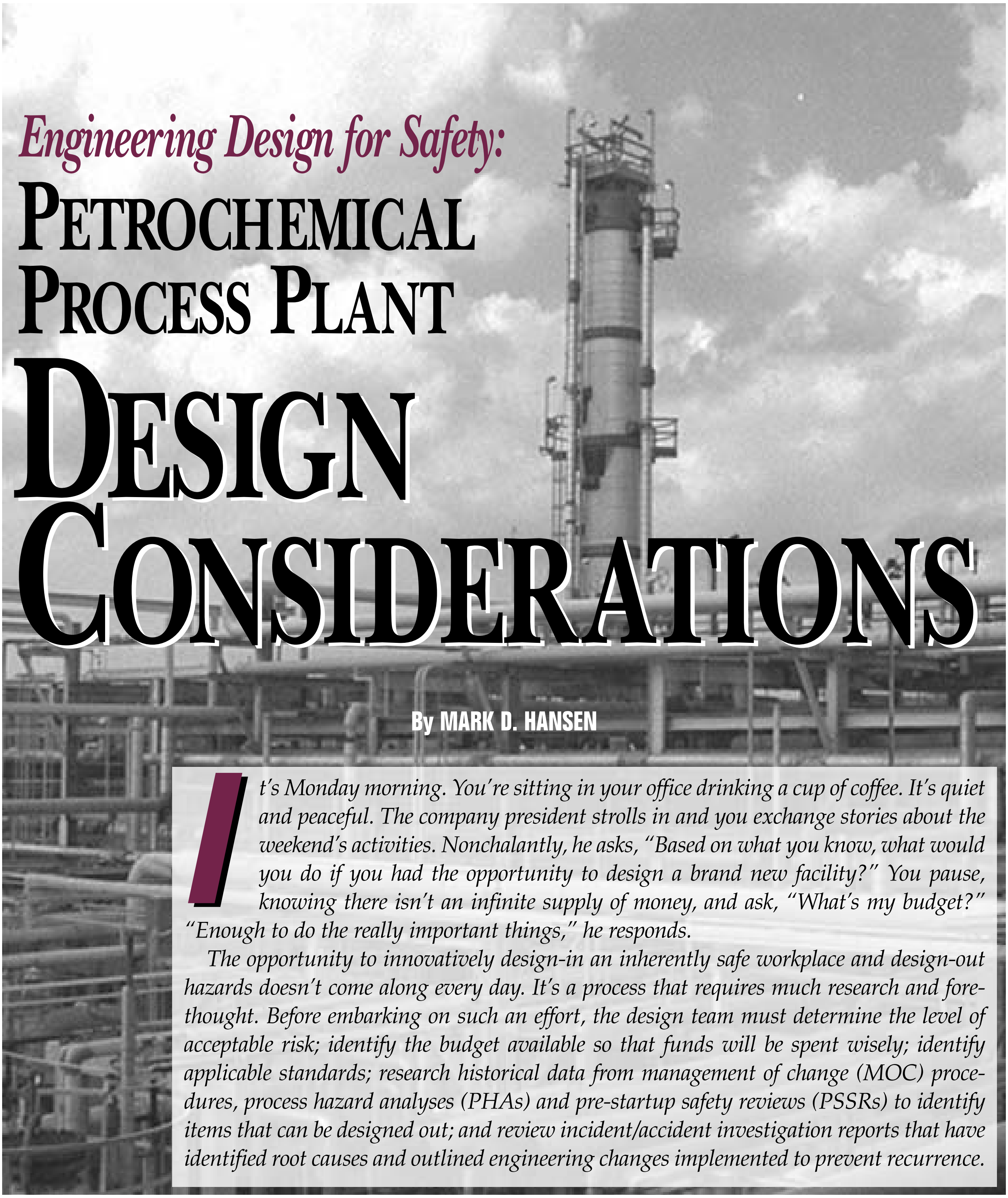

Engineering Design for Safety: Petrochemical Process Plant Design Considerations

By MARK D. HANSEN

It's Monday morning. You're sitting in your office drinking a cup of coffee. It's quiet and peaceful. The company president strolls in and you exchange stories about the weekend's activities. Nonchalantly, he asks, "Based on what you know, what would you do if you had the opportunity to design a brand new facility?" You pause, knowing there isn't an infinite supply of money, and ask, "What's my budget?" "Enough to do the really important things," he responds.

The opportunity to innovatively design-in an inherently safe workplace and design-out hazards doesn't come along every day. It's a process that requires much research and forethought. Before embarking on such an effort, the design team must determine the level of acceptable risk; identify the budget available so that funds will be spent wisely; identify applicable standards; research historical data from management of change (MOC) procedures, process hazard analyses (PHAs) and pre-startup safety reviews (PSSRs) to identify items that can be designed out; and review incident/accident investigation reports that have identified root causes and outlined engineering changes implemented to prevent recurrence.

SETTING THE STAGE

One of the most important steps in this process is to determine the level of acceptable risk. Risks can be evaluated qualitatively and/or quantitatively.

Qualitative risk analysis is the most widely used method. The risk matrix is a common approach (Figure 1). Although based on intuitive reasoning and the engineer's experience, this technique can help determine the relative risk of each incident scenario and identify risk-reduction methods. The objective is to determine how the severity and/or frequency of identified hazards can be mitigated. For example, installing water spray systems, reducing hazardous material inventory or improving flare system design can help reduce risk from high to moderate or moderate to low.

Quantitative risk analyses are performed using engineering techniques and computer models that analyze an incident scenario in order to determine its impact. Such analyses assess what damage may occur from a fire, explosion and/or toxic release and how frequently it will occur. Potential impacts (e.g., fatalities, injuries, equipment loss, environmental damage) are systematically estimated to determine an incident's magnitude and severity.

The level of acceptable risk must be weighed against historical information regarding similar incidents within the industry. For example, several serious incidents—causing considerable human casualties and large property losses—have occurred in the last 15 years, leading to greater attention being focused on facilities that use, manufacture, store or handle highly hazardous materials.

If one examines the impact of several recent incidents in the process and refining industries (as summarized in Tables 1 through 6), the significant financial losses and business interruption costs caused by such accidents become clear. As these data show, one can cite myriad reasons to design-in safety and design-out hazards.

DETERMINING THE BUDGET

Another key step is to identify the overall budget for constructing the new facility. For example, suppose the budget is $200 million; assume that this total includes the costs of material, labor, property, permitting, engineering drawings and documentation.

With all costs included, the safety budget should be (as a general rule) one to five percent of the total budget (in this case, $1 to $5 million). This allocation would include all safety-related systems—from fire water systems to control room design. Using the dollar value of PHAs, MOCs, PSSRs and incident/accident recommendations can provide cost justification for this budget. Engineering economy principles can facilitate cost-justification exercises, while sales and profit margin data can illustrate cost avoidance (Table 7). This budget also includes use of economies of scale, such as using similar equipment for alarm systems, firefighting equipment and gear, and operating procedures and training systems.

RESEARCH APPLICABLE STANDARDS

Researching applicable design standards for recommended guidelines and criteria is a challenge. Myriad standards may be involved—ranging from those developed by American National Standards Institute (ANSI) and American Petroleum Institute (API), to those promulgated by National Fire Protection Assn. (NFPA) and American Society for Testing and Materials (ASTM). To facilitate this process, sample design recommendations and criteria follow.

Process Area Layout

The use of "inherently safe" practices should be incorporated early in the design process. Standard siting practices include the following.

- Provide good access to all areas by wide-surface roads that form a gridded network; this permits firefighting from any side.
- Locate heaters and fired equipment upwind (based on prevailing winds) of process equipment.
- Point horizontal tanks away from equipment or occupied buildings.
- Buildings designed to house flammables should be open structures.
- Locate process areas at least 150 feet from tankage and utility areas.
- Locate flare stacks at least 175 feet downwind of any floating roof tanks.
- Locate all service buildings outside potential blast areas when feasible.

Fire Water System

Fire water should be supplied to each process block and tank farm from a gridded fire main system. This system should be installed according to applicable NFPA standards and have many well-located sectional valves and hydrants. In addition, the following factors should be considered.

- Size underground piping and pumps to handle two adjacent incidents.
- Loop mains should not be less than eight inches in diameter.
- Use electrically driven fire pumps with 100-percent diesel backup.
- Site fire pumps at two locations.
- Design the overall system to work for a minimum of eight hours at full capacity, with additional capacity at reduced rates.

Design Criteria

- **NFPA 24, Installation of Private Fire Service Mains and Their Appurtenances**
- **NFPA 20, Installation of Centrifugal Fire Pumps**
- **NFPA 14, Installation of Standpipe and Hose Systems**

Electrical Reliability

Electrical power service design for a process unit should include:

- dual primary service feeds with two main breakers and a tie breaker with power drawout main;
- tie and feeder distribution panel breakers;
- automatic transfer system for main and tie breakers, with capability for manual transfer;
- emergency power generation or battery system with uninterruptable power supply that can provide for safe shutdown of the process.

Locations that require classified electrical installations should be identified according to Article 500 of the National Electrical Code (NEC). This code also specifies the class and group of equipment required in those areas. Conduit seals must also be installed as outlined.

Cable Trays

Where possible, cable trays should be routed away from potential fire exposures. Installations should be located so as to allow ready access for repair or removal. Other key design features:

- Run power and instrument cables in separate trays.
- Locate cable trays above pipeways and take measures to prevent them from being used to support other equipment.
- Protect trays that traverse high-potential fire areas either by fireproofing, or with flame shields or water spray systems.
- At cable penetrations, select a UL-listed fire seal whose rating is at least equivalent to the wall rating.

One of the most important steps in this process is to determine the level of acceptable risk.

•Ensure that cable jackets satisfy UL-1277 flame test.

Design Criteria

- **•NFPA 70, NEC Articles 318 and 500**
- **•API 2030, Guidelines for Application of Water Spray Systems**
- **•API 2218, Fireproofing Practices in Petroleum and Petrochemical Processing Plants**

Fireproofing

Fireproofing should be provided on all load-bearing structural steelwork to full height, including fin-fan support structures. This protection should cover:

•exterior vessel support skirts, legs, lugs and anchor rings;

•interior skirt surfaces if flanges or valves are located inside skirt or if the potential for updrafts exists within the skirt;

•horizontal members and cross-bracing (if load-bearing);

•horizontal and vertical pipe rack supports up to at least the first level.

A three-hour-rated protection should be provided on all steel structures and equipment supports; a one-hour-rated protection should be provided on cabling and piping supports.

Design Criteria

- **•API 2218, Fireproofing Practices in Petroleum and Petrochemical Processing Plants**

Cooling Towers

A pre-design assessment should be performed to identify the business interruption exposure presented by loss of a cooling tower. Based on results, cooling towers that are constructed of combustible materials or containing combustible fill materials should be protected in the following ways.

•Utilize low-flame spread (per ASTM E-84) materials for stacks, louvers, fill, drift eliminators and sheathing.

•Provide a minimum fire break separation of 50 feet from process areas.

•Provide combustible gas detectors.

•Provide lightning protection (connected to a grounding system) on cooling towers located in fields not surrounded by taller buildings or structures.

Design Criteria

- **•NFPA 214, Standard on Water-Cooling Towers**

Fire Suppression Systems

An integrated system of hydrants, monitor nozzles and water spray systems should be installed within each process unit to support both automatic and manual firefighting efforts. The location and concentration of monitor nozzles and water spray systems depends on the degree of unit congestion, nature of haz-

FIGURE 1 Risk Matrix

Probability of Success / Category	A. Frequent (1) Event likely to occur once or more per year	B. Probable (2) Event likely to occur once every several years	C. Occasional (3) Event likely to occur once in a facility's lifetime	D. Unlikely (4) Event unlikely but not impossible
I. Catastrophic (1) Personnel: life-threatening Environment: large, uncontrolled release Equipment: major damage resulting in loss of unit	1	2	3	4
II. Critical (2) Personnel: severe injury Environment: moderate, uncontrolled release Equipment: moderate, resulting in unit downtime	2	4	6	8
III. Marginal (3) Personnel: lost-time injury Environment: small, uncontrolled release Equipment: minor damage resulting in unit slowdown	3	6	9	12
IV. Negligible (4) Personnel: minor injury Environment: small, controlled release Equipment: negligible damage	4	8	12	16

High: Requires Action (cells 1, 2, 2) — Moderate: Further Study Required (cells 3, 4, 6, 3, 6) — Low: Investigate as Time Permits

TABLE 1 Review of Serious Industrial Losses

INCIDENT	IMPACT
Baton Rouge, LA – December 1989 Refinery pipeline rupture	$43 million damage; damage to off-site houses
Pasadena, TX – October 1989 Petrochemical – Vapor cloud explosion	$500 to $725 million damage; severe business interruption
St. Croix, Virgin Islands – September 1989 Refinery (Hurricane Hugo)	$60 million damage; extensive damage to storage tanks
Martinez, CA – September 1989 Refinery – H_2 and hydrocarbon release	$50 million damage, massive firefighting effort
Morris, IL – June 1989 Petrochemical – Vapor cloud explosion	$41 million damage; 40 acres of plant damaged
Richmond, CA – April 1989 Refinery - H_2 gas fire	$90 million damage; two years to repair plant
Antwerp, Belgium – March 1989 Petrochemical – Column exploded	$77 million damage; business interruption of $267 million

ards involved and types of equipment to be protected. General design guidelines include the following.

•Provide fixed monitor coverage so that process areas which require protection can be reached by two monitor streams.

•Set design radius for the monitor streams at 81 feet.

TABLE 2 Loss Trends

5-Year Intervals

PERIOD	NUMBER OF LOSSES	LOSSES ($BILLIONS)
59-63	6	0.15
64-68	13	0.48
69-73	24	0.51
74-78	30	1.18
79-83	45	1.29
84-88	32	1.54

TABLE 3 Loss Distribution

Type of Complex

OPERATION	PERCENT	LOSSES ($MILLIONS)
Refineries	40	40.1
Petrochemical	17	34.4
Terminals	13	25.8
Plastics/Rubber	9	23.8
Chemical	8	18.5
Natural Gas	7	52.2
Pipelines	2	45.6
Miscellaneous	4	24.6

TABLE 4 Cause of Losses

CAUSE	PERCENT	LOSSES ($MILLIONS)
Mechanical Failures	41	36.0
Operational Error	19	38.6
Unknown	17	25.9
Process Upset	10	40.7
Natural Hazard	5	43.2
Design Error	4	60.5
Sabotage/Arson	4	19.0

•Locate monitors at least 50 feet from the nearest hazard or use motor-operated remote-controlled devices.

•Install water spray systems over vessels, pumps and compressors that handle/store:

- •flammable or combustible liquids above 500ºF or their auto-ignition temperature;
- •flammable or combustible liquids at greater than 500 psi;
- •liquefied flammable gas.

•Perform modeling of fire water system performance to ensure that adequate water supply, pump pressure and flow rates are available to provide coverage needed.

Design Criteria

•NFPA 15, Water Spray Fixed Systems for Fire Protection

•NFPA 11, Standard for Low-Expansion Foam and Combined Agent Systems

•API 2030, Application of Water Spray Systems for Fire Protection in the Petroleum Industry

Drainage and Diking

Unit drainage system should slope from the center of the process unit to perimeter trenches and/or impoundment basins. Other key guidelines:

•Ensure that paved surfaces have at least 1 percent slope (2 percent for unpaved surfaces).

•Grade paving away from pipe racks.

•Where feasible, remote impounding should be located 50 feet away with good drainage; this is preferred to diking.

•Slope surfaces within dikes for at least five feet or to the tank wall, whichever is less.

•Design diking/containment systems to handle the largest spill potential *plus* the associated firewater load. Minimum system capacity should be 110 percent of the largest vessel volume.

•Dike tanks individually. Where multiple tanks are contained within a single dike, an intermediate curb (minimum of 18 inches) should be provided between individual tanks.

Design Criteria

•NFPA 30, Flammable & Combustible Liquids Code

Process Pumps

These guidelines should be observed when installing process pumps that handle flammable/combustible liquids.

•Pumps should have double mechanical seals, with compatible barrier fluid.

•Pumps should be located outside containment dikes.

•Water spray protection should be provided over critical pumps; such protection should activate automatically through the temperature and/or flammable gas detection systems.

Design Criteria

•NFPA 15, Water Spray Fixed Systems for Fire Protection

Emergency Isolation Valve

An emergency isolation valve (EIV) is a protective device that isolates piping or equipment in the event of a dangerous situation. It should provide automatic as well as remote actuation by one of the following methods:

•air, nitrogen or hydraulic pressure to open with spring to close; air or nitrogen connection to the EIV should be made with a melt-out tubing so that it functions as a fusible link;

•heat-actuated with spring to close;

•pneumatic operation;

•electrically operated.

Other guidelines:

•Ensure that all components of the EIV assembly can withstand 15 minutes of fire exposure.

•Provide an alternate power supply where necessary.

•Ensure that pneumatic EIVs have sufficient air for two valve strokes; they should also have a dedicated emergency reservoir for closing.

•Label EIV controls, which should be operable from the control room and from a safe location.

•Locate EIVs as close as possible to vessel/equipment flanges.

•Make provisions that allow for online testing without process disruption.

EIVs should be located:

•at battery limit of production units;

TABLE 5 Equipment Involved in Cause

EQUIPMENT	PERCENT	LOSSES ($MILLIONS)
Piping	31	41.9
Tanks	17	40.5
Reactors	13	28.5
Miscellaneous	9	34.7
Process Drums	7	25.5
Marine Vessels	6	32.0
Unknown	5	25.0
Pumps	5	19.2
Heat Exchanger	3	24.0
Process Towers	3	53.8
Heaters/Boilers	1	28.8

TABLE 6 Ignition Source

SOURCE	PERCENT	LOSSES ($MILLIONS)
Unknown	53	38.5
Open Flame	12	32.0
Chemical Reaction	9	26.0
Electrical Equipment	5	16.5
Internal-Combustion Engine	6	49.0
Auto-Ignition	4	34.1
Lightning	3	39.1
Hot Surface	3	39.4
No Ignition	3	18.7
Sabotage/Arson	2	43.5
Static	1	14.5
Cutting/Welding	1	16.0

•around all critical process equipment (e.g., reactors, furnaces);

•where inventories of flammable or combustible liquids in a single vessel or interconnected vessels exceed 10,000 gallons (including storage areas);

•where inventories of liquefied flammable gases in a single vessel or interconnected vessels exceed 1,300 gallons (including storage areas).

Design Criteria

•API 2510, Design and Construction of LPG Installations

Control Room Design

As part of the initial design phase, the team should consider locating the control room away from potential blast areas, based on applicable modeling. If not feasible, these guidelines should be followed.

•Take steps to ensure that all materials of construction are non-combustible.

•Provide hydrocarbon and toxic gas detection on return-air intake. It should be designed to alarm and shutdown ventilation at 25 percent LEL.

•Ensure that the enclosure is positively pressurized to 0.10 inches of water.

•Locate the air inlet for the ventilation system above the building.

•Install self-closing external doors that have the same pressure resistance as the control room walls.

•Blastproof criteria should be designed for life safety to withstand the following overpressure loadings: 10 psi for 20 milliseconds; 3 psi for 100 milliseconds.

Design Criteria

•API 2510, Design and Construction of LPG Installations

•FM Data Sheet 7-45S, Process Control Houses

Smoke Detection Systems

Smoke or heat detectors should be installed in the following areas: control rooms; MCC rooms; battery rooms; below raised floors with significant runs of cable; online process analyzer buildings/sheds; and gas turbine houses. All site alarms should be routed to the control room.

Design Criteria

•NFPA 72E, Standard on Automatic Fire Detectors

Combustible Gas Detection

Combustible gas detectors should be located near rotating equipment and in other areas that may contain significant quantities of flammable liquid and hydrocarbon vapor. Specific locations may include:

•control room intake, interlocked to shut down the ventilation system at 25 percent LEL;

•near exchangers, reactors and dryers;

•around storage and process drums;

•around furnaces and compressors;

•above hydrocarbon pumps;

•at main unit sewer outlet.

Design Criteria

•NFPA 70, National Electrical Code

•ANSI/ISA-RP 12.13, Part II, Installation, Operation and Maintenance of Combustible Gas Detectors

Fixed Vibration Monitoring

A pre-design assessment should be conducted on each piece of rotating equipment that will be installed to determine the potential for business interruption exposures created by loss of such equipment. The assessment should also consider the potential for a life-threatening situation or serious environmental impact. Based on results, such equipment should be fitted with fixed vibration monitoring. It should be noted that while equipment designated as critical tends to have high horsepower (> 500 hp), the hp by itself is not a prerequisite for criticality.

Design Criteria

•API 670, Vibration, Axial Position and Bearing Temperature Monitoring Systems

•API 678, Accelerometer-Based Vibration Monitoring Systems

Storage Tanks

The design of atmospheric (up to 0.5 psig) and low-pressure (up to 15 psig) storage tanks should conform to referenced API standards. High-pressure vessels should be designed according to the ASME Boiler and Pressure Vessel Code. Protection, level alarms and tank spacing should conform to the following guidelines.

•Locate storage areas at least 150 feet from other hazardous areas. Recommended tank-to-tank separation criteria is:

<10,000 barrels (bbls) = 0.5 diameter
10,000 to 50,000 bbls = 1.0 diameter
>50,000 bbls = 1.5 diameter
250,000 bbls = special consideration

•Equip those tanks that store more than 25,000 gallons of Class 1 flammable liquids with independent high (HLA) and high level alarm (HHLA) systems. The alarms should signal at 30 and 15 minutes, respectively, prior to overfill based upon the maximum pumping rate to a constantly attended location.

TABLE 7 Sales Required to Cover Losses

Yearly Incident Costs	Profit Margin				
	1%	2%	3%	4%	5%
$1,000	100,000	50,000	33,000	25,000	20,000
5,000	500,000	250,000	167,000	125,000	100,000
10,000	1,000,000	500,000	333,000	250,000	200,000
25,000	2,500,000	1,250,000	833,000	625,000	500,000
50,000	5,000,000	2,500,00	1,667,000	1,250,000	1,000,000
100,000	10,000,000	5,000,000	3,333,000	2,500,000	2,000,000
150,000	15,000,000	7,500,000	5,000,000	3,750,000	3,000,000
200,000	20,000,000	10,000,000	6,666,000	5,000,000	4,000,000

As these data show, one can cite myriad reasons to design-in safety and design-out hazards.

Alarms should also be interlocked to permit pump and isolation valve shutdown.

•Install foam systems in all cone and internal floating roof storage tanks.

•Pipelines should incorporate all welded construction in immediate sphere or tank areas.

•Locate the pumps outside the containment areas.

•Install and interlock remote-operated isolation valves to allow actuation by the fire/gas detection systems.

Design Criteria

- **API 650, Welded Steel Tanks for Oil Storage**
- **API 620, Design and Construction of Large, Welded, Low-Pressure Storage Tanks**
- **API 2021, Fighting Fires In and Around Flammable and Combustible Liquid Atmospheric Storage Tanks**
- **API 2510A, Design and Construction of LPG Gas Installations**
- **NFPA 11, Standard for the Installation of Low-Expansion Foam**

Pressure Relief Valves/Rupture Disks

Design criteria for these valves/disks is detailed in the referenced API standards. Although allowed by code, use of rupture disks by themselves are discouraged in tanks that contain highly hazardous materials because they do not close after opening; this may result in continuing release of toxic materials to the atmosphere. Other key considerations in the area:

•Provide redundancy for safety valves to permit on-line removal and testing.

•Provide rupture disks with a positive means of detecting a failure or rupture, through one of the following methods (listed in order of preference):

- continuity check that constantly monitors resistance across the disk;
- excess flow valve, provided an environmental review is performed;
- pressure gauge located downstream of the disk.

Design Criteria

- **API RP 520, Sizing, Selection and Installation of Pressure-Relieving Devices in Refineries**
- **API RP 521, Guide for Pressure-Relieving Systems**
- **NFPA 30, Flammable and Combustible Liquids Code**

Process Control

Hardware devices and software control systems should be able to provide safe, efficient control under normal process conditions, as well as a timely response in an emergency. To facilitate this, the control system should feature:

- numerous terminal display units;
- reliable valve position indicators;
- software fault tolerance;
- built-in system redundancy and failover;
- programming capability for complex control and shutdown actions;
- installed hardware to permit on-stream trip testing with final element and shutdown testing.

CONCLUSION

At first glance, this may seem like an abundance of information and design criteria to monitor and incorporate. The design team will likely reach a point where it may not be able to verify that every minute detail has been designed into the new facility. At some point, the engineering and design phase must stop and construction must begin.

During the design stage, as the team works through these tasks, it should view its mission as akin to eating an elephant. At times, it may appear the team will never finish. But each day, a bit more gets done, until the project is complete. In the end, these efforts will be rewarded by the satisfaction of knowing that potentially life-threatening hazards have been designed out, and safety has been designed in. ■

REFERENCES

Alderman, J.A. "PHA-A Screening Tool." Presentation at 1990 Health & Safety Symposium.

American Petroleum Institute. *Management of Process Hazards.* API Recommended Practice 750. Washington, DC: API, 1990.

Bird, F.E. and G.E. Germain. *Practical Loss Control Leadership.* Atlanta: Institute Publishing, 1990.

DeHart, R.E. and E.J. Gremillion. "Process Safety: A New Culture." Presentation at Occupational Safety & Health Summit, 1992.

Dept. of Defense. *System Safety Program Requirements.* MIL-STD-882C. Washington, DC: DOD, 1993.

Dept. of Labor. "Process Safety Management of Highly Hazardous Chemicals, Explosives & Blasting Agents." 29 CFR 1910.119. Washington, DC: U.S. DOL, Occupational Safety & Health Administration, 1992.

E.I. duPont deNemours & Co. *Process Risk Reviews Reference Manual.* Wilmington, DE: E.I. duPont, 1998.

The Environmental Protection Agency. "Chemical Process Safety Management." Section 304, Clean Air Act Amendments of 1990.

The Environmental Protection Agency. "Prevention of Accidental Releases." Section 301, paragraph 1, Clean Air Act Amendments of 1990.

Guidelines for Hazardous Evaluation Procedures. 2nd ed. New York: American Institute of Chemical Engineers, 1992.

Guidelines for Technical Management of Chemical Process Safety. New York: Center for Chemical Process Safety, American Institute of Chemical Engineers, 1989.

Hawks, J.L. and J.L. Mirian. "Create a Good PSM System." *Hydrocarbon Processing.* Aug. 1991.

Krembs, J.A. and J.M Connolly. "Analysis of Large Property Losses in the Hydrocarbon and Chemical Industries." Presentation at 1990 NPRA Refinery and Petrochemical Plant Maintenance Conference.

Lees, F.P. *Loss Prevention in the Process Industries.* London: Butterworth, 1980.

"Large Property Damage Losses in Hydrocarbon-Chemical Industries: A 30-Year Review." 13th ed. New York: M&M Protection Consultants.

O'Lone, E.J. "Datapro, Document Imaging Systems, Management Issues." *Client/Server Computing.* June 1993: 1-8.

NUS Training Corp. "OSHA's Process Safety Management of Highly Hazardous Chemicals in Plain English." Gaithersburg, MD: NUS Training Corp., undated.

Renshaw, F.M. "A Major Accident Prevention Program." *Plant/Operations Progress.* July 1990.

Sherrod, R.M. and M.E. Sawyer. "OSHA 1910.110 Process Safety Management: Its Effect on Engineering Design." Presentation at System Safety Conference, July 1991.

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