

# COMPUTER-BASED AIDS FOR PRESSURE RELIEF CONTINGENCY ASSESSMENT

R K Tanner,

Department of Chemical and Process Engineering, Heriot-Watt University

Assessing relief contingencies is the most difficult task in pressure relief design and the techniques involved are not well described in the literature. Computer-based aids have been developed for identifying and quantifying contingencies. The advantages of these aids are in providing assistance to engineers not expert in the field and in allowing contingencies to be recognised, quantified and possibly eliminated early in the design process.

Pressure relief	Overpressure	Underpressure
Expert system	Computer-based aids	

## INTRODUCTION

Pressure relief is an important aspect of process design. It needs to be considered whenever there is the possibility of operation above (known as "overpressure") or below ("underpressure") allowable equipment working pressures. If changes to operating conditions or equipment design are impractical, then a relief system is necessary to eliminate the potential for equipment rupture and release of hazardous materials.

Six stages to pressure relief design can be identified :

1. Division of the process into sections (known as "isolatable systems"), each of which can become isolated through valve closure or line blockage and consequently exposed to pressures outside the allowable limits;
2. Identification and quantification of potential causes of overpressure and underpressure, known as the relief "contingencies";
3. Selection of the appropriate relief device, normally either a relief valve or bursting disc;
4. Sizing of the relief device to handle the necessary relief flow rate to avoid the hazardous condition;
5. Design of the pipework associated with the relief device;
6. Disposal of the relieved fluids.

Stage 1 follows from a careful analysis of the process flow sheet. There are well established guidelines for stages 3, 5 and 6. Stage 4, sizing of the relief device, is straightforward for single phase relief; sizing for a two-phase relief is more difficult but there are several researchers such as Morris (1) who are working in this area and developing design methods.

The most difficult task is stage 2, contingency assessment. There are many potential contingencies and all need to be identified. For instance overpressure can be a result of inflow from a high pressure source, heat input causing either thermal expansion, an increase in vapour pressure or vapour generation, or due to heat generation resulting from a chemical reaction. Correspondingly, underpressure can be due to outflow from the equipment, heat removal or heat absorption due to a reaction. The required relief flow,

whether it be vapour, liquid or two-phase, needs to be calculated for each contingency and the relief device sized for the greatest flow.

Considering the importance of relief contingency assessment in process design, the topic is surprisingly poorly described in the literature. Process safety texts such as those by Lees (2) and Wells (3) describe some of the more common contingencies but are not sufficiently comprehensive to act as a design guide, although Parry's recent book dedicated to pressure relief design (4) does cover the subject more thoroughly. The most detailed references are the American Petroleum Institute (API) publications; Recommended Practices 520 (5) and 521 (6) together with Standard 2000 (7) for storage tank relief. As with most design codes, these can be difficult to follow unless one is already familiar with them. Many larger companies have their own design guides, often based on the API codes but incorporating in-house expertise, but these can be so comprehensive as to be unwieldy.

There is a need for further design aids to help systematically identify and quantify relief contingencies, and this paper describes some computer-based aids developed at Heriot-Watt University. Pressure relief design has previously been suggested as an appropriate application for an expert system by Bunn and Lees (8) and a recent Annual Report by the Health and Safety Commission (9) highlighted the development of aids of this type as an area of particular interest to increase efficiency and retain in-house experience.

Although an expert system is being developed by an HSE/industry consortium to help relief sizing for explosions (10), the author is unaware of any available software for the more common case when the pressure rise is less rapid. This is surprising considering the number of packages available for other aspects of process safety, such as HAZOP-PC for documenting Hazard and Operability Studies (11) and SAFETI for carrying out Hazard Analysis (12).

### DESCRIPTION OF THE DEVELOPMENTS

These developments have been carried out using two PC based programming tools, one running on DOS [Crystal (13)] and the other on Windows [KnowledgePro Windows (14)]. They both incorporate a largely syntax free programming language which allow advisory systems of the type described to be relatively easily developed. The developments fall into three categories :

#### 1. On-line Design Guide

An on-line design guide, if well structured and incorporating good help facilities, can be much more user-friendly than the traditional "paper" version, providing rapid access to the required information. There are also some specific advantages of an on-line design guide for relief contingency assessment :

1. By helping the user to approach the design in a systematic way, it can ensure that all potential overpressure and underpressure contingencies are identified. Wilday (15) emphasises the importance of ensuring all contingencies are identified in pressure relief design.
2. Relief design is a discipline which is regularly refined as a result of

operating experience. This is demonstrated by Fitt's description of ICI's relief design practices (16). If the software is well structured, changes can be easily incorporated. Furthermore if it is based on a main-frame computer, one can ensure that the most up-to-date methods are used throughout the company.

To demonstrate the potential of an on-line design guide, one has been developed to assist with the assessment of pressure relief contingencies for storage vessels. Built-in expertise is accessed through user responses to simple questions. This allows the relevant contingencies to be identified and the appropriate means of quantification to be recommended for each.

Several types of storage vessel can be identified; atmospheric storage for liquids held at a temperature below their normal boiling point, pressurised or refrigerated storage for liquefied gases, and gas storage. For each type, there are many possible variables in the design. For instance the vessel may be spherical or cylindrical, it may have a fixed or floating roof and there may be a means of heating or cooling the contents. However all potential contingencies can be conveniently divided into a number of categories. This categorisation for overpressure in liquid storage vessels is shown in Figure 1. Conditions under which the contingencies can be eliminated are shown on the right-hand side of this Figure. This may result from the inherent tank design (eg tank able to withstand maximum upstream pressure) or due to control measures (eg high level trip does not allow tank to become liquid full).

Figure 2 demonstrates this design guide in use. The top half of this Figure lists the questions asked and the responses from the user. In the example illustrated, the first seven questions are intended to allow contingencies to be either ruled in or out. For instance from the user responses to the first two questions, the built-in expertise eliminates rollover as a contingency because the vessel is not refrigerated and eliminates overpressure due to inflow of a heating medium because the tank is not heated.

The last two questions allow appropriate advice to be given once the relevant contingencies have been identified. All the questions require either a simple yes/no input or the selection of a single response from a list, and there is a help screen associated with each question to aid the user. The final summary screen for this example is shown in the bottom half of Figure 2. The methods for quantifying the contingencies are only summarised but the source of the information is given in case the user wants further guidance.

## 2. An Aid for Relief System Synthesis

As with storage vessels, generic over- and underpressure contingencies can be identified for other items of process equipment. For instance vapour relief is necessary to handle overpressure due to loss of reflux in a distillation column whilst liquid relief may be needed to protect against the effects of thermal expansion of the contents of totally liquid filled equipment.

In practice, the isolatable system may well be a combination of several items of equipment rather than a single item. An aid has been developed to allow relief contingencies to be identified based on the components of the isolatable system together with expert questioning specific to those

components. A previous development by Niida *et al* (17) identifies contingencies from user responses but takes no account of the composition of the isolatable system and therefore the questioning has to be more extensive.

Figure 3 shows two successive screens illustrating how the user builds up the isolatable system. The items of equipment are chosen in the order they occur in the isolatable system by locating the cursor over a graphical representation of each, as shown in the top half of figure 3. The more common items of process equipment are included, namely pump/compressor, heat exchanger, storage vessel, separating column and reactor. All "new input lines" to the system are included as these are also potential high pressure sources. Once the items have been selected, the isolatable system is displayed as shown in the bottom half of figure 3. For the example illustrated, this system consists of a reactor with two input lines, pre-cooling and pump discharge. Editing facilities allow the system to be easily changed or extended.

The user is asked a number of questions based upon the composition of the isolatable system. The top half of Figure 4 lists the questions and user responses for the system in Figure 3. The questioning depends upon the items of equipment involved (eg whether the exchanger is a heater or cooler) as well as any interactions between these items (eg whether a loss of cooling results in a pressure in the reactor in excess of the design pressure). The first two questions are designed to rule in or out fire relief and liquid thermal expansion as possible contingencies. The bottom half of Figure 4 shows the final summary screen for this example, listing the appropriate overpressure and underpressure contingencies.

A tool of this type is particularly valuable early in the design process when it is relatively easy to design out contingencies or to make changes that can reduce the relief load. For instance in the example illustrated, knowing that one of the overpressure contingencies is coolant flowing into the process side, then the process side design pressure could be increased to withstand the coolant pressure. All too often relief design is carried out late in the design process when changes to reduce relief load are difficult if not impossible.

### 3. Calculation Tool

To develop a tool for quantifying pressure relief contingencies is an ambitious undertaking due to the complexity of many of the calculations involved [for instance those developed by DIERS for reactor relief (18)] and the need for physical property data applicable at the relief conditions. However, such a tool can be a powerful design aid. To demonstrate this potential, a system has been developed for quantifying the contingencies for pressure relief on the shell side of a shell and tube heat exchanger. Assuming that the shell can withstand the maximum upstream shell side pressure, three major overpressure contingencies can be identified :

a. Tube Rupture This contingency must be considered if the tube side pressure exceeds the shell side design pressure. The system developed calculates the flow rate from the tube side into the shell assuming single phase liquid or gas flow, depending upon the condition of the tube side fluid.

For liquid flow in the tubes, as is the case for the example illustrated in Figure 7, the flow rate  $F$  (kg/s) is given by :

$$F = A [ 2 \rho_L (P_t - P_s) ]^{0.5} \quad [1]$$

where :  $A$  is the area for flow ( $m^2$ ). An area of twice the tube cross-section is used, as recommended in API 520 (5)

$\rho_L$  is the liquid density ( $kg/m^3$ )

$P_t$  is the tube side pressure ( $N/m^2$ )

$P_s$  is the shell side relief pressure ( $N/m^2$ )

b. Shell Side Isolation This contingency assumes that the inlet and outlet valves on the shell side are closed but that flow has continued through the tubes. With the warmer fluid through the tubes, two distinct contingencies can be identified; if the maximum tube side temperature is below the boiling point of the shell side liquid, then unless there is a very big temperature differential or unless the liquid inventory is very large, a nominal sized relief valve is all that is necessary to handle the relief flow resulting from thermal expansion. However if the shell side liquid is allowed to boil, a relief valve handling a vapour flow  $R$  (kg/s) is required, where :

$$R = \frac{Q}{L_v} \quad [2]$$

where :  $Q$  is the heat transferred (kW) calculated for the new temperature driving force, assuming the normal tube side flow rate and inlet temperature and a constant shell side temperature equal to the boiling point of the shell side fluid at the relief pressure.

$L_v$  is the latent heat of vaporisation of the shell side fluid at the relief pressure (kJ/kg)

c. Fire API 520 (5) recommends that the following equation should be used to determine the rate of heat absorption by the shell side fluid  $Q$  (kW) if exposed to fire :

$$Q = 43.2 F_{env} A_w^{0.82} \quad [3]$$

where :  $F_{env}$  is the environment factor, accounting for any fire resistant insulation

$A_w$  is the wetted area ( $m^2$ ), in this case the total external area of the shell

Once  $Q$  has been calculated, the vapour generation rate  $R$  (kg/s) can be determined using equation [2].

Figure 5 shows the structure of this design aid. Initially the user is questioned to see whether any of the contingencies can be eliminated. For

instance, if the shell side design pressure is greater than the tube side pressure, contingency a does not need to be considered and the amount of data that the user needs to enter is appropriately reduced.

Fire relief is often the governing contingency; that is the one resulting in the maximum required relieving rate and therefore on which the relief device is sized. However, there are circumstances under which fire relief can be ruled out. It is generally eliminated as a contingency when the equipment is buried or well above ground level. A number of other factors affect the likelihood of overpressure due to a fire; these include the quantity and flammability of any release in the vicinity that could fuel the fire, drainage around the equipment and precautions taken to avoid an ignition source. A method has been incorporated to quantify these factors in order to assess the need for fire relief. The basis of this method is shown in Figure 6.

Figure 7 shows the output from the system for the exchanger illustrated. The relief rates associated with each contingency are presented in tabular form. The advantage of this type of aid is the ability to recalculate the relief load for changes in the design variables; variables can be changed as shown in the left-hand screen, and after inputting any revised physical property data that is needed, the new relief rates are calculated as shown in the right-hand screen. For the example illustrated, the load has been recalculated for an increased shell side relief pressure, the addition of fire resistant insulation and an increased tube side flow.

As with the system described in 2, above, an aid of this type is valuable early in the design process, for instance to assess ways of reducing the necessary size of the relief stream disposal system. It is also useful when plant modifications are considered, to check for any changes to necessary relieving rates, as illustrated by the significant increase required by increasing the octane flow to 20 kg/s for the example in Figure 7.

### CONCLUDING REMARKS

Pressure relief contingency assessment is relatively poorly described in the literature and is therefore a potential area of development for computer-based aids. On-line design guides of the type described in 1, are particularly useful for engineers not expert in contingency assessment as they are very user-friendly.

The developments described in 2, and 3, for relief system synthesis and contingency quantification are important for demonstrating the potential of such aids. A logical future step would be an attempt to incorporate aids of this type into flowsheeting simulation packages where the detailed flowsheet, operating conditions and physical property data are already available. This would allow full relief assessment to be carried out in parallel with the main process design.

### ACKNOWLEDGEMENTS

The author would like to thank George Greiss, Steven Mitchell, Grant Newberry, Douglas Reid and Robert Venables for their help in developing these aids during their undergraduate studies and likewise Ronan Flanagan during his MSC

studies. The co-operation of staff at Exxon at Mossmorran and Zeneca at Grangemouth is also appreciated.

### NOMENCLATURE

A	Area for flow from ruptured heat exchanger tube ( $m^2$ )
$A_w$	Wetted area ( $m^2$ )
F	Liquid flow through ruptured heat exchanger tube (kg/s)
$F_{env}$	Environment factor
L	Liquid relief rate (kg/s)
$L_v$	Latent heat of vaporisation (kJ/kg)
$P_s$	Shell side relief pressure ( $N/m^2$ )
$P_t$	Tube side pressure ( $N/m^2$ )
Q	Heat absorption rate (kW)
R	Required vapour relief rate (kg/s)
V	Vapour relief rate (kg/s)
$\rho_L$	Liquid density ( $kg/m^3$ )

### REFERENCES

- Morris, S.D., 1990, J Loss Prev Process Ind, 3, July, 303.
- Lees, F.P., 1980, Loss Prevention in the Process Industries, Butterworth-Heinemann, Oxford.
- Wells, G.L., 1980, Safety in Process Plant Design, George Godwin Limited, London.
- Parry, C.F., 1992, Relief Systems Handbook, IChemE, Rugby.
- American Petroleum Institute, 1990, Recommended Practice 520, Sizing, Selection and Installation of Pressure-Relieving Devices in Refineries, 5th Edition.
- American Petroleum Institute, 1990, Recommended Practice 521, Guide for Pressure-Relieving and Depressuring Systems, 3rd Edition.
- American Petroleum Institute, 1992, Standard 2000, Venting Atmospheric and low Pressure Storage Tanks (Non-Refrigerated and refrigerated), 2nd Edition.
- Bunn, A.R. and Lees, F.P., 1988, Chem Eng Res Des, 66, 419.
- 1988/89 Annual Report from the Health and Safety Commission.
- Santon, R.C., Postill, A., Furman, T.T., Vadera, S., Byers-Brown, W. and Palmer K.N., 1991, Proc IChemE Symposium No 124, 317.
- HAZOP-PC, computer software distributed by Cremer & Warner Ltd.
- SAFETI, computer software distributed by DNV Technica Ltd.
- Crystal, computer software distributed by Intelligent Environments Ltd.
- KnowledgePro Windows, computer software distributed by Knowledge Garden Inc.
- Wilday, A.J., 1991, Proc IChemE Symposium No 124, 243.
- Fitt, J.S., 1974, Loss Prevention and Safety Promotion, 1, 317.
- Niida, K., Itoh, J., Umeda, T., Kobayashi, S. and Ichikawa, A., 1986, Chem Eng Res Des, 64, 373.
- AIChE, 1992, Emergency Relief Systems for Runaway Chemical Reactions and storage Vessels, New York.
- Dow's Fire and Explosion Index Hazard Classification Guide, 1987, AIChE, New York, 6th Edition.

Contingency	How contingency can be eliminated
Vessel liquid full (i) during filling (ii) thermal expansion	High level trip to avoid vessel becoming liquid full Vessel withstands maximum upstream pressure
Outbreathing requirement (i) during filling (ii) increase in ambient temperature	Floating roof, pressurised storage Vessel can withstand vapour pressure at maximum ambient temperature
Gas blowthrough Failure of heating source	No gas input lines exist. Vessel can withstand maximum supply pressure. High pressure trip shuts off gas supply
(i) increase in liquid temperature (ii) rupture of heating coil	Tank not heated. Vessel can withstand vapour pressure at maximum possible temperature. High temperature trip shuts off heating source. Electric heating vessel can withstand maximum heating medium pressure
Puking Rollover	Tank not heated Water never present; temperature controlled below 100 degC Not refrigerated liquefied gas storage
Fire	Fire not a credible event due to : - vessel well above ground level or buried - no flammable materials present - good drainage around vessel

Figure 1: Overpressure Contingencies for a Liquid Storage Vessel



What type of storage?	:	<input type="checkbox"/> Liquid	<input type="checkbox"/> Liquefied Gas	<input type="checkbox"/> Gas
Is the tank heated?	:	NO		
Is there a floating roof?	:	NO		
Will the level control system allow the tank to become liquid full?	:	NO		
Are there any gas inputs?	:	NO		
Is the tank buried?	:	NO		
Is a build-up of flammable material around the tank possible?	:	YES		
Minimum flash point of any release	:	<38°C	<input type="checkbox"/> >38°C	non - flammable
Tank wetted area when full	:	<20m <sup>2</sup>	<input type="checkbox"/> 20-93m <sup>2</sup>	93-200m <sup>2</sup> > 200m <sup>2</sup>

Quantifying Relevant Relief Contingencies		
Overpressure	- Vapour outbreathing during tank filling 107m <sup>3</sup> /hr per 1m <sup>3</sup> /hr max filling rate	(API 2000)
	- Fire Heat input (kW) = 244(wetted area, m <sup>2</sup> ) <sup>0.500</sup>	
	Press <input type="checkbox"/> HELP to see ways of reducing heat input	(API 2000)
	Design vapour relief rate = $\frac{\text{Heat Input}}{\text{Latent heat of contents}}$	
Underpressure	- Vapour inbreathing during emptying tank 1m <sup>3</sup> /hr per 1m <sup>3</sup> /hr max pumping out rate	(API 2000)

Figure 2 : Illustrated Example of Storage Vessel Relief Design Guide

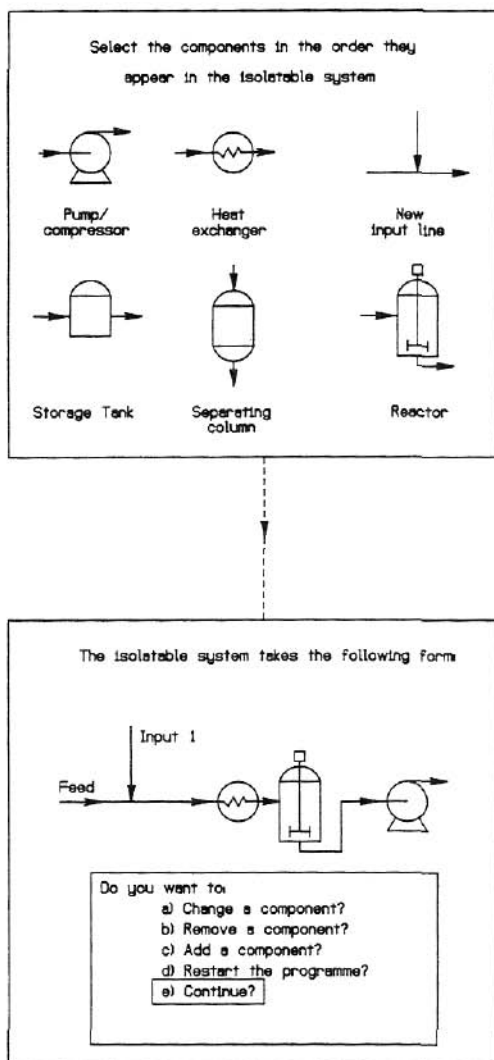


FIGURE 3 : RELIEF SYSTEM SYNTHESIS

Is the equipment burted or more than 10m above ground level?	No
Does the control system allow the system to be liquid filled?	No
Is the maximum faed supply pressure above the equipment design pressure?	No
Is the maximum input 1 supply pressure above the equipment design pressure?	No
Is the process fluid being heated or cooled?	Cooled
Is the coolant pressure above the equipment design pressure?	Yes
Is the maximum attainable pressure in the reactor as a result of loss of cooling in excess of the equipment design pressure?	No
Is a gaseous product formed during the reaction?	Yes
If the reactor vessel was overcooled, would the gas formed condense or be absorbed by the liquid present?	Yes
Pump or compressor?	Pump
Can the equipment downstream withstand the maximum pump discharge pressure?	Yes
Can the pumping continue with the inlet valve to the equipment closed?	Yes
Can the equipment withstand full vacuum?	No

<u>Relief Contingencies Needing Further Investigation</u>	
Overpressure	- Fire
	- Coolant leaking into process side
Underpressure	- Gas condensation and absorption in reactor
	- Pumping out with inlet valve closed

Figure 4 : Identifying Potential Relief Contingencies for the Isolatable System in Figure 3

RELIEF CONTINGENCIES

a. <u>Tube rupture</u>	b. <u>Shell side isolated with Tube side flow continuing</u>	c. <u>Fire</u>
<u>When contingencies ruled out:</u>	No isolation valves, or operating instructions ensure they are never closed with tube side fluid flowing	See Figure 6
Maximum Shell side > design pressure	Closure of isolation valves shuts off tube side flow	✓
<u>Data required to assess contingency:</u>	Warmer fluid in shell side	✓
Exchanger external surface area		✓
Fireproof insulation - thermal conductivity - thickness		✓ ✓
Shell side latent heat at relief conditions		✓
Tube side inlet temperature		✓
Tube side flow		✓
Shell side bpt. at relief pressure		✓
Tube surface area		✓
Tube diameter		✓
Shell side relief pressure		✓
Tube side pressure		✓
Tube side specific heat		✓
Tube side density		✓

Figure 5 | Calculation Tool for Heat Exchanger Relief Assessment

<u>Criteria</u>	<u>Weighting</u>		
	0	1	2
Height above ground	< 2m	2m to 6m	> 6m
Drainage	Ground slopes towards equipment	Up to 1 in 25 slope away	> 1 in 25 slope away
Details of spillage around equipment	> 20	Between 10 and 20	< 10
	> 100 tonnes	10 - 100 tonnes	< 10 tonnes
Safeguards against ignition source (1 mark for each, maximum of 2)	1) Area classification applied 2) Permit to work system enforced 3) Control of ignition sources onto plant		

Rule out fire relief if total weighting is > 5

Figure 6 : Assessing the Need for Fire Relief

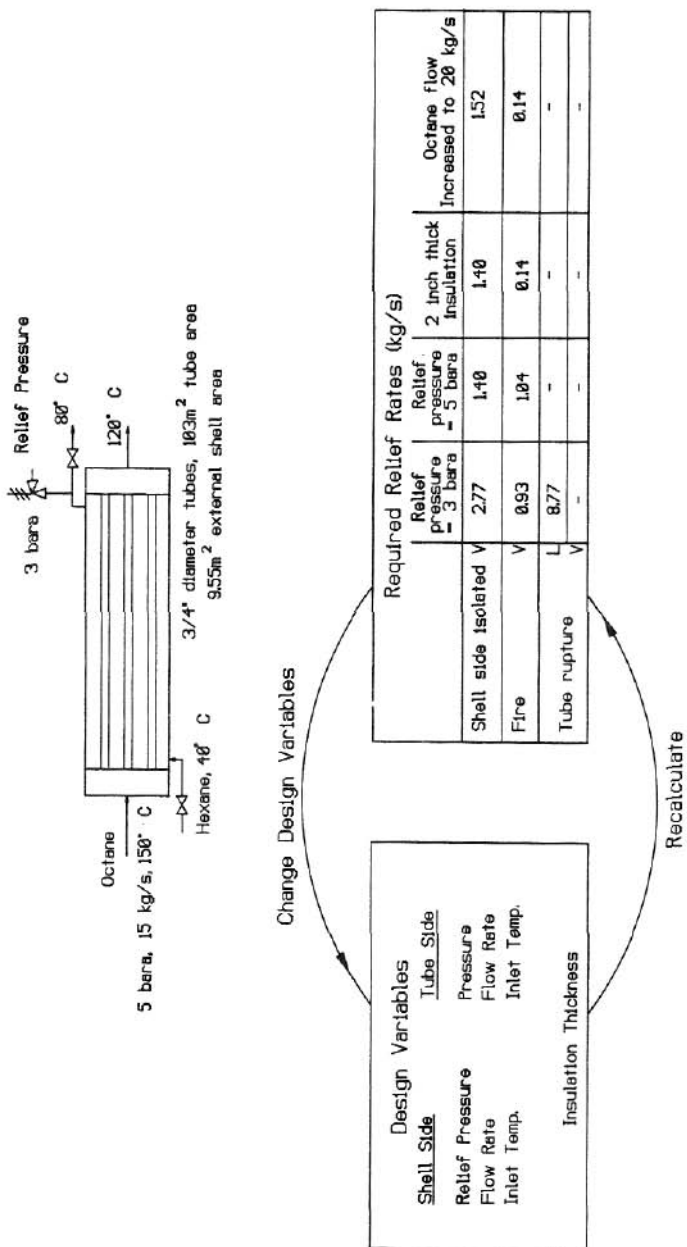


Figure 7 : Sensitivity Calculations on Required Relief Rates