

# ***LTA 4***

## *NASA - AMATYC - NSF Project Coalition*

*Kennedy Space Center*

**Just Say “NO” to Cracks in the Space Shuttle**

*Mathematics for Engineering Technology*

**Mechanical  
Materials**



*Capital Community-Technical College*



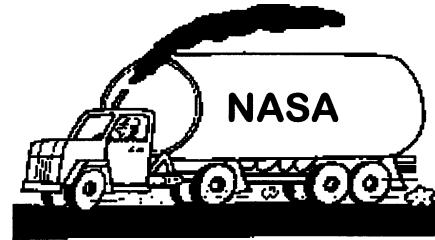
Spherical tank that is labeled “LIQUEFIED HYDROGEN FLAMMABLE GAS” (Bottom Right) provides one of the key energy components and the tank on the tall tower (Middle Right) provides water for sound suppression during launch of the Space Shuttle.

## LTA 4

### Just Say “NO” to Cracks in the Space Shuttle

#### The Background

As a Mechanical Engineer at NASA’s Kennedy Space Center, Eric Thaxton analyzes cracks that occur in various structures. His main concern is examining and evaluating fractures in metallic structures. These fractures can be found in such things as tubes, pipes, liquid storage tanks, ocean liners, bridges, the Space Shuttle, or components for the space station.



If a crack reaches its critical stage, the crack will then expand at the speed of sound and the structure will most likely burst with possible catastrophic consequences. When engineers realized that cracks were often the cause for a structure bursting, the need for experts in cracks emerged. The intensive study of cracks is a relatively new field in Mechanical Engineering called Fracture Mechanics. As a result, great strides have been made in detecting and analyzing cracks, especially cracks that were previously undetected. The use of ultrasound and x-rays enables the engineer to make these detections.

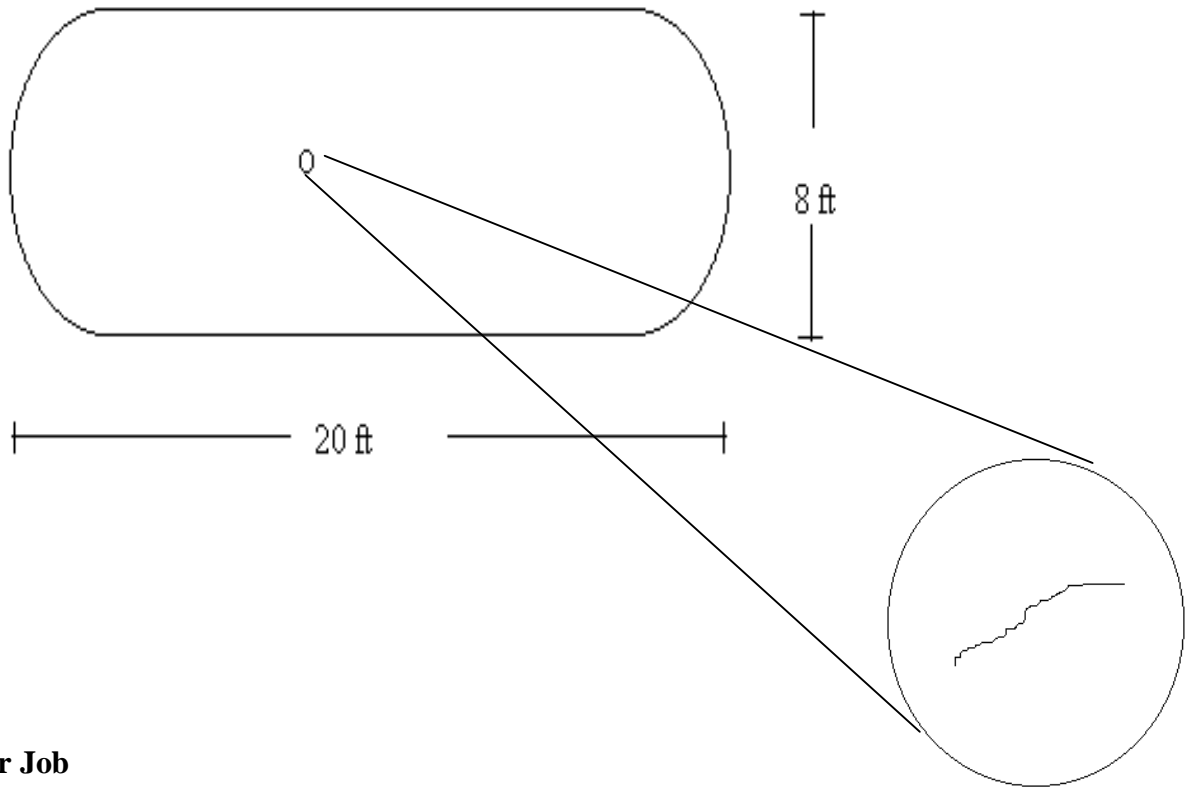
Environmental concerns necessitate that we reuse or extend the current use of metal structures that would previously have been abandoned. With pressure vessels (liquid storage tanks with the liquid under pressure) priced in the hundreds of thousands of dollars, economic and budgetary concerns also demand the wise recycling of these structures. Obviously, safety must be an overriding concern of the engineers charged with the decision on continued use.

#### The Problem

Recently, Eric Thaxton was asked to examine an abandoned storage tank which had been used years ago by the Air Force to store highly corrosive and toxic monomethyl hydrazine. Project personnel asked Eric to help decide, from a structural standpoint, if the tank could be repaired and salvaged as a water storage tank or if it would be necessary to purchase a new tank. A new tank would cost approximately \$100,000 and delay the project for the 6 months to a year needed to manufacture a new tank.

Figure 1 shows a drawing of the tank and a magnification (from the drawing) of the area where the crack was found. The crack has been magnified from the drawing so that it corresponds to its actual size. What is the length of the crack in inches? Approximate the length by measuring it from end to end.

**Figure 1**



**Your Job**

You will determine whether to recommend no corrective action relative to the crack (because the crack does not endanger the tank) or corrective action (repair or replace the tank).

Before introducing the mathematics that applies to cracks, think about a gas-filled pipe on which you have found a crack. The crack does not go all the way through the pipe wall. This is similar to a cut on a car or bicycle tire that does not go all the way through the rubber. What conditions are likely to make the crack grow larger and rupture the pipe? To help organize your thinking about this, answer the following questions.

The first step is to get a pipe and actually measure each of the following characteristics in either inches (in) or millimeters (mm), depending on what system (customary or metric) you are using for other information. Also make a diagram of the pipe that shows each of the measurements. Be sure to label your answers with the units of measurement.

- The inside diameter of the pipe = \_\_\_\_\_
- The outside diameter of the pipe = \_\_\_\_\_
- The outside radius of the pipe = \_\_\_\_\_
- The inside radius of the pipe = \_\_\_\_\_
- The thickness of the pipe wall = \_\_\_\_\_

The next step is to think about how changes in the following characteristics affect the likelihood that a crack on a tank will actually develop into a rupture. As you consider each characteristic, assume that all the other characteristics remain constant.

- 1) **Pressure:** If you increase the pressure of the gas, will the crack be more or less likely to rupture the pipe? In considering this question, think about a bicycle tire that has been almost cut through by a piece of glass. If you continued to pump air into the tire, what do you expect would happen?
- 2) **Thickness of pipe wall:** If you decrease the thickness of the pipe wall (make the wall thinner), will the crack be more or less likely to rupture the pipe?
- 3) **Radius of pipe:** If you increase the radius of the pipe (but keep the wall thickness unchanged), will the crack be more or less likely to rupture the pipe? In arriving at a conclusion, think about a small tube, such as a blood vessel (an artery), that has a very thin wall and imagine a crude oil transfer pipe of radius 2 feet that has the same wall thickness as the vein. Under the same pressure, which is more likely to burst?
- 4) **Stress on pipe:** By considering 1, 2, and 3, complete the following sentence by choosing the correct answers. The vulnerability of a pipe to being ruptured by a crack, referred to as the stress on the pipe, [increases, decreases] if the pressure is increased, [increases, decreases] if the wall thickness is decreased, and [increases, decreases] if radius of the pipe is increased.
- 5) **Length of crack:** If you increase the length of the crack, will the crack be more or less likely to rupture the pipe?
- 6) **Stress Intensity Factor:** By considering 4 and 5 complete the following sentence by choosing the correct answers. The likelihood that a crack will rupture a pipe, referred to as the stress intensity factor, [increases, decreases] if the length of the crack is increased and [increases, decreases] if the stress on the pipe is increased.

You will need the following formulas and terms to solve this problem. As used here, a tank is a pipe.

**Stress Intensity Factor**

$$K = s \cdot \sqrt{p \cdot a}$$

**Thin Wall Stress**

$$s = \frac{P \cdot r}{t}$$

where

$a$  = crack half length, crack is  $2a$  long (in or mm)

$\sigma$  = stress (psi or MPa)

$K$  = stress intensity factor (psi-in<sup>1/2</sup> or MPa-mm<sup>1/2</sup>)

Note: in<sup>1/2</sup> is pronounced 'root inches', psi represents pounds per square inch, and

MPa represents MegaPascal, the metric unit for pressure

$P$  = pressure in pipe (psi or MPa)

$r$  = arithmetic mean or average radius of pipe (in or mm)

$t$  = wall thickness (in or mm)

## Exercises

- 1) A 28 mm long crack is found in an airplane wing. The stress in that area of the wing is 112 MPa. What is the stress intensity factor for this crack?
- 2) An axle shaft in a car has two cracks in it. Crack 1 has a length of 0.2 inches and a stress of 50,000 psi. Crack 2 has a length of 0.1 inches and a stress of 100,000 psi. Which crack has a higher stress intensity factor, or are they the same?
- 3) Suppose a tank has  $P = 600$  psi with an average radius of 12 feet. Construct a table of values of  $\sigma$  versus  $t$ . Describe the relationship between the thickness of the wall and  $\sigma$ .
- 4) In a steel tank  $\sigma$  is known to be 14,000 psi. The smallest crack that can be detected is 0.25 in, which happens to be the largest crack allowed. What is the range of values for  $K$  for a safe tank?

## Back to the Problem

### Criterion 1

Eric has provided your team with the **allowable** value of  $K$ , the Stress Intensity Factor for a crack. The allowable value of  $K$  was determined by finding the **critical** value for the Stress Intensity Factor  $K_c$  from a table, by deciding what the safety factor would be, and then by dividing  $K_c$  by the safety factor. The safety factor is usually a number between 1 and 3.

$K_c$ , the critical value, is the actual point at which the crack will expand at the speed of sound. For this tank, Eric has determined that an **allowable** value for  $K$  is 100,000 psi-in<sup>1/2</sup>. The wall thickness of the tank is 3/8 of an inch, and the average radius of the tank is 48 inches. The pressure on the tank is approximately 110 pounds per square inch (psi). According to this information and the information from Figure 1, is the crack safe (does not require corrective action) or unsafe (requires corrective action)? [Note on terminology: The word “allowable” in either of the expressions, “the allowable stress” or “the allowable stress intensity factor” actually means “maximum allowable” unless the context indicates a range of allowable values.]

### Criterion 2

Another criterion for determining whether a crack can pose a problem is if it goes all the way through the wall. As a rule, if the length of the crack is greater than 2 times the thickness of the wall, then you can assume the crack goes almost all the way through the wall. If the crack goes all the way through, you will get a leak. This may or may not result in the crack exceeding the allowable Stress Intensity Factor, but it would still require that the tank be scrapped (if it cannot be repaired). According to this new information, does the crack in the tank go almost all the way through and thus pose a problem?

## The Lamé Equation

Engineers use the following rule of thumb: If the ratio of the radius of the structure to the wall thickness is greater than six, then use the Thin Wall Stress equation. Otherwise, engineers use a different equation, called the **Lamé Equation** (pronounced “La-May”).

$$S = P \frac{r_o^2 + r_i^2}{r_o^2 - r_i^2}$$

$\sigma$  = stress (psi or MPa)

$P$  = pressure in pipe (psi or MPa)

$r$  = average radius of pipe (in or mm)

$r_o$  = outside radius (in or mm)

$r_i$  = inside radius (in or mm)

## Exercises

For each of the following exercises, calculate the radius to wall thickness ratio to determine which equation (Thin Wall or Lamé) should be used. Unless otherwise specified, use only that equation when calculating stress.

- 5) A pipe has an outside radius of 2.375 inches and an inside radius of 2.07 inches. What is the average radius and the wall thickness? If the pressure is 6,000 psi, what is the stress by the thin-wall equation and by the Lamé equation?
- 6) A tank has an inner radius of 35 inches and an outer radius of 36 inches. The maximum stress the material can withstand is 120,000 psi. What is the highest pressure the tank can withstand?
- 7) A thin-wall pipe needs to have a radius of 30 mm and to withstand a pressure of 10 Mpa. It will be made of aluminum with an allowable stress of 100 Mpa. What is the required wall thickness? If the pipe was made of steel with an allowable stress of 250 Mpa, what would the required wall thickness be then? Construct a table showing stress as a function of wall thickness.
- 8) A pipe has a 0.25 inch crack. The pipe has an outside radius of 24 inches and a wall thickness of 1.5 inches. The pressure in the pipe is 600 psi. The pipe is made of steel with an allowable stress intensity factor of 75,000 psi-in<sup>1/2</sup>. What is the allowable stress on the pipe? Is it safe to operate at the given pressure? What is the maximum allowable pressure for the pipe?

## The Project

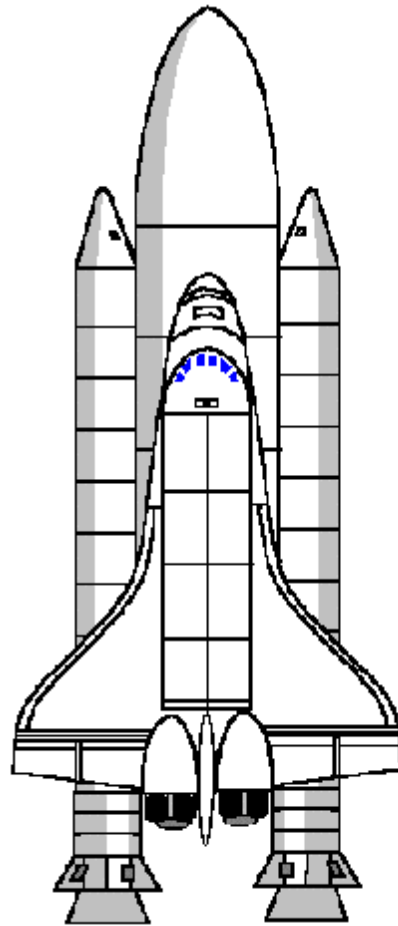
In the early days of the Shuttle program, scientists and engineers collaborated to design and develop the Solid Rocket Boosters (SRBs). An integral part of the Shuttle, the two SRBs provide the initial thrust for lift off. One of the many issues concerning NASA's fracture mechanics engineers was, "Given the size and pressure requirements, what is the optimal wall thickness for each SRB?"

This project allows you and your team to experience some of the problems that face engineers who analyze cracks.

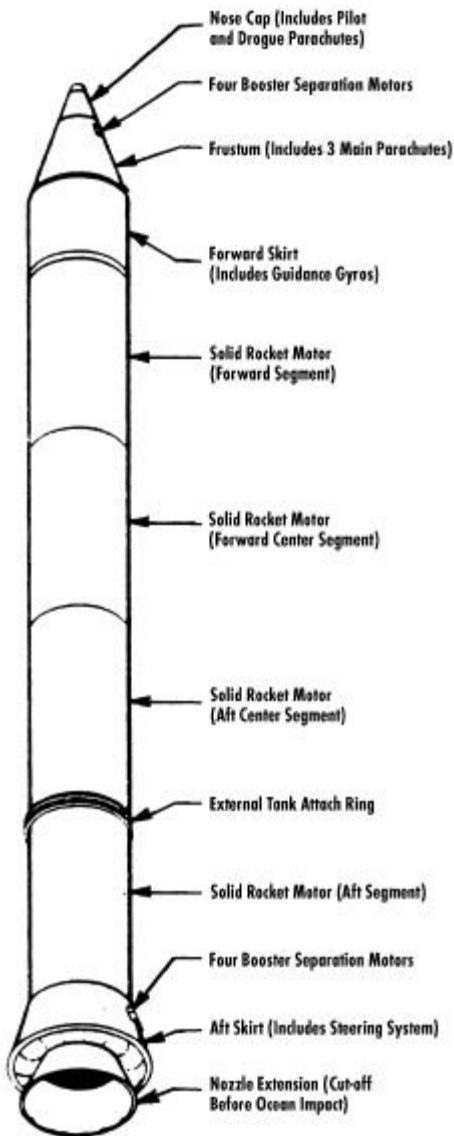
- 1) Each SRB is constructed from high strength steel. Another team has decided that the outside diameter must be 12.2 feet in diameter. The pressure will be about 900 psi. Eric has informed your team that the SRB can withstand a stress of 130,000 psi. Use the Thin Wall Equation to determine your team's recommendation for the SRB wall thickness.

After the boosters separate from the Shuttle, they descend by parachute into the Atlantic Ocean off the Florida coast. Retrieved by ship, the SRBs are returned to Kennedy Space Center for refurbishment and reuse. Before they can be reused, each section must be visually inspected for cracks. Technicians can *calculate* the Stress Intensity Factor,  $K$ , for each crack and compare the  $K$  to the *allowable* Stress Intensity Factor. The allowable Stress Intensity Factor is determined by a variety of considerations including the critical Stress Intensity Factor,  $K_c$ , and safety issues. For the SRB it has been determined that the allowable Stress Intensity Factor for a crack is  $100,000 \text{ psi-in}^{1/2}$ .

- 2) With input from all the working scientists and engineers, the consensus was that the wall thickness of the SRB should be one-half inch. Use the Lamé Equation to judge whether a portion of the SRB with a crack that is  $5/16$  inch requires corrective action. (Note: In this situation, you are asked to use the Lamé Equation even though the Thin Wall Equation could be used since the ratio of the radius to the wall thickness is greater than 6.)



- 3) Rather than repeatedly calculating the Stress Intensity Factor, Eric has asked your group to prepare a graph of  $K$  versus length of the crack. Your graph will allow the inspector to determine rapidly the status of a crack in the wall of the SRB. After each inspection, the values,  $K$  and  $2a$ , can be recorded so that crack growth and other possible results can be evaluated. Assume that any crack in the SRBs that is one inch or longer is imminently critical or subject to breakthrough and is repaired, so your graph does not need to include those values.



- 4) Using your graph, determine the Stress Intensity Factor and the action that should be taken for cracks of length 0.1 inch, 0.25 inch, and 0.3 inch.
- 5) Two unrelated, simultaneous changes at NASA have caused your graph to become obsolete. Further studies have determined that a safer allowable Stress Intensity Factor for a crack is  $85,000 \text{ psi-in}^{1/2}$ . Personnel changes demand that you provide the inspectors with a table of values that allow them to use the measured length,  $x$ , of the crack to determine  $K$ . Construct such a table with a domain of  $0 \leq x \leq 0.5$  and increments of 0.05. Your table must clearly indicate the values of  $K$  which will lead you to recommend corrective action (repair or replacement of the tank) relative to the associated cracks.

**Graphics Credit** Tank Truck, *Desk Gallery/Zedcor, Inc. 1994*