A CHEMICAL ENGINEERING INVESTIGATIVE PROJECT FOR SECONDARY SCHOOL STUDENTS

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Engineering faculties around the world must constantly work to ensure that they attract high quality students to their courses, but unfortunately, prospective students often have a poor appreciation for engineering. They are unaware of the diversity of challenges and opportunities that await them in an engineering career.

A number of strategies exist to raise the profile of engineering for students in secondary schools. One activity involves engineering academics either visiting the schools or playing host to the students on college campuses. Another method is to furnish secondary-school mathematics teachers with real engineering design problems that can be solved by the application of relatively simple mathematical concepts.

This paper describes a challenge in chemical engineering design that can be answered in the classroom by applying logic and a knowledge of the volumes of cylinders and rectangular prisms. The problem can be presented to different grade levels by selecting individual parts and can either be carried out by individuals or as a team exercise. It was presented to groups of secondary-school mathematics teachers in 1994 and 1995, and it has since been incorporated into the secondary school syllabus in a number of schools in Victoria, Australia.[1]

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The problem involves the design of a bulk liquid chemical storage facility—a tank farm. Students are asked to design a facility to store a given volume of liquid while considering such design aspects as bund (berm) wall height and thickness, tank spacing, maintenance access, and allowance for fire-fighting water. A presentation to mathematics teachers in as little time as forty-five minutes can provide sufficient information for them to return to their schools and tailor the material to their individual requirements.

BACKGROUND MATERIAL

The information session for the teachers begins with an introduction to the use of tank farms. It is important to give the teachers local examples of where tank farms can be found. In the case of Melbourne, we refer to a bulk liquid chemical storage facility located at Coode Island, less than 4 km from the downtown area. This facility is well known locally due to a major fire at the site in August of 1991. We show video footage of the facility and the fire and emphasize the fact that because of proper facility design, all the spilled liquid chemicals and fire-fighting water was contained within the site. As the video is shown, we point out the bunds, the position of the tanks within the bunded compounds, and the pipe tracks.

While some may argue that it is unwise to highlight an incident that brought bad publicity to the local chemical industry, we feel it is important to emphasize that good engineering design helped to contain a dangerous situation. We describe and discuss the important safety aspects of

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design and bring attention to the relevant standards and government regulations as a way of showing how engineers must work within the framework of government rules and restrictions. In Victoria, reference is made to the appropriate Australian Standard, AS 1940-1988 The Storage and Handling of Flammable and Combustion Liquids, and the Dangerous Goods (Storage and Handling) Regulations of 1989. Local equivalents would be substituted as appropriate.

In order to limit the problem, only upright cylindrical tanks are considered. We point out that these tanks must be built within a bunded area that will contain any spill. The government regulations and standards require that the spill containment compound enclosed by the bund has a net capacity equivalent to the largest tank in the compound, plus ten percent of the capacity of the second largest tank, plus a volume equal to the output of the fire-fighting sprinkler system over a period of twenty minutes. These figures vary depending on the particular standard or government regulation.

We give the teachers the following information with respect to the design requirements of the spill containment compound:

1. *The ground within the bund must slope gently away from the tank to prevent accumulation of liquid around the base of the tank. Any liquid spill must drain to a sump within the bunded area.*
2. *The bund wall must be no higher than 1.5 m above the compound floor to ensure adequate ventilation around the tanks and to allow quick egress from the compound in an emergency.*
3. *The bund wall must be impervious to, and compatible with, the dangerous chemicals stored within the compound.*
4. *The bund must be designed to withstand the hydrostatic head when full.*
5. *The perimeter of the spill compound must be located a sufficient distance from all tanks within the compound to prevent a leak from the surface of the tank spilling over the bund outside the compound. The minimum distance between a tank and the bund wall is one-half the height of the tank above the top of the bund wall.*
6. *The bund wall must have a flat section at the top not less than 600 mm wide.*
7. *Incompatible chemicals may not be stored within the same bunded area.*
8. *The bunded area may contain no equipment, with the exception of the tanks and the pipes that service them. Pumps are not permitted within the spill collection area.*
9. *The minimum distance between any two tanks in the same collection area depends on the diameters of the two tanks:*
   - *If neither tank exceeds 6 m in diameter, the distance between them shall be not less than either one-third of the diameter of the larger tank or 1 m, whichever is the greater.*
   - *If one of the tanks is more than 6 m, but neither is more than 20 m in diameter, the distance between them shall be not less than one-half of the diameter of the larger tank.*
   - *If one of the tanks is 20 m or more in diameter, the distance between it and any other tank shall not be less than 15 m.*
10. *Where the aggregate capacity of the tanks in any compound exceeds 10,000 m^3, intermediate bunds of at least half the height of the main bunds or 600 mm, whichever is the lesser, shall be provided so that any subdivision so created contains tanks having an aggregate capacity not exceeding 10,000 m^3, or a single tank if such tank exceeds that capacity.*

Not all the design requirements listed above are used in the calculations that follow. For example, the third and fourth points relating to the physical design of the bund are provided for the general information of the teacher and student, but are not required in the actual calculations. It is important, however, that this type of background information is included.

A WORKED EXAMPLE

The teachers are given a worked example for the design of a facility to store 26,000 bbl of oil. The oil is to be stored in four identical tanks located within a single containment area. We begin by performing a unit conversion to obtain an oil volume of 4134 m^3. If a maximum height restriction of 9.1 m is arbitrarily set for the four tanks, then the minimum diameter for each of the tanks is found to be 12.1 m. Alternatively, the tanks could be required to be half as high as they are wide. A height of 6.9 m and a diameter of 13.8 m would be calculated.

Next, we calculate the minimum volume of the spill containment area necessary to satisfy government regulations. We recall that the minimum volume *equals* the volume of the largest tank *plus* 10% of the next largest tank *plus* a 20-minute supply of fire-fighting water. If we arbitrarily assume a volumetric flow rate for the fire-fighting water of 30 m^3/min, and we recall that the four tanks are identical, then

$$\text{Minimum Volume} = 1034 + 0.1 \times 1034 + 600 = 1737\ \text{m}^3$$

Regulations demand a bund wall be no higher than 1.5m. Assuming an average depth of 1.4 m within the spill compound, we then calculate that 1241 m^2 is the minimum area of the spill containment compound available to contain the liquid.

The spill compound is to be square, with the four tanks equally spaced in a square pattern within it (see Figure 1). If each tank has a diameter of 12.1 m, we then calculate the minimum length of one side of the compound. Letting L be the length of one side of the compound and assuming the bund walls are vertical, we find

$$\text{Area} = L^2 - 4\frac{\pi d^2}{4}$$

where the second term accounts for the area taken up by the bases of the four tanks. Therefore

$$1241 = L^2 - \pi(12.1)^2$$

or

$$L^2 = 1701 \qquad \text{or} \qquad L = 41.2\ \text{m}$$

So the length of one side of the compound is 41.2 m.

We then ask whether this length is practical. Would a compound with this length satisfy the spacing requirements of the government regulations? Consider the spacing between the tanks and between the tanks and the bund walls. The minimum distance, d_{TT}, between adjacent tanks is one-half the diameter of the largest tank. The minimum distance, d_{TB}, between a tank and a bund wall is one-half the height of the tank above the level of the top of the bund wall.

If	tank diameter	=	12.1 m
	tank height	=	9.1 m
	bund wall height	=	1.5 m

then

$$d_{TT} = \frac{12.1}{2} = 6.1\ \text{m}$$

$$d_{TB} = \frac{(9.1 - 1.5)}{2} = 3.8\ \text{m}$$

Considering Figure 2, we see that the minimum length of one side, L_{min}, is given by

$$\begin{aligned} L_{min} &= d_{TB} + d + d_{TT} + d + d_{TB} \\ &= 2 \times 3.8 + 2 \times 12.1 + 6.1 \\ &= 37.9\ \text{m} \end{aligned}$$

Since 41.2 m is greater than the minimum length required to satisfy the minimum spacing requirements, this length is practical.

The degree of difficulty of the above problem can be increased by requiring the calculation of the optimum tank height-to-diameter ratio so that the area occupied by the spill- containment compound is a minimum. Letting $\alpha = h/d$, we find

$$V_{Tank} = \frac{\pi d^2 h}{4} = \frac{\pi \alpha d^3}{4}$$

and thus

$$d = \sqrt[3]{\frac{4V_{Tank}}{\pi\alpha}} \qquad \text{and} \qquad h = \sqrt[3]{\frac{4V_{Tank}\alpha^2}{\pi}}$$

Denoting the containment area by A_{cont} to find

$$A_{cont} = L^2 - \frac{4\pi d^2}{4}$$

$$\Rightarrow L = \sqrt{A_{cont} + \pi d^2}$$

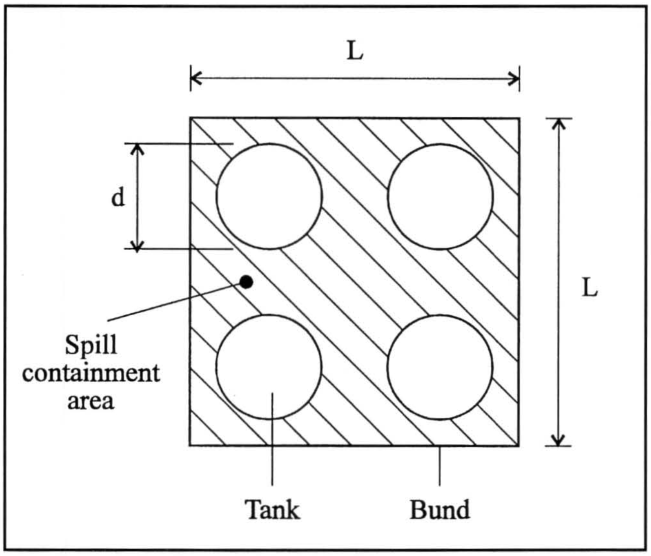

Figure 1. *View of the spill-containment compound showing the location of the four identical tanks.*

$$\begin{aligned} L_{min} &= 2\,d + 2_{TB} + d_{TT} \\ &= 2\,d + 2\left(\frac{h - 1.5}{2}\right) + \frac{d}{2} \\ &= 2.5\,d + h - 1.5 \end{aligned}$$

The minimum area of the compound occurs when

$$L = L_{min}$$

$$\sqrt{A_{cont} + \pi d^2} = \frac{5}{2} d + h - 1.5$$

$$\sqrt{A_{cont} + \pi\left(\frac{4\,V_{Tank}}{\pi\alpha}\right)^{2/3}} = \left(\frac{5}{2} + \alpha\right)\sqrt[3]{\frac{4\,V_{Tank}}{\pi\alpha}} - 1.5$$

We know that $V_{Tank} = 1034\ m^3$ and $A_{cont} = 1241\ m^2$. Solving the equation, we obtain $\alpha = 2.25$. Therefore

$$d = 8.36\ m, \quad h = 18.8\ m, \quad \text{and} \quad L = 38.2\ m$$

In performing the above calculations, a number of simplifying assumptions have been made to allow the problem to be applied in the classroom without unnecessary complications. The problem, however, still retains a number of important engineering considerations.

This exercise has been developed so that it can be pitched to different grade levels. Younger students may be asked to perform the basic calculations, while more senior or capable students may be required to perform optimization calculations. In performing the calculations, the junior students might be told to assume that the ground within the spill-collection compound is flat. More advanced students, however, might be told that to prevent any spilled liquids from collecting around the base of the tank, the floor of the compound slopes away from the tank. They would then have to assume that the tank is located at the apex of a flat cone and that they must account for this change of depth within the spill-collection compound in their calculations.

CASE STUDY: A TANK FARM FOR A SMALL REFINERY

The tank farm for a small refinery must be able to store the unrefined oil as well as a range of products that can include different grades of gasoline, diesel fuels, and lubricating oils. These liquids would be stored in tanks of different sizes in a number of different spill-containment compounds.

A class exercise that could be developed by the teacher would involve the preparation of a neat, scaled plan of such a tank farm. Each student or group of students could be responsible for performing the design calculations for a single containment compound. The plan would include the individual tanks and containment compounds as well as showing the location of roads and pipe reservations.

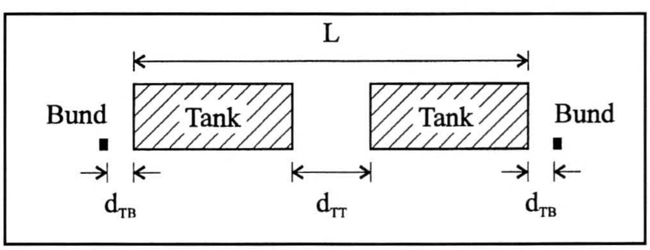

Figure 2. *Side view of the spill-containment compound.*

In designing the tank farm, the following points should be considered;

- *The width of the pipe reservation will range between 2 and 4 m. The reservation is outside the bund and runs between the tanks and the loading points.*
- *The width of the roadways between the compounds will be about 8 m for side roads and 10 m for main roads.*
- *Compounds with tanks storing different liquids should not share a common bund.*
- *The minimum number of tanks required for any one product is three.*
- *Several additional tanks should be included in the plan to increase flexibility of refinery operation.*
- *The largest tank on site should be no larger than 21 m high and 46 m in diameter. The next largest size would be 17 m high and 41 m in diameter.*

These figures have been arbitrarily set as a guide for the teachers.

CONCLUDING REMARKS

Many of the calculations presented to the teachers can be automated by the students using spreadsheet packages such as Microsoft Excel. Students would then be able to see how varying parameters such as the tank aspect ratio, bund wall height, and number of tanks can affect factors such as the required area for the spill compound.

Whether they are teaching simple algebra or more advanced calculus, mathematics teachers at any grade level are often confronted by students with questions such as "Why are we learning this?" and "What is this used for?" Examples of real engineering problems such as the one described above, albeit in simplified form, allow the teachers to answer some of these questions. This sort of activity not only helps to raise the profile of engineering in secondary schools, but it also provides mathematics teachers with a valuable resource. This exercise has been greeted enthusiastically whenever it has been presented to teachers.

REFERENCES

1. Shallcross, D.C., "Investigative Project in Engineering: Designing a New Coode Island," *Proc. of the Mathematics Association Victoria 32nd Ann. Conf.*, Mathematics Association of Victoria, Melbourne, Australia (1995) ❐