Experiment to find out the effect of changing blade radius, of the rotor of the helicopter, on the velocity of the blades and the downforce produced

Personal Engagement

Thirty minutes to midnight. We were minutes away from a new beginning. Just as families converged on their screens, anticipating the countdown, the flames began to rise.

One person dead and 14 injured in the Dubai hotel fire (Richards, Raven)

These words flashed right before my eyes. Although many were rescued, these unfortunate 15 people still had to suffer the consequences. The importance of helicopters in rescue situations was made more than clear to me, having witnessed this tragedy.

This led to the decision of finding out how the radius of the blades of a helicopter would affect the downforce produced by the blades. My thinking was that if we were able to replicate the same downforce with a lower power supply, an increase in power supply would lead to a greater downforce and effectively reduce flying time, making more rescue missions possible. This has many possible implications for our society, considering how many fires break out in houses, (1,240,000 in 2013 in US alone) (Michael Karter). Maybe with this research, an accident such as the one in Dubai could be avoidable in the future.

Fluid dynamics amazes me. The logic in this field is intricate and complex, providing more reason to undertake this project. Aerodynamics is another field which highly interests me, including modelling airplanes and other airborne devices to maximize efficiency.

Discussing forces in the classroom made me think about forces in the real world, where there are opposing forces as well. Forces and aerodynamics together made me think about how the reduction of air resistance is the key to greater acceleration and speed.

After the event on New Year's Eve, I decided that combining my knowledge of physics and my passion for aerodynamics, I could look towards what factors affect the efficiency of helicopters, thus the production of downforce and effectively the flying time thereby allowing for more successful rescue missions.

Research Question

How does the radius of the blades (ranging from 9 to 15cm) of the rotor of the helicopter (remote controlled), affect the lift force (N) produced provided that the power supplied (watts), temperature of air (°C) and size of helicopter and motor remains constant?

Aim

The aim of this experiment is to find out the relationship between the radii of the blades (cm) of the rotor of the helicopter and the downforce produced (N). This is done with the power being kept constant as this directly affects the velocity of the blades as indicated by the equation $P = \frac{mv^2}{2t}$. Temperature is another factor remaining constant due to this affecting the density of the air, which could affect the mass of air pushed downward again affecting the lift force. As stated before, this has many implications in rescue missions due to increased downforce allowing for reduced flying time.

Background Information

Helicopters are very useful for firefighting, search and rescue, etc. This abundance of essential uses thus creates the issue, that speed is very important. If we are able to manipulate the lift force, in a way such that the power remains the same while the lift force produced increased, then this would make more of the impossible rescue missions firefighting expeditions possible.

The physics behind helicopters is actually quite simple. Helicopters work differently to most other airborne transport modes such as aircrafts. It all starts with the engine, however unlike most engines producing thrust (forward force), this engine, is used to power the rotors and spin the blades of helicopters. (The Helicopter Page)

Helicopters use the turboshaft engines as their primary source of lift or upward force comes from the revolving blades. What happens in the engine is that first the air is compressed into the compression chamber, and here it reacts with the fuel. This creates an explosive reaction, creating a lot of force and energy. This energy passes over, and spins a generator, converting this chemical energy to electrical energy. This electrical energy is converted to mechanical energy and then the kinetic energy of the blades. These blades essentially work like spinning wings, spinning and creating a sort of wall, which pushes air down. This creates downforce the ground, and so the Newtonian force produced, is the lift of the helicopter, which counters the force due to gravity and allows the helicopter to go in the air. (The Helicopter Page)

Each blade is an airfoil (aerofoil), basically with a curved top and straight body and bottom. Thus, as this blade spins, the air is forced over the curve, and then thrown down, to produce the downforce/lift. The pitch (angle) of the blades with respect to the normal (ground) partially determines the lift force produced and so pilots use this to hover, descend or ascend. Thus if the lift is greater than the weight, the helicopter ascends, if they are equal then it hovers and if weight is

Figure 1 Image of helicopter taken from Amazon.com

greater, then the helicopter descends. (The Helicopter Page)

One common inquiry is the reason for the tail rotor, and the main reason that this is such an essential component to helicopters is based on Newton's third law of Motion, the force that one object exerts on another, is equal to, and of the same nature, but in the opposite direction of the force that the other object exerts on the first. Thus, the rotational force (torque) produced by the blades should turn the fuselage and the rest of the body of the helicopter the other way, and so this tail rotor is used to counteract this torque force. (The Helicopter Page)

Hypothesis

If we were to decrease the radius (cm) of the blades on the rotor of the remote-controlled helicopter, then I believe that the velocity of the blades will increase. If we think of this from a purely energy transfer matter, it makes sense.

The same amount of electrical energy is being supplied to the blades to convert into kinetic energy given by $\frac{1}{2}mv^2$. Reducing the radius of the blades leads to lower mass, and this should lead to increased velocity. This is because the same amount of electrical energy is equated to the kinetic energy, thus with decreasing mass of the blades, velocity must increase as mass is indirectly proportional to the square of the velocity.

This thus creates a dilemma as although the velocity of the blades increases, the surface area decreases which means that the mass of air thrown downward decreases. In my opinion, the lift force should decrease, as the material used to make the blades has a very low density thus the loss in weight should be minimal in comparison to the change in volume of air thrown down per second, as a result of the change in surface area. (MIT)

Also, looking at fluid dynamics, the blades are actually a thin disk, pushing down the air, as according to Bernoulli's principle. (University of Winnipeg) This means the mass of the blades should be negligible. Thus, since the mass of the blades is negligible as compared to the change in surface area, lift force should fall with radius.

Since the volume of air thrown down per second falls, the mass of fair also falls as the density of air is a constant. Using $p = mv$, we can find the momentum of the air, and since the mass of air falls, and the velocity changes minimally, the change in momentum per second falls. By Newton's second law of motion, the force exerted would be low as well as $F = \frac{m\Delta v}{\Delta t}$. Thus, the lift force should fall with radius of the blades.

Variables

Independent Variable	The independent variable will be the radius of the blades on the rotor (cm). The range is from 9cm to 15cm, with the intervals being 1cm. This is the independent variable as the radius is changed to see the effect it has on the upward acceleration of the helicopter, thus the resultant force, and hence the lift force. The uncertainty is ±0.1cm for the radius due to the lack of precision of the ruler and the wings being curved as well.
Dependent Variable	The raw dependent variable is the reading of the balance which is the change in the mass of the helicopter (g) with uncertainty ±0.01g. This change in mass will be used to calculate the processed dependent variables which are the lift force and the average lift force.
Control Variable	Mass for each IV (±0.01g) – Can be controlled by using the same helicopter for all trials and independent variables. Needs to be controlled because the mass can affect the value of the lift force. The mass of the blades is what primarily determines the velocity thus, changing masses lead to changing velocities and therefore, changing lift force values.
	Type of Helicopter – Can be controlled by using the same helicopter for all trials and independent variables. Needs to be controlled because if different helicopters are used, then all the mechanics are different including the size of the battery, therefore this is no longer a viable and correct experiment.
	Power supplied – Can be controlled by drawing a marking using a pencil to 1/4th the power on the remote control and ensure that for each trial, that the rudder and line lineup. Needs to be controlled because if the power is changed, the lift force will also change as the power affects the speed at which the blades turn, and if the speed increases then so does the lift force.

Uncertainties

The uncertainties include the lift force for the helicopter due to the varying mass of air thrown down as the helicopter is powered up, which in turn makes the average lift force an uncertainty.

Apparatus

- 1 x Remote Controlled Helicopter
- 1 x Sandpaper
- 1 x Scissor
- 1 x Plastic Ruler
- 1 x Marker
- 1 x Weighing Balance (±0.01g)
- 1 x 5cm square box weighing no more than 175g

Safety and Environmental considerations

Wear safety goggles for protection against the blades and reduce power consumption by not using the full capacity of the helicopter's power supply.

Method

1. Take the remote controller of the helicopter and measure the distance the power controlling rudder can shift.
2. Take a quarter of this and use the marker to make a mark.
3. Put the rudder in place and extend the line from the mark to the rudder to help provide similar power for each trial.
4. Measure the radius of the blades and note it down
5. Take the helicopter and place it on the acquired box. This can also be a wooden block as long as the weight conditions as indicated in the materials are met.

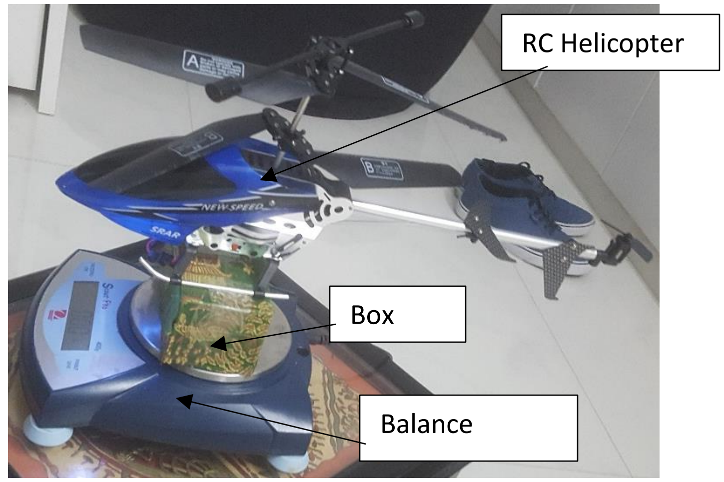


Figure 2 Picture of my Setup

6. Tape the helicopter from the legs to this box, using strong electrical tape to ensure stability.
7. Place this helicopter with the box on the weighing balance
8. Press the zero-offset button, thus showing the mass as 0g. This means that when the power is supplied, the figure will be the change in the mass as according to the balance, which is essentially the lifted mass.
9. Switch on the helicopter.
10. Line up the rudder and the mark, using the extended line drawn
11. Wait for 10 seconds, allowing for the lift force to reach a constant and then note down the value.
12. Switch off the helicopter
13. Repeat steps 8-12 six more times
14. Cut the blades by 1cm, ensuring the shape of the edge remains the same using sandpaper, to ensure that the air patterns around the blades aren't affected
15. Charge the helicopter until the green light appears
16. Repeat steps 6-13
17. Repeat steps 14-16 until blade radii of 9cm

Table 1: Raw Data

Table listing the change in mass of the helicopter and the box as measured by the balance after blades begin spinning							
Radius of Blades(±0.1cm)	**Lifted Mass (±0.01g)**						
	Trial 1	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Trial 6**	**Trial 7**
9.0	55.28	54.60	55.23	54.19	53.87	54.24	55.07
10.0	66.33	65.87	65.34	64.98	64.95	65.86	65.15
11.0	80.27	79.28	79.44	79.34	78.64	79.03	79.43
12.0	94.70	94.36	92.80	92.98	93.21	93.85	93.27
13.0	104.80	103.77	103.65	103.06	102.98	103.45	103.29
14.0	117.45	116.58	115.76	115.06	115.56	115.09	114.56
15.0	130.20	129.65	127.64	126.54	125.94	128.01	127.89

Table 2: Processed Data; Lift Force

Table listing the lift force by the helicopter on the box after blades begin spinning as calculated by converting the change in mass shown in the balance in grams to kilograms and multiply by the acceleration due to gravity							
Radius of Blades(±0.1cm)	**Lift Force**						
	Trial 1	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Trial 6**	**Trial 7**
9.0	0.54	0.54	0.54	0.53	0.53	0.53	0.54
10.0	0.65	0.65	0.64	0.64	0.64	0.65	0.64
11.0	0.79	0.78	0.78	0.78	0.77	0.77	0.78
12.0	0.93	0.92	0.91	0.91	0.91	0.92	0.91
13.0	1.03	1.02	1.02	1.01	1.01	1.01	1.01
14.0	1.15	1.14	1.13	1.13	1.13	1.13	1.12
15.0	1.28	1.27	1.25	1.24	1.23	1.25	1.25

Sample Calculation

Lift Force = $Average\ mass \times \frac{9.8}{1000}$

Lift Force = $55.28 \times \frac{9.8}{1000}$

Lift Force = 0.54 N

Table 3: Processed Data; Average Lift Force

Table listing the average lift force by the helicopter on the box after blades begin spinning	
Radius of Blades(±0.1cm)	**Average Force (N)**
9.0	0.54
10.0	0.64
11.0	0.78
12.0	0.92
13.0	1.02
14.0	1.13
15.0	1.25

Sample Calculation

Average Lift Force = $\frac{0.54+0.54+0.54+0.53+0.53+0.53+0.54}{7}$

Average Lift Force = 0.54 N

Table 4: Processed Data; Uncertainties

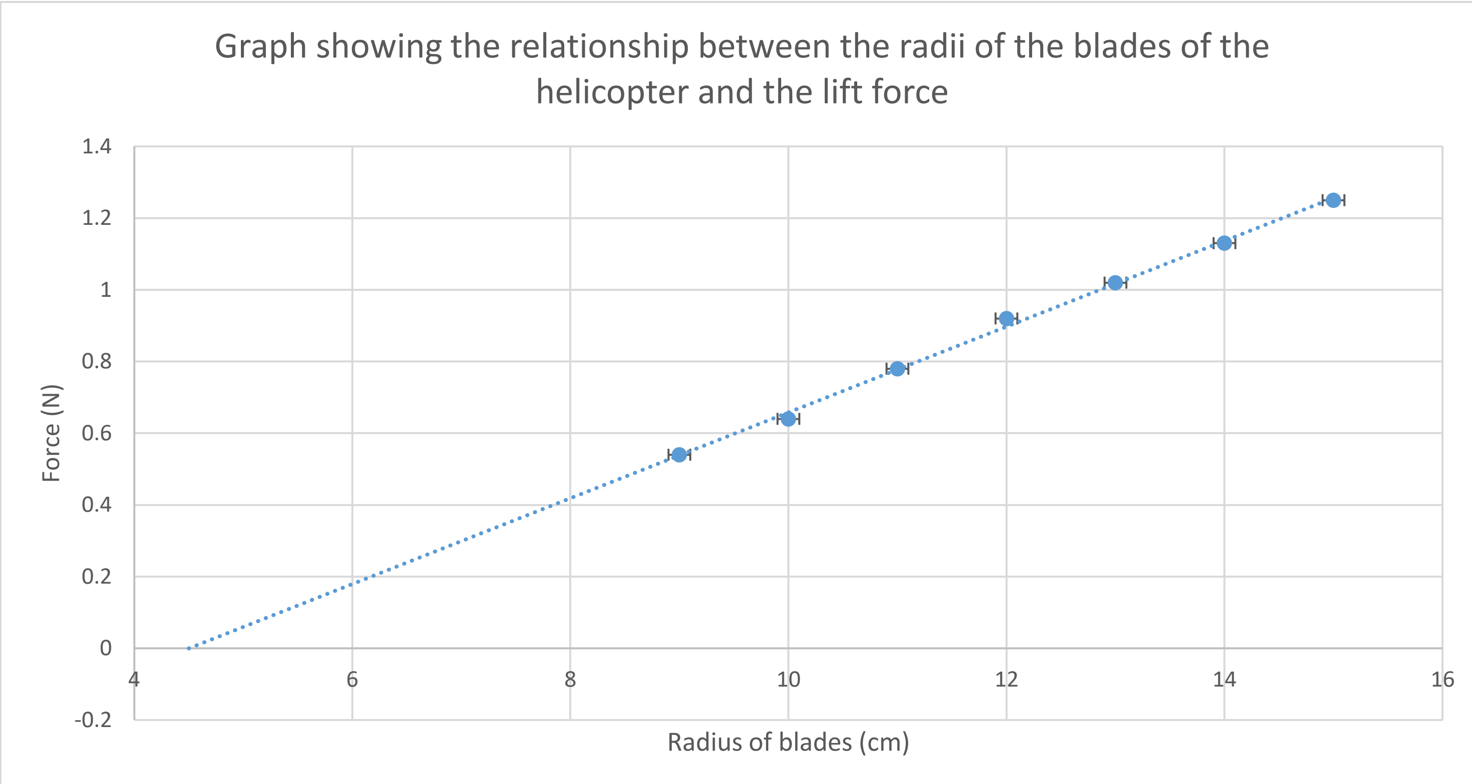
Table listing the uncertainties of the lift force by the helicopter with different radii for the blades	
Lift Force (N)	**Uncertainty**
0.54	±0.01
0.64	±0.01
0.78	±0.01
0.92	±0.01
1.02	±0.01
1.13	±0.01
1.25	±0.02

Sample Calculation

Uncertainty = $\sqrt{\frac{(0.54-0.54)^2+(0.54-0.54)^2+(0.54-0.54)^2+(0.53-0.54)^2+(0.53-0.54)^2+(0.53-0.54)^2+(0.54-0.54)^2}{7}}$

Uncertainty = ±0.01 N

Graph 1:



Most vertical error bars are unnoticeable due to how precise the results were. The horizontal error bars are as a result of the uncertainty of the ruler.

Table 5: Processed Data; Efficiency

Table listing important figures for efficiency using equation for power				
Radius (±0.5cm)	**Velocity (ms^{-1})**	**Theoretical Lift Force (N)**	**Actual Lift Force (N)**	**Efficiency/Percentage yield**
9.0	8.05	1.01	0.54	53.5
10.0	7.51	1.08	0.64	59.3
11.0	7.04	1.16	0.78	67.2
12.0	6.65	1.22	0.92	75.4
13.0	6.30	1.29	1.02	79.1
14.0	6.00	1.36	1.13	83.1
15.0	5.73	1.42	1.25	88.0

$P = \frac{1}{2} \rho A v^3$ (Reuk.co.uk)

where P = power (W) = 8.14 watts according to the battery of the helicopter

ρ = density of air (kgm^{-3}) = 1.225kgm^{-3}

A = area the wind is passing through the wind mill - perpendicular to the wind (m^2)

v = wind velocity (ms^{-1})

This equation is derived from the equation for kinetic energy which is $KE = ½\,mv^2$. Power is the change in energy over time which could be written as $P = \frac{mv^2}{2t}$ which can also be written as $P = \frac{v^2}{2} \times \frac{m}{t}$.

$\frac{m}{t}$ is essentially the mass flow rate which according to fluid mechanics can be written as:

$\frac{m}{t} = p \times A \times v$. Together, we come up with the equation as shown above.

Sample Calculation (Wind Speed)

$$P = \frac{\rho A v^3}{2}$$

$$8.14 = \frac{1}{2} \times 1.225 \times (0.092 * pi) \times v^3$$

522.26 = v^3

V = 8.05ms^{-1}

Sample Calculation (Lift Force)

$P = Fv$

8.14 = F x 8.05

F = 1.01N

Sample Calculation (Efficiency)

$$Efficiency = \frac{Actual}{theoretical} \times 100$$

$$Efficiency = \frac{0.54}{1.01} \times 100$$

Efficiency = 53.5%

Conclusion

The graph for the radius of the blades compared to lift force produced shows that the lift force produced was greatest at 15cm. This occurred when all other factors such as power supplied (watts), temperature of air (°C) and size of helicopter remained constant. This clearly shows a positive correlation between the radius of the blades and the lift force produced. The reason for this is that the surface area decreases exponentially (area of flat circular disk πr^2) while the change in mass is negligible due to the low density of the material used to create the blades. Thus, the same amount of electrical energy was being put in to push considerably less air as the radius falls. Since the same amount of energy is provided to less air, the velocity of the air increases. Since $P = Fv$, Force and velocity are inversely proportional thus as the velocity increases, the lift force decreases. (MIT) This however is contradictory considering the fact that an increase in velocity means that the blades should actually be producing a greater downforce. However, this is unseen in the experimental values as well as the theoretical values.

I learned that this has to do with Newton's Second Law, which states that the force is equal to the rate of change of momentum. Although the velocity increases, the mass of air falls due to the reduction in the surface area caused by the lower radius. $F = \frac{m\Delta v}{\Delta t}$ and as stated in the hypothesis, although the velocity increases, it increases minimally. (MIT) However, the change in the surface area is exponential in nature as a result of the area for a circle. We assume the blades create a circle due to Bernoulli's principle, which states that the blades are a thin circular disk pushing air down. With this exponentially decreasing surface area, the change in mass is much more drastic than the change in the velocity. This therefore means that the lift force falls as the radius falls.

Bernoulli's principle also states that an increase in the speed of the moving fluid leads to a fall in the pressure. Pressure is directly proportional to the force thus a fall in the magnitude of the pressure field leads to the downforce produced falling accordingly. (University of Winnipeg)

In my hypothesis, I assumed velocity to decrease with radius however I was approaching that from a circular motion perspective. In reality, due to the decreased mass of air receiving the same electrical energy, the velocity of the air increases as all the electrical energy is converted to kinetic energy. $KE = \frac{1}{2}mv^2$ and since mass falls, velocity must rise.

I was however, able to rightfully predict the positive correlation between the radius of the blades and the downforce produced, based on basic observations of helicopters in my past. There is also definite physics to prove the correlation. Bernoulli's principle is based on the law of conservation of energy, and according to this principle, an increase in the kinetic energy would lead to a simultaneous decrease in the static pressure. Since pressure is directly proportional to force, the falling pressure due to increased velocity and falling radius means that the lift force falls with the radius.

I had no anomalous results as shown by the straight-line trend however this seems odd considering that although I tried to keep the curvature of the wings constant, it did change. There was however a huge systematic error as indicated by the x intercept being at around 4.5cm. This could be attributed to the torque force, which would negate some of the lift force, thus indicating 0 N of lift force at 4.5cm radius. This could not be corrected in the experiment as none of the RC helicopters had functioning tail rotors.

I believe that my method had considerable flaws considering the large systematic error however this was much better than my previous method. My original idea was to look at the time taken for the helicopter to rise to a certain point, then using SUVATs, calculate the net force and hence the downforce produced. However, once I bought the helicopter, I realized the difficulty associated with this method considering that the helicopter doesn't rise straight up. This led me to almost changing my IA however I was so interested in this topic that I decided to find a way around this. This led me to deciding to run a cable through the blade and attaching it to two fixed points thus the helicopter would only be able to move between these two points, however the motion of the blades made this very difficult. Finally, after considerable discussion with my friends and teacher about changing this IA entirely, I had a sudden realization that since I'm looking at force, I could use a balance. This was due to the fact that the balance measures mass using the normal force thus if I stuck the helicopter to a known mass and started the power supply to the rotor, this would help me get the change in the normal force of the helicopter in terms of mass thus multiplying by 9.8 would give the change in normal force.

Looking at the efficiency table, we see that not only is the lift force greatest with the 15cm blades but also the efficiency however this is most likely due to the curvature of the blades as when the blades were cut, the shape was slightly altered. This does however have implications for helicopter manufacturers as they can see that lift force as well as efficiency increases with radius however they must take care considering here the mass of the blades is negligible however in the real-life situation, the mass is considerably large thus the assumption of negligible mass lost cannot be taken into account.

Evaluation

Limitations	How it affects the results	Realistic improvements
Reading on Balance continuously changing	It can affect the average calculations thus increasing the systematic error.	The only possible way to change this would be to come up with a new method as with this method, the acceleration of the wind is not constant thus there will always be varying values.
Curvature of the wings	If the wings are more curved, then the volume of air being pushed down increases thus affecting the velocity of the air as well as the downforce produced thus it would be unfair to conclude any relationship between radius and downforce produced.	In cutting the blades, the curvature of the blades is also changed. To avoid this, I could buy blades of different sizes already cut in which the curvature has been accounted for.
Torque force from generator	The torque force adds to the net force thus making the lift force appear greater than it really is.	No realistic improvement considering all helicopters are dependent on these motors. To reduce the effects, I could increase the mass of the helicopter to reduce the torque force effect.

Works Cited

"THE HELICOPTER PAGE." *THE HELICOPTER PAGE*. N.p., n.d. Web. 06 July 2016. <http://www.helicopterpage.com/html/jet.html>.

"Power Market Fundamentals." *Power System Economics* (2009): n. pag. MIT. Web. <http://web.mit.edu/windenergy/windweek/Presentations/Wind%20Energy%20101.pdf>.

"REUK.co.uk - The Renewable Energy Website." *Calculation of Wind Power*. N.p., n.d. Web. 06 July 2016. <http://www.reuk.co.uk/Calculation-of-Wind-Power.htm>.

"Robot Check." Air Hogs, Mission Alpha Ultimate Mission RC Helicopter - Black. Amazon, n.d. Web. 11 Dec. 2016. <https://www.amazon.com/Air-Hogs-Mission-Ultimate-Helicopter/dp/B019HOZY1O/ref=sr_1_3?ie=UTF8&qid=1481485557&sr=8-3&keywords=Helicopter%2BAir%2BHog>.

"Bernoulli's Principle." Bernoulli's Principle. University of Winnipeg, n.d. Web. 11 Dec. 2016. <http://theory.uwinnipeg.ca/mod_tech/node68.html>.

Richards, Chris, and David Raven. "Thousands in Miracle Escape from Dubai Hotel Blaze as 'flames Were Outside'" Dubai Hotel Fire. Mirror, 31 Dec. 2015. Web. 11 Dec. 2016. <http://www.mirror.co.uk/news/world-news/dubai-hotel-fire-one-killed-7100180>.

Karter, Michael J. "NFPA Journal." Fire Loss, September October 2014. NFPA, n.d. Web. 11 Dec. 2016. <http://www.nfpa.org/news-and-research/publications/nfpa-journal/2014/september-october-2014/features/2013-fire-loss>.