GARY CARSON, EQUAMARK, USA, MAKES THE CASE FOR STRICT STANDARDS AND AUTOMATION IN OIL STORAGE TANK ENGINEERING AND DESIGN.
The recent tragic earthquake in Japan brings into sharp focus the importance of enforcing engineering and building codes when constructing. Even with some of the most stringent regulations in the world, the outcome in such extreme situations can be catastrophic, but this only serves to highlight the importance of employing appropriate standards when engineering and designing buildings and industrial facilities: oil storage tanks are no exception. Storage tanks in refineries and chemical plants contain large volumes of flammable and hazardous chemicals. A small accident could lead to multi million dollar property losses, days of lost production and potentially months of investigations. Larger accidents could also spark permanent shutdowns, ongoing lawsuits, stock devaluations or company bankruptcies.

Organisations such as American Petroleum Institute (API); American Institute of Chemical Engineers (AIChE); American Society of Mechanical Engineers (ASME) and National Fire Protection Association (NFPA) publish engineering guidelines and standards for the construction, material selection, design and management of storage tanks and related facilities. These standards have been updated a number of times and even though most companies adhere to them, tank accidents and failures still occur. There is certainly room for improvement.

**Causes of tank failure**

Most oil storage tank damage is attributable to age deterioration, corrosion or (in some locations) seismic motions. Oil storage tanks deteriorate with the passage of time due to rust, fatigue or cracks. Many tanks are subject to harsh environments because they are proximate to a saltwater environment, while the loads of continuous charging and discharging add to the wear. Damage can lead to leakage of a hazardous material, disastrous fires and environmental damage.

A study by Elsevier© (2005 Elsevier ltd.) reported on an analysis of storage tank accidents using information collected from various sources, including published reports from March, McLennan, Persson and Lonnermark; books by CPC,
Pekalski, and Lees; CSB incident news; and databases from UQ, IChemE, PAJ, and USNOAO. The study analysed accidents at 242 bulk oil storage tanks located across the world over the past 40 years. These tanks stored such materials as crude oil, gasoline, fuel oil and diesel. The most common type of tank in the study was the atmospheric external floating roof tank followed by the atmospheric cone top tank.

**Accident assessment**

The Elsevier study examined the locations where storage tank accidents and failures were most common:

- **Petroleum refineries:** 47.9%.
- **Terminals and pumping stations:** 26.4%.
- **Petrochemical plants:** 12.8%.
- **Oil fields:** 2.5%.
- **Other types of industrial facilities (e.g., power plants, gas plants and pipelines):** 10.3%.

A variety of causes were cited for these incidents: lightning, human error, poor maintenance, equipment failure, sabotage, crack and rupture, leak and line rupture, static electricity and open flames. Human error was involved in 30% of the accidents: substandard operations and poor maintenance were common trends. Fire and explosion occurred in 85% of all accidents, presenting a major risk to property and lives.

**Major accidents**

According to the Elsevier report, the average property loss in the 10 largest storage tank damage incidents was valued at US$ 114 million by 2002 rates (approximately US$ 150 million according to 2010 rates). The largest accident in the study occurred in 1986, when sparks from a flame cutting torch ignited fuel from a tank spill in the dike of the tank facility, located in Greece. The fire spread and destroyed 10 of the 12 crude oil tanks. Another major accident occurred in 1968 in the Netherlands, when frothing in a hot oil and water emulsion reacted with volatile material, causing a fire that destroyed a hydrocarbon and sulfur plant, as well as 80 storage tanks. In the US in 1978, a tank failure at a complex in Texas City, Texas, USA caused a leak that ignited, destroying 11 tanks. Many accidents could have been avoided through good engineering practices.

**Failing tank roofs**

Among the equipment failure accidents in the report, 11 cases involved a sunken roof. The typical external floating roof tank has an open topped cylindrical steel shell with a roof that floats on the surface of the stored liquid. A seal system around the floating roof’s perimeter reduces evaporation of the stored liquid. As the liquid level in the tank is raised or lowered, the roof floats with the changing level and the seal system slides against the tank wall. If the roof is out of balance or if the tank body is distorted, it may not function properly. Floating roofs can also sink after a heavy storm due to inadequate drainage, allowing flammable vapours to be ignited by lightning or static charge.

When designing a tank with a simple cone roof, the calculations to be made are very simple. However, large span roofs require a supporting structure, otherwise they would collapse under their own weight. This presents a clear structural problem: to calculate the type of structure that would support the roof, an engineer would have to make several time consuming trial calculations. A conventional structure is comprised of ring girders and rafters supported by columns. When designing a roof today, many designers and engineers believe that a computer and appropriate software is required. A common example of software for tank design and engineering analysis is Intergraph® TANK™, which can deliver accurate and quick results on complicated issues such as roof design and tank structure.

**Avoiding collapse**

Another problem that could potentially lead to the destruction of a storage tank is internal pressure. API 650 allows a maximum pressure of 2.5 psi, but even this amount of pressure multiplied by the cross section of the tank can produce enough force to lift the tank foundation. In 1990, a tank foundation collapse at an Amerada Hess facility in Perth Amboy, New Jersey, USA led to tank failure that created a 6 million gal. lake of oil around the damaged unit.

**Figure 1.** In 1990, a tank foundation collapse at an Amerada Hess facility in Perth Amboy, New Jersey, USA led to tank failure that created a 6 million gal. lake of oil around the damaged unit.

**Figure 2.** In 1988, a catastrophic tank failure occurred without warning at an Ashland facility in Floreffe, Pennsylvania, USA discharging 3.7 million gal. of diesel, with 500 000 gal. ending up in a nearby river. The failure was due to an undetected flaw in the base metal of the tank.

**Figure 3.** Software output for supported cone roof tank design shows results for column, girder, rafter rings and roof plates, ensuring the integrity of the tank by using the latest industry code.
design force is 30 lbs/ft² on a flat projected surface at 100 mph, becoming 67.5 lbs/ft² at 150 mph. Yet, many engineering consultants in the hurricane prone south eastern part of the country recommend designing for 150 mph winds. However, neither standard addresses uplift forces on the roof, despite the fact that hurricane force winds can cause an uplift force exceeding the weight of the roof plate.

The Standard Building Code (SBC) used in Florida states that structures with pitched roofs must apply a pressure coefficient that causes an uplift force on the roof, a point that would include cone roofs on tanks. According to a published report from TEAM Consultants, the winds of Hurricane Andrew in 1992 tested some of these standards when two large oil storage tanks 200 ft in diameter by 48 ft high with flat bottoms and cone roofs experienced a direct hit from the storm. Uplift forces broke the roof to shell weld in several areas around the perimeter. However, this weld is designed to be intentionally weak so that if there is an explosion, it will fail and the roof dislodge before the sidewalls fail. The perimeter top angle failed in many areas, causing buckling and flat spots in the upper tank shell. Rafters went into compression, with some breaking loose, while some of the support columns were also twisted. Despite the considerable damage, the roofs did not blow off and no product was lost.

In high winds, an empty tank is vulnerable to shell collapse. Wind girders in the form of rings are sometimes required to enforce the shell in its true cylindrical shape. Wind can also overturn an empty or near empty tank, especially if the height to diameter ratio is high. In this case, the tank must be bolted to the foundation and the required number and size of the bolts must be calculated. Using the proper tank design software is a sensible and easy solution for addressing these issues.

### Earthquakes

While factors affecting tank corrosion and failures are complicated, protecting against earthquake damage requires the consideration of a different set of factors. These include seismic waveforms and intensity level; the tank’s base and ground conditions of an installation; the tank structure; and the quantity of the tank contents. Thus, tank safety in areas of seismic activity is contingent upon the state of age deterioration and the tank’s structural resistance to an earthquake:

- A 1964 earthquake in Japan caused large amplitude oil sloshing in storage tanks. Several tanks near the sea overflowed and caught fire. Then, a tsunami spread blazing oil over the water, igniting 149 neighboring tanks and a number of residential houses.
- A 1978 earthquake in Japan cracked two heavy oil storage tanks, causing a large quantity of oil to be released into the sea.
- A 2003 earthquake damaged 29 tanks and ignited one tank at a Hokkaido, Japan refinery.
- The 2010 Haiti earthquake caused oil storage tank failures and spills that escaped the containment area and spread into the sea.
- During the 1964 Alaska earthquake, approximately 45 seconds of violent shaking caused an oil storage tank to fail as its bottom moved away.
- At Seward, an oil storage tank caught fire and leaked its contents, spreading flaming petroleum over the waterfront. The fire burned the rolling stock, the electrical generation plant and several homes.
- The 2003 Tokachi-oki earthquake in Japan produced a long period of strong ground motions that caused major liquid sloshing in oil storage tanks, which in turn caused severe damage.

The Tokachi-oki earthquake resulted in formulation of stronger regulations to address the sloshing problem. The natural period of sloshing depends on the tank diameter and the liquid height, but is generally between 3 – 15 secs. The power of the ground motion during this time determines the excitation of sloshing. Excitation of liquid sloshing rarely correlates with the seismic intensity because of the difference of frequency. An undetectable earthquake with a long period of ground motion might produce a delayed emergency response even though it can cause liquid sloshing and fire. If the floating roof sinks, the situation is very serious and could lead to a full surface tank fire.

### Engineering for seismic zones

Normal building codes such as ASCE-7 (American Society of Civil Engineers) provide procedures for analysing structures in the event of seismic activity. These codes are not entirely applicable to storage tank design, as storage tanks contain liquid, thus complicating their response to a seismic event. During a seismic disturbance, the liquid is mobile and sloshing independently of the tank structure, with a tendency to climb up one side of the tank. This causes a local hoop stress in the wall of the tank, which could cause a rupture and spill if ignored, as has occurred in many earthquakes. The seismic calculation is complicated and tedious to implement manually, but the Intergraph TANK software program assesses automatically in accordance with specific seismic codes of proven reliability, ensuring accuracy.

### Subsidence and failure of foundations

Often, tanks are not mounted on solid foundations (e.g. concrete) because foundations of this nature are expensive. Examples of possible substitutes include tamped down sand or sand mixed with diesel oil and/or bitumen. In time, the dynamic influences on the tank can cause it to sink into the foundation, causing the floor and shell of the tank to buckle.

A tank farm should be surveyed periodically to ascertain the current state of the tanks. If distortion is detected, the engineer must make a potentially highly expensive decision on whether the tank is to remain in service, be relocated/repaired or scrapped altogether.

The API 653 standard procedure takes this decision out of the hands of the engineer. Tanks are surveyed using an instrument that can measure the subsidence at various points around the tank. The engineer must then input the data and use the API 653 procedure to determine the extent of subsidence. However, this calculation is very tedious and prone to human error. A tank software program with this application will do it quickly and automatically.

### Deciding when to scrap a tank

A software program can be utilised to determine whether to continue a tank in service or repair it. The software analyses and offers a solution for whether to proceed with use in continuous service or to take steps to correct the amount of distortion. This can be an important undertaking when considering the various types of tank failures and accidents that might occur, especially given that any potential for wind and/or seismic occurrences increases the risk of continuing to use a worn out tank.

As refineries continue to spring up all over the world, both in increasingly hostile environments and closer to residential centres, the use of software that increases the likelihood of detailed, accurate and fast information pertaining to tank design is quickly becoming an invaluable asset to engineers. With this in mind, the days of manual tank design truly appear to be gone.
shell and annular plate off the foundation. In conjunction with wind, installation of holding down bolts is a necessity.

It is also conceivable that a partial vacuum can exist in the tank; the tank wall and roof must be able to accommodate this partial vacuum. Rapid emptying of any tank can produce a partial vacuum sufficient to collapse the shell and rupture the roof to shell joint. As such, it is always wise to fit a properly functioning vacuum breaker. A vacuum collapse is a serious occurrence: thus, calculating for pressures from a vacuum in tank design can involve a fairly lengthy, detailed analysis. Employing the appropriate software is one method to expedite the task.

Preventing hazards
A number of major incidents have been caused by cracks and ruptures: tank cracks, body ruptures, roof holes and flange cracks, which in turn caused spillages of such hazardous materials as crude oil, hydrochloric acid, sulfuric acid, molten sulfur and sodium cyanide solution. Cracks usually occur at the bottom or at the welding edges of tanks, while spills that occurred at seashores and riverbanks have released large quantities of hazardous contents into the water. The study cites a number of examples:

- A crack at the bottom of a crude oil storage tank at a Taiwan refinery in 1970 was caused by the slow subsidence of the foundation.
- A crack at the bottom plate of a tank at a refinery’s port released 7.5 million ltrs of heavy oil into the sea.
- A crack in a storage tank at a Texas oil and chemical company allowed oil to escape, leading to a fire.
- A flange crack of an oil tank at a Texas oil and chemical company caused spillages of such hazardous materials as crude oil, hydrochloric acid, sulfuric acid, molten sulfur and sodium cyanide solution.
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Figure 4. Shell settlement diagrams plot the measured settlement around the tank against the planar cosine curve, as shown in this image from Intergraph® TAnK™.

Figure 5. In Aug 2005, Hurricane Katrina caused millions of gallons of oil to spill from storage tanks. In Chalmette, 1700 homes were polluted by 7.6 million ltrs of mixed crude that escaped from a nearby tank farm.

Crude oil spills from storage tanks at refineries in Taiwan and the UK were caused by the corrosion of the tank bottom.
- At another UK facility, the corrosion of a defective tank weld caused 12 t of sodium cyanide solution to spill into the ground and a nearby river.
- In 1993, a worker at a Taiwan refinery fell into a tank through a rust hole on the roof.
- A flange crack of an oil tank at a Texas oil and chemical company allowed oil to escape, leading to a fire.
- The bottom portion of a newly fabricated tank containing hydrochloric acid failed at an Illinois lighting plant, allegedly due to fabrication error.
- A crack in a storage tank at a Pennsylvania terminal released 92 400 bbls of diesel oil into the river.
- In Japan, a crack at the bottom plate of a tank at a refinery’s port released 7.5 million ltrs of heavy oil into the sea.

Tank shell integrity
Computing the required thickness of the storage tank shell courses is a fairly simple process that is nevertheless important to preventing failure of the shell. Tanks over 200 ft in diameter are more complicated. The variable point method of calculation for these tanks is long and requires the use of technology. In the design of storage tanks, the pressure proportionally increases with depth of the liquid. As a result, the shell thicknesses in lower sections of the tank are designed to be thicker than in higher shell courses. The designer must therefore calculate for each shell course in order to arrive at an economical structure. Tank software can address the task faster and easier, offering the capability for the design to be modified and quickly analysed.

Hurricanes and typhoons
The extreme weather that arrives with hurricanes/typhoons can cause huge damage to oil storage tanks:
- In 1989, Hurricane Hugo destroyed 14 storage tanks in a tank farm in St. Croix, Virgin Islands.
- In 1970, Hurricane Celia with its 150 mph winds damaged 30 storage tanks in Corpus Christi, Texas.
- When Hurricane Ike struck near Houston, Texas in 2008, damage to facilities caused a reported half million gal. of crude oil to spill into the Gulf of Mexico, bayous and marshes.
- The storm surge flooded a facility on Goat Island, causing 266 000 gal. of oil to vanish into the bay and gulf.

Hurricane Katrina
Although the events surrounding Hurricane Katrina in August 2005 were unusually severe (the storm is now ranked among the worst environmental disasters in US history), they exemplified the rule that tanks must be designed with the ability to withstand strong winds. The storm made landfall near New Orleans with winds of 112 -x130 mph and a storm surge of 8 - 12 ft. The Mississippi River’s levee system failed, and the storm surge inundated many oil refineries, lifting and dislodging oil storage tanks, many of which released oil into the river, bay and sea. One oil tank at a refinery in Meraux spilled more than 1 million gal. of oil into the surrounding neighborhoods and canals. The storm caused approximately 44 oil spills, totalling 9 million gal.

Designing for high winds
The AWWA D100 and API-650 standards for tank design used in the US provide for 100 mph winds. Both standards increase wind force in proportion to the square of the wind speed. The standard