EUROPEAN CHEMCAD SYMPOSIUM 1999

RELIEF & BLOWDOWN

in

BATCH PROCESSES

by
John E. Edwards

Contents

1.0 Introduction

2.0 Relief System Layout
2.1 Pressure Relief Devices
2.2 Relief System Piping and Headers
2.3 Containment System
2.4 Treatment System

3.0 Relief System Sizing
3.1 Design Fundamentals
3.1.1 Vessel and Vent Flow Models
3.1.2 Heat Models
3.2 CHEMCAD Utility – Relief Device Sizing

4.0 Relief System Header

Appendices

I Input Data
II Relief Piping Equivalent Length
III External Fire Heat Absorption
IV Estimation of Heat Transfer Area from Total Area

References

1. HG Fisher et al, “Emergency Relief Design using DIERS Technology”, Diers/AIChE 1992.
2. J. Wilday and J. Etchells, “Workbook for Chemical Reactor Relief System Sizing”, HSE Contract Research Report 136/1998.
3. S.S. Grossel, “Design and Sizing of Knock-Out Drums/Catchtanks for Reactor Emergency Relief Systems”, Plant Operations Progress (Vol 5, No.3) July 1986.
4. “Sizing Selection and Installation of Pressure Relieving Devices in Refineries”, API 520 6th Edition March 1993
5. “Guide for Pressure Relieving and Depressuring Systems”, API 521 4th Edition March 1997
6. “Venting Atmospheric and Low-Pressure Storage Tanks”, API 2000 4th Edition September 1992

1.0 Introduction

To achieve safe operation of chemical reactors processing exothermic reactions requires a combination of Preventative and Protective Measures.

Preventative Measures include:

- Automatic control systems including the use of an independent hardwired alarm and trip system.
- Provision for appropriate manual intervention.

Protective Measures mitigate the consequences of a runaway reaction and include:

- Emergency pressure relief.
- Crash cooling.
- Reaction inhibition.
- Drown out.

This paper reviews the techniques associated with emergency pressure relief and the value of CHEMCAD as a design tool in this important area of Process Engineering.

The advantages of a pressure relief system are:

- Different and independent failure modes to the preventative measures.
- Provides relatively passive means of protection.
- Provides adequate protection if all other systems fail.

The emergency pressure relief system is considered the ultimate protection. The primary basis of safety for overpressure protection is based on prevention involving management control procedures and instrument protective systems.

Emergency pressure relief may not be appropriate due to economical, environmental or technical considerations. In such cases, appropriate preventative measures must be relied on.

The design of emergency relief systems for exothermic batch reactors requires a thorough understanding of the reaction conditions including:

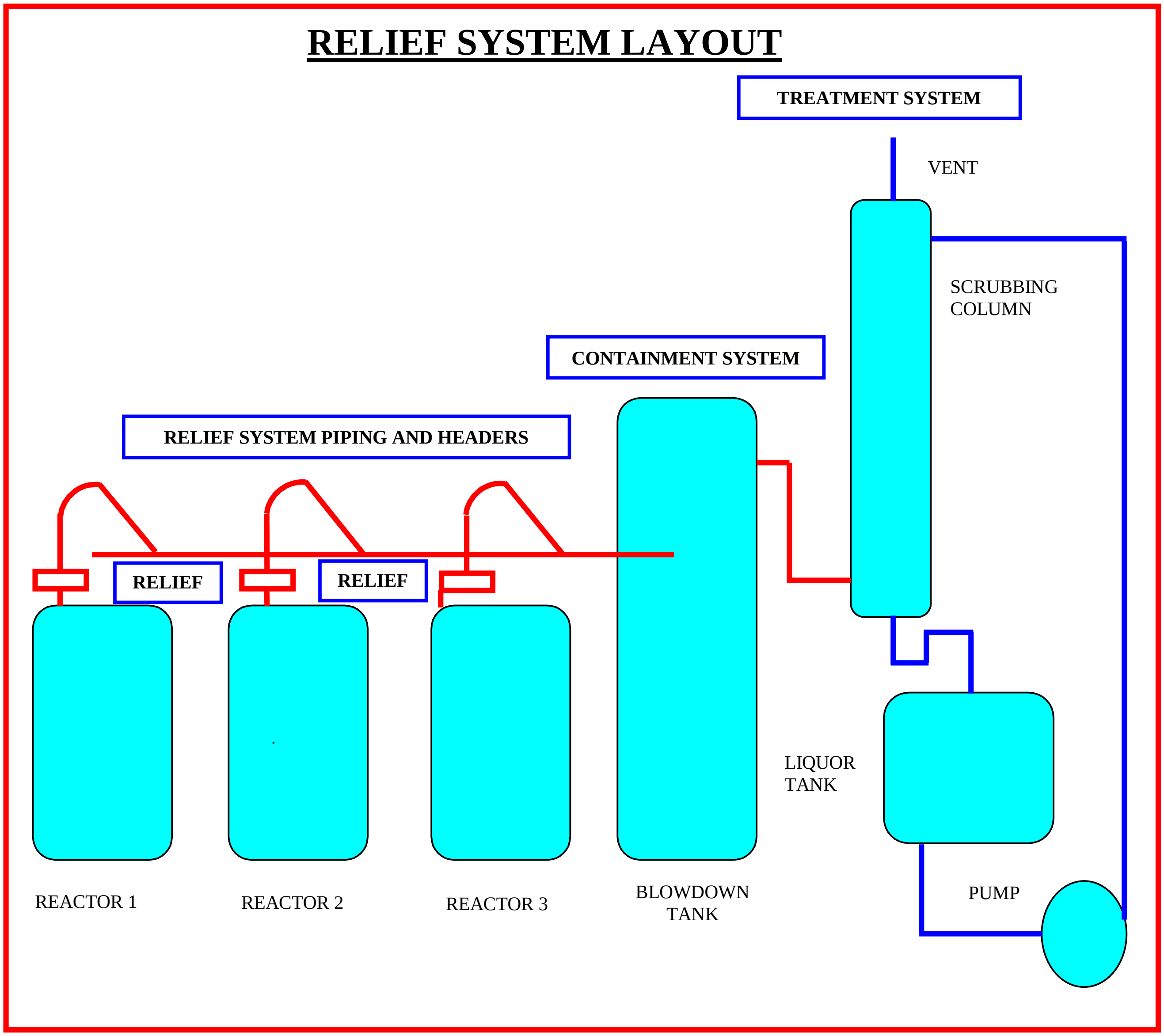
- The credible maloperations and system failures that might occur during reaction.
- The kinetics of the reaction under runaway conditions.
- Whether the reaction pressure is from vapour, gas or both.
- The flow regimes in the vessel and relief system during relief.
- The design and layout of the relief system.

Significant research has been carried out particularly by the Design Institute for Emergency Relief Systems (1) (DIERS) and a recent publication in the UK by the Health and Safety Executive (2) Workbook for Chemical Reactor Relief System Sizing is a useful design tool.

2.0 Relief System Layout

The emergency relief system comprises certain key components:

- Primary pressure relief device.
- Relief system piping and headers.
- Containment system.
- Treatment system.



2.0 **Relief System Layout** (Cont.)

2.1 **Pressure Relief Devices**

The pressure relief device is either a relief valve, a bursting disc or a combination of the two. On chemical reactors the bursting (rupture) disc is most favoured due to being able to handle the following conditions:

- Rapid pressure rise with full relief area available.
- Toxic fluids where no leakage past a safety valve is permitted.
- Corrosive fluids that may cause progressive deterioration of a safety valve.
- Fluids that may deposit solids or gums that interfere with safety valve operation.

The major disadvantages of bursting discs are as follows:

- Require a larger allowance between the operating and the set pressure.
- If the operating and the set pressures are too close, the disc can fail prematurely due to pressure pulsations.
- Loss of containment of reactor contents on operation i.e. valve does not reseat.

To mitigate against loss of containment due to operation of a bursting disc sized for the worst case scenario the installation of a smaller bursting disc/relief valve combination in parallel set at a lower relief pressure can be considered. This smaller system operates in the event of nuisance pressure build-ups due to maloperation without loss of containment.

The relief pressure at which the relief device is fully open should be set at the lowest pressure practicable consistent with preventing nuisance operations. The reasons for this are:

- For most exothermic runaway reactions, the reaction rate and heat release rate increases exponentially with temperature. For a vapour pressure system, a low relief pressure means a low relief temperature and hence a relatively low rate of heat release. The relief area required is directly proportional to the rate of heat release by the reaction.

- For a relief system venting a two-phase mixture, pressure relief acts to remove reactants from the reactor. A low relief pressure allows a greater margin between the relief pressure and maximum permitted pressure, and advantage is taken of this by the sizing methods to yield a smaller relief area.

The specified relief pressure for a bursting disc is subject to a tolerance of up to ± 10% of the gauge pressure and reduces with increasing temperature. Bursting disc capacity is reduced significantly by the use of a vacuum support.

2.0 Relief System Layout (Cont.)

2.1 Pressure Relief Devices (Cont.)

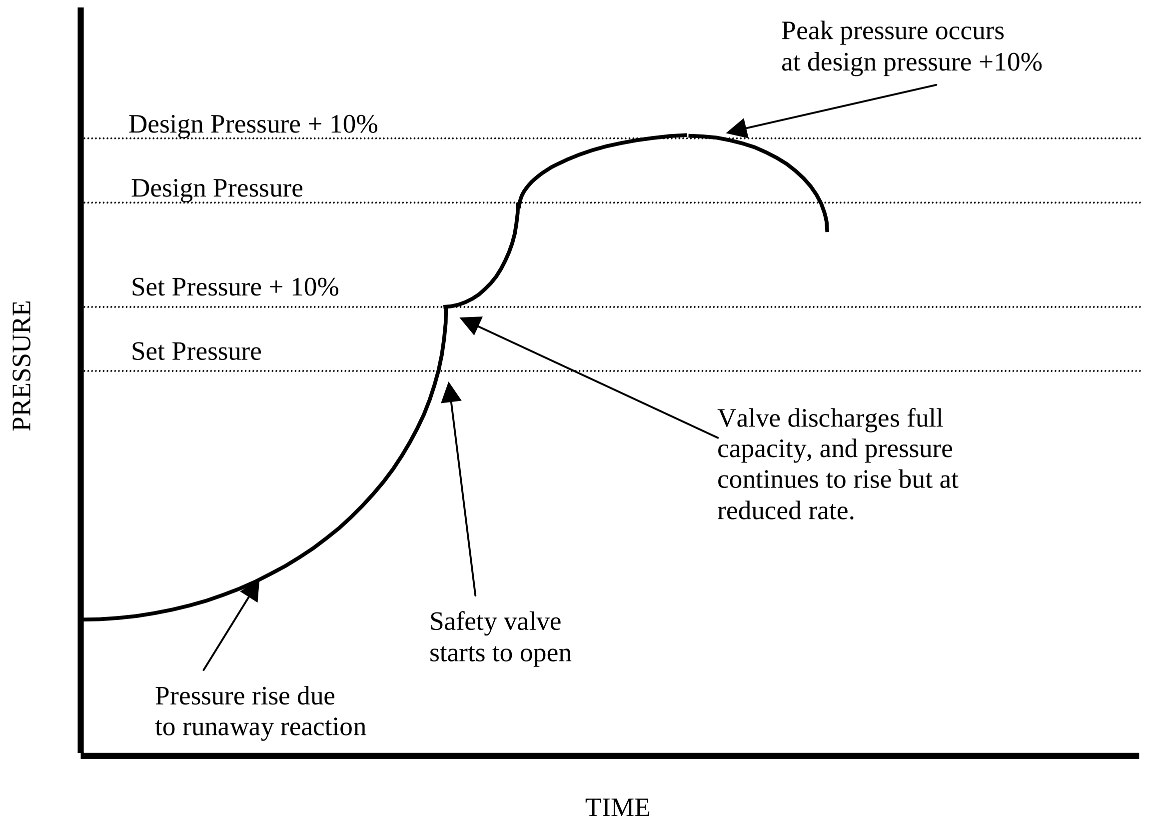
CHEMCAD computer runs quote the relief area required for a specified device discharge coefficient, 0.625 for a bursting disc. The diameter required is calculated on this basis with no allowance for vacuum support. When using vacuum supports the % free area is reduced by 0.6 (size range 100 – 200mm) and the bursting disc diameter to provide the area required is calculated accordingly.

The requirements for the design of the relief system sizing can be summarised:

- The equipment design pressure plus permitted accumulation is not exceeded.
- The pressure relief system is as small as possible consistent with the above clause.
  A small relief system minimises cost, disposal requirements and the potential rate at which material could be discharged to the environment.

CHEMCAD facility Relief Device under Equipment Sizing is used for design.

Pressure Versus Time for a Runaway Reaction with an Optimum Size of Relief Valve



2.0 **Relief System Layout** (Cont.)

2.2 **Relief System Piping and Headers**

The flow capacity of a bursting disc is determined by the piping system rather than by the disc itself.

Key features of the relief system piping design can be summarised:

- Branch pipe from reactor to the header to be not less than the outlet diameter of relief device.
- Branch pipe to enter main header as a 45 degree T, flow through branch.
- All 90° bends to have maximum R/D consistent with layout constraints.
- Main header to slope towards the blowdown drum and enter tangentially.
- Consideration to be given to nitrogen inerting to prevent explosive mixtures.
- Provision of adequate inspection and test facilities to ensure headers are clear.

CHEMCAD Relief Device sizing requires knowledge of the inlet and outlet piping configuration which may not be available.

A specific design involved reaction vessels being fitted with 150mm diameter bursting discs venting via individual 150mm diameter headers to a common 250mm diameter vent main which is routed directly to a $30M^3$ emergency catch tank. The total equivalent length for relief device sizing was taken as 56M . (Refer Appendix II).

2.0 Layout of the Relief System (Cont.)

2.3 Containment System

In many instances the discharge stream from an emergency relief system is a two-phase vapour liquid mixture. The stream is routed to a blowdown/knock out drum designed to disentrain the liquid from the vapour to allow discharge to atmosphere or for downstream treatment. The justification for the blowdown drum is:

- Prevents release of hot, toxic and corrosive liquid resulting in potential safety hazards and environmental damage.
- Prevents release of flammable droplets leading to vapour cloud explosion.
- Allows downstream treatment of toxic vapours for treatment in a wet scrubber, flare or incinerator.

There are many designs of blowdown drum depending upon the circumstances but key features include:

- Tangential inlet into a vessel of sufficient diameter to effect good vapour – liquid separation.
- Total volume sufficient to hold the estimated carryover, typically two times the volume of the largest reactor connected to the relief system.
- Adequate instrumentation monitoring for level and pressure detection.
- Appropriate facilities for drainage and material handling.
- Appropriate facilities for quenching reaction mixtures.

The blowdown drum dynamics in relation to rate of pressure rise can be modelled in CHEMCAD using the Excel UnitOp and the Depressurize Utility (CHEMCAD Help Section 12.3).

Sizing of the blowdown drum is beyond the scope of this paper, however, methods are presented in (3) which would allow an Excel model to be developed and interfaced with CHEMCAD as required.

2.0 Layout of the Relief System (Cont.)

2.4 Treatment System

Vapours vented from exothermic reactions are normally treated by contacting with a scrubbing liquor to provide fast chemical reaction. The vapours are contacted in a random packed tower with suitable hydraulic design parameters and packed height for mass transfer/reaction.

CHEMCAD in conjunction with Excel provides a powerful design tool for this process. The following key features of design are:

- Tower diameter, packing selection and hydraulics determined from SCDS3 UnitOp and CHEMCAD Equipment Sizing - Packing. SCDS3 configuration for an absorber is used with Condenser Mode 0 and Reboiler Mode 0.

- Packed height is determined from model in Excel Unit Op on the SCDS inlet.

- Fast chemical reaction involves an exotherm and CHEMCAD is used to carryout the thermal design of the system which involves ensuring adequate circulating liquor volume and flow with adequately sized heat exchanger to control system temperature.

- Atmospheric dispersion is determined from model in Excel UnitOp on the SCDS outlet.

- Column hydraulics design involves:

  Ensuring adequate liquor circulation flow to satisfy minimum wetting rate for the packing.

  Packing adequately loaded (liquid/gas ratio) for mass transfer.

  Column loading should not exceed 80% flood this may have to be achieved by limiting the vapour rate with a restriction orifice in the blowdown tank vent line sized using CHEMCAD Equipment Sizing Orifice.

3.0 Relief System Sizing

3.1 Design Fundamentals

3.1.1 Vessel and Vent Flow Models

The reader is referred to References 1 and 2 and CHEMCAD Help Section 13.11 for further details.

In relief system design there are three main types of system to be considered depending on the nature of the reaction.

- **Vapour pressure systems**

  The pressure generated by a runaway reaction is entirely due to the vapour pressure of the reacting mixture, which rises as the temperature of the mixture increases during a thermal runaway.

- **Gassy systems**

  The pressure generated by a runaway reaction is entirely due to a permanent gas which is evolved by the chemical reaction.

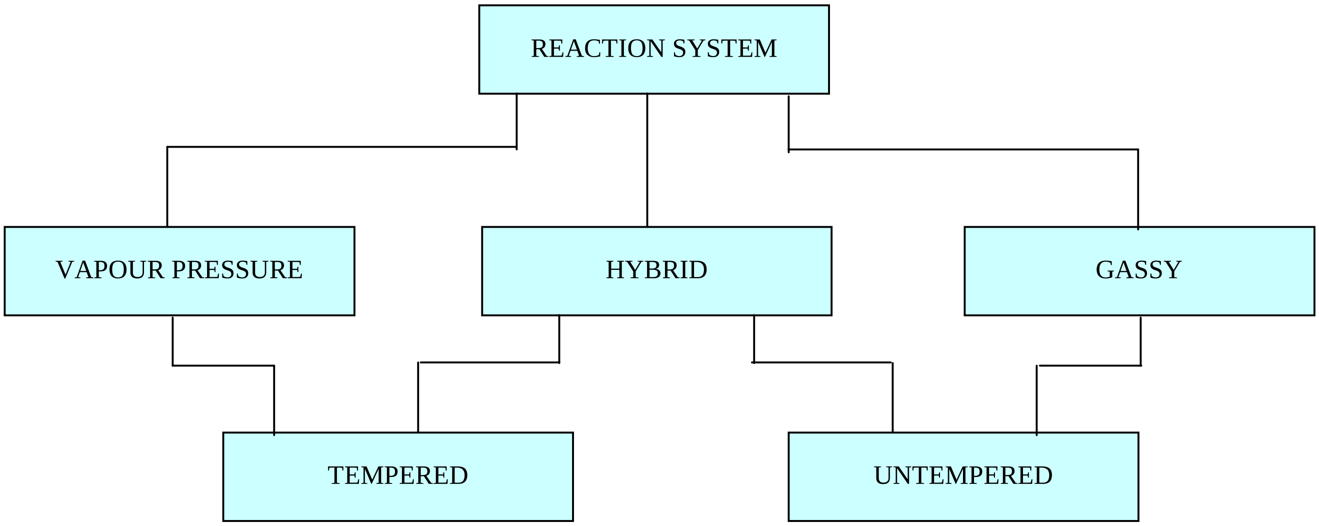
- **Hybrid systems**

  The pressure is due to both the evolution of a permanent gas and increasing vapour pressure with increasing temperature.

Vapour pressure systems are **tempered** in that the temperature and reaction rate is controlled during relief due to latent heat removal.

Gassy systems are **untempered** in that pressure relief does not control the temperature or reaction rate.

Chemical Reactor System Types



3.0 Relief System Sizing (Cont.)

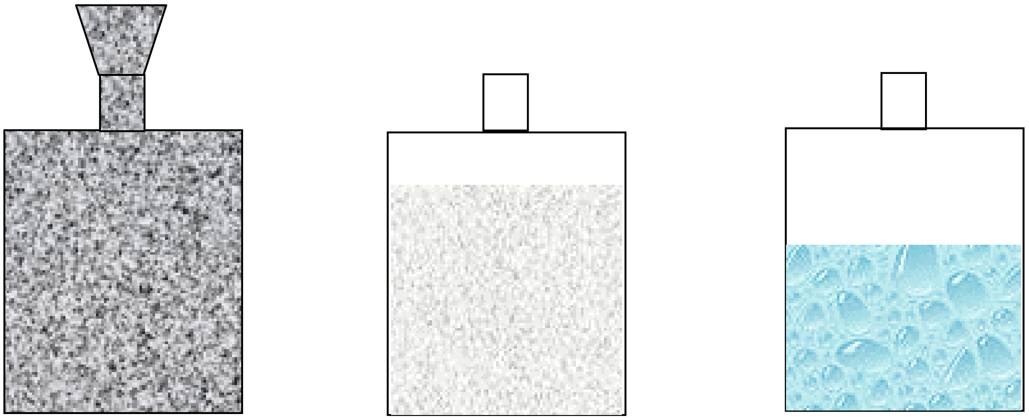
3.1 Design Fundamentals (Cont.)

3.1.1 Vessel and Vent Flow Models (Cont.)

The two-phase flow regime within the venting vessel will influence the fraction of gas or vapour within this two-phase mixture. The vessel flow regimes considered are:

- **Homogeneous**
- **Bubbly**
- **Churn-turbulent**

Vessel Flow Regimes



Homogeneous Bubbly Churn-turbulent

Level swell, depending on reactor level, results in venting of a two-phase mixture typical of gassy and hybrid systems.

Foamy systems invariably will vent a two-phase mixture throughout the relief period.

Two phase flow models for Relief Device Sizing to be considered are:

- **Homogeneous equilibrium model (HEM)**

  Assumes uniform mixing of phases across the pipe section – no phase slip, thermal equilibrium, and vapour/liquid equilibrium. (Recommended by DIERS).

- **Equilibrium rate model (ERM)**

  Assumes no flashing in the relief system until the choke point and then flashing at equilibrium rate at the choke point.

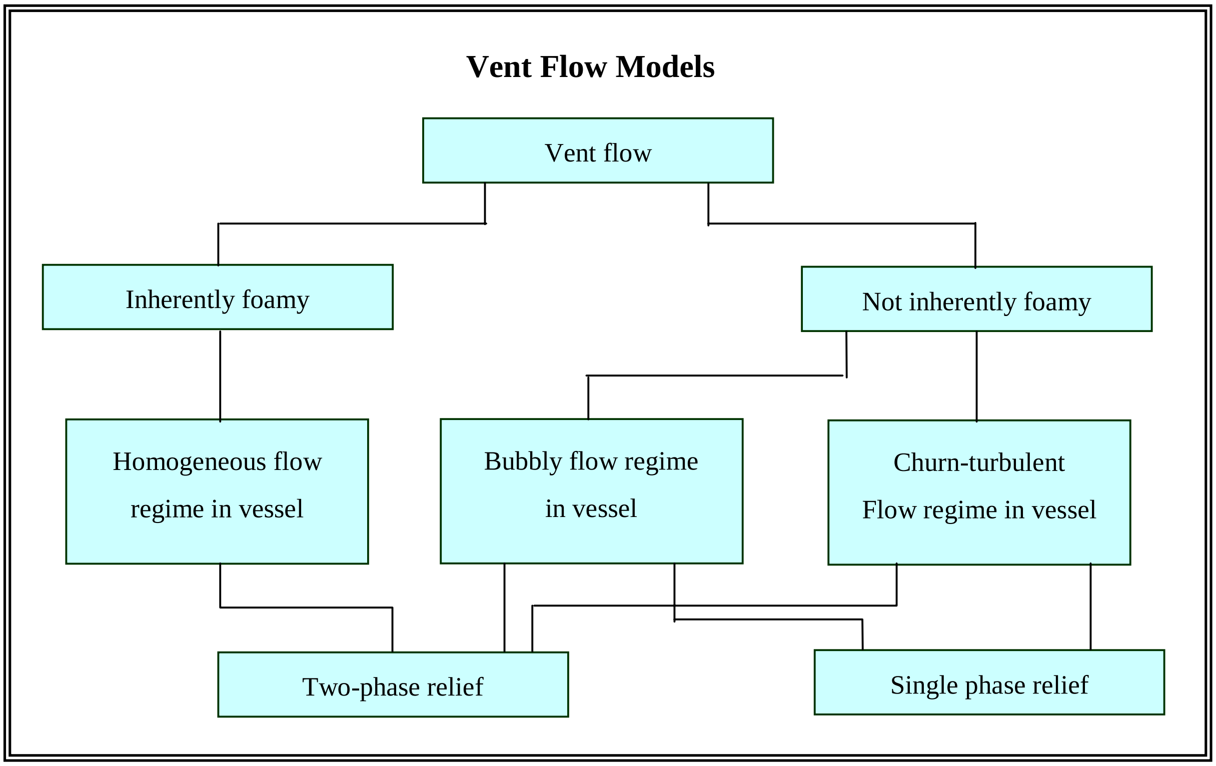
- **Henry Fauske model (HNE)**

  Neglects friction and assumes two-phase relief system flow is not choked which is less conservative.

3.0 **Relief System Sizing** (Cont.)

3.1 **Design Fundamentals** (Cont.)

3.1.1 **Vessel and Vent Flow Models** (Cont.)



The vessel and vent flow models should be established experimentally. The following assumptions are considered conservative (safe):

- **For tempered systems**

  Two-phase rather than vapour relief.
  Homogeneous vessel behaviour.
  Homogeneous equilibrium model (HEM) for relief system flow.

- **For untempered systems**

  Two phase relief at the point of maximum gas generation rate.
  Level swell behaviour in the reactor which minimises early loss of reactants by relief e.g. churn turbulent.
  Homogeneous equilibrium model for relief system flow.

3.0 Relief System Sizing (Cont.)

3.1 Design Fundamentals (Cont.)

3.1.2 Heat Models

For relief device sizing from exothermic reactions experimental data is required from reaction screening techniques (1) (2) to establish the maximum rate of pressure rise and maximum rate of temperature rise.

Heat input rates can be user defined from a knowledge of the thermal characteristics of the reaction system and associated jacket services. This is particularly useful when considering operational and control system failure modes such as maximum heat input from jacket systems.

Heat input rates can also be as a result of external fire. This has received extensive investigation by several organisations including API, NFPA and OSHA.

Refer to Appendix III for establishing heat inputs from
API 520 (4) / API521 (5) (operating pressure > 15 psig)
API 2000 (6) (operating pressure $\leq$ 15 psig).

Vent flow model single-phase vapour is usually appropriate for external fire cases.

Where,
Q = total heat absorption — Btu/hr
A = total wetted surface — ft^2
F = environmental factor (4, 5) — (API 521 Table 5)

In API 520/API 521 the heat input Q is determined from:

$Q = 21000\,FA^{0.82}$ with adequate drainage and fire fighting equipment
$Q = 34500\,FA^{0.82}$ without adequate drainage and fire fighting equipment

In API 2000 for low pressure storage tanks the heat input Q is determined from:

$Q = 20000\,A$ in the range $0.4 \times 10^6 < Q < 4 \times 10^6$ Btu/hr
$Q = 199300\,A^{0.566}$ in the range $4 \times 10^6 < Q < 9.95 \times 10^6$ Btu/hr

Appendix IV summarises the design basis for estimation of the heat transfer areas for the different standards.

A vent flow rate can be specified which allows for consideration of regulator failure and enables reaction gas evolution rates to be considered.

3.0 **Relief System Sizing** (Cont.)

3.2 CHEMCAD Utility – Relief Device Sizing

Refer to CHEMCAD Help Section 13.11.

The relief device sizing Utility is a comprehensive module giving consideration to all the relevant design fundamentals.

To use the module the following procedure has been applied:

- Prepare the vessel design parameters input data table (Appendix I).
  Diameter, cylinder length, dished end depth ratio (h/R), liquid level.

- Prepare process parameters input data table (Appendix I).
  Components, charge details weight and mole fractions.

- Define component list and thermodynamics.
  For common organic solvent based systems.

Equilibrium K	Ideal Vapour Pressure.
Enthalpy H	SRK or Latent Heat.

  Alternatively use Expert.

- Set up Flow Sheet with Reactor Inputs and Vent Manifold using Pipe Simulator UnitOp.

- Define stream compositions.
  Set vapour mole fraction and stream pressure at relief device set pressure and flash to obtain temperature.

- Complete Relief Device Sizing entry data.
  - Assign relevant Stream Number from Flowsheet.
  - Mode Design for new device.
    Rating for existing device.
  - Device Type including coefficient of discharge from manufacturer's data. Caution with bursting discs with vacuum support.
  - Select Vessel Model and Vent Model based on knowledge of process. Alternatively, use conservative Homogeneous Vessel and HEM Vent Flow model. For external fire single-phase vapour is usually appropriate.
  - Specify Heat Model.
    For external fire API 2000 is conservative compared with API 520/521.
    API 520/521 with inadequate drainage/fire fighting facilities and Environmental Factor F = 1.0 is conservative.
  - Valve selection – use calculated size for rating case.
  - Complete inlet/outlet piping details.
    Results should be printed out for each Stream as completed.

4.0 Relief System Header

The CHEMCAD Pipe Simulator UnitOp (Refer to CHEMCAD Help Section 7.15) is used to Design and Rate the relief manifold.

The vent conditions are available from the relief device sizing runs, which are now entered into the relevant streams using the relief temperature, and stream pressures set at 1 bar initially. (i.e. negative pressure at blowdown tank after first simulation run).

Isothermal flow conditions are assumed at the relief discharge temperature. If this was not available the temperature at the relief device set pressure was taken.

Actual flow conditions will be between isothermal and adiabatic conditions. For most cases the more conservative isothermal conditions are recommended.
(Reference API 521(5), p 58, 5.4.1.3.2.)

It should be noted that the Mixer UnitOp allows a reverse calculation on one Input only and operates like a low selector (i.e. the highest input pressure being blocked).

The Pipe Simulator modules are set in forward calculation O Rating (Default) sizing option. The steady state model is run on a trial and error basis until the relief device outlet stream pressures equals the blowdown tank pressure plus the appropriate branch and main header pressure drops.

The model can be run for an individual reactor relief or for coincident reactor relief cases in the event of external fire. The vessel fire zones are established based on plant layout and operations.

The model allows for the prediction of the maximum back pressure on the relief device attributable to the vent manifold pressure drop.

Provided the manifold back pressure (P_B) does not result in $P_B/P \leq 0.55$, where P is the inlet pressure, flow through the relief device is sonic (choked) providing maximum flow.

If we have a maximum blowdown tank pressure P_T and a minimum equipment design pressure P_D provided

$$P_D \geq \frac{P_T + \text{Vent} \quad \text{Manifold}\,\Delta P}{0.55}$$

the system will not suffer any reduction in capacity at the maximum blowdown tank pressure. Where the equipment design pressure is such that sonic velocity cannot be maintained the maximum allowable back pressure and the reduction in relief capacity is considered for specific cases. The reduction in relief device capacity can be determined by applying the appropriate back pressure in the Relief Device Sizing module.

To study the effects of a single reactor relieving the Pipe Simulator can be run in Sizing Option 4 “Given size and P_{OUT}, backcalculate P_{IN}”.

Convergence parameters should be set in Calculation Sequence Autocalc. The model reverse calculates from a preset blowdown tank pressure to establish relief device back pressure.

Appendix 1

Vessel Design Parameters

Vessel (Device)	Material	Volume l	Pressure		Physical Parameters		Dished End Parameters				Liquid Level m
			Design barg	Set Barg	Diameter M	Tan-Tan m	Top hd/R	Base hd/R	Base Depth m	Base Volume l	
Reactor 1	SS	4000	2	1.9	1.8	2.286	0.5	0.5	0.46	756	0.949
Reactor 2	GL	7000	6.9	4.0	2.134	1.677	0.453	0.5	0.533	1231	1.168
Reactor 3	GL	7000	6.9	4.0	2.134	1.677	0.453	0.5	0.533	1231	1.532

Process Parameters

Vessel (Device)	Process Specification						
	Fluid	Volume l	Liquid ρ kg/m^3	Weight kg	Mol wt kg/kmole	Liquid kg/kmole	Liquid Mole fraction
Reactor 1 (BD01)	Toluene	2000	867	1734	92	18.850	1.000
Reactor 2 (BD02)	DCM	3500	1326	4641	85	54.600	1.000
Reactor 3 (BD03)	Toluene	1000	867	867	92	9.424	0.138
	DCM	3500	1326	4641	85	54.600	0.800
	$SOCl_2$	300	1640	492	118	4.169	0.062
		4800		6000		68.190	1.000

Appendix II

Relief Piping Equivalent Length

A specific design was based on the following:

Relief device inlet and outlet piping diameter = 150mm.
Main header diameter = 250mm.

The total equivalent length of a typical vessel branch was taken as 45.1 m, based on 4 x standard 90° elbows, 1 x 45°T flow through branch, 1 x sudden expansion ($d_a/d_b = 0.6$) and 15 m straight pipe.

The total equivalent length of the main header with proposed 250 mm diameter was taken as 85.2 m based on 6 x 45°T flow through run, 1 x sudden expansion and 22 m straight pipe.

All equivalent lengths can be referred to the same size by the resistance coefficient K relationship (reference Crane Pub 4.10M Equation 2-5 p2 –10).

$$K_a = K_b \left(\frac{d_a}{d_b} \right)^4$$

where ‘a’ defines K and d with reference to the pipe size to which all resistances are to be expressed, and where (reference Crane Pub 4.10M Equation 2-4 p2 – 8).

$$K = f \left(\frac{L}{D} \right)$$

Assuming the friction factor f is constant in both pipes we have:

$$\left(\frac{L}{D} \right)_a = \left(\frac{L}{D} \right)_b \left(\frac{d_a}{d_b} \right)^4$$

In our case we will refer to 150 mm diameter,

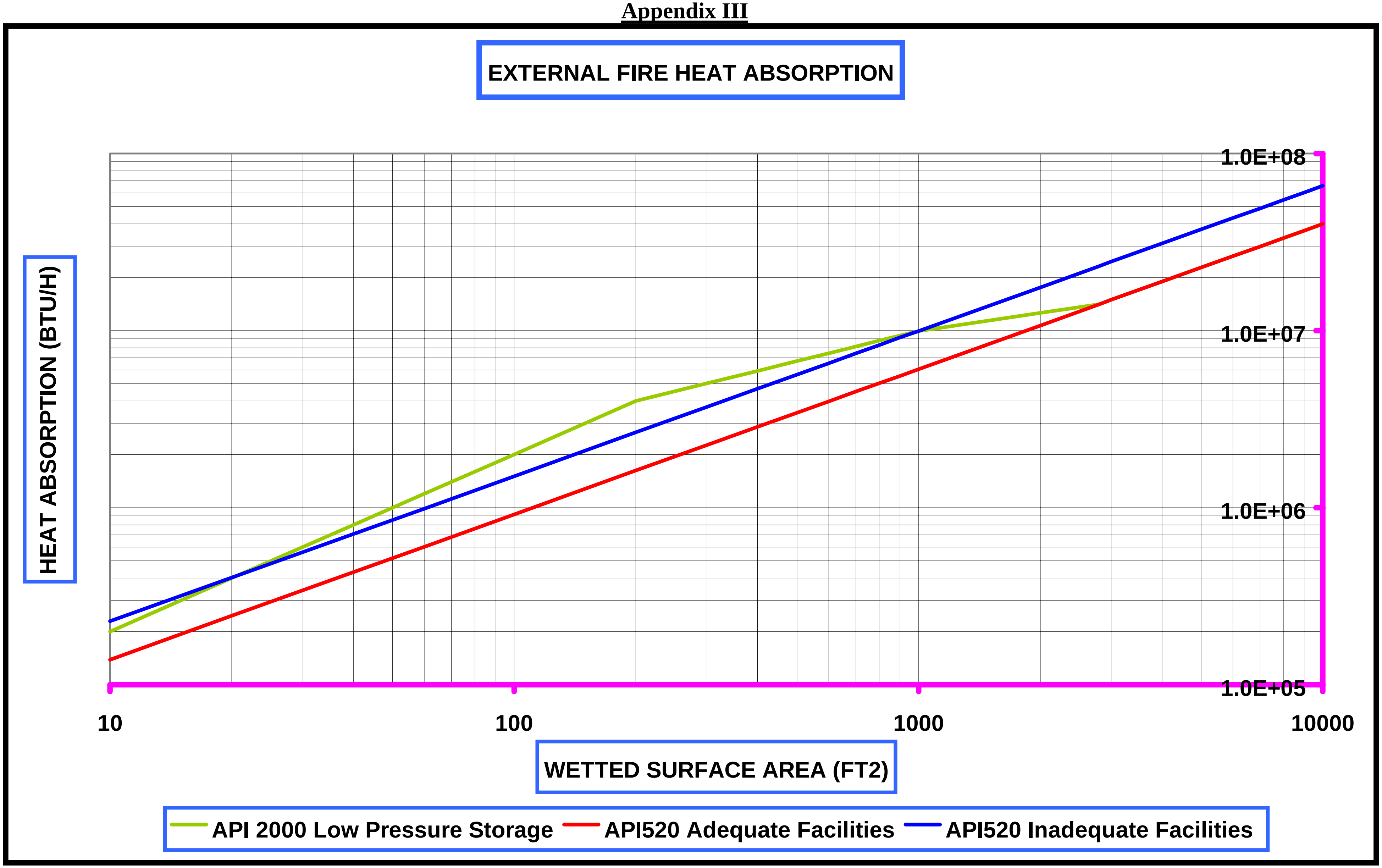
$$\frac{d_a}{d_b} = \frac{150}{250} = 0.6$$

Main header equivalent length referred to 150mm diameter

$$\left(\frac{L}{D} \right)_{150} = 85.2 \text{ x } (0.6)^4 = 11.1$$

Total equivalent length for relief vent = 45.1 + 11.1 = 56.

Appendix III



Appendix IV

Estimation of Heat Transfer Area from Total Area

EQUIPMENT	AGENCY GOVERNING THE EQUIPMENT OPERATION		
	NFPA-30 & OSHA 1919.106	API-520 & API-521 Operating Pressure > 15 psig	API-2000 Operating Pressure ≤ 15 psig
1. Sphere	55% of total exposed area.	Area up to the maximum horizontal diameter or up to the height of 25 ft., whichever is greater.	As in API-520/521.
2. Horizontal Tank	75% of total exposed area. If under 200 ft^2, use 100% of total exposed area.	Area equivalent to the average inventory level up to the height of 25ft.	75% of total exposed area.
3. Vertical Tank	100% of total exposed area for the first 30 ft. Exclude bottom area if the bottom is flat and supported on ground.	Area equivalent to the average inventory level up to the height of 25 ft.	As in OSHA.
4. Process Vessel	-	Area equivalent to the average inventory level up to the height of 25 ft.	-
5. Fractionating Column	-	Area equivalent to liquid level in bottom, and reboiler if part of the column, plus liquid hold up from all trays up to a height of 25 ft.	-

Note: Compressed Gas Association and Chlorine Institute consider total calculated area as the heat transfer area.