Fire Versus Non-Fire Contingencies: A Study of Pressure-Relief Device Sizing Risks

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There are tens of thousands of industrial manufacturing facilities operating throughout the world. Each chemical plant, petroleum refinery, pharmaceutical plant and other manufacturing facility has equipment and piping systems that operate under pressure. In the event of excessive overpressure, equipment or piping failures could result in economic loss to business, environmental contamination, and health and safety risks. To reduce such risks, equipment and piping systems that operate under pressure must be protected from excessive overpressure. This is accomplished with the installation of pressure-relief devices, which must be properly sized and specified for the intended service conditions. More specifically, overpressure protection is provided by pressure-relief devices that are sized, selected, specified and installed for the postulated governing overpressure contingency. To adequately size a pressure-relief device to provide overpressure protection for equipment and piping, several relief event scenarios always should be considered. In the U.S.A., federal and state regulations require operating industrial facilities to have risk management programs in place that include the design basis for safety-relief systems installed to protect pressurized equipment from overpressure. For new installations, the pressure-relief system design philosophy should be established during the project design phase. However, for process facilities that have been in operation for many years, the original design basis and calculations for the safety-relief devices often are no longer available. For existing pressure-relieving installations, fitness-for-service assessments should include verification of the relief device size and specification, and review and substantiation of required documentation. This paper presents results from a study intended to examine which overpressure relief contingency, if any, most often governs the size of relief devices that are used to protect equipment and piping systems. The required elements of a pressure-relieving system sizing and documentation program are described. The author emphasizes seven relief contingencies to be considered when sizing pressure-relief devices. Some restrictions and limitations of the codes and standards that are applied for design guidance of pressure-relieving systems are challenged. For this study, relief device sizing data was compiled from a number of chemical and petrochemical project applications to provide a reasonable sample of contingencies that governed the sizes of existing and new safety-relief valves and rupture disks. The study results show that a significant number of pressure-relief devices presently installed in the U.S.A. likely are undersized. This further suggests that, worldwide, an alarming number of pressure-relief devices may be undersized. [DOI: 10.1115/1.2141638]

Introduction

Worldwide, there are enormous numbers of equipment and piping systems that operate under pressure within industrial manufacturing facilities. The 2000 Census reports that, within the U.S.A. alone, there are 2200 petroleum plants, 13,425 chemical plants, and 16,292 plants related to the plastics and rubber industry [5]. Within these facilities, fluids under pressure are contained in vessels and equipment, and transferred through piping to other equipment. Particularly in chemical plants, these pressure containing systems handle a wide range of fluids. For example, fluids handled in a chemical plant may be nonhazardous, nonflammable, noncorrosive, hazardous, flammable, corrosive, toxic or lethal, or combinations of these.

Statutes and regulations, as well as sound engineering practice, dictate that pressure containing equipment and piping systems must be protected from excessive overpressure. Such overpressure protection is accomplished with the installation of relief devices, mainly relief valves and/or rupture disks, that are sized, specified and installed for a governing overpressure contingency [1–4].

It is common for chemical production facilities, as well as petroleum refineries, to have a few hundred pressure-relief devices installed. Even small manufacturing facilities can have 50 or more relief devices. Given this, several million relief devices are installed in chemical, petroleum and related industrial facilities within the U.S.A., and millions more are installed in production plants throughout the world, to protect equipment and piping systems from excessive overpressure [2,3].

In the early 1900s, after experiencing considerable loss due to petroleum product storage tank fires, oil companies embarked on studies to develop engineering methods for sizing and specifying pressure-relief devices for fire exposure conditions to protect vessels in oil refineries [6]. Through adoption of requirements by the ASME Pressure Vessel Code and procedures published in API Standards, the chemical industry benefited for a long time from the early work on vessel overpressure protection that was initiated

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by the oil industry. Concerns by the chemical industry for vessel overpressure from process runaway reactions surfaced in the 1970s with related research work by the Design Institute for Emergency Relief Systems, known as DIERS [3,7,8].

In the United States, the Federal Clean Air Act mandated the requirements for calculations and documentation to verify that the size of an existing relief device is adequate for the governing contingency [9]. Many states have passed laws that enforce these public safety concerns. These laws mandate risk management programs for hazardous substances that require design standards reviews, hazard assessments, the process technical design basis, and the equipment design basis for the operating system. This includes documentation and assessment of the relief system design.

Safety-relief devices are specifically sized, specified and installed for some governing overpressure contingency. These relief contingencies are the scenarios of the pressure and temperature conditions that can develop in equipment and piping systems, necessitating consideration for overpressure protection. Widely applied standards for pressure-relieving devices and systems in the chemical process industry include the ASME BPV Code Section VIII [10,11], API RP 520 [12,13], API RP 521 [14], API Std. 2000 [15] and NFPA 30 [16].

Conventional wisdom suggests that sizing for a given safety-relief device most likely will be governed by the fire exposure event. This risky assumption has evolved because of several factors, including [1,3]:

- the empirical orifice sizing equations are based on fire test results;
- unsubstantiated engineering viewpoints have been passed down through generations;
- many relief device product vendors are not system engineers and typically use 'canned' programs, which often are applied arbitrarily with fire exposure as the primary basis; and
- entry-level engineers are not mentored adequately as companies have downsized.

While fire exposure obviously is significant and must be considered along with all of the other contingencies for any given application, review of the literature neither proves nor disproves the assertion that fire exposure usually governs the pressure-relief device sizing. Thus, one can reasonably contend that other relief contingencies at least equally frequently may govern the relief device size [1,3].

The primary purpose of this study is to determine which overpressure relief contingency, if any, most often governs in the sizing of pressure-relief devices. The engineering relevance of this concern has international interests and implications, and the concerns apply to existing as well as new pressure-relief device installations.

Overpressure Relief Requirements

ASME BPV Code Section VIII. Bernstein and Friend provide a review and discussion of the ASME Code safety valve rules [17]. However, Bernstein and Friend understate the lack of Code coverage for determining the required relief loads. Aside from defining the overpressure limits above the vessel maximum allowable working pressure (MAWP), few guidelines for overpressure relief load determination are given in the ASME BPV Code Section VIII [10,11].

For pressure vessels, the requirements for overpressure protection are given in paragraphs UG-125 through UG-137 of the ASME BPV Code Section VIII [10,11]. These requirements include limitations on the acceptable types of pressure-relief devices, overpressure limits versus the vessel design rating, acceptable installation of the relief devices, pressure settings and set pressure tolerances, and qualification and marking for ASME certified pressure-relief devices.

The ASME BPV Code requires that all pressure vessels must be provided with pressure-relief devices for overpressure protection. Likewise, the ASME piping codes also require that overpressure protection be considered [18,19]. It is the responsibility of the owner to ensure that the required pressure-relief devices are installed. The ASME Code establishes some vessel conditions that require overpressure protection, and it provides some equations to size relief devices for the conditions. However, the ASME Code neglects to provide any guidance to determine the relief load for specific overpressure scenarios, nor does the ASME Code reasonably identify the various overpressure contingencies that could occur [2].

The ASME Code design factors of safety generally are in the range 3 to 5. The 10% overpressure above the MAWP is an arbitrary and conservative overpressure relief margin. Relief devices are sized and installed to protect equipment from infrequent emergency overpressure situations. As such, higher overpressure margins above the vessel MAWP can be justified. Until recently, the ASME Code hydrotest pressure had been 1.5 times the vessel design pressure. This suggests that, for some relief scenarios, it could be reasonable to allow a 50% overpressure above the vessel MAWP up to the pressure that produces the minimum specified yield stress in the vessel [2].

API RP 520. API RP 520 [12,13] applies to the sizing, selection and installation of pressure-relief devices for equipment that has a MAWP of 15 psig or greater. This standard covers pressure-relief devices for unfired pressure vessels and related equipment against overpressure from operating and fire contingencies.

API RP 520 provides basic definitions related to pressure-relief systems, descriptions of various types of pressure-relief devices, descriptions of the various operational and emergency relief contingencies that should be considered, and applicable sizing equations. This standard provides equations to approximate the relief loads for some contingencies, and describes various conditions for which relief loads can be approximated by fundamental engineering principles. Some commonly applied API relief device sizing equations are given in Table 1; refer to the nomenclature for clarifications.

When the environmental factor is unity, i.e., $F=1$, the required relief orifice area can be 3.3 times greater than that for the factor $F=0.3$, which is most often used. This is an important consideration in sizing relief devices for the fire exposure contingency.

API RP 521. The API RP 521 [14] supplements the design basis of API RP 520, emphasizing the pragmatic aspects to be considered by designers and plant operating personnel, for the design, installation and operation of pressure-relieving and depressuring systems.

API RP 521 emphasizes the potentials for overpressure, and cites operator error as a potential source of overpressure. Transient events, including the possibility of process runaway reactions, are identified as overpressure concerns. Contrary to the ASME Codes, API RP 521 suggests that instrument controls are needed to warn of conditions beyond the equipment design limits so that appropriate corrective action can be taken. API RP 521 further suggests that, if a pressure-relief device is impractical, high-integrity protective systems can be used to prevent overpressure and/or overtemperature.

API Std. 2000. API Std. 2000 [15] covers the venting requirements for aboveground atmospheric and low-pressure storage tanks.

While not intended for pressure vessels that are designed for pressures greater than 15 psig, some pertinent information is given that is applicable to pressure vessels, namely fire resistant insulation criteria and a basis for emergency relief venting for fire exposure.

NFPA 30. NFPA 30 [16] covers normal and emergency venting

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Table 1 Commonly applied API relief valve sizing equations

Condition	Equation [12,15]	
Heat absorbed by vessel exposed to fire	$Q = 21{,}000\mathrm{FA}^{0.82}$	(1)
	$Q = 34{,}500\mathrm{FA}^{0.82}$	(2)
	$Q = 20{,}000\mathrm{A}$	(3)
Critical flow (gas or vapor)	$A_0 = \dfrac{W}{CK_dP_1K_b}\left(\dfrac{TZ}{M}\right)^{1/2}$	(4)
Sub-critical flow (gas or vapor)	$A_0 = \dfrac{W}{735F_2K_d}\left(\dfrac{TZ}{MP_1(P_1 - P_2)}\right)^{1/2}$	(5)
Hydraulic expansion (liquid)	$q = \dfrac{BH}{500\mathrm{Gc_p}}$	(6)
Liquid flow	$A_0 = \dfrac{q}{38K_dK_wK_v}\left(\dfrac{G}{P_1 - P_2}\right)^{1/2}$	(7)

for aboveground tanks. The normal venting is for tank “breathing” during normal operation, and the emergency relief venting is for fire exposure. While the emphasis of NFPA 30 is for atmospheric and low-pressure tanks, parts of this code also apply to pressure vessels.

The NFPA 30 Code permits a low-pressure API Std. 650 vertical tank to be constructed with a floating roof, or a weak roof-to-shell seam, to provide emergency overpressure relief venting [20].

The experimental work for NFPA 30 on the basis of emergency venting tables was developed by API. Hence, the NFPA 30 equations and curves for emergency venting requirements during fire exposure are duplicated in API Std. 2000 [15].

Relief Contingencies

The relief contingencies are the scenarios of conditions that necessitate overpressure relief protection. For each relief device, the following contingency categories should be considered [2,3]:

1. External fire
2. Exchanger tube failure
3. Control valve or actuated valve failure
4. Cooling failure
5. Blocked outlet
6. Hydraulic expansion
7. Process upset

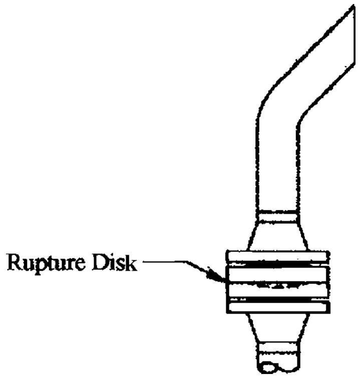

Fig. 2 Rupture disk

Relief loads are approximated by calculation, or otherwise determined. For example, fire heat loads and relief rates are computed based on known vessel geometry and relieving fluid characteristics; but the relief rate for a blocked outlet may be determined by the maximum discharge rate of an upstream pump or compressor.

The relief loads for each relief device requirement are unique; and, therefore, it is essential to be unbiased when calculating and determining the governing relief contingency.

Scope of Study

The scope of this study is limited to pressure-relief devices specified to protect equipment and piping which operate at pressures of 15 psig or greater. The pressure-relief devices considered are reclosing safety-relief valves of the direct spring-loaded type, and non-reclosing rupture disks. The relief valves and rupture disks are installed individually, or in combination (see Figs. 1–3). These pressure-relief devices commonly are used for the chemical process and petroleum refinery industries [1,3,4].

Compared to other industries, the chemical process industry presents special challenges in the wide variety of fluids that are handled, including the fluid characteristics, process kinetics and physical installations that influence the relief rates.

The data utilized in this study was compiled from the author’s records of related work for various applications on a number of projects, spanning the past 10 years. This provided results of sizing calculations and determination of the governing overpressure relief contingency to be investigated for a significant representative sample of relief devices in various process service applications [1,3,4].

The relief devices considered in this study were from installations at seven different chemical process plants. The information from these facilities, coupled with the author’s experience, suggests that an expected number of relief devices installed with

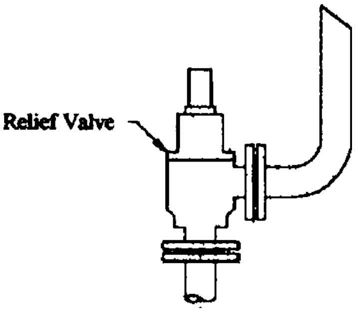

Fig. 1 Safety-relief valve

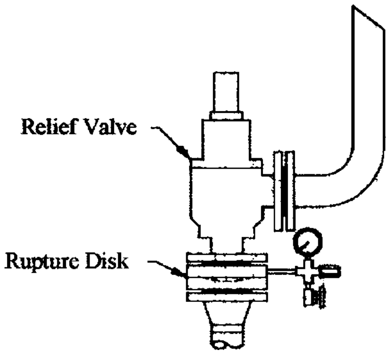

Fig. 3 Combination rupture disk and safety-relief valve

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respect to the size of the chemical facility could be within the following ranges [1,3,4]:

Size of Chemical Plant Facility	Number of Relief Devices
Small	50-100
Medium	100-250
Large	250-500

This study evaluated the size requirements for a total of 120 relief valves and rupture disks, including 67 relief valves and 53 rupture disks.

The sample size of the 120 relief device items considered for this study represents about 12% of the total expected number of relief devices in the chemical facilities that were the source of the relief device data [1,3,4].

Method and Procedure

For each relief device application assessed, the following data were identified [1,3]:

- new or existing installation
- type of relief device installation
- vessel or equipment dimensions and geometry
- specified set pressure, backpressure and overpressure
- operating pressure and temperature
- fluid state being relieved
- credible relief scenarios that were considered
- governing relief contingency
- device size
- materials of construction of the relief device
- orifice area provided
- orifice area required
- whether an existing relief device is adequate or undersized
- available relief capacity for the governing relief contingency
- relief thrust load influence

The seven primary relief contingencies, listed above under "Relief Contingencies", were considered for each relief device.

The required relief device size is determined by defining all of the credible relief contingencies, computing the relief load (rate of release) for each contingency, and then computing the required relief device size based on the governing relief load contingency.

For the credible relief contingencies, the relief loads were calculated or otherwise determined. The required relief orifice areas then were sized to accommodate the relief rates. The calculations for the relief contingencies were based on the API equations, and application of fundamental engineering principles for fluid flow and heat transfer. Several of the applied equations are given in Table 1.

The compiled data has been grouped into four specific interest areas, namely: Total Devices, Relief Valves (RV), Rupture Disks (RD), and Combination Relief Valves and Rupture Disks (RV/RD). The types and quantities of pressure-relief devices included in the study are presented in Table 2. Note that of the total number of devices evaluated, 35% were for new relief device installations and 65% were for existing relief device installations.

Since there are seven contingencies considered for each relief device, potentially 840 relief calculations could be required for this study. However, some calculations apply to both the relief valve and the rupture disk requirements; and other calculations, while considered, were not required because certain contingencies clearly would not govern or were not credible. As such, there actually were 213 sets of detailed calculations to support this study [1,3].

Table 2 Types of relief devices

Type	New	Existing	Total
RV (single)	22	14	36
RV_c (combined with RD)	5	26	31
Total RVs	27	40	67
RD (single)	10	12	22
RD_c (combined with RV)	5	26	31
Total RDs	15	38	53
Combination RV/RD	10	52	62
Total Devices	42	78	120

Relief Device Sizing Documentation

Relief device sizing methods and procedures are the same for new design installations and for existing installations. Also, the necessary information to verify the size of a relief device for an existing installation essentially is the same as that needed to size a relief device for a new installation. However, more information should be available and some additional steps are needed to evaluate an existing relief device. For both new and existing installations, proper documentation and record keeping is extremely important [2,3].

To properly evaluate the relief device system requirements, considerable detailed information is needed. Required information for both new installations and existing installations includes the following. This information would be developed for new installations, and such documentation must be maintained for existing installations [2,3].

- process flow diagram
- process description
- operating conditions, including upsets and transients
- piping and instrumentation diagram
- pipeline list
- piping specifications
- specified set pressure
- specified overpressure
- fluid characteristics at operating and relief conditions
- vessel or protected equipment drawing and design information
- insulation specifications
- relief device installation sketch, including dimensions, piping configuration and supports

An evaluation of an existing relief device installation can be categorized as a fitness-for-service evaluation. This is comprised of several parts [2,3]:

1. Design information gathering and review
2. Inspection of the relief device installation
3. Repair shop inspection/relief valve calibration
4. Review existing calculations, or provide new calculations, to verify the size of the relief device size
5. Report and documentation

A brief description of each of these parts follows.

1. Design Information

   To verify the size of an existing relief device system, the following information and actions are required, in addition to that listed above:

   - Existing relief device hardware data, including manufacturer, size, model and materials of construction
   - Relief device nameplate data

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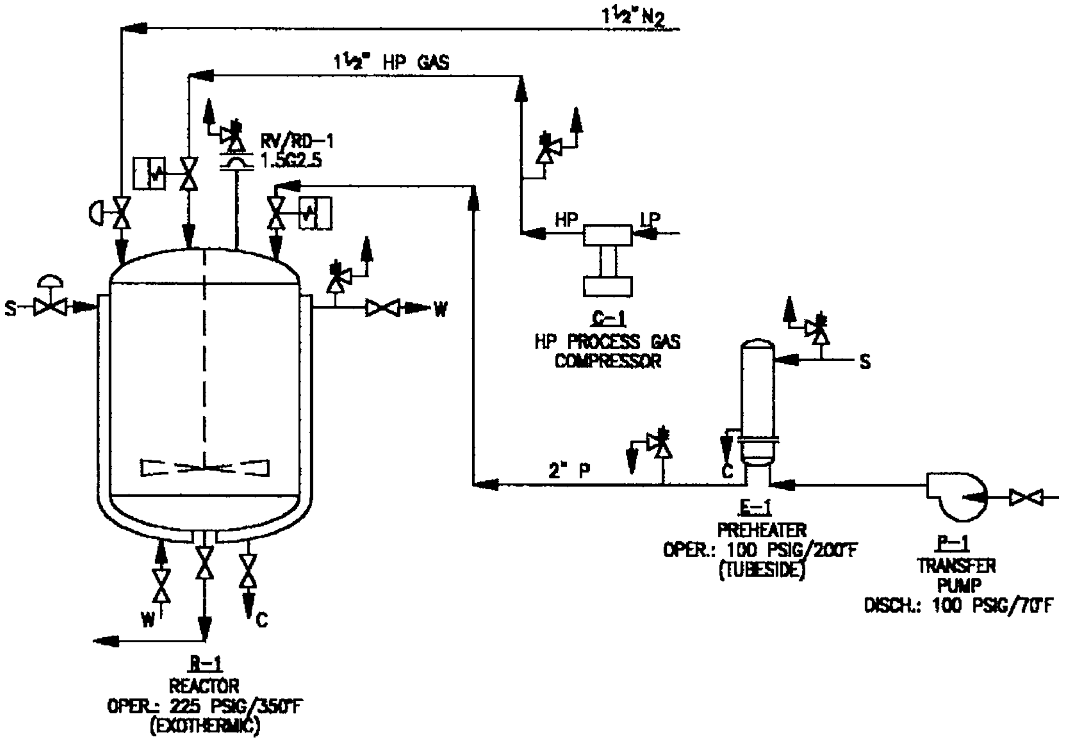

Fig. 4 Example chemical batch reactor system schematic

- Inspection reports and history of testing and calibration
- Field verification survey

If any information is unavailable, then it may need to be developed; otherwise, conservative assumptions should be made and documented.

2. Installation Inspection

A field-inspection is required of the as-installed configuration of the relief device system, including the relief device or devices, the inlet and outlet piping, and any associated instrumentation and hardware. Nameplate data should be recorded; and a field sketch should be made of the relief device installation, including dimensions, and support types and locations.

3. Shop Inspection/Valve Calibration

To ensure that existing relief devices are reliable and will properly function, periodic inspection, calibration and repairs must be carried out by following proper procedures [21]. Plant maintenance records must be maintained for inspection and testing of the existing relief devices. Inspection and testing frequencies are established by the owner based on the service, prior history, and impact of a relief system malfunction or failure on equipment and personnel safety. To an extent, this now is required by federal and state regulations.

4. Sizing Calculations

If existing sizing calculations are available, then they should be reviewed for compliance. Otherwise, new calculations are required to verify the relief device size.

The required relief device size is determined by defining all of the credible relief contingencies, computing the relief load (rate of release) for each contingency, and then computing the required relief device size based on the governing relief load contingency. All seven relief contingencies must be considered for each relief device that is being evaluated (see "Relief Contingencies" above).

5. Documentation

The results of the relief device fitness-for-service evaluation should be documented properly. The report should include:

- a summary of the relief devices and the findings (i.e., whether or not the existing device size and specification is adequate)
- references to the specific documentation used as a basis for the evaluation (i.e., PFDs, P&IDs, equipment drawings, data sheets, process data, etc.)
- a field sketch of the relief device installation
- a brief description and background of the equipment being protected, the detailed sizing calculations for each credible contingency considered, and the findings from the calculations
- supplemental calculations as appropriate for the installation (e.g., relief device inlet and outlet piping size, relief thrust reaction forces, and equipment nozzle stresses)
- conclusions and recommendations for each evaluated relief device

The report should be dated and identified such that subsequent revisions can be documented to incorporate corrections and changes to the relief device installation.

The documentation for all relief devices should be considered "living documents" for the life of the operating facility.

Example Relief Valve Sizing

To illustrate the relief device size calculation procedure, consider the example of an existing chemical batch reactor system schematic shown in Fig. 4 [1]. For this example, the existing 1.5G2.5 combination relief valve and rupture disk, RV/RD-1, was

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Table 3 Example RV/RD - 1 sizing summary

	Contingency	Cause	Condition	Heat Load	Flow Rate	A_o Required
1.	External fire	Reactor engulfed in fire.	Vapor generated by effective wetted area.	2 ,500, 000 BTU/hr	10,040 lb/hr	0.538 in.^{2}
2.	Exchange tube failure	Note: Not a credible relief scenario for RV/RD-1; exchanger E-1 is protected by separate relief devices and operates at less pressure than the RV/RD-1 set pressure.				
3. a)	N_2 control valve failure	N_2 feed control valve fails open.	Maximum flow through 1.5 in. piping.	-	13,517 lb/hr	0.666 in.^{2}
b)	Process gas compressor actuated valve failure	Process gas feed valve actuator fails open.	Maximum compressor rated capacity.	-	4,000 lb/hr	0.219 in.^{2}
4.	Cooling failure	Jacket circulating cooling water fails.	Loss of control of exothermic reaction.	5,456,000 BTU/hr	7,275 lb/hr	0.348 in.^{2}
5.	Blocked outlet	Note: Not a credible relief scenario for RV/RD-1; blocked jacket water outlet valve or condensate outlet valve is protected by a separate relief device.				
6.	Hydraulic expansion	Note: Not a credible relief scenario for RV/RD-1; liquid thermal expansion of line 2"P is protected by a separate relief device.				
7.	Process upset	Loss of process reaction control.	Process runaway reaction.	6,500,000 BTU/hr	8,667 lb/hr	0.443 in.^{2}

evaluated to determine if the relief devices are sized adequately to provide overpressure protection for the existing batch reactor, R-1.

The vertical stainless steel reactor, R-1, has a capacity of 1,100 gallons and normally operates at 85% capacity. The reactor MAWP is 250 psig at 400°F, and its maximum operating conditions are 225 psig at 350°F (Fig. 4). The batch reaction is exothermic. The relief valve and rupture disk are specified to relieve and burst, respectively, at the reactor MAWP. Since the relief valve is installed to accommodate multiple contingencies, a 10% overpressure is applied.

The actuated valves and control valve are automatically activated by computer interface to feed the batch mixture constituents into the reactor. This includes the process liquid feed through the transfer pump P-1 pipeline, the compressor C-1 process gas feed, and the nitrogen feed.

The seven pressure-relief contingencies were considered; and their causes and conditions are summarized in Table 3.Of these, three categories-exchanger tube failure, blocked outlet and hydraulic expansion-were determined to be not credible. For the credible overpressure considerations, the relief rates and required relief areas, A_o required, are described below. The relief valve and rupture disk sizes were determined by the applicable API RP 520 equations [12,15]. The results for this example are summarized in Table 3.

For this example, contingency 3a listed in Table 3, the nitrogen control valve failure scenario, governs the combination rupture disk and relief valve size. The existing size "G" orifice (0.503 in.^{2} API) is undersized. The relief valve should be replaced with a size "H" orifice (0.785 in.^{2} API) to satisfy the governing overpressure relief contingency. The relief area provided by the existing 1.5 in. diameter rupture disk is adequate. If practical, the existing pressure-relief valve could be fitted with a large orifice; otherwise, a new pressure-relief valve will be required.

External Fire. The external fire relief rate was computed by the API method as follows. For the known geometry, the reactor wetted area was calculated to be 125 ft^2.

Heat load, applying the most conservative API equation [Eq. (3)] and environmental factor (unity):

$$Q = 20\,000A = (20\,000)(125) = 2\,500\,000 \text{ BTU/hr}$$

Process fluid properties:

$$L = 249 \text{ BTU/lb and } M = 44.05$$

Relief flow rate:

$$W = \frac{Q}{L} = \frac{2{,}500{,}000}{249} = 10{,}040 \text{ lb/hr}$$

Required relief orifice area [Eq. (4)]:

$$A_o = \frac{W}{K_c C K_d P_1 K_b}\left(\frac{TZ}{M}\right)^{1/2} = \frac{10{,}040}{(0.90)(315)(0.975)(289.7)(1)}\left(\frac{(810)(1)}{44.05}\right)^{1/2}$$

$$A_o = 0.538 \text{ in.}^2 \text{ required}$$

N_2 Control Valve Failure. The upstream 500 psig N_2 supply is reduced to 225 psig with the N_2 pressure control valve at the reactor. The N_2 control valve could fail open, and the N_2 flow rate through the valve and 1.5 in. NPS feed piping to achieve the 250 psig set pressure at RV/RD-1 was calculated to be 3053 CFM, or 13 517 lb/hr. At this stage of the reaction, the temperature would be 100°F.

N_2 properties:

$$k = 1.41, \quad C = 357 \text{ and } M = 28$$

Required relief orifice area [Eq. (4)]:

$$A_o = \frac{13{,}517}{(0.90)(357)(0.975)(289.7)(1)}\left(\frac{(560)(1)}{28}\right)^{1/2}$$

$$A_o = 0.666 \text{ in.}^2 \text{ required}$$

Process Gas Compressor Actuated Valve Failure. The process gas compressor is a positive displacement machine. The actuated valve at the reactor can fail open; and, from the manufac-

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turer's literature, the gas compressor capacity is 4,000 lb/hr. At this stage of the reaction, the reactor ullage temperature would be at 200°F.

Process gas properties:

$$k = 1.19, \quad C = 336 \text{ and } M = 30.07$$

Required relief orifice area [Eq. (4)]:

$$A_o = \frac{4000}{(0.90)(336)(0.975)(289.7)(1)}\left(\frac{(660)(1)}{30.07}\right)^{1/2}$$

$$A_o = 0.219 \text{ in.}^2 \text{ required}$$

Cooling Failure. The conventional jacket on the reactor provides either steam heating or water cooling as required for the batch reaction. Under normal conditions, if the cooling water circulation is starved or stopped, the batch reaction temperature will rise to 250°F. The process data shows that such loss of cooling control of the exothermic reaction could result in a maximum heat load of 5,456,000 BTU/hr. The process exotherm is known to be 750 BTU/lb.

Process gas properties:

$$k = 1.13, \quad C = 330 \text{ and } M = 44.05$$

Relief flow rate [Eq. (8)]:

$$W = \frac{5{,}456{,}000}{750} = 7{,}275 \text{ lb/hr}$$

Required relief orifice area [Eq. (4)]:

$$A_o = \frac{7275}{(0.90)(330)(0.975)(289.7)(1)}\left(\frac{(710)(1)}{44.05}\right)^{1/2}$$

$$A_o = 0.348 \text{ in.}^2 \text{ required}$$

Process Upset. While a rare event, it is known that a spontaneous process runaway reaction has occurred during the batch reaction. This runaway reaction would generate a heat load of 6,500,000 BTU/hr and the temperature would rise to 350°F.

Relief flow rate [Eq. (8)]:

$$W = \frac{6{,}500{,}000}{750} = 8{,}667 \text{ lb/hr}$$

Required relief orifice area [Eq. (4)]:

$$A_o = \frac{8{,}667}{(0.90)(330)(0.975)(289.7)(1)}\left(\frac{(810)(1)}{44.05}\right)^{1/2}$$

$$A_o = 0.443 \text{ in.}^2 \text{ required}$$

Results and Findings

The results tabulated in Table 4 show that there is no discernable statistical difference between external fire and non-fire contingencies when all relief devices are considered.

If only new relief devices are considered, overpressure relief contingencies other than external fire significantly govern the relief device size by a 2 to 1 factor.

When only existing relief devices are considered, external fire contingency governs, but only by a 1.26 to 1 margin. However, the existing relief device sizing possibly was prejudiced, at least to some extent, by the general sense that fire exposure was presumed the likely governing contingency; and, thus, other contingencies may not have been considered reasonably or adequately in the original sizing of the existing relief devices.

In the raw data calculations, examination of the relief area provided, A_p, versus the relief area required, A_r, for the relief devices under consideration shows that a significant 17.5% of all relief devices evaluated were determined to be undersized for the governing relief conditions. However, a number of the relief devices in this study were for focused evaluations to assess specific problems. To more closely examine this, the results of the undersized existing relief devices were grouped as an unbiased subset by the given project, and this is presented in Table 5. From this, it can be explored as to whether a single device, small group of devices, or a large number of devices in a given project may render any different observations [1,3].

Table 4 Governing contingencies

Table	Frequency (%)	
	Fire	Non-Fire
All Relief Devices		
RVs and RDs	45.0	55.0
RVs only	44.8	55.2
RDs only	45.3	54.7
RV/RDs only	61.3	38.7
Mean %	49.1	50.9
New Relief Devices		
RVs and RDs	31.0	69.0
RVs only	29.6	70.4
RDs only	33.3	66.7
RV/RDs only	40.0	60.0
Mean %	33.5	66.5
Existing Relief Devices		
RVs and RDs	52.6	47.4
RVs only	55.0	45.0
RDs only	50.0	50.0
RV/RDs only	65.4	34.6
Mean %	55.8	44.2

Considering the total existing relief devices listed in Table 5, a surprisingly high 26.9% of the existing relief devices were determined to be undersized for the governing relief conditions.

Of the sources listed, Projects "B" and "C" are for existing relief devices on two different process streams of the same plant. Combined, there are 57 relief devices for Projects "B" and "C"; and, from Table 5, 12.3% of the existing relief devices evaluated for that site were determined to be undersized.

As stated earlier in this paper, there are about 13,425 chemical plants, and 31,917 combined chemical, petroleum and related manufacturing plants, in the U.S.A. [5]. Assuming an average of 100 relief devices per production plant, and applying the 12.3% to 26.9% result range, it is estimated that about 165,000 to 361,000 relief devices in existing chemical plants, and about 393,000 to 859,000 relief devices in these combined existing manufacturing facilities, within the U.S.A. are undersized [1].

Some conclusions as a result of this study are:

1. In general, considering all pressure-relief devices, the fire exposure contingency and the relief contingencies other than fire exposure govern the size of pressure-relief devices about equally.

Table 5 Undersized existing relief devices

Project	Total Existing Relief Devices	Undersized Existing Relief Devices	% of Undersized Relief Devices
B	13	4	31
C	44	3	7
E	5	2	40
F	3	0	0
G	1	0	0
J	10	10	100
L	2	2	100
Total	78	21	

Note: Only the existing relief devices that were evaluated are included in Table 5.

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2. A significant number of pressure-relief devices in existing installations likely are undersized; and this presents serious potential danger to public safety, to the environment, to plant personnel, and to the facility.
3. Fitness-for-service evaluations should be implemented for existing pressure-relief device installations, including inspection, relief size verification, and documentation.

Nomenclature

A = total wetted surface of equipment, ft^2
A_o = effective valve relief orifice area, in.^2
A_p = relief area provided, in.^2
A_r = relief area required, in.^2
B = cubicle coefficient of thermal expansion of liquid per °F
C = coefficient determined from specific heat ratio, k, of gas or vapor
c_p = specific heat of liquid, BTU/lb-°F
c_v = specific heat of vapor, BTU/lb-°F
F = environmental factor per API RP 520
F_2 = coefficient of sub-critical flow (API RP 520, Fig. 29)
G = liquid specific gravity
H = heat transfer rate, BTU/hr
k = specific heat ratio=c_p/c_v
K_b = capacity correction factor for backpressure
K_c = combination capacity correction factor
K_d = effective coefficient of discharge
K_v = viscosity correction factor
K_w = backpressure capacity correction factor, liquid service
L = latent heat of liquid, BTU/lb
M = molecular weight of gas
P_1 = upstream relieving pressure, or set pressure plus allowable overpressure plus atmospheric pressure, lb/in.^2 absolute
P_2 = backpressure, lb/in.^2 absolute
Q = total heat load, BTU/hr
q = volumetric flow rate, gal/min
r = ratio of backpressure to upstream relieving pressure, P_2/P_1 (required for F_2)
T = relieving temperature of inlet gas, °F
W = mass flow rate, lb/hr
Z = gas compressibility factor

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