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Conceptual design of pressure relief systems

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Abstract

Conceptual design of pressure relief systems is an important stage in the design of a safe process plant. The conceptual design stage consists of the following steps: deciding on the location of pressure relief devices, selecting the general type of pressure relief device for each identified location, i.e. safety valve and/or bursting disc (rupture disc), or other relief device, and selecting the special features for the chosen device type. Some regulations, codes and standards, and a decision tree for the selection of a relief device have been described in the literature. This paper presents four decision trees that have been developed for the different steps in the conceptual design stage. Only positive pressure in pressure vessels is considered here.

Keywords: Pressure relief system; Safety valve; Bursting disc; Rupture disc

1. Introduction

An important responsibility of a chemical plant designer is to ensure that a plant under design can be operated safely. One of the hazardous situations that can arise during operation is the subjection of a system to a pressure higher than that for which it was designed. This can be caused by maloperation, instrument failure, external fire, thermal expansion or some other reasons. If the system is not protected, the excess pressure may lead to a catastrophic failure causing mechanical damage, loss of valuable material, emission of toxic chemicals and possibly loss of life. Therefore, pressure relief systems are needed to protect personnel and equipment from the undesirable consequences of excess pressure.

The design of a pressure relief system consists of two stages: conceptual design and relief system sizing. The Design Institute for Emergency Relief Systems has carried out systematic and comprehensive studies of relief system sizing, particularly for reactors and two-phase relief (Fisher, Forrest, Grossel et al., 1992; DIERS 1995, 1998). However, for conceptual design, there have only been some guidelines, and recommended practices (Parry, 1994; CCPS, 1993, 1998; Duxbury, Rushton & Crooks, 1998; Crowl & Louvar, 1990; Jenett, 1963; Isaacs, 1971), together with regulations, codes and standards (API RP 520, 1990; API RP 521, 1990; API STD 2000, 1992). Due to differences in detail and coverage, the application of the different guidelines may provide different results for an identical situation. A prudent approach would be to review all applicable guidelines, codes, standards, etc., prior to choosing a design basis.

It will be very helpful if appropriate decision trees can be built according to existing guidelines, codes, standards, etc. Parry (1994) proposed a decision tree for deciding whether to use safety valves or bursting discs. The decision tree is also presented in CCPS (1998) with slight modifications. In our work, we have identified that the decision tree requires further revision and additional decision trees are needed for the other steps in the conceptual design stage.

This paper presents four decision trees for different purposes in the conceptual design stage. For the sake of simplicity we focus our attention on pressurised systems without explosion risk, i.e. without gas/vapour/dust/condensed-phase explosion risk. Also we consider only the relief of positive pressure, i.e. not vacuum, in pressure vessels.

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2. Conceptual design

In the conceptual design of pressure relief systems, the first step is to decide which plant locations require pressure relief devices. The type of pressure relief device for each identified location should be specified in the second step. Although special devices may be required for exceptional circumstances, the most common method of protection against excess pressure is through the use of safety valves and/or bursting discs (rupture discs) which discharge to the atmosphere, a containment vessel, or via a disposal system such as a flare or scrubber. The types of pressure relief device considered in this paper are limited to safety valves, bursting discs or combinations of both. After the selection of the general type of relief device, the specific type of safety valve and/or bursting disc should be chosen in the third step.

3. Location of pressure relief devices

The step of specifying the location of relief devices requires the review of every plant item in the process. Since some plant items have two or more separate streams,[1] we designate the part of a plant item that has a separate stream flow as a chamber. Thus, the engineer must decide whether a pressure relief device is required for every chamber.

The decision tree for deciding whether pressure relief devices are needed for a plant item is shown in Fig. 1. Six questions are involved for every chamber. The following discusses the rationale behind these questions.

(1) What are the sources of excess pressure to the chamber?

The designer of excess pressure protection systems must consider all scenarios that could constitute a hazard and evaluate them in terms of the pressure generated and/or the rates at which the fluids must be relieved. The identification of scenarios leading to excess pressure is discussed in Parry (1994), CCPS (1993), API RP 520 (1990), API RP 521 (1990), API STD 2000 (1992) and Duxbury et al. (1998). The former five are of the same approach, which essentially seeks to identify every possible cause (maloperation, malfunction, failure, etc.) then consider the consequences. This approach is not structured or efficient because time may be spent on finding many causes that lead to the same relief demand. Another approach, originally suggested in ICI in the 1970s by J. E. Hodson et al., and further developed there, is to first identify the sources (as distinct from causes) of excess pressure, e.g. sources of heat, pressure, etc. Methods using this basic idea can be formulated in various ways; one detailed procedure has been developed by Duxbury et al. (1998). Using this method there is usually no need to try to identify multiple causes. It is usually sufficient to identify the potential sources of excess pressure and recognise (or assume) that they could be applied to the vessel in question, and then make a safe worst-case calculation of the consequent flowrate for each source and provide relief accordingly. However, if relief is not provided, or will not be adequate for the above worst case, then it will indeed be necessary to identify all the causes. Also care is needed if a source can be applied to one vessel via more than one port, though this situation is rare. Because there are always fewer sources than causes, this approach is more structured and efficient. It also lends itself particularly well to classifying the various relief demands identified. Therefore, the approach of identifying sources, instead of causes, is used as a basis in this work.

The process designer should first identify all the sources of excess pressure. The sources identified should be documented to form part of the plant design safety assessment record. It is of the utmost importance that such a record be reviewed before making any plant or process modifications.

(2) Is the chamber connected to other items without any possible closures or blockages?

If items are connected together without any possible closures or blockages then it may be possible for these items to be treated as a single item of equipment and provide only one pressure relief device. However, this is not generally considered good practice. It must be noted that a blockage may be caused by valve failure, valve maloperation, solid, liquid (perhaps frozen) trapped in a U-bend or other events. Also care must be taken to ensure that any future modifications do not invalidate the relief. Examples of accidents due to connecting pipes being blocked are given in Kletz (1998a, 1998b, pp. 119–121). Great care must be taken before answering yes to the question.

If the answer is no, the chamber needs a pressure relief device unless there is a reason for not installing one — see (4) below. If the answer is yes, the decision depends on the answers to the questions that follow.

(3) Are the inter-connections of large enough diameters to permit adequate relief flow via another of the connected chambers?

The inter-connections are in effect part of the relief from one chamber to another. Calculation is required to answer this question.

(4) Are there any reasons for not installing pressure relief devices?

For example, a reason may be the presence of an adequately reliable instrumented protective system that can prevent excess pressure in the stream. The normal control system, or a simple trip, will not be adequate.

[1] A separate stream is defined as a stream that does not mix with another stream within the same plant item. For example, a shell and tube heat exchanger consists of two separate streams, one in the tube side and the other in the shell side.

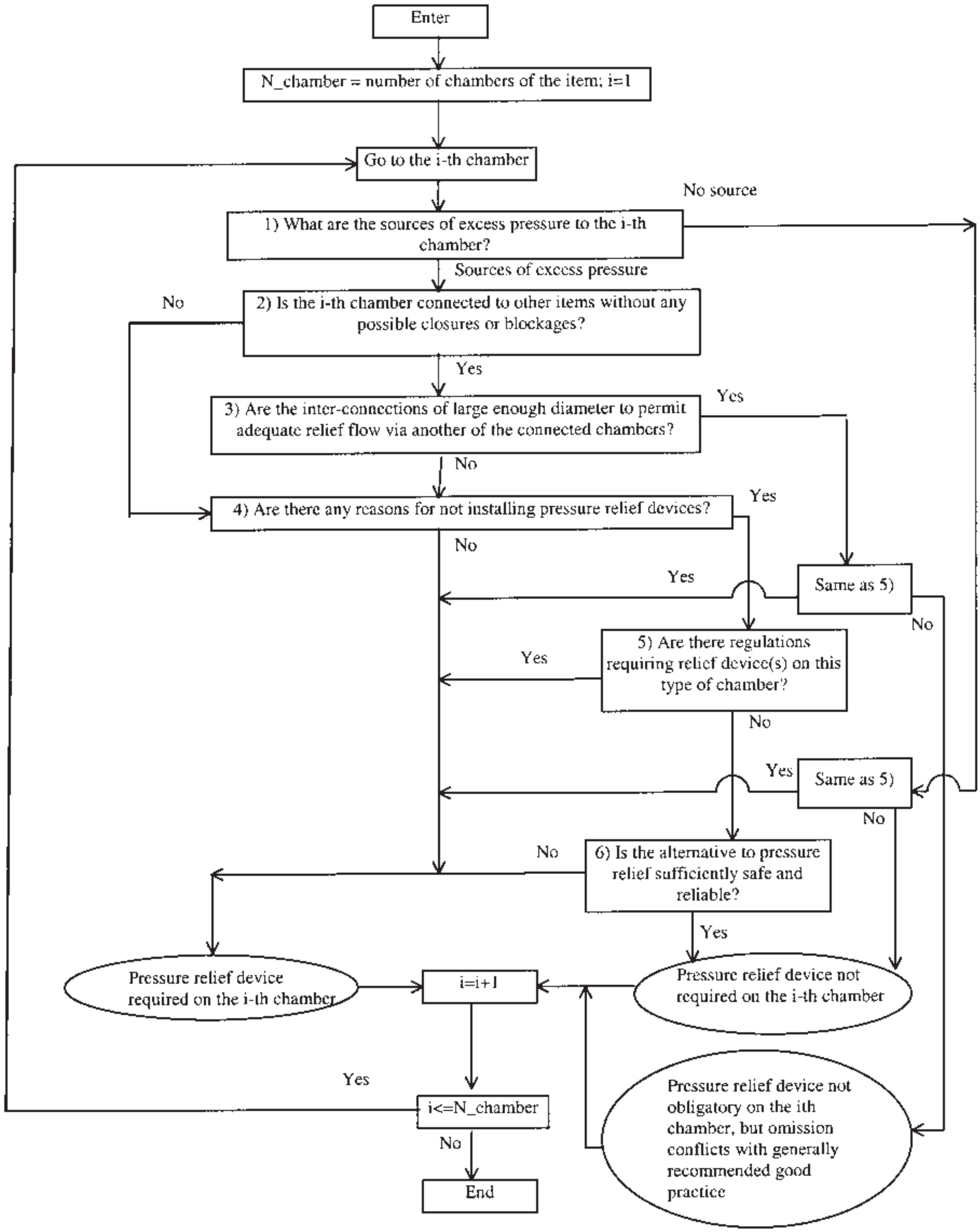

Fig. 1. Decision tree for location of the pressure relief device.

Great care must be taken before answering yes to this question.

(5) Are there regulations requiring relief devices on this type of chamber?

There are legal regulations for one or more relief devices on some types of vessel, e.g. boilers, air receivers, and steam receivers. If the answer to this question is yes, then one or more pressure relief device(s) are required.

(6) Is the alternative to pressure relief sufficiently safe and reliable?

Only when it is absolutely sure should the answer yes be given. (To answer this question it may be necessary to identify all *causes* whereby this source might be applied to this chamber.)

4. Selection of type of pressure relief devices

Once the need for pressure relief is established for a given location, the process engineer is required to select a suitable type of device, i.e. safety valve, bursting disc, or other relief device. Only safety valve, bursting disc, and combinations of both are considered here.

The decision tree for selecting between safety valves and bursting discs is shown in Fig. 2. It is similar to the one given by Parry (1994) and CCPS (1998), but with some modifications. Eighteen questions are involved. Questions 1–4, 7, 10, 12 and 13 are not considered in Parry (1994) and CCPS (1998). The rationales for all the questions are given below. It should be noted that if both safety valve and bursting disc are used in parallel then slightly different pressures should be set for them, to prevent chattering and causing excessive vibration, or unnecessary operation of the larger device.

(1) Is the pressure rise too rapid for a safety valve?

If the expected pressure rises so rapidly that the inertia of a safety valve would not provide a satisfactory response then one or two bursting discs in parallel or in series should be used instead. In other words, the safety valve option should not be used. This is an important

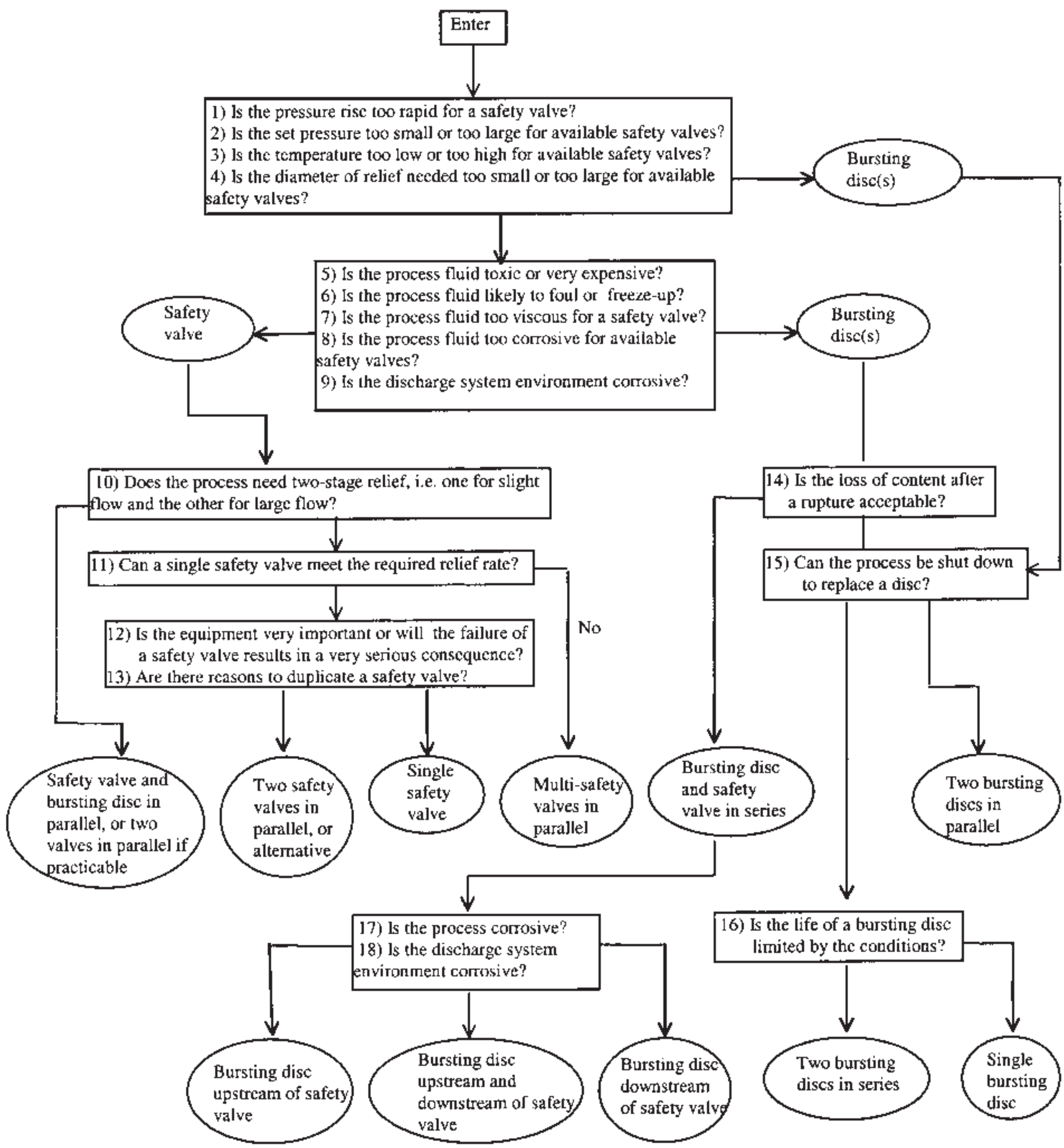

Fig. 2. Decision tree for selection of relief devices.

modification to the work of Parry (1994) and CCPS (1998). The application of their decision trees may incorrectly lead to the selection of a bursting disc and a safety valve in series.

(2) Is the set pressure too small or too large for available safety valves?

(3) Is the temperature too low or too high for available safety valves?

(4) Is the diameter of relief needed too small or too large for available safety valves?

If the answer to any of these four questions is yes then a safety valve is not suitable because it is difficult to manufacture.

(5) Is the process fluid toxic or very expensive?

If the answer is yes, any leakage through a safety valve is not acceptable. Therefore, the use of a bursting disc should be indicated.

(6) Is the fluid likely to foul or freeze-up?

(7) Is the process fluid too viscous for a safety valve?

If the answer to question (6) or (7) is yes, the fluid would impair the operation of the safety valve. The use of a bursting disc should be indicated. It should be noted that some materials have unusual properties. For example, the viscosity of sulphur increases with a rise in temperature above 200°C.

(8) Is the process fluid too corrosive for available safety valves?

(9) Is the discharge system environment corrosive?

If the answer to question (8) or (9) is yes, the life of the safety valve would be limited. The use of a bursting disc should be indicated.

If the answers to questions (5)–(9) are all no, the use of a safety valve should be indicated.

(10) Does the process need two-stage relief, i.e. one for slight flows, and the other for large flows?

If the answer is yes, use a safety valve and a bursting disc in parallel.

(11) Can a single safety valve meet the required relief rate?

If the answer is no, use multi-safety valves in parallel, or two valves in parallel. (The set/bursting pressures would be different, so that the larger device does not operate unnecessarily.)

(12) Is the equipment very important or will the failure of a safety valve result in a very serious consequence?

If the answer is yes, consider two safety valves in parallel, or other alternatives as appropriate. Take into account the possibility of common-cause failures, e.g. blocking by the process fluid causing deposits could affect two valves as much as one.

(13) Are there reasons to duplicate a safety valve?

This may be called for by law or standards, e.g. British Standards require two safety valves on large boilers. If the answer is yes, use two safety valves in parallel. For example, if a component in a large continuous plant is operated without any scheduled shutdowns, duplication of a safety valve is essential for inspection and testing. There are rules about how the two valves should be connected. It should not be possible to isolate the vessel from relief at any time. Any isolation valves below the safety valves should be interlocked so that only one can be closed at a time. Do not rely on procedures.

(14) Is the loss of content after a rupture acceptable?

Once the bursting disc option is indicated, this question should be answered with respect to economic and environmental considerations. If the answer is yes, a safety valve is not needed and only bursting disc(s) should be used. If the answer is no, use a bursting disc and a safety valve in series. It should be noted that with a bursting disc in front of a safety valve, if there is a pinhole on the disc, the pressure in the interspace builds up and the disc will not rupture until the pressure is up to twice the normal bursting pressure. It is therefore essential to provide a weep hole in the space between the disc and the safety valve (see BS5500, section 2.10). Similar precautions are required when the valve is before the disc.

(15) Can the process be shut down to replace a disc?

If only the bursting disc option is used then question (15) needs to be answered. If the answer is no, use two bursting discs in parallel, with interlocked valves, so that only one can be closed at a time. If the answer is yes, turn to question (16).

(16) Is the life of a bursting disc limited by the conditions?

If the answer is yes, use two bursting discs in series. This avoids a discharge in the event that the disc in contact with the process fails prematurely. If the answer is no, use a single bursting disc.

(17) Is the process corrosive?

(18) Is the discharge system environment corrosive?

Questions (17) and (18) need to be answered to decide the arrangement of the safety valve and the bursting disc in series. If the process conditions are corrosive and the discharge system is either open or non-corrosive then a bursting disc upstream of a safety valve is preferred. If these conditions are reversed then use a bursting disc downstream of the safety valve. If conditions are unfavourable on both sides, use bursting discs upstream and downstream of the safety valve. In all cases, the space between a safety valve and a bursting disc must be monitored and vented.

Finally, it must be pointed out that if an equipment item has two or more chambers, the process engineer needs to consider the consequences of mixing the separate streams, in case of leakage from one chamber to another. Mixing of separate streams may change the properties of the process fluid and great care must be taken.

5. Selection of special features for safety valves

In stage 2, if a safety valve is suggested as the type of relief device then the special features of the safety valve need to be decided in stage 3. Based on Parry (1994), CCPS (1993, 1998) and Zappe (1991), the decision tree developed for the selection of typical safety valves is shown in Fig. 3. Eight questions are involved. The rationale for these questions is given below.

(1) Is the set pressure very high?

(2) Is the diameter needed very large?

If the answer to question (1) or (2) is yes and the fluid is clean then use a pilot-operated safety valve because the resulting overall force on the safety valve is very large. This is difficult for a direct-loaded valve.

(3) Is the margin between operating and set pressure tight?

If the answer is yes and the fluid is clean then use a pilot-operated safety valve.

(4) Is the process fluid toxic or flammable, or does it affect the environment?

If the answer is no, the fluid can usually be released to the atmosphere directly. Thus, a direct-loaded safety valve of the open type can be adopted.

(5) Does the backpressure vary greatly?

Usually, the major decision of a process designer is whether to employ a conventional or a balanced safety valve. The pressure conditions at the outlet of the safety valve govern this choice. Superimposed backpressure will affect the valve opening pressure, and a balanced safety valve should be considered. Built-up backpressure may affect valve lift and flow. Usually a balanced bellows safety valve is recommended when built-up backpressure (gauge) is expected to exceed 10% of set pressure (gauge).

(6) Is the safety valve upstream of a bursting disc?

If the answer is yes, use a balanced safety valve because any leakage from the safety valve may result in

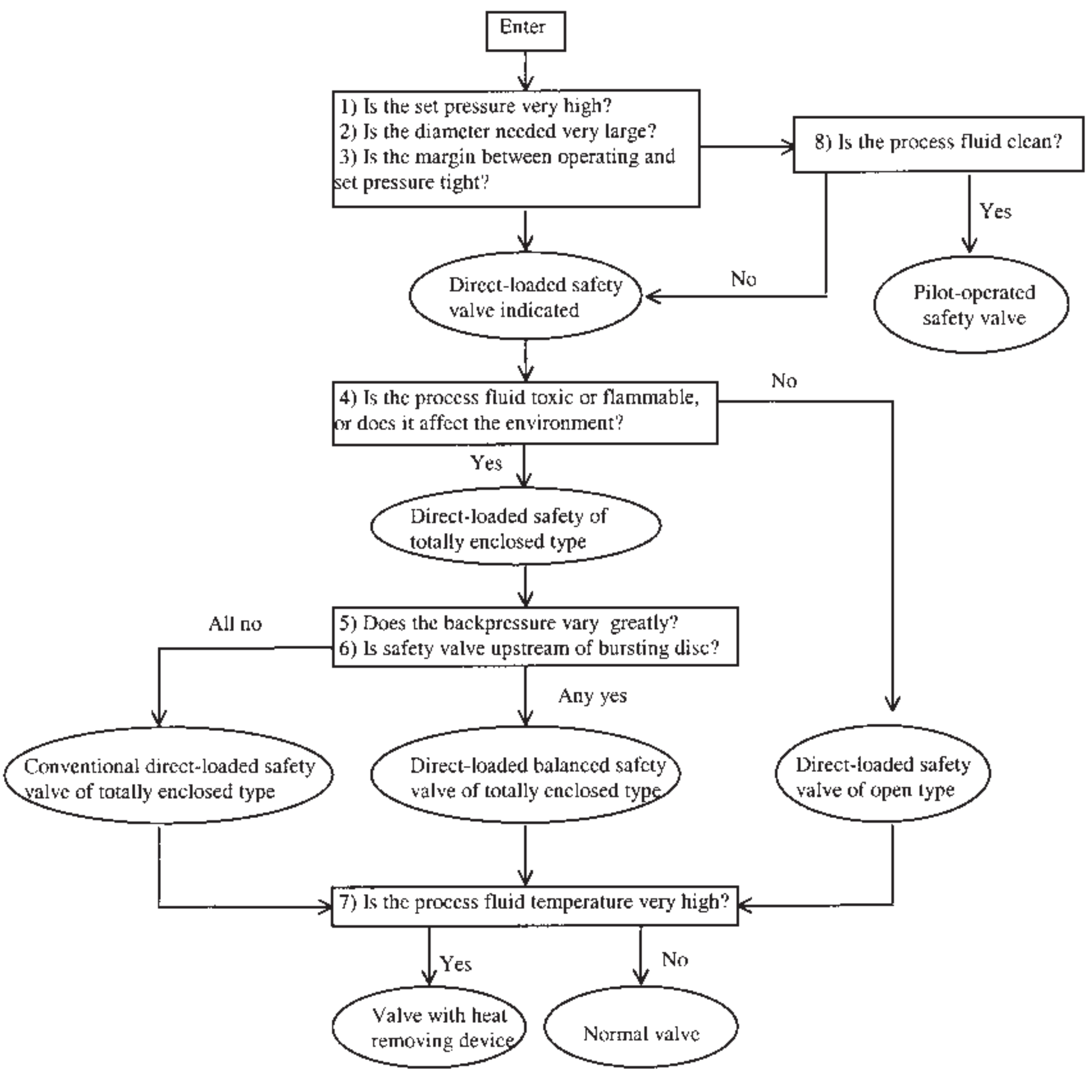

Fig. 3. Decision tree for selection of typical safety valves.

a change of backpressure. The interspace should however in any case be monitored and vented.

(7) Is the process fluid temperature very high?

If the answer is yes, a heat-removing device is needed in the valve to protect the valve.

Having made a preliminary selection, consult safety valve manufacturer for full details relevant to the application.

(8) *Is the process fluid clean?*

A pilot operated safety valve can be relied on to operate satisfactorily only if the process fluid is clean, such as water.

6. Selection of special features for bursting discs

In stage 2, if a bursting disc is chosen as the type of relief device, then the special features of the bursting disc need to be decided. Based on Parry (1994), CCPS (1993, 1998) and Ma and Ding (1994) a decision tree that has been developed for the selection of special features of bursting discs is shown in Fig. 4. Seven questions are involved. The rationale for these questions is given below.

(1) Is excess pressure caused by liquid expansion?

If the answer is yes, a reverse domed disc should not be used because liquid expansion may cause “roll-over” of the disc without bursting it, and it will then have a much higher bursting pressure.

(2) Is the disc upstream of a safety valve?

(3) Is spark forbidden?

If the answer to question (2) or (3) is yes, a conventional domed disc should not be used because it causes fragments on bursting.

(4) Is the disc subject to pulsating pressure?

If the answer is yes, a conventional domed type disc should not be used since it might burst due to fatigue.

(5) Does the available margin between working pressure and design pressure demand a tight tolerance of bursting pressure?

If the answer is yes, use a reversed domed disc since a conventional domed disc is appropriate only when there is a large margin (30% or more) between working pressure and design pressure.

(6) Is a long working life (more than 2 years) essential?

If the answer is yes, use a reversed domed disc.

(7) Is the disc subject to reverse pressure?

If the answer is yes, a reverse pressure support is needed for the conventional dome type disc because the reverse pressure may easily result in the disc reversing — it may then fail, or subsequently fail to operate at the correct pressure.

Modern bursting discs have many special features, so always consult the manufacturer and provide a detailed specification sheet.

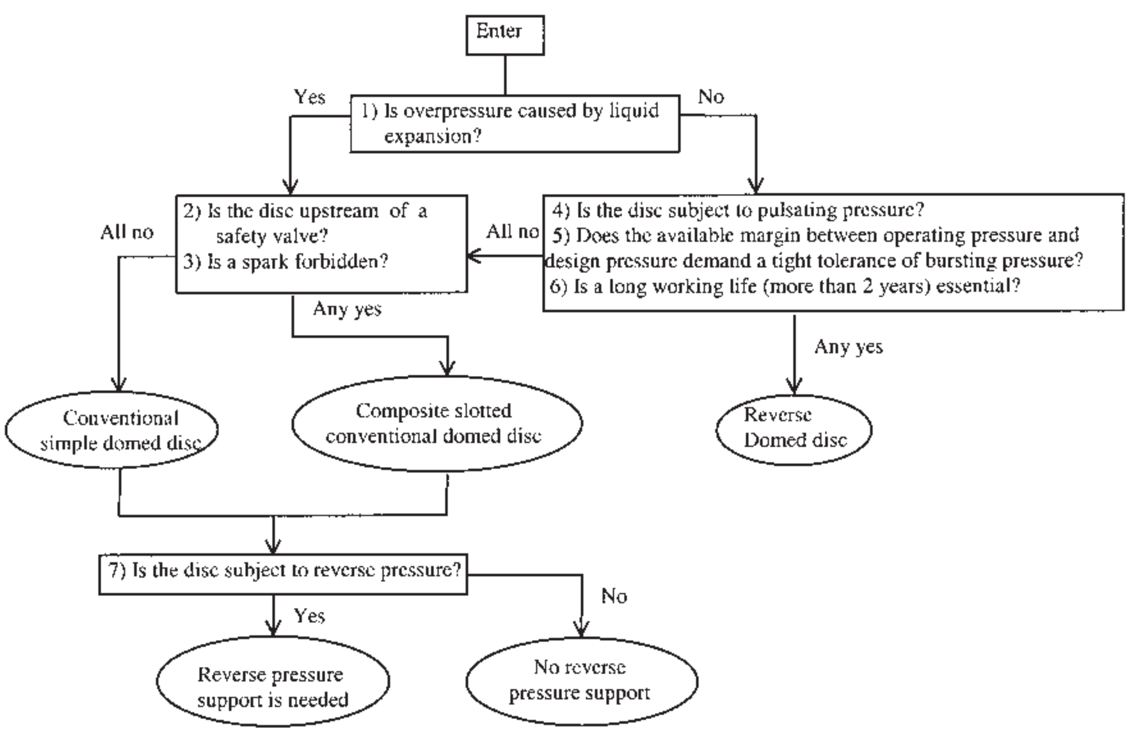

Fig. 4. Decision tree for selection of typical bursting discs.

7. Conclusions

Regulations, codes and standards need to be considered in all stages of the conceptual design of pressure relief systems. This can make the design task very complicated and time consuming. In order to carry out the conceptual design efficiently, four decision trees have been developed in this paper for the different steps in the conceptual design. The first tree is used for selecting the location of pressure relief devices. Once a plant item has been identified as requiring pressure relief, the second tree is used to guide the selection of a general type of pressure relief device, i.e. safety valve and/or bursting disc. The third and fourth decision trees are used for selecting the special features of safety valves and bursting discs, respectively. It should be noted that only the relief of positive pressure (i.e. not vacuum), in pressure vessels, is considered in this work. Also for the sake of simplicity we focus our attention on pressurised systems without gas/vapour/dust/condensed-phase explosion risk. The result of our studies is a step towards formalising some of the knowledge in conceptual design of pressure relief systems. Thorough testing and evaluation will be required to turn the decision trees into practical design tools.

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