

## Lab 12: Hot Air Balloon Competition\*

Introduction to Engineering and Design, Section Z5

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\*The illustrations and data in this report are taken from multiple reports. They are included solely as examples and should not be understood to represent actual data.

## Abstract

The objective of “Lab 12: Hot Air Balloon Competition” was to design and build a hot air balloon and enter it in a competition. The competition was judged by a ratio that used time afloat in seconds, the cost of the balloon in dollars, and the payload (paperclips) the balloon carried. The highest ratio won.

On its first trial, the balloon achieved a ratio of 0.00. On its second trial, the balloon achieved a ratio of 6.25. It placed second among five balloons in the competition.

The first-place balloon achieved a highest ratio of 8.79. The third-place balloon achieved a highest ratio of 4.84. The two remaining balloons tied for fourth with ratios of 0.00.

## Introduction

While hot air balloons are primarily used for recreation and advertising, these lighter-than-air aircraft have uses in the sciences. The NASA Balloon Program uses zero-pressure balloons, which are open at the bottom and have ducts, for short flights and super-pressure balloons, which are enclosed and do not allow the gas inside them to escape, for longer flights. Super-pressure balloons (Figure 1) can lift up to 8,000 lb of equipment to high altitudes to gather data on the atmosphere or Earth (NASA, 2017).



Figure 1: NASA Super-Pressure Balloon (NASA, 2017)

More common types of hot air balloons are dirigibles, blimps, and aerostats.

Dirigibles have steel frames and use bags of light gas for lift. Blimps are large helium balloons with motors. Aerostats are blimps that are attached to the ground. Some aerostats are not attached to the ground and are used as weather stations or radar platforms. These aerostats can climb to 15,000 ft (NYU Tandon, 2023).

The Ideal Gas Law, gas density, and the Principle of Archimedes explain why hot air balloons float.

The Ideal Gas Law (1) predicts that when a body of gas is heated, it will expand. With that expansion, its mass will remain the same, but its volume will increase and its

density will decrease making it lighter. Another body of gas with the same mass, but a lower temperature can have a much higher density.

$$PV=nRT \quad (1)$$

In the Ideal Gas Law, P is the gas pressure, V is the volume of gas, T is the absolute temperature of the gas, and n is the number of moles of gas. The universal gas constant R has a value of  $0.0821 \text{ L} \cdot \text{atm/mol} \cdot \text{K}$  (NYU Tandon, 2023).

The Principle of Archimedes says that these differences in temperature and gas density lead to the tendency of masses of hot air and hot air balloons to rise.

Archimedes' principle says that when a body is immersed in a fluid, which can be a liquid or a gas, it displaces the fluid around it. As a result of that displacement, a force called buoyancy is exerted on the body that is equal to the weight of the displaced fluid (NYU Tandon, 2023).

When the air inside a hot air balloon has the same temperature as the air surrounding the hot air balloon, that buoyant force is equal to the weight of the air in the balloon. When the air in the balloon is hotter than the ambient air, the net upward force is greater than the weight of the air in the balloon. If the combined weight of the balloon's structure, payload, and the air inside it is less than the buoyant force, the balloon will rise.

This lab was a competition. Balloons were designed and built using only the materials in Table 1. Most of the materials had a cost.

Table 1: Materials with Price List (NYU Tandon, 2023)

Material	Unit	Cost per unit (\$)
Drawing paper	One sheet	\$0.10
Tissue paper	One sheet	\$0.10
8½ x 11 paper sheets	One sheet	\$0.05
Kevlar string	30 cm	\$0.05
Adhesive tape	30 cm	\$0.03
Plastic straws	One straw	\$0.00

Once constructed, the balloons were held over a heater to fill them with hot air. The balloons were required to carry a payload of paperclips. Performance was judged by a ratio (2) that used time afloat in seconds, the cost of the materials used to build the balloon in dollars, and the payload or the number of paperclips carried (NYU Tandon, 2023).

$$\frac{\text{Time afloat (s)}}{\text{Cost (\$)}} \times \text{Payload} \quad (2)$$

The competition rules required that the design be approved before it was entered in the competition, the balloon's volume could not exceed 1.00 m<sup>3</sup>, all materials used to build the balloon had to be purchased, no purchased materials could be returned for credit, time afloat was the elapsed time from when the balloon first rose to when it returned to its starting position, and if the balloon did not rise, time afloat was 0.00 s.

All balloons were allowed three trials. Violating any rule resulted in disqualification though no balloons were disqualified in this competition (NYU Tandon, 2023).

That the rules had a maximum allowed volume suggested that constructing a balloon with a volume as close to  $1.00 \text{ m}^3$  as possible was a winning strategy. A greater volume would result in a greater displacement of ambient air and a greater buoyant force pushing the balloon upward. That greater buoyant force would also mean that the balloon could carry a higher payload and since payload was the multiplier in the competition ratio that should result in a higher ratio. But cost was in the denominator so limiting cost would also tend to increase the ratio.

## Procedure

The materials used to design and build the hot air balloon were three sheets of tissue paper, one sheet of drawing paper, 30.00 cm of Kevlar string, and 30.00 cm of adhesive tape. Other materials used that had no cost were straws, a glue stick, a heater, scissors, and a stopwatch.

Ideas were discussed for a hot air balloon design and research on hot air balloons was conducted on the web. A design was agreed on and it was rendered using Adobe Illustrator (Figure 2). The design initially used a tissue paper bag and top for the

balloon with a ring of drawing paper holding the bottom of the balloon open. That opening was reinforced with straws. The design was reviewed and approved.

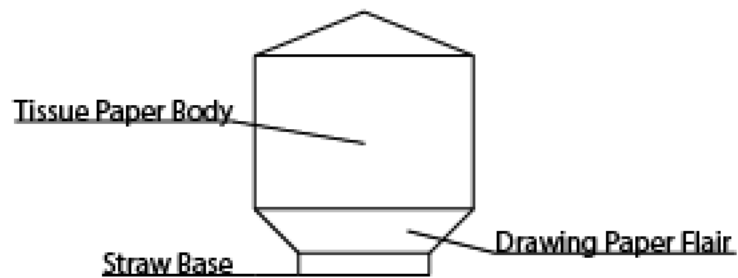


Figure 2: Sample Design for the Hot Air Balloon

Two sheets of tissue paper were laid side by side on a lab table and both were folded in half along their length. Using the glue stick, glue was applied along the width of one sheet of tissue paper. That width was then pressed on the width of the second sheet of tissue paper so they overlapped by roughly 2.50 cm. The remaining widths of the now one sheet of tissue paper were glued together forming a tube made of tissue paper.

The tube of tissue paper was held up and the diameter of the opening was measured. The remaining sheet of tissue paper was folded in half and two circles that had diameters that were larger than the tube's diameter were created using the scissors.

Those two circles were glued together using the glue stick. The tube was held up and the circles were glued on one end of the tube (Figure 3).



Figure 3: Balloon Top Being Applied

Using scissors, the sheet of drawing paper was cut in the middle along its length to create two pieces of drawing paper that had the same width and length. The two pieces were glued together at their width with an overlap of 2.50 cm. The same was done at the other end of the now single strip of drawing paper forming a ring. The ring was glued to the opening of the balloon. Two straws were taped together to form a large



plus sign. That plus sign was then taped into the balloon opening to keep the drawing paper ring from closing (Figure 4).

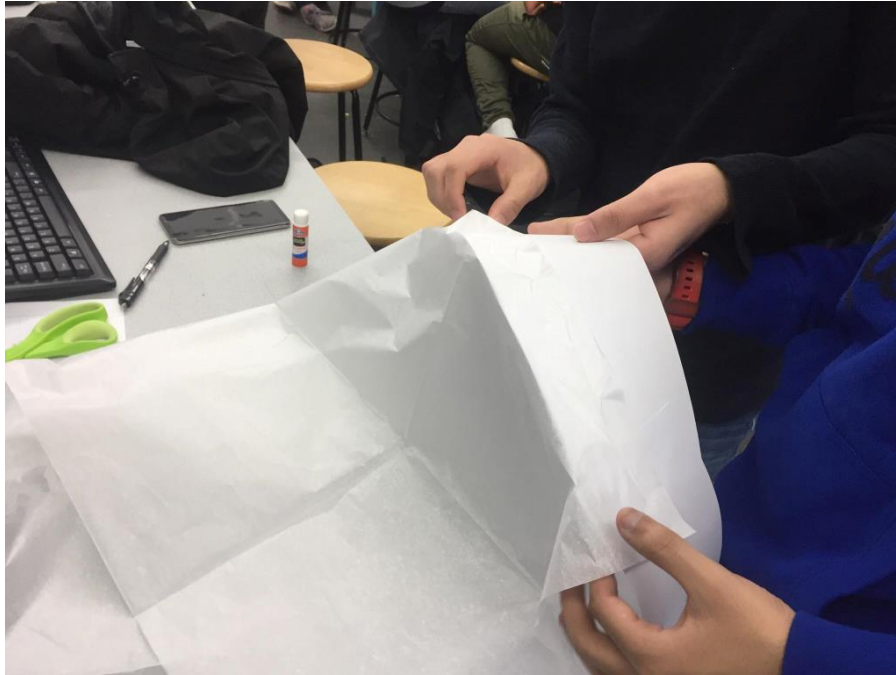


Figure 4: Hot Air Balloon Under Construction

The balloon was taken into the hallway and 12 paperclips were evenly placed on the drawing paper ring. It was held over the heater until the balloon was filled with hot air and then it was released. The balloon fell to the floor immediately and had a time afloat of 0.00 s.

The balloon was returned to the lab. The drawing paper ring and the straws were removed from the design. A few holes that were detected when the original design was held over the heater were sealed with the glue stick. Three paperclips were attached to

the new design and it was taken to the hall for a second trial. It was held over the heater and released once the balloon inflated.

#### Data/Observations

The hot air balloon placed second out of five balloons in the competition with a ratio (3) of 6.25. The second-place balloon achieved a ratio of 0.00 on its first trial because it had no time afloat. On its second trial, the balloon had a time afloat of 1.00 s with a payload of three paperclips.

$$\frac{1.00 \text{ s}}{\$0.48} \times 3.00 = 6.25 \quad (3)$$

Its volume was 0.48 m<sup>3</sup>. It had two trials and its cost was consistently \$0.48 (Table 2).

Table 2: Cost of the Hot Air Balloon

Material	Unit	Cost per unit (\$)
Drawing paper	One sheet	\$0.10
Tissue paper	Three sheets	\$0.30
Kevlar string	30 cm	\$0.05
Adhesive tape	30 cm	\$0.03
	Total	\$0.48

The final design of the second-place hot air balloon cost \$0.48. One sheet of drawing paper, three sheets of tissue paper, 30.00 cm of Kevlar string, and 30.00 cm of adhesive tape were purchased to build the balloon though most of the adhesive tape

and all of the Kevlar string were not used in the design. The drawing paper was used in the initial design, but discarded in the design that produced a time afloat (Figure 7).

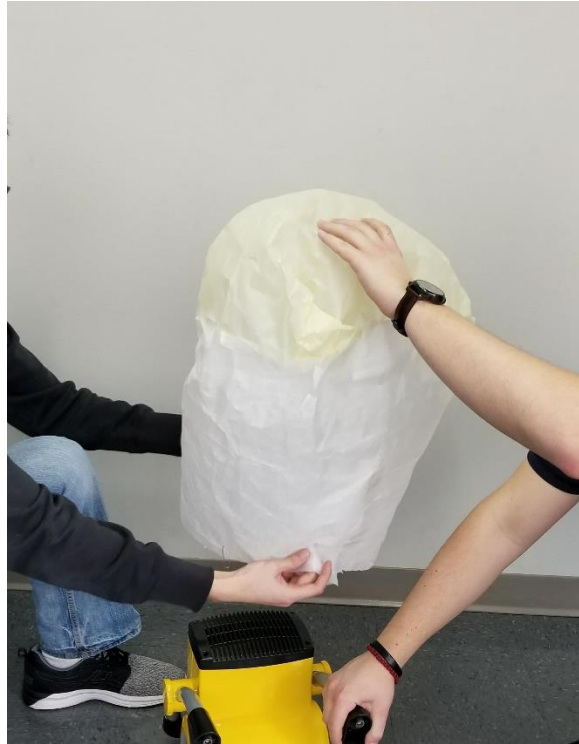


Figure 7: Hot Air Balloon, Final Design

The three balloons that had a time afloat had costs that ranged from \$0.28 to \$0.96 with an average cost of \$0.57 and a median cost of \$0.48. Their payloads on their best trials were either two or three paperclips. Their times afloat ranged from 1.00 s to 1.55 s with an average time afloat of 1.26 s and a median time afloat of 1.23 s. Two balloons had no time afloat and were not ranked in the competition (Table 3).

Table 3: Hot Air Balloon Competition Results

Trial #	Cost (\$)	Time Afloat (s)	Payload	Ratio	Highest	Rank
1	\$0.28	0.00 s	2	0.00		
2	\$0.28	1.23 s	2	8.79	8.79	1
3		-				
1	\$0.48	0.00 s	12	0.00		
2	\$0.48	1.00 s	3	6.25	6.25	2
3		-				
1	\$0.96	1.55 s	3	4.84	4.84	3
2		-				
3		-				
1	\$0.18	0.00 s	4	0.00	0.00	4
2	\$0.18	0.00 s	2	0.00		
3	\$0.18	0.00 s	4	0.00		
1	\$0.31	0.00 s	8	0.00	0.00	4
2		-				
3		-				

The first-place balloon achieved a ratio of 8.79 on its best trial (Figure 5). Its volume was 0.60 m<sup>3</sup>. Its cost remained \$0.28 over its two trials. It had a time afloat of 1.23 s on its second trial with a payload of two paperclips.



Figure 5: First-place Balloon

The third-place balloon had a single trial producing a ratio of 4.84 (Figure 6). Its volume was  $0.50 \text{ m}^3$ . It had a payload of three paperclips with a time afloat of 1.55 s and a cost of \$0.96.



Figure 6: Third-place Balloon

The two remaining balloons had times afloat of 0.00 s on every trial and their ratios were 0.00.

## Conclusion

Collectively, the items that were used in the initial second-place balloon design, but discarded in the design that produced a time afloat cost \$0.18. Had those items not been purchased, the second-place balloon's cost would have been \$0.30. Assuming its time afloat and payload remained 1.00 s and three paperclips, respectively, its ratio would have been 10.00, putting it into first place.

At 1.23 s, the first-place balloon had a time afloat that was comparable to the time afloat for the second-place balloon. At two paperclips, the first-place balloon carried a smaller payload than the second- and third-place balloons, which carried three paperclips each. Its lower cost at \$0.28 won first place.

At 1.55 s, the third-place balloon had a time afloat that was nearly double the times afloat of the first- and second-place balloons. It carried the same payload as the second-place balloon at three paperclips, but its higher cost at \$0.96 guaranteed a third-place finish.

The balloons that did not achieve a time afloat are not considered here because those designs were not competitive. They must be redesigned.

The original design strategy for the second-place balloon was to have a volume that was as close to 1.00 m<sup>3</sup> as possible, but that was not achieved. The first- and third-place balloons had greater volumes than the second-place balloon though the difference in volume between the second- and third-place balloons was small at 0.02 m<sup>3</sup>. While the first-place balloon had the highest volume, the data show that its lowest cost among the three balloons that had a time afloat determined its rank in the competition. The higher cost of the third-place balloon among the three balloons that had a time afloat determined its rank.

The original design strategy for the second-place balloon was to increase volume and limit cost. Both components of the ratio did not receive sufficient attention in the design. The unused materials purchased for the second-place balloon accounted for 37.00 % of the cost of that balloon. Those purchases were not used in the balloon design that had a time afloat so they did not increase the second-place balloon's volume. They only increased the cost. Just eliminating the unused materials would put the second-place balloon into first place with a ratio of 10.00 (4).

$$\frac{1.00 \text{ s}}{\$0.30} \times 3.00 = 10.00 \quad (4)$$

It is possible that increasing the volume of the second-place balloon would increase its time afloat and payload, but the data indicate that would necessarily

increase cost. That would present a substantial burden for a new balloon design to overcome when eliminating the cost of the unused items alone moves the second-place balloon into first place.

The data produced in this exercise show that a complete design strategy must consider cost and cannot weigh only those elements of a design that may improve performance.

#### Contribution Statement

In this lab, I engaged in the brainstorming and design processes. Teammates took turns developing the design in Adobe Illustrator to produce a rendering of the balloon design. When making the physical balloon, I was responsible for gluing the components of the balloon and making sure that all of the components were securely attached. After the first trial, I found the small holes in the original balloon and repaired them. My contributions to this exercise were important because my ideas and observations improved the balloon design and I continued to contribute improvements as the balloon was modified between trials. This allowed the team to improve our strategy and work off of each other's ideas.



## Works Cited

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