# COMPARISON OF PRESSURE RELIEF AND INSTRUMENT PROTECTIVE SYSTEMS BY MEANS OF A CASE STUDY [1]

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Pressure relief systems are required to protect personnel and equipment from the danger of overpressure. One alternative method is an instrument protective system (trips). In this paper, the alternatives of pressure relief and an instrument protective system are compared for a case study involving a crude oil separator in an oil field. An instrument protective system is designed for the case study in order to meet reliability criteria. A comparison is made in terms of cost, spurious trip rate and individual risk.

Key words: Pressure relief, Instrument protective system, Redundancy, Diversity, Cost, Risk.

## INTRODUCTION

Pressure relief systems provide the means for protecting personnel and equipment from the effects of overpressure caused by the abnormal operation of a process. Pressure relief systems range from the single relief valve or rupture disk connected to a vent pipe on a single vessel, to the more complex piping systems involving many relief valves that are manifolded into a common header. A review is given by Parry [1]. Relief systems include downstream disposal equipment such as flares or scrubbers if required. Pressure relief systems have the advantages that they are readily available, well accepted and, in most cases, well understood. There are, however, problems with the use of pressure relief systems, highlighted by the accident at Bhopal. Also as plants get bigger, the cost of relief valves and of the associated flare or absorption systems become disproportionately large. The disadvantages of the use of pressure relief systems have been discussed by Wilday [2].

One method of avoiding relief devices is by the use of stronger vessels (containment). Another means of protection against excess pressure is to use instrument protective systems (IPS) also known as trip systems. IPS can be used as protective measures to reduce the frequency of an anticipated undesirable event. Often the event to be avoided will have consequences involving loss of capital equipment, production, injury to or loss of life, and/or environmental damage. The IPS is arranged to intervene automatically so that plant personnel are able to maintain the production process.

[1] The views expressed in this paper are those of the authors and do not necessarily reflect the policy of the Health and Safety Laboratory nor the Health and Safety Executive.

The selection and specification of an appropriate configuration for a trip system is a skilled task. The selected trip system should first satisfy the safety concerns, but likewise address production and operational issues, such as false tripping of the process. There are several trip system configurations available for use in process safety applications. These range from a single trip to triplicated or higher configurations. Examples are given by Lawley and Kletz in [3].

The objective of this paper is to present a comparison between pressure relief and IPS systems including reliability, frequency of spurious operation, cost and risk. This comparison is carried out for a case study of an oil separator in an oil field.

## REVIEW OF RELIABILITY CRITERIA

Wilday [4] reviewed criteria for allowing the use of IPS in place of conventional relief systems. The following is a summary:

1. HSE [5][6] suggest that a system failure resulting in major accident, might be tolerable at a frequency in the range of $10^{-6} - 10^{-4}$ per year.
2. Lawley and Kletz [3] proposed that an IPS could replace a relief system if it were 10 times as reliable.
3. Scilly [7] suggested that an IPS should be at least as reliable as a relief system and should also meet major hazards criteria if appropriate.

It should be remembered that an IPS and a relief system operate in different ways. A relief system may provide some protection against overpressure events for which it has not been designed; an IPS will not. A relief system may open above its nominal set pressure and still save the vessel; if an IPS has failed it will remain failed irrespective of the pressure.

## CASE STUDY

Figure 1 shows a crude oil separator. A hydrocarbon mix at 75 bara (oil, gas, and water) from an inlet header (with flow rate of oil 41,950 kg/hr, gas 4,450 kg/hr and water 20,000 kg/hr) flows to the separator. The pressure is maintained at 16 barg by a pressure indicator controller, PIC-1, acting on valve PV-1, on the gas to the down stream knock-out drum. The separated water is sent for disposal under level control by LC-1 acting on the valve LV-1. Oil is transferred by pumps P-1, P-2. The oil phase level is controlled by LC-2 acting on valve LV-2 at the pump deliveries. Crude oil low level switch LSL-2 stops the transfer pumps P-1, P-2, in the event of low level. Crude oil high level switch LSH-2 will start the standby pump, in case of high level. Water low level switch LSL-1 closes the water outlet block valve BV-1 in the event of low water level. The separator is protected against overpressure by a safety valve SV set at the separator design pressure of 27 barg.

## RELIEF SYSTEM RELIABILITY

The relief system components are connected in series. The system reliability may then be determined by computing the reliability of the subsystems and then that of the system itself. The reliability of the relief system may be found by fault tree analysis. The fault tree of the relief system is shown in Figure 2. Failure of the relief system may be caused by the failure of any of its components: the safety valve, discharge header, knock-out drum, seal drum or flare. Failure rate data have been found from the literature [8]. The failure rates of the relief system elements have been found as follows:

| Component | Failure rate $hr^{-1}$ |
|---|---|
| Pressure relief valve | $1.1 \times 10^{-6}$ |
| Discharge header | $1.36 \times 10^{-6}$ |
| Knock out drum | $4.9 \times 10^{-7}$ |
| Seal drum | $1 \times 10^{-6}$ |
| Flare | $2.07 \times 10^{-7}$ |

Table 1. Failure rate of pressure relief components

The system is assumed to be maintained and inspected every year. The probability of failure of the pressure relief valve can be expressed as the fractional dead time of the one-out-of-one protective system ( $FDT = 0.5\lambda T$ ). The probability of failure of the other components is given by $p(t) = \lambda t$ , when $\lambda t << 1$. Therefore, the probability of the total relief system failure can be calculated as follows: $p_{RS} = FDT_{SV} + p_{DH} + p_{KO} + p_{SD} + p_F$

| | |
|---|---|
| $FDT$ of pressure relief valve | 0.005 |
| Probability of failure of discharge header | $3.8 \times 10^{-3}$ |
| Probability of failure of knock out drum | $4.2 \times 10^{-3}$ |
| Probability of failure of seal drum | $8.7 \times 10^{-3}$ |
| Probability of failure of the flare | $1.8 \times 10^{-3}$ |
| Probability of failure of total relief system | 0.024 |

Table 2. The probability of failure of pressure relief elements and total relief system

The probability of failure of the relief system is found to be 0.02.

## INSTRUMENT PROTECTIVE SYSTEM

The occurrence of blockage of the separator outlets (oil, gas and water) and continuous inflow would lead to overpressure of the separator. The IPS must, therefore, be capable of isolating the source of pressure. An IPS has been designed for the separator in order to meet a reliability target. Lawley and Kletz [3] proposed that an IPS may replace a conventional relief system if it is 10 times as reliable. Therefore the target $FDT$ of the protective system is taken as 0.002. Efforts have been made to achieve the target reliability of the IPS by using redundancy and diversity. Possible configurations are shown in Figures 4 and 5.

## IPS RELIABILITY CALCULATIONS

The fractional dead time $(FDT_T)$ of a system gives the probability that it is in the failed or non-functioning state. The fractional dead time can be estimated as the sum of the fractional dead times for component or system failure $(FDT_C)$, human error in proof testing $(FDT_H)$, on-line testing duration $(FDT_t)$, and common cause failures $(FDT_{CC})$:

$$FDT_T = FDT_C + FDT_H + FDT_t + FDT_{CC} \tag{1}$$

A derivation of this equation can be found in [9]. The FDT and operational failure rates are given in [10]. Common cause, or systematic, failure occurs when failure of a single subsystem causes all or part of the protective system to fail. Sources of common cause failure (CCF) are environmental conditions, design errors, manufacturing errors, and operational or maintenance failures. CCF is typically calculated using the $\beta$ factor model. CCF certainly should not be ignored in the reliability calculations. A discussion of CCF is provided in the literature [11].

## REDUNDANT CONFIGURATIONS

In these configurations, the system is composed of a high high level switch and automatic shut off valve. The channels operate independently. They are in parallel and arranged to provide the level of operational redundancy required, that is, for the 1oo2 (one out of two) configuration, the two systems are parallel, independent and each switch operates a trip valve; for the 1oo2cc (cross connected) configuration, each switch can shut off both trip valves; for the 2oo3 configuration (voting), two out of three high high level switches must agree to shut off the trip valve. See Figure 4. Levels of redundancy beyond triplicated systems are rare in the industrial environment, and are very difficult to justify economically [12].

For the purpose of reliability calculations equation (1) was used. $FDT_C$ can be calculated from literature data. $FDT_H$ can be found by assuming one error occurs every 1000 tests. $FDT_t$ can be found by assuming the duration of an on line test is one hour. The reliability of the IPS has been found with and without common cause failure. The results are presented in Table 3 in terms of the test interval required to meet the target reliability.

| Configuration m-out-of-n | Test interval, weeks | Test interval, weeks | Target *FDT* |
|---|---|---|---|
| | Without CCF | With CCF | |
| 1oo1 | Impossible | Impossible | 0.002 |
| 1oo1(2v) | Impossible | Impossible | 0.002 |
| 1oo2(1v) | Impossible | Impossible | 0.002 |
| 1oo2(2v) | 9.5 | 8.5 | 0.002 |
| 1oo2cc | 13 | 11.5 | 0.002 |
| 1oo3(1v) | Impossible | Impossible | 0.002 |
| 1oo3(2v) | 15 | 13.5 | 0.002 |
| 2oo3 | 10 | 9 | 0.002 |

Table 3. The test intervals required to achieve the target reliability using system redundancy.

## DIVERSE CONFIGURATIONS

For diverse configurations, the system is composed of a high high level switch and a high pressure switch which operate independently on an automatic shut off valve. For the 1oo2 configuration, the valve may be shut off by both switches; for the 1oo2cc configuration, both switches shut off both valves; for the 1oo3$^*$ configuration, the high high level switch shuts off one trip valve, and one of the two pressure switches shuts off the other trip valve. For the 1oo3$^{**}$ configuration, one of the two high high level switches may trip one valve, and the high pressure switch shuts off the other valve. For 1oo3$^*$ cc and 1oo3$^{**}$ configurations each sensor can shut off one valve or both valves. See Figure 5. The results are shown in Table 4 in terms of the test interval required to meet the target reliability.

| Configuration, m-out-of-n | Test interval, weeks | Test interval, weeks | Target *FDT* |
|---|---|---|---|
| | without CCF | With CCF | |
| 1oo2(1v) | Impossible | Impossible | 0.002 |
| 1oo2(2v) | 9 | 8.5 | 0.002 |
| 1oo2cc | 12.5 | 11.5 | 0.002 |
| 1oo3 * | 11 | 10.7 | 0.002 |
| 1oo3 ** | 11.5 | 10.5 | 0.002 |
| 1oo3 * cc | 15 | 13.5 | 0.002 |
| 1oo3 ** cc | 15 | 13.5 | 0.002 |

Table 4. The test intervals required to achieve the target reliability using system diversity.

## SPURIOUS TRIPS

The duplication and triplication of a protective system increases its reliability, but also increases the spurious trip rate. This also impacts on safety because during shut down and start-up cycles, the process is operating in its most hazardous state. Operation under these conditions should be minimised for reasons of both safety and operability. Calculated spurious trip rates are given in Tables 5 and 6.

| Configurations m-out-of-n | Spurious trip rate year $^{-1}$ | Meets reliability target ? |
|---|---|---|
| 1oo1 | 1 | No |
| 1oo1(2v) | 1 | No |
| 1oo2(1v) | 1 | No |
| 1oo2(2v) | 1 | Yes |
| 1oo2cc | 1 | Yes |
| 1oo3(1v) | 1 | No |
| 1oo3(2v) | 2 | Yes |
| 2oo3 | 1 | Yes |

Table 5. Spurious trip rates of IPS with redundancy.

| Configurations m-out-of-n | Spurious trip rate year $^{-1}$ | Meets reliability criteria? |
|---|---|---|
| 1oo2(1v) | 1 | No |
| 1oo2(2v) | 2 | Yes |
| 1oo2cc | 2 | Yes |
| 1oo3 * | 2 | Yes |
| 1oo3 ** | 2 | Yes |
| 1oo3 * cc | 2 | Yes |
| 1oo3 ** cc | 2 | Yes |

Table 6. Spurious trip rates of IPS with diversity.

## COST COMPARISONS

### Relief system cost

The capital and operating costs for a flare system depend on many factors such as the availability of steam, the size of the flare, the composition of the waste gas and the frequency of flaring.

The basic data from the case study were used to calculate the size of the relief system elements. The safety relief valve size was calculated using API 520-1990 [13]. A $J$ orifice safety valve was selected and a 6 inch diameter discharge line was found to be required [14]. API-RP-521[15] gives an approach for the sizing of a flare stack based on the effects of radiation. The flare stack size was found to be 6 inch. The distance between the flare stack and the plant was taken as 300 feet.

The relief system cost in 1996 was calculated from data and indices from the literature. The capital cost was found to be £ 119,000. The operating cost of the flare is mainly due to the purge gas cost. The purge gas rate required to prevent any oxygen in the flare riser is given in [16] as follows: $Q = 0.003528d^{x}$, with $x = 3.46ka \times 10^{-3}$, where $ka = 2.38$ for $CH_4$.

The annual cost of the relief system has been found by modifying the method of Rushton [17] as the sum of the cost of the relief system, the cost of failure on demand and the operating cost:

$$V_{R.S} = C_1 + \delta pH + C_O \tag{2}$$

The total annual cost of the relief system was calculated using equation (2) at different demand rates. The results are shown in Table 7.

| Demand rate demand/yr. | 0.01 | 0.1 | 0.5 | 1 |
|---|---|---|---|---|
| Cost of relief system £/yr. | 12,500 | 14,300 | 22,300 | 32,300 |

Table 7. Cost of the relief system at different demand rates.

### Protective system cost

The capital cost of IPS channels (material and installation) which meet the target reliability for both redundancy and diversity were calculated and the results are shown in Tables 9 and 10.

The total annual cost of the protective system can be calculated using the method proposed by Rushton [17]. The optimal configuration is that for which the sum of the costs of the trip system, the cost of failure on demand, the cost of spurious trips, and the cost of genuine trips is minimal.

$$V = nC + \delta(FDT)H + \gamma S + \delta(1-(FDT))S \tag{3}$$

The cost of the trip system is taken to be the cost of proof testing. The proof test interval is that which is required to meet the target FDT. Attempts have been made to include the effect of increase of demand rate due to false trips and start-ups. The total annual cost of the protective system was calculated using equation (3) for redundant and diverse configurations and by using associated costs due to loss of production and hazard (per occurrence) shown in Table 8. By keeping all the parameters constant with the exception of the demand rate (0.01, 0.1, 0.5, 1 demand/yr.). The results of the calculations are shown in Tables 9 and 10.

| | |
|---|---|
| FDT | 0.002 |
| $T_r$ hr | 4 |
| $C_t$ £/test | 1000 |
| H £ | $1\times10^6$ |
| $S$ £ | 20,000 |

Table 8. Parameters for the cost calculations.

1- Redundancy

| Configuration | Capital cost £ | V £/yr. | V £/yr. | V £/yr. | V £/yr. |
|---|---|---|---|---|---|
| m-out-of-n | | $\delta = 0.01$ | $\delta = 0.1$ | $\delta = 0.5$ | $\delta = 1$ |
| 1oo1 | - | - | - | - | - |
| 1oo1(2v) | - | - | - | | - |
| 1oo2(1v) | - | - | - | - | - |
| 1oo2(2v) | 8,600 | 27,000 | 29,000 | 37,800 | 48,800 |
| 1oo2cc | 8,600 | 26,000 | 28,000 | 36,800 | 47,800 |
| 1oo3(1v) | - | - | - | - | - |
| 1oo3(2v) | 9,300 | 45,100 | 47,100 | 55,900 | 66,800 |
| 2oo3 | 9,300 | 27,100 | 29,100 | 37,900 | 48,800 |

Table 9. Capital and total annual cost of protective systems using redundancy versus demand rate.

2 - Diversity

| Configuration | Capital cost £ | V £/yr. | V £/yr. | V £/yr. | V £/yr. |
|---|---|---|---|---|---|
| m-out-of-n | | $\delta = 0.01$ | $\delta = 0.1$ | $\delta = 0.5$ | $\delta = 1$ |
| 1oo2(1v) | - | - | - | - | - |
| 1oo2 | 8,300 | 47,000 | 49,000 | 57,800 | 68,700 |
| 1oo2cc | 8,300 | 46,000 | 48,000 | 56,800 | 67,700 |
| 1oo3 * | 9,200 | 46,100 | 48,100 | 56,900 | 67,800 |
| 1oo3 ** | 9,200 | 46,100 | 48,100 | 56,900 | 67,800 |
| 1oo3 * cc | 9,200 | 46,100 | 48,100 | 56,900 | 67,800 |
| 1oo3 ** cc | 9,200 | 46,100 | 48,100 | 56,900 | 67,800 |

*Table 10. Capital and total annual cost of protective systems using diversity versus demand rate.*

## RISK ANALYSIS

The blockage of the outlets, failure of the protective system and continuous inflow would lead to the failure of the separator. It is assumed that no additional fuel other than that present in the system at the time of the incident contributes to the release [9]. It is also assumed that the contents of the vessel would be lost instantaneously. In order to find the incident outcomes for the release, the event tree shown in Figure 3 has been constructed. The oil in the separator is non-volatile and thus the main combustion hazards are from the flammable gas which would be released on vessel failure. Only 25 kg of flammable gas would be released. From the event tree, the following incident outcomes are taken for the risk analysis:

- Fireball due to immediate ignition
- VCE due to delayed ignition
- Overpressure due to vessel failure
- Missiles

It was found that the fireball had the main consequences for people. The possibility of a vapour cloud explosion was ruled out because of the small quantity of flammable gas and the unconfined nature of the site. The overpressure from vessel failure was predicted to be low. Although missiles could kill people, the probability of hitting someone is very low.
The individual risk from immediate ignition was evaluated using the following expression [18].

$$I.R. = p_{rel} \times p_{ii} \times p_c \tag{4}$$

- The probability of release due to a blockage of the outlet and failure of the trip system on demand has been found to be $4.5 \times 10^{-6}$ event/yr.,
- The probability of immediate ignition is 0.3.
- A probability of 1 of death or severe injury for people within the location when the hazardous event occurred, has been assumed.

Therefore the total individual risk is $1.35 \times 10^{-6}$ yr.$^{-1}$
This compares with the HSE criterion (1) that a risk of $10^{-6}$ per year could be taken to be broadly acceptable.

## DISCUSSION

It was found that an IPS could be designed which met the criterion of failure frequency < $10^{-4}$ per year and approaching $10^{-6}$ per year, and the criterion of having a reliability ten times as high as the pressure relief system. These findings are sensitive to the reliability data used in the calculations and it was difficult to find values in the literature. It is therefore felt that a substantial safety factor should be applied to the reliability calculation results. In the case of comparison with major hazard criteria, a safety factor approaching 2 orders of magnitude is available in meeting the tolerable criterion of $10^{-4}$ per year. However, this would only be tolerable if the risk had been reduced 'as low as reasonably practicable' (ALARP). The consequences of vessel failure for this case study (vessel containing non-volatile oil plus a small amount of flammable gas) are less than for separators containing, for example, pressurised liquefied flammable or toxic gas. Future case studies will look at such systems. However, for this case study it can be concluded that safety requirements can be achieved using an IPS in place of pressure relief.

If an IPS is to be used for protection, then the cost formula proposed by Rushton [17] can take account of the effect of both test interval and spurious trips. The lowest cost configuration which met the reliability constraints was 1oo2cc with the second longest test interval for redundancy and diversity. However, for this case study, the annual cost of the relief system, including capital depreciation, is less than that for an IPS, so that pressure relief would be chosen.

## CONCLUSIONS

1. It was possible to design an IPS for the separator case study which met the reliability requirements for use instead of pressure relief.
2. The capital cost of the relief system was more than the IPS, but the relief system anuual cost was less than IPS, so that pressure relief was the better option.
3. The best IPS configuration, on the grounds of cost, test interval and spurious trip rate was 1oo2cc with the second longest test interval for redundancy and diversity.
4. Reliability data for IPS and relief system calculations are hard to find and of dubious quality. This means that the above calculations are subject to some uncertainties.
5. The chosen case study provides a particular set of consequences of a vessel failure. Further work is planned which will look at separators containing different materials in order to look at different consequence levels.

## NOMENCLATURE

| | |
|---|---|
| $C$ | Annual cost (per channel) of a trip system (£ year$^{-1}$) |
| $C_1$ | Cost of relief system (£ year$^{-1}$) |
| $C_O$ | Operating cost of relief system (£ year$^{-1}$) |
| $C_t$ | Proof test cost (£) |
| $d$ | Flare diameter (inch) |
| $FDT_C$ | Fractional dead time due to component failure. |
| $FDT_{CC}$ | Fractional dead time due to common cause failure. |
| $FDT_H$ | Fractional dead time due to human error. |
| $FDT_{SV}$ | Fractional dead time due to failure of safety valve. |
| $FDT_t$ | Fractional dead time due to duration of on-line testing. |
| $FDT_T$ | Total fractional dead time. |
| $I.R.$ | Individual risk (year$^{-1}$) |
| $H$ | Cost of hazard (£) |
| $m$ | Number of channels that must survive for the trip system to survive. |
| $n$ | Number of channels in the trip system. |
| $p$ | probability of failure. |
| $p_C$ | Casualty probability. |
| $p_{DH}$ | Probability of failure discharge header |
| $p_F$ | Probability of failure of flare |
| $p_{KO}$ | Probability of failure of knock out drum |
| $p_{ii}$ | Probability of immediate ignition. |
| $p_{rel}$ | Probability of release. |
| $p_{RS}$ | Probability of failure of the relief system. |
| $p_{SD}$ | Probability of failure of the seal drum |
| $p_{SV}$ | Probability of failure of the safety valve |
| $Q$ | Purge flow (ft$^3$/sec) |
| $S$ | Cost of a spurious trip (£) |

| | |
|---|---|
| $t$ | Time (year) |
| $T$ | Proof test interval (year) |
| $T_r$ | Repair time (year) |
| $V$ | Total annual cost of trips and hazards (£ year$^{-1}$) |
| $V_{R.S}$ | Total annual cost of the relief system (£ year$^{-1}$) |
| $\beta$ | Percentage of total failures due to common cause failures. |
| $\lambda$ | Failure rate (year$^{-1}$) |
| $\gamma$ | Operational failure rate of the trip system (year$^{-1}$) |
| $\delta$ | Demand rate (year$^{-1}$) |

* two pressure switches and level switch

** two level switches and pressure switch

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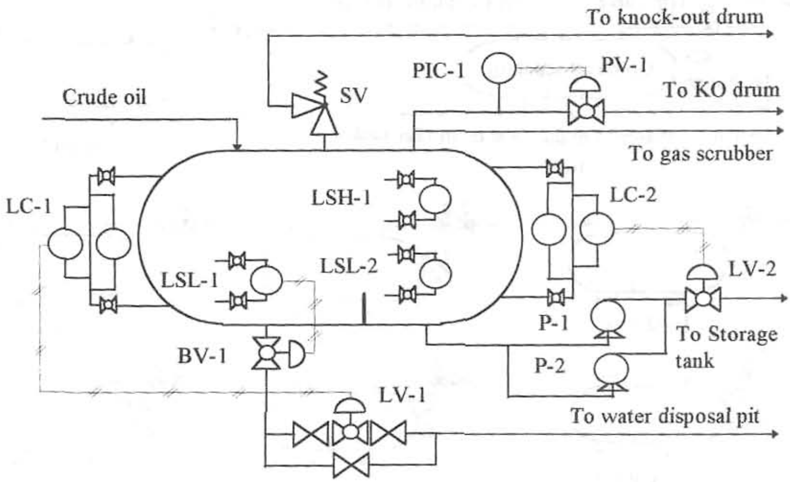


Figure 1. Crude oil separator

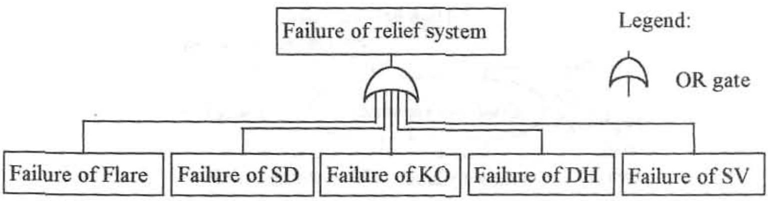


Figure 2. Relief system fault tree

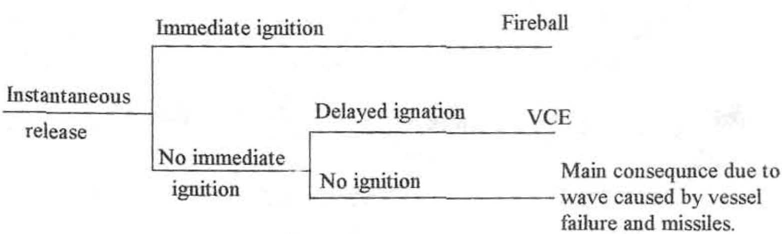


Figure 3. Event tree

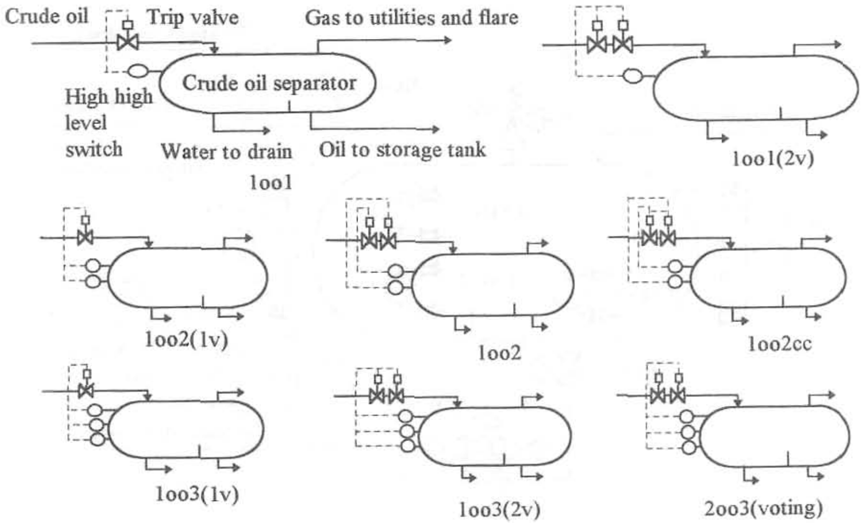


Figure 4. Piping and instrument diagram (redundancy)

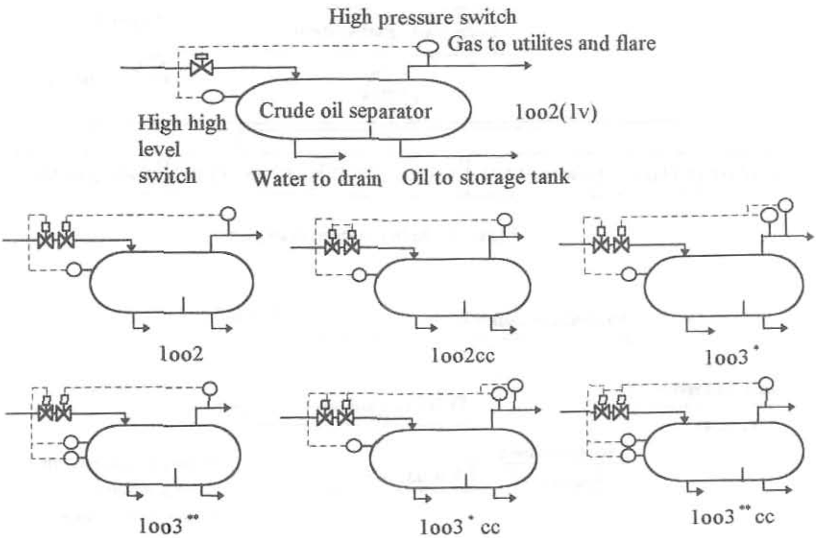


Figure 5. Piping and instrument diagram (diversity)