x 1"	330	68.6	10.4
V200	¾" x 1"	330	20.2	10.4
V300	¾" x 1"	330	42.0	10.4
V400	¾" x 1"	330	20.2	10.4
Chiller #3				
V100	¾" x 1"	330	42.0	10.4
V200	¾" x 1"	330	20.2	10.4
V300	¾" x 1"	330	42.0	10.4
V400	¾" x 1"	330	20.2	10.4

Table 2: 3-Way Valve and PRV Data

ANSI/ASHRAE 15 and ANSI/IIAR 2 also require sizing of a common discharge header based on the sum of the rated capacities of the PRVs that are expected to operate simultaneously. Since these three chiller units are collocated in a single machine room, for this example, simultaneous PRV operation is evaluated.

Determine allowable PRV backpressures.

Normative appendices of ANSI/ASHRAE 15 and ANSI/IIAR 2 include the requirement that the built-up backpressure imposed on any conventional spring loaded PRV must not exceed 15% of the relief set point unless there is a specific manufacturer's recommendation. Thus the maximum allowable back pressure is:

$$\boldsymbol{P_{allowable\ backpressure} = 0.15 \times P_{set\ pressure}}$$

Equation 2

For our example, the allowable backpressure for all PRVs is then 45 psig.

Donald M. Papa then Senior Product Engineer at Anderson Greenwood in his influential *Hydrocarbon Processing* article on how backpressure affects safety valve performance wrote:

"As a rule, conventional (direct spring operated) valves should not be vented into closed headers or long tailpipes."

Papa based this conclusion on typical valve data he collected and presented in the article for conventional spring operated valves which are commonly used in ammonia refrigeration service. He concluded that conventional valves operating at 110% of set pressure experience rapid and substantial capacity reduction when they experience backpressures of 15% and greater. While conventional PRVs are routinely vented into closed headers and long tailpipes, it must be emphasized that this only be done when the backpressure has been confirmed as acceptable.

Determine allowable PRV inlet losses.

Code (ASME BPVC UG-135(b)(1)) requires non-recoverable PRV inlet loss be evaluated. ASME BPVC non mandatory Appendix M-6 indicates that non-recoverable inlet losses be limited to less than 3% of set pressure. While this 3% limit does not represent binding *Code* or regulation for the ammonia refrigeration industry, it does represent a recognized and generally accepted good engineering practice (RAGAGEP) and has been used in our example as a basis for determining acceptable non-recoverable PRV inlet loss.

$$\boldsymbol{P_{allowable\ inlet\ loss} = 0.03 \times P_{set\ pressure}}$$

Equation 3

For our example, the allowable inlet loss for all PRV's is then 9 psi.

Detail the vent piping systems.

In order to properly evaluate a PRV vent it is essential that accurate isometric drawings or a complete inventory of the piping system components be available. When available, this detail is then easily used to validate the system design. We have used the software application, Korf Hydraulics, which allows easy input of this data through a drop and drag graphical interface. All protected equipment, PRVs and piping components can be shown.

Figure 2 shows the Korf worksheet with the example system. In this example:

- Each protected vessel is shown as a source, CH1-V100, CH2-V100, CH1-V200, etc. Operating conditions in each vessel are input through drop down menu selections and user input. For our case we have examined the *Code* required air basis and have later repeated the analysis on an ammonia basis as a point of interest.
- Each piping segment is shown as a line, L11, L12 etc. Piping details are again input through drop down menus and user input. Ammonia or air properties are based on line inlet and outlet conditions and are calculated as explained in the next section.
- Other piping segments such as tees and reducers can be added to complete the piping circuit.
- Finally, in our example a water diffusion tank is shown at the discharge.

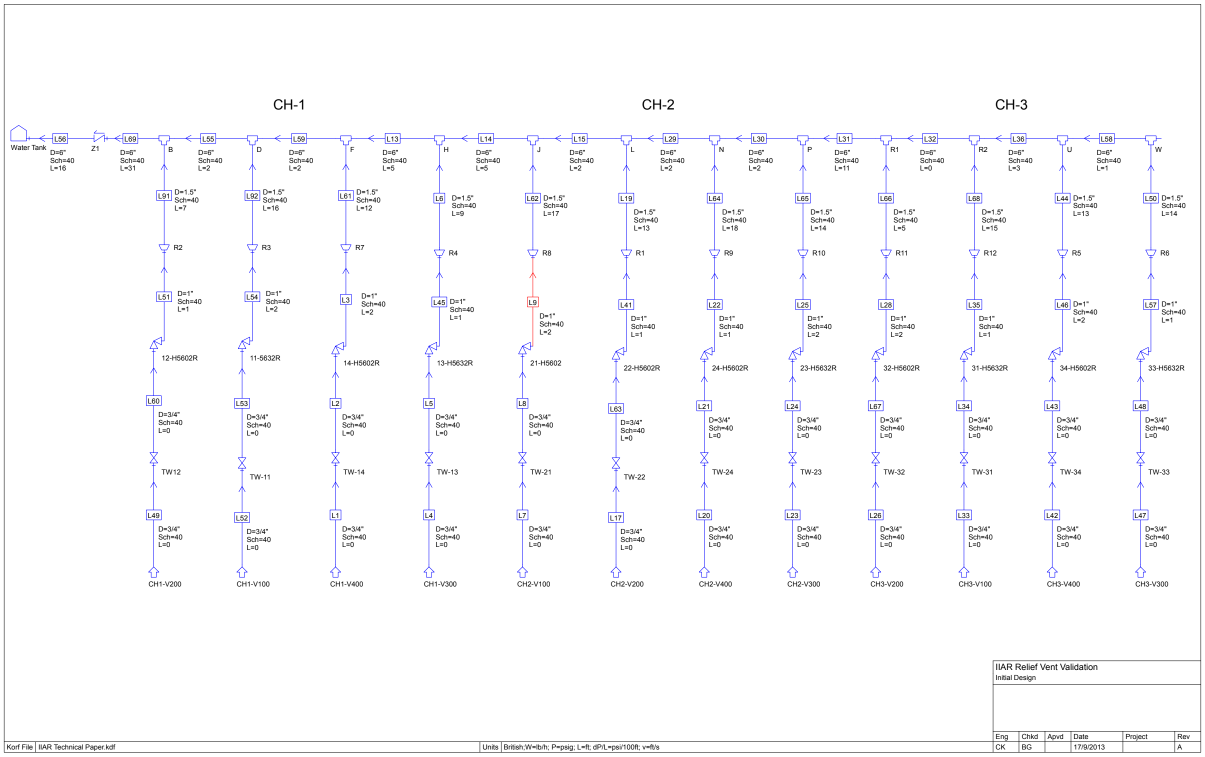

Figure 2: "Korf Worksheet – System Schematic"

Calculate inlet losses and back pressures.

All calculations were performed using Korf Hydraulics version 3.2 (Korf). Korf is an advanced fluid flow software application that is intended for analyzing liquid, gas and two phase flow in pipes and piping networks. It is extremely flexible and allows the user to specify any valid combination of flows, pressures and equipment sizes.

Korf simulates the vent piping system using a formulation of the governing equations of compressible flow as shown in ANSI/ASHRAE 15 equation H-1 and IIAR 2 Appendix A. This pressure drop relationship is equivalent to that presented in Crane Technical Paper 410 and IRC equation 40.

Korf estimated the pipe frictional factor from the Chen equation, which is non-iterative but essentially identical to the Colebrook equation shown in the IRC pamphlet as equation 42.

The friction factor depends on the absolute pipe roughness. Korf Hydraulics allows the user to modify the roughness but the default of 0.0018 inches was used as it is identical to that in ANSI/ASHRAE 15 and ANSI/IIAR 2.

Korf supports the Crane L/D and Hooper 2-K methods to estimate loss in pipe fittings. ANSI/ASHRAE 15 and ANSI/IIAR 2 rely on the equivalent length (EL) method based on EL values such as those shown in the IIAR *"Piping Handbook."* Table 3 summarizes the equivalent length and corresponding L/D value. The L/D value is essentially constant for different pipe sizes and we have chosen the L/D approach for our method here.

Pipe			90 Std		90 Long		Tee Mixing into Branch		Tee Mixing into Header	
Dia	Sch	ID	ft	L/D	ft	L/D	ft	L/D	ft	L/D
1	80	0.957	1.8	22.6	1.3	16.3	4.6	57.7	2.4	30.1
1.25	80	1.278	2.4	22.5	1.7	16.0	6.2	58.2	3.2	30.0
1.5	80	1.500	2.8	22.4	2	16.0	7.3	58.4	3.8	30.4
2	40	2.067	3.9	22.6	2.7	15.7	10	58.1	5.2	30.2
2.5	40	2.469	4.7	22.8	3.3	16.0	12	58.3	6.2	30.1
3	40	3.068	5.8	22.7	4.1	16.0	14.6	57.1	7.7	30.1
4	40	4.026	7.6	22.7	5.4	16.1	19.5	58.1	10.1	30.1
Average				22.6		16.0		58.0		30.2
Crane				20		14		60		30

Table 3: L/D to Equivalent Length Comparison

Korf accounts for pressure to velocity conversions in most pipes and fittings. Due to typically high velocities in PRV discharge piping, this effect is not negligible. For example, for ammonia conditions of 500 ft/s and 0.1 lb/ft^3 one velocity head is roughly 3 psi.

Korf uses a semi-rigorous approach in describing tees where frictional loss depends on area and gas flow ratios of the connecting pipes. For both reducers and tees Korf accounts for pressure to velocity conversion, consequently there is always a pressure rise across pipe expansions.

It is worth noting that, based on our experience, a pressure drop is often shown at pipe outlets due to the incorrect application of the following equation in Crane.

$$\boldsymbol{P_1 - P_2 = \left[\rho\left(v_2^2 - v_1^2\right) / 2g144\right] + \left[\left(K_1 \rho v_1^2\right) / 2g144\right]}$$

Equation 4

At the pipe outlet:

$$\boldsymbol{v_2 = 0} \qquad \boldsymbol{K_1 = 1}$$

Returning:

$$\boldsymbol{P_1 - P_2 = \left(-v_1^2 + v_1^2\right)\left(\rho / 2g144\right) = 0}$$

Equation 5

Equation 5 shows no pressure change at the outlet to atmosphere. A common error, based on our experience, is to ignore the first term in the Crane equation and thus get a pressure drop at the outlet of a pipe.

Korf warns the user if pipe outlet velocity is sonic. For product streams, control valves and orifices, Korf will automatically increase pipe exit pressure to the sonic velocity limit.

Control or 3-way valves in Korf are based on the ANSI/ISA equations. Other methods often assume pressure drop across three way valves is small and does not account for density changes. Korf always corrects for density changes and will correctly predict choked flow. Choked flow pressure drop is represented by the xT value for a control valve. Since the xT value is not known for the three way valves under study and is not described within ANSI/ASHRAE 15 or ANSI/IIAR 2 an xT value of 1 was used to best simulate those methods.

Finally, Korf was run in hydraulics and heat and mass balance (HMB) mode. This allowed for the input of the fluid composition (in this case air) for all upstream vessels. Korf then determined the subsequent fluid properties from flash calculations.

Korf was also run, for informational purposes, on an anhydrous ammonia basis.

Figure 3 shows the Korf Worksheet with the flows (W) in pounds per hour of air and segment inlet and outlet pressures in psi. Results are also tabulated in Table 4.

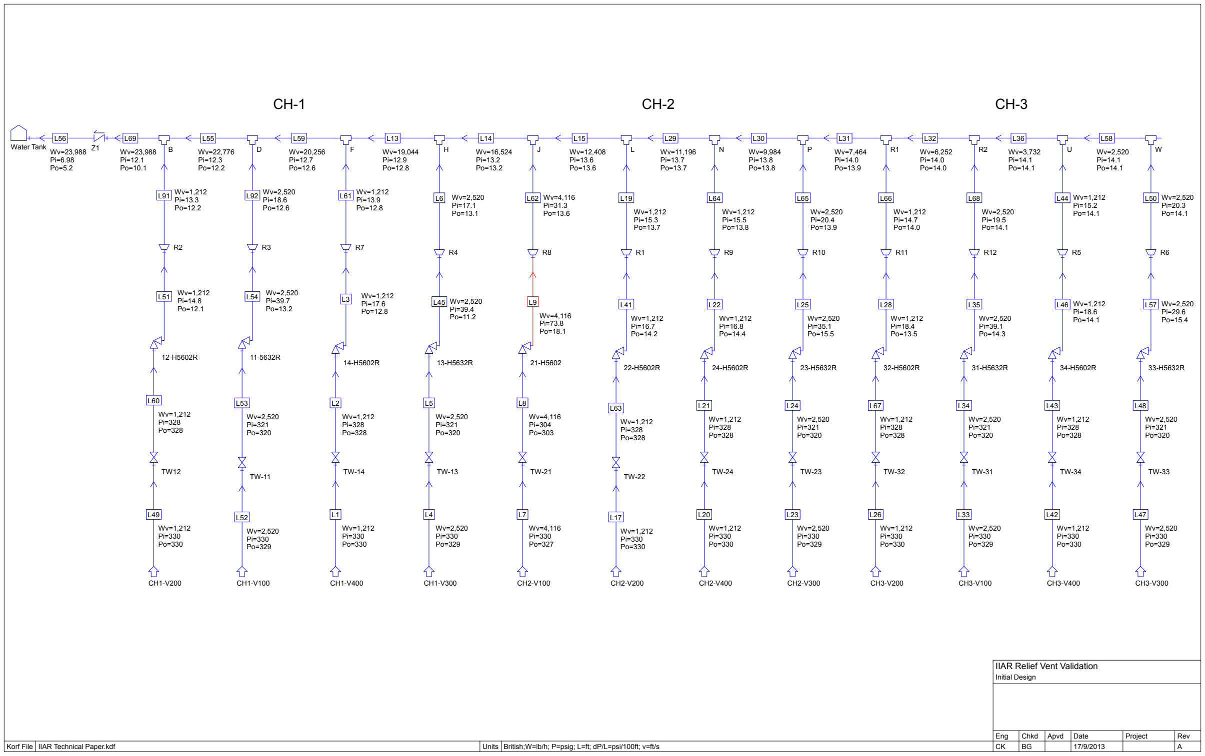

Figure 3: “Korf Worksheet – Initial Design Calculated Pressures”

Vessel	Rated Capacity	P_{set}	Inlet Pressure Drop		Back Pressure	
			Allowable	Actual	Allowable	Actual
	lb_{air}/h	psig	psi	psi	psi	psi
Chiller #1						
CH1-V100	2520	300	9.0	9.6	45.0	39.7
CH1-V200	1212	300	9.0	2.2	45.0	14.8
CH1-V300	2520	300	9.0	9.6	45.0	39.4
CH1-V400	1212	300	9.0	2.2	45.0	17.6
Chiller #2						
CH2-V100	4116	300	9.0	26.6	45.0	73.8
CH2-V200	1212	300	9.0	2.2	45.0	16.7
CH2-V300	2520	300	9.0	9.6	45.0	35.1
CH2-V400	1212	300	9.0	2.2	45.0	16.8
Chiller #3						
CH3-V100	2520	300	9.0	9.6	45.0	39.1
CH3-V200	1212	300	9.0	2.2	45.0	18.4
CH3-V300	2520	300	9.0	9.6	45.0	29.6
CH3-V400	1212	300	9.0	2.2	45.0	18.6

Table 4: Calculated Pressures

Discussion

The resulting calculated inlet losses and backpressures experienced by the PRV's in our example system for the simultaneous release case show the following:

Five of the examined valves (CH1-100/300, CH2-300, and CH3-100/300) are expected to experience marginally high non recoverable inlet losses, 9.6 versus 9.0 psi. The 3% inlet loss criteria is not *Code* binding and it is typical to find marginally high inlet losses in anhydrous ammonia refrigeration service due to the relatively small sizes of the industry standard 3-way valves as compared to full port valves used in other industries. Further, while it is beyond the scope of this paper, it should be noted that valve manufacturers routinely publish information for PRVs in ammonia refrigeration service that indicate operation at higher inlet loss values is acceptable. However, in order to properly use this information calculations are required to determine the adjusted capacity of the valve, a process which we do not generally endorse nor choose to present here.

One of the valves (CH2-V100) is expected to experience an inlet loss and back pressure that are significantly above the maximum allowable limits, which may affect the desired performance. It is recommended to replace the PRV and increase the size of the inlet piping, 3-way valve and outlet piping to reduce the inlet loss and back pressure to within acceptable limits. See Table 5 and Table 6 for results.

Figure 4 shows the final system configuration on an air basis and Figure 5 shows the same configuration, for comparison, on an ammonia basis.

Vessel	PRV				3-Way Valve
		Size	$P_{accumulated}$ (psig)	Rated Capacity (lb_{air}/min)	C_v
Chiller #2					
V100		1¼"x 1½"	330	65.0	20.0

Table 5: Final CH2-V100 Configuration

Vessel	Rated Capacity	P_{set}	Inlet Pressure Drop		Back Pressure	
			Allowable	Actual	Allowable	Actual
	lb_{air}/h	psig	psi	psi	psi	psi
Chiller #2						
CH2-V100	3900	300	9.0	5.7	45.0	35.7

Table 6: Final CH2-V100 Pressures

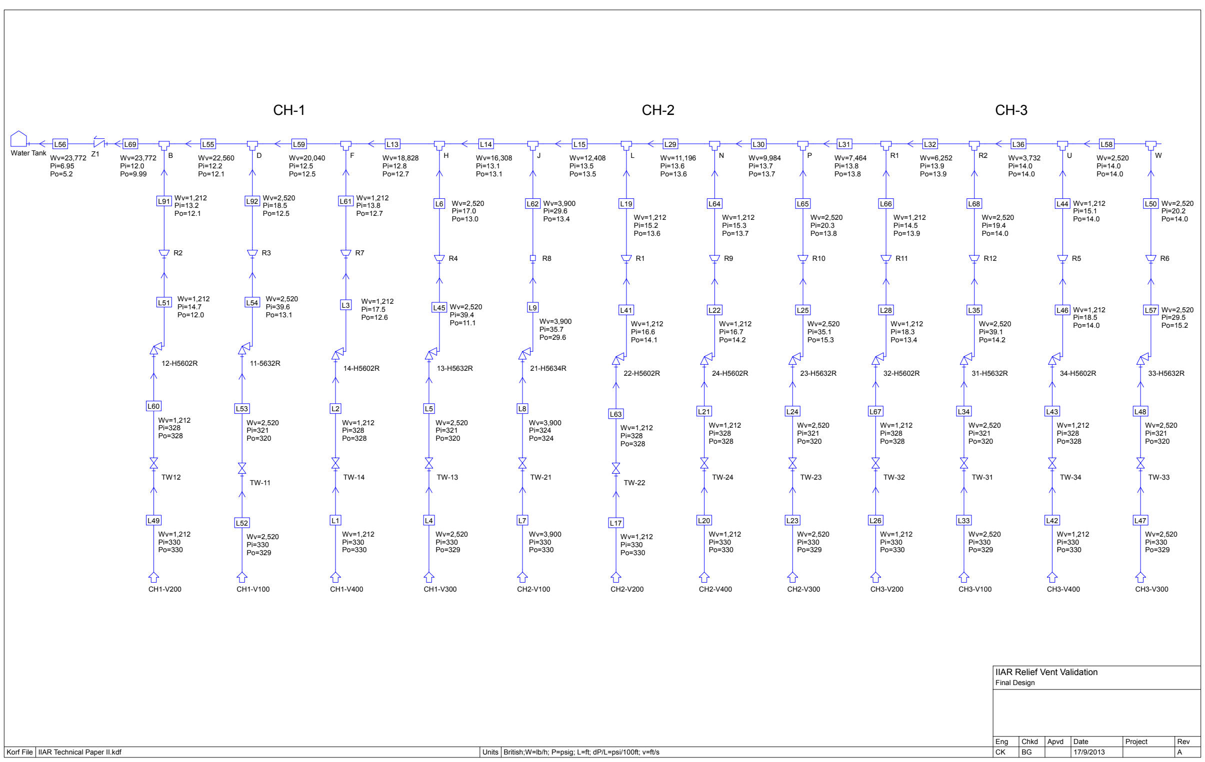

Figure 4: "Korf Worksheet – Final Design Calculated Pressures Air Basis"

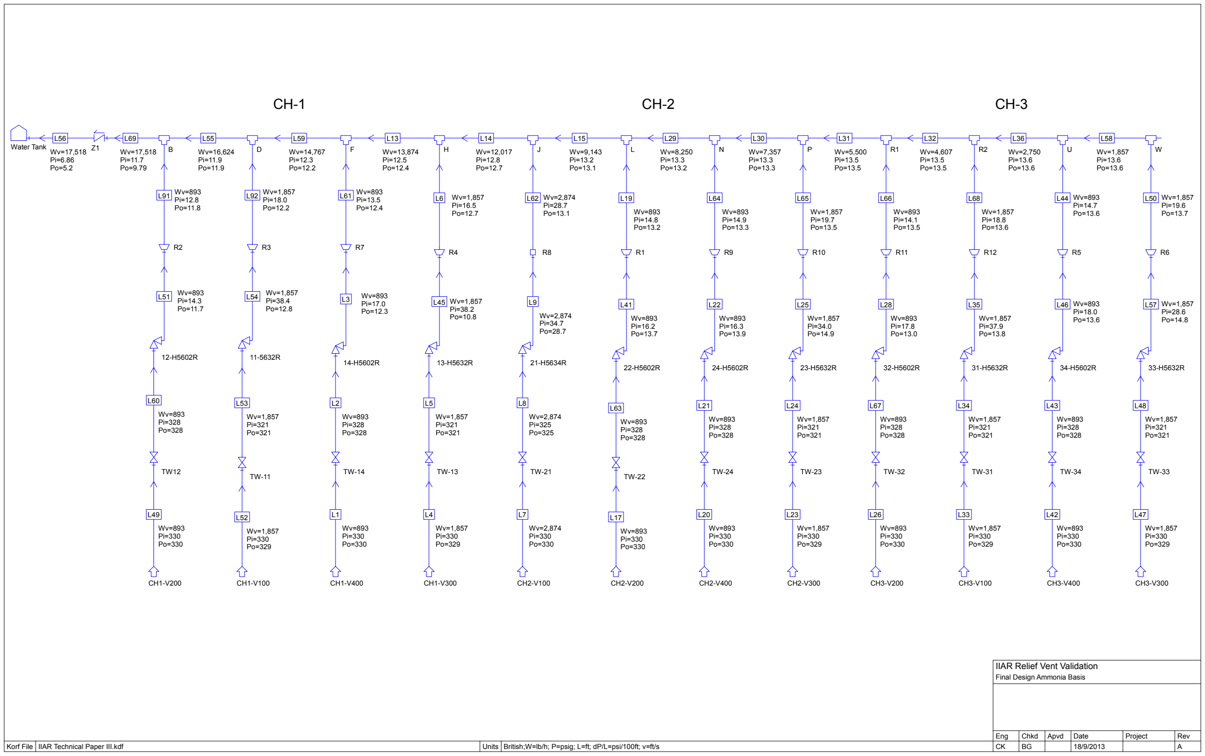

Figure 5: "Korf Worksheet – Final Design Calculated Pressures Ammonia Basis"

Conclusions

- Provided the ammonia refrigeration system design is well documented, with readily available as built isometric drawings and specifications for installed equipment, very little effort is required to comprehensively evaluate and document a relief vent system using the method presented here.
- The method captures *Code* requirements including subsequent adopted reference standards such as ANSI/ASHRAE 15, and ANSI/IIAR 2.
- Korf Hydraulics, our chosen software application, is a comprehensive, easily managed and inexpensive method to document and perform fluid flow analysis associated with piping in ammonia refrigeration systems.
- Korf Hydraulics uses the same underlying equations as ANSI/ASHRAE 15, ANSI/IIAR 2, AIChE and API. It therefore represents recognized and generally accepted

good engineering practice (RAGAGEP) and consequently produces results which are immediately useful to the ammonia refrigeration community.

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