IMPACT OF VOLCANIC ACTIVITY ON AMC CHANNEL OPERATIONS

GRADUATE RESEARCH PROJECT

Matthew D. Meshanko, Major, USAF

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Matthew D. Meshanko, BS, MA

Major, USAF

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Matthew D. Meshanko, BS, MA
Major, USAF

Approved:

______________//signed//___________________ 28May2014
William A. Cunningham, PhD Date

Abstract

The basic foundation of airpower promotes unique capabilities and inherent advantages to achieve strategic, operational, and tactical objectives for the nation. Air mobility and its associated core competencies are seated appropriately under this airpower umbrella. Exploiting its inherent speed and tremendous range allows air mobility to become rapid global mobility. The core competency of rapid global mobility, the lifeblood of sustained combat operations, presents itself as one of the greatest military advantages in the world.

Understanding the importance of rapid global mobility to the United States' National Security Strategy (NSS), and subsequent National Military Strategy (NMS), is paramount when analyzing the impact of its interruption. The eruption of the Icelandic volcano Eyjafjallajokull on April 14, 2010 significantly affected Air Mobility Command's (AMC) ability to execute rapid global mobility, and more specifically, its sustained channel network. The ash impediment created by the eruption perpetuated system disruptions that threatened the Air Force's ability to sustain combat operations abroad.

This research proposal examines the total number of AMC channel missions affected by the events that transpired on 14 April 2010. Additionally, this research details the eruption's impact on individual channel mission events, aircraft, passengers and cargo, targeting second and third-order effects within the mobility system. Finally, this research determines the mean channel mission deviation experienced during this same period of time.

To my wife and two daughters

Acknowledgments

Thank you to all of the subject matter experts at USTRANSCOM and AMC who provided me with the critical information and data to make this project possible. Additionally, I would like to thank Ms. Pamela Bennettbardot for her assistance with the research process. I would like to express my sincere appreciation to my advisor, Dr. William Cunningham, and my sponsor Dr. Donald Erbschloe, for their guidance, support, and feedback throughout the year.

Matthew D. Meshanko

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I. Introduction

Background

The basic foundation of airpower promotes unique capabilities and inherent advantages to achieve strategic, operational, and tactical objectives for the nation. According to basic Air Force doctrine, "airpower's speed, range, flexibility, and versatility are its outstanding attributes in both space and time" (Curtis E. Lemay Center, 2014). Air mobility and its associated core competencies are seated appropriately under this airpower umbrella. Exploiting its inherent speed and tremendous range, air mobility is successfully able to "transform global mobility into rapid global mobility" and become the "key to maintaining global presence and a rapid response capability" (United States Air Force, 2014). The core competency of rapid global mobility, the lifeblood of sustained combat operations, presents itself as one of the greatest military advantages in the world. According to Air Force Doctrine Document (AFDD) 2-6, "rapid global mobility provides the United States with unequaled reach underpinning our nation's role as a global power" (United States Air Force, 1999).

Consequently, airpower's overreliance on this speed, range, and three-dimensional perspective, which differentiates itself from other forms of military power, can be devastating. These basic tenants of airpower, which facilitate unique and valuable capabilities, can paralyze military operations if they are not properly exploited. Understanding the importance of rapid global mobility to the United States' National Security Strategy (NSS), and subsequent National Military Strategy (NMS), is paramount when analyzing the impact of its interruption. The eruption of the Icelandic volcano Eyjafjallajokull on April 14, 2010 significantly affected Air Mobility Command's (AMC) ability to execute rapid global mobility. Dr. Langston, Professor Emeritus of Engineering at the University of Connecticut, described the catastrophic event as projecting "ash clouds as high as 30,000 feet, directly into some of the world's most traveled airspace" (Langston, 2011). This ash impediment created system disruptions that threatened the Air Force's ability to sustain combat operations abroad.

Problem Statement

The sudden eruption of Iceland's Eyjafjallajokull volcano, following 190 years of dormancy, caused severe disruptions in the established North Atlantic airflow pattern. While lasting less than one month, the porous ash released into the air became a seemingly insurmountable obstacle for all air traffic—civilian and military alike. Hazardous to the internal components of most aircraft engines, hundreds of flights had to be diverted or delayed. Subsequently, EUROCONTROL completely shut down entire blocks of airspace, impacting dozens of airports across Europe. In particular, Air Mobility Command C-5s and C-17s had to be rerouted across the Pacific Ocean on their way to Iraq and Afghanistan—resulting in an increase of mission duration, delivery time to the customer and overall cost. This begs the question: ***What impact did the 2010 eruption of Iceland's Eyjafjallajokull volcano have on AMC channel operations?*** What makes this problem critically important is the fact that volcanic activity, both a natural and unpredictable threat, has no territorial boundaries. The indiscriminate nature of volcanic activity can be frustrating to combatant commanders who require the time-sensitive delivery of both passengers and cargo. AMC aircraft, which routinely operate in locations affected by sporadic volcanic activity, have to adapt in order to exploit the advantages of rapid global mobility. Environmental disasters, such as volcanic eruptions, infringe on the Air Force's ability to carry out its respective missions, thus ultimately impacting America's national defense. Furthermore, by analyzing this 2010 Eyjafjallajokull case study, AMC can determine whether or not it is cost effective to invest in technology that will enable mobility aircraft to penetrate volcanic ash clouds or simply reroute mission essential traffic, as necessary.

Research Objective

The primary goal of this research is to determine the extent in which a volcanic event in the North Atlantic, such as the eruption of Iceland's Eyjafjallajokull volcano, impacts AMC channel operations. In order to make this determination, there are five investigative questions that need to be addressed.

Investigative Questions

Investigative Question 1: How many AMC channel missions were disrupted due to the eruption of Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010?

Investigative Question 2: How many individual AMC channel mission events were disrupted due to the eruption of Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010?

Investigative Question 3: How many of each type of aircraft were disrupted due to the eruption of Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010?

Investigative Question 4: How many passengers and how much cargo was disrupted due to the eruption of Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010?

Investigative Question 5: What was the mean mission deviation for AMC channel missions disrupted due to the eruption of Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010?

The nature of this research lends itself to a case study analysis. By using the 2010 Eyjafjallajokull case study, this research will facilitate a deeper understanding of these quantifiable factors and, in turn, produce discernable figures for use in the decision-making process. The hypothesis is volcanic activity negatively impacts AMC channel operations with a reduction in mission completion and on-time departure rates, as well as the degradation of scheduled passenger and cargo movement. Additionally, the results of this study may propel AMC leadership to increase funding for future research and development efforts or invest in new technologies that mitigate the impact of volcanic activity. Furthermore, there are numerous considerations that need to be addressed in order to justify such an investment.

These considerations include:

Consideration 1: What is the probability that an event of this magnitude will occur again?

Consideration 2: What other alternatives or courses of actions are available to mitigate the suspected mission degradation following a volcanic event?

Consideration 3: Is the capability necessary in order to properly execute the current National Security Strategy, and subsequently, the National Military Strategy?

Consideration 4: Is the capability necessary in order to preserve the inherent advantages of the core competency rapid global mobility?

Consideration 5: If necessary, what extent of the force will need this capability? (e.g., size of fleet, particular weapon system)

Research Focus

This research will focus on the tangible effects that volcanic activity has on AMC channel operations. The two main areas of interest include mission velocity and disruption potential. In particular, viewing this problem from a mission-impact perspective would benefit AMC tremendously. Also, this research will shed light on the volcanic phenomena and its impact on traditional air routes, including the possible saturation of these routes by commercial air carriers during such an event. This research will be accomplished in conjunction with an analysis of the commercial industry to gain critical insight on how AMC's commercial and business partners address this issue.

Overall, this research is meant to predict the expected level of mobility system disruption during a volcanic event.

Methodology

This research project will be quantitative in nature. The research problem and its associated methodology will be fitted to the 2010 Eyjafjallajokull case study. The data set, consisting of all AMC eastbound and westbound flights for the duration of the 2010 eruption, will be provided by AMC/A9 and the 618 TACC/XOND. Specifically, the researcher will take the data and sort it to differentiate between contingency, special airlift (SAAM) and standard channel missions. After compiling this refined data set, the researcher will then analyze specific characteristics of those particular channel missions. The analysis will include mission duration, route, delay information, cargo and aircraft type. This analysis will result in the calculation of the average deviation for a standard channel mission disrupted by the 2010 volcanic event.

Assumptions/Limitations

The following overarching assumptions apply to this research project in order to set a baseline for calculations regarding the impact of volcanic activity on AMC channel operations.

Assumption 1: Following the case study approach, the volcanic event studied and the data analyzed will be that of the Icelandic volcano Eyjafjallajokull.

Assumption 2: All aircraft were operated in accordance with their technical-order manuals.

Assumption 3: All flights were conducted in accordance with computer-generated flight plans (CFP) provided by the 618 TACC.

Assumption 4: All missions that were "in execution" when the event occurred or that were dispatched shortly after the eruption were deemed "mission essential" by the appropriate authorities and were directed to continue their respective missions until completion.

Assumption 5: The missions affected by the 2010 Eyjafjallajokull eruption included those destined for both Iraq and Afghanistan.

Assumption 6: Due to the scope of this research project, the data analysis will only include those missions that were affected in the North Atlantic region.

Additional assumptions that pertain specifically to mission calculations and other data analysis are outlined in the methodology chapter.

Implications

The intent of this research is to be used as a decision-making tool for AMC. The validity of the model depends heavily on the accuracy of the data provided both by AMC/A9 and 618 TACC/XOND. This research can be synthesized and applied in numerous settings with a multitude of variable changes. For example, AMC can make specific inferences concerning the impact potential volcanic activity has on aeromedical missions. Provided with these findings, AMC leadership will have access to pertinent information concerning disrupted aircraft routes in the North Atlantic region. Applying these same principles, AMC can then develop contingency plans for other volcanic hotspots around the world. From this critical insight, AMC leadership can refine policy and procedures in order to mitigate the impact volcanic activity has on AMC channel operations. For instance, leadership can alter crew duty day limitations in order to compensate for longer aircraft routes. Additionally, leadership may find it beneficial to bolster enroute infrastructure in order to handle increased throughput at alternate locations due to the presence of volcanic activity. Finally, leadership can assess the impact of a volcanic event during periods of increased operations, such as OPERATION ENDURING FREEDOM and OPERATION IRAQI FREEDOM, or analyze the problem during periods of relative peace—supporting normal operations or a humanitarian crisis. Simply put, by taking the information produced by this model, AMC leadership will be able to make specific inferences about potential mobility system disruptions caused by volcanic activity.

II. Literature Review

Chapter Overview

The objective of the literature review is to provide the background necessary to guide the reminder of the research project. In particular, this literature review will "describe theoretical perspectives and previous research findings regarding the problem at hand" (Leedy & Ormrod, 2010). This chapter will discuss the history, timeline, dimensions and impact of the Icelandic volcano Eyjafjallajokull. Next, a discussion ensues on other volcanic hotspots located around the world, along with pertinent information on eruption frequency and severity levels. The third portion of this review discusses the implications, past and present, of mobility system disruptions caused by natural disasters, such as volcanic eruptions. Finally, the chapter discusses tactics, techniques and procedures used to combat the effects of volcanic emissions, as well as methods available to mitigate their impact on the overall mobility system. Having a basic understanding of these areas is essential when analyzing the impact Eyjafjallajokull had on AMC channel operations.

Eyjafjallajokull Overview

On March 20, 2010, after 190 years of dormancy, Iceland's Eyjafjallajokull volcano began to slowly emit small amounts of fluid magma directly under its ice cap. Over the course of the next twenty-six days, the rate and amount of magma expelled would dramatically increase. Furthermore, the magma and ice mixture would throw clouds of fine volcanic ash as high as 30,000 feet into the atmosphere, on its way over the Atlantic and across Northern European airspace (Langston, Jet Engines and Erupting

Volcanoes, 2011). While the events preceding April 14, 2010 were not considered particularly alarming, the eruptions that followed would lead to the largest European airspace shutdown since World War II. Figure 1 below is Iceland's Eyjafjallajokull volcano during the eruption that occurred on 14 April 2010.

Figure 1: Eruption of Iceland's Eyjafjallajokull Volcano (Brooker, 2010)

In the early morning hours of April 14, 2010, after three weeks of moderate volcanic activity, the main chamber of Iceland's Eyjafjallajokull volcano erupted releasing 750 tons of volcanic material per second into the atmosphere (Budd, Griggs, Howarth, & Ison, 2011). While some of the larger projectiles simply fell back to earth, billions of tiny fragments lingered for days in some of the busiest airspace in the world.

Hazardous to aircraft engines, the volcanic glass and ash aloft prompted European aviation authorities to close the airspace on the evening of April 14, 2010. This vast airspace would remain closed until April 20, 2010. This six-day shutdown of European airspace was the longest in history as the events of September 11th only grounded flights for three days (Russell, 2010). While the airline industry suffered losses of $200 million dollars per day, including 100,000 flights cancelled and eight million affected passengers, United States Air Force mobility missions were also impacted by this event (Langston, Jet Engines and Erupting Volcanoes, 2011).

Iceland's Geological Importance

Iceland is one of the most active volcanic settings in the world. The location and behavior of volcanoes are a direct result of tectonic plate boundaries and the dynamic nature of the earth's crust. What makes Iceland unique is the fact that approximately one-tenth of the country is currently covered in ice—or glaciated. The interaction between hot magma and ice magnifies the intensity of a volcanic event and creates an airborne ash and gas hazard for people, livestock and even aircraft. In the article *Now that the dust has settled…the impacts of Icelandic volcanic eruptions*, the author illustrates this point by stating "magma that comes into contact with water and ice tends to erupt violently; rapid cooling of magma causes it to become granulated into tephra on contact with ice and water, generating hydro-magmatic or phreatic activity and profuse quantities of ash, which can be lofted and deposited" (Tweed, 2012). Figure 2 below illustrates the migration of the ash hazard throughout the duration of Eyjafjallajokull's eruption cycle.

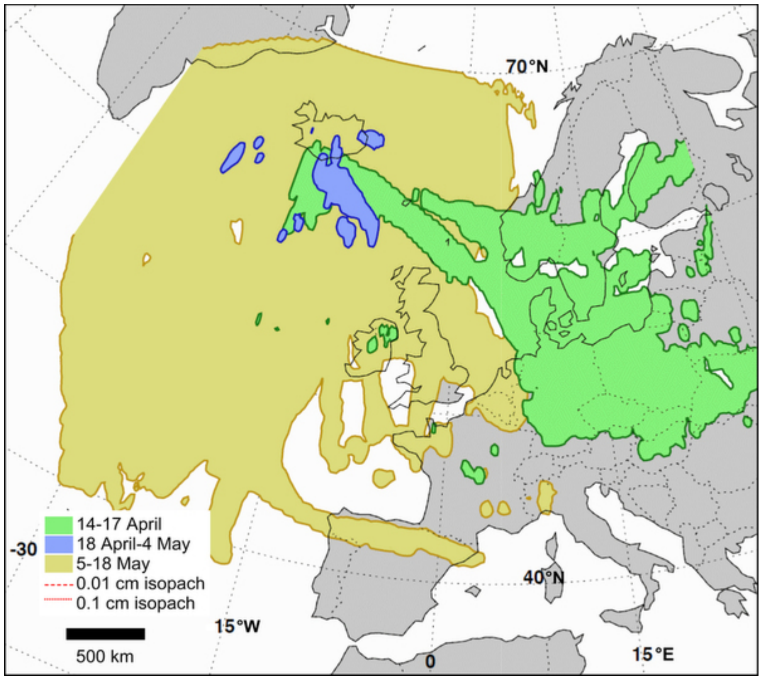

Figure 2: Ash Detected Outside Iceland within 40°–70°N and 40°W–30°E (Scientific Reports, 2014)

The potential for tectonic plate movement underneath Iceland creates a persistent threat. Volcanic activity creates multiple hazards that can disrupt everything from entire civilizations to modern day mobility systems. With hazards ranging from lava flows to heavy ash clouds, these events happen more frequently than one may think. Over the course of Iceland's 16-million-year history, it is estimated that there have been over 250 eruptions in just the last 1,100 years alone (Tweed, 2012). While Iceland has experienced a tremendous amount of volcanic activity, there are a few historical examples that closely mimic the eruption that occurred in April of 2010. Analyzing these volcanic events will shed light on the impact that such hazards could have in the future.

Icelandic Case Studies

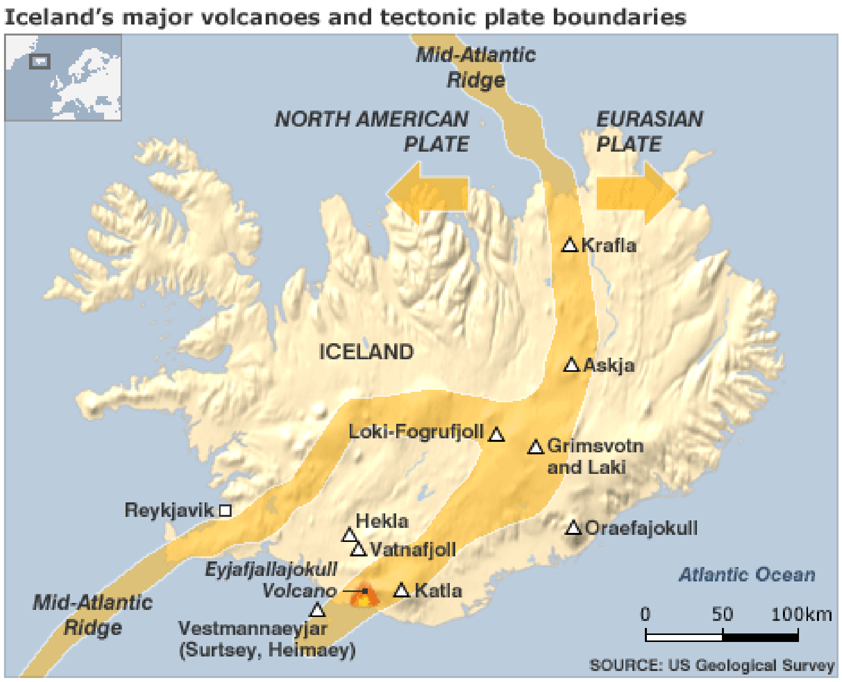

Figure 3: Location of Iceland's Major Volcanoes (BBC, 2014)

While a majority of eruptions include some sort of ash cloud emission, there were three recorded eruptions in Iceland’s past that spewed a significant amount of material into the atmosphere. They include the Oraefajokull eruption of 1362, the Lakagigar eruption of 1783-1784 and the Katla eruption of 1918. Of note, the severity of all three of these eruptions was exacerbated by abnormal weather patterns at the time. The impact that abnormal weather patterns have on a volcanic event, including Eyjafjallajokull’ s eruption in 2010, can be found in the environmental factors section of this report. Figure

3 above depicts the location of these three specific volcanoes, as well as other major volcanoes situated on the island.

The Oraefajokull eruption of 1362 is widely considered to be Iceland's largest historical eruption and the largest eruption in Europe since the destruction of Pompeii by Vesuvius in AD 79 (Tweed, 2012). From its 14 peaks, over the course of several months, the volcano was estimated to have emitted up to 10 km^3 of ash and gas. By comparison, that is over 33 times the amount released by Eyjafjallajokull in 2010. Oraefajokull's ash buried the surrounding farms and churches, making them virtually uninhabitable for over 40 years. Oraefajokull erupted again in 1727-1728; however, the emission was insignificant.

The Lakagigar eruption of 1783-1784 is best known for its significant output of gasses and aerosols over its eight month eruption period. In addition to emitting over seven million tons of hydrogen fluoride and 110 million tons of sulfur dioxide, the gasses triggered a significant drop in ambient air temperature (Tweed, 2012). In combination with the resulting climate change, a high pressure cell located over Western Europe kept the ash and gas suspended for months. As a result, persistent dry fog, violent thunderstorms with excessive lightening and sulfur-enriched air were documented all throughout northwest Europe (Tweed, 2012).

The Katla eruption of 1918 is the most similar volcanic event to the Eyjafjallajokull eruption of 2010. As a matter of fact, both volcanic systems are located on the eastern side of Iceland and both reside under thick ice caps. Historically, whenever Eyjafjallajokull erupts, Katla is not long behind. Katla, which erupts approximately twice a century, erupted in 1721, 1755, 1823, 1860 and 1918—indicating that a major eruption is long overdue (Tweed, 2012). Like Eyjafjallajokull, Katla erupted with very little warning. As a matter of fact, the only indicators that the 2010 Eyjafjallajokull eruption was imminent were a series of small earthquakes that started in early March (Simmon, 2014). In both cases, these volcanoes generated large quantities of volcanic ash and abundant lightning strikes as a consequence of the electrically-charged nature of the eruption column (Tweed, 2012).

These three historical examples have striking similarities to the Eyjafjallajokull event in 2010, with the main difference being the duration of the eruption cycle. However, the 2010 eruption of Eyjafjallajokull brought attention to the transnational nature of these hazards. While the eruption initially occurred over Iceland, the ash and gas spread to impede international aviation and cause severe disruptions in global transportation.

Environmental Factors

Human preoccupation with volcanic activity dates back to the beginning of recorded history. Today's scientists have used everything from cave paintings to journal entries in order to try and understand eruption patterns, effects and threats. Pioneers like Gilbert White, a naturalist, was able to extensively document Icelandic volcanic activity from his home in Hampshire in 1783. During that year, the volcanic fissure on Iceland known as Laki cracked and produced an enormous ash cloud that could be seen all the way from White's home in England (Hamilton, 2010).

The following was written in a letter by White:

> The summer of the year 1783 was an amazing and portentous one, and full of horrible phenomena…By my journal I find I had noticed this strange occurrence from June 23rd to July 20th inclusive, during which period the wind varied to every quarter without any alteration in the air. The sun, at noon, looked as blank as a clouded moon, and shed a rust-colored, ferruginous light on the ground, and floors of rooms; but was particularly lurid and blood-coloured at rising and setting.
>
> Gilbert White

What White was describing in his letter back in 1783 was the introduction of porous ash particles into a stagnant air system. This same phenomenon occurred during Eyjafjallajokull's eruption in 2010 which prolonged the airspace closure. In April of 2010, a combination of the volcano's location, an unusually stable jet stream, and anticyclones over the North Atlantic forced the ash particles to congregate amidst some of the world's busiest air traffic routes (Budd, Griggs, Howarth, & Ison, 2011). Hence, environmental factors are extremely important considerations when trying to predict the duration of such an event.

Hazards to Aviation

While Eyjafjallajokull's tephra, the scientific term for volcanic rock, reached altitudes of approximately 30,000 feet, it is commonly believed that these fragments can travel as high as 100,000 feet. Ash, a subset of tephra, is less than 2 millimeters in diameter. Clouds of volcanic ash pose a real threat to aircraft, and specifically, their jet engines. The ash is not the soft powdery kind from a wood fire, but is composed of bits of pulverized rock ranging typically from millimeter size (e.g., sand) down to the micrometer size (e.g., clay particles) (Langston, Jet Engines and Erupting Volcanoes, 2011). The minuscule sizes of these smaller particles increase the propensity for aircraft to inadvertently fly through these conditions simply because they cannot be seen by the naked eye. For example, when Iceland's Mount Mekla erupted in 2000, a DC-8 with sophisticated research equipment onboard was sent to study the event. Although the aircraft remained 200 miles north of the predicted ash plume, upon landing, the crew discovered that they had unknowingly flown for over seven minutes through the ash cloud. (Langston, Asking for Trouble, 2010).

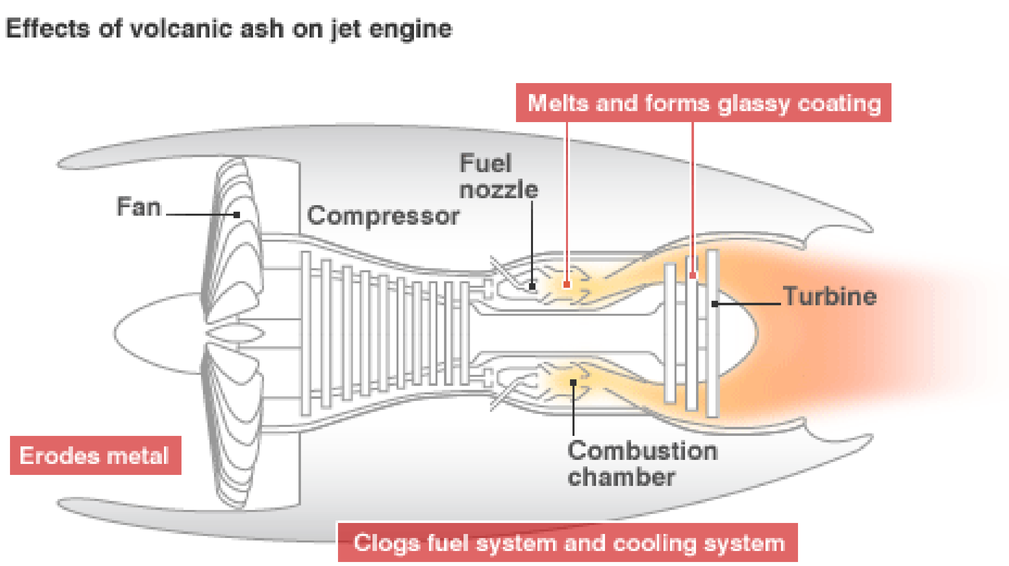

Figure 4: Effects of Volcanic Ash on Jet Engines (BBC, 2014)

When ash is ingested, it sandblasts jet engine blades and inlet vanes. At high enough concentrations, the ash melts into a molten glassy state that blocks critical avenues of the engine's airflow. This blockage can lead to compressor surges, compressor stalls and even engine flameouts. Boeing reported that in the last 30 years more than 90 jet-powered commercial airplanes have encountered volcanic ash clouds leading to significant aircraft damage (Langston, Jet Engines and Erupting Volcanoes, 2011). Fortunately, there have not been any fatalities to date related to the ingestion of volcanic ash. Figure 4 above illustrates the effect that volcanic ash has on a typical jet engine.

It has been proven throughout history that volcanic ash and aviation do not complement each other well. Their first significant meeting, a wartime one, occurred on March 22, 1944 when Mount Vesuvius erupted (Brooker, 2010). Enough tephra and ash descended on Pompeii airfield to destroy 88 B-25 bombers. Consequently, this was the United States' largest single loss of aircraft in World War II—64 were destroyed during the attack on Pearl Harbor (Brooker, 2010).

Figure 5: U.S. Troops at Mount Vesuvius in 1944 (Brooker, 2010)

Figure 5 above depicts United States' troops monitoring the progress of Mount Vesuvius in March of 1944. However, the impact of volcanic ash is not relegated to military aircraft. Two of the most disturbing incidents, involving long-range commercial aircraft, occurred in the 1980s.

In 1982, one hour after the eruption of the Galunggung Volcano in Java, Indonesia, a British Airways 747 lost all four engines at a cruising altitude of 37,000 feet. After descending unpowered to 13,000 feet, the crew was successfully able to restart one of their engines. Shortly thereafter, the crew was able to restart two additional engines and recover the aircraft at a nearby airport. Of note, the crew could not see through the ash-blasted windscreens and the engines sustained significant erosion damage (Brooker, 2010). In 1989, a KLM 747 inadvertently flew through an ash cloud produced by Alaska's Mount Redoubt. Shortly after penetration at 25,000 feet, the KLM 747 lost all four of their engines, only to restart two engines after reaching approximately 13,000 feet. Even though both aircraft were in the ash cloud for only a few minutes, the subsequent repair costs were enormous. The Redoubt encounter cost the airline $80 million dollars (at 1990 prices) and the price for a new Boeing 747 in 2010 was approximately $250 million dollars (Brooker, 2010).

Given the tremendous cost and delays associated with the Eyjafjallajokull eruption in 2010, the question becomes—what threat do volcanic emissions pose to aircraft and their engines? Remarkably, the answer is quite simple. There are numerous ways that volcanic emissions damage or degrade aircraft in flight, and surprisingly, its detrimental effects are not limited to the aircraft's engines. In a majority of eruptions, the emissions consist of large amounts of sulfur dioxide. When mixed with naturally occurring water vapor found within the atmosphere, this sulfur dioxide transforms into a sulfuric acid compound that expedites corrosion in passing aircraft. While the study of this phenomenon is still in its infancy, the only guard against such corrosion is a costly, expanded aircraft inspection cycle.

The sharper ash fragments, such as volcanic glass and quartz, scratch the external surfaces of the aircraft, damaging the glass, plastic and metal components. As a matter of fact, smaller fragments can even infiltrate the aircraft exterior and affect critical instrumentation and internal air supplies. As moving parts of the engine erode with the introduction of ash, of most concern, are the ash deposits that accumulate on the fuel nozzles, in the combustion chamber and within the turbine section of the engine. This ash can restrict both the introduction of fuel into the engine, as well as airflow through the engine, resulting in a significant reduction of engine thrust.

Michael G. Dunn, a professor and director of the Gas Turbine Laboratory at Ohio State University, found that there are five dominant ash ingestion factors of immediate concern to a flight crew. Specifically, these five factors include ash material deposits occurring on the high turbine inlet guide vanes, blocking of the turbine vanes or blade cooling holes, erosion of the fan and compressor blades, degradation of the engine fuel control system, and deposition of carbon-like material on the fuel nozzles (Langston, Asking for Trouble, 2010). As turbine inlet temperatures approach 2,000 degrees Fahrenheit, the ash melts and quickly becomes a glass-like substance. This molten ash coats many internal engine components, hardens as it cools and creates blockages which impede the safe operation of the engine, and subsequently, the aircraft. Figure 6 below shows the buildup of material deposits on engine vanes.

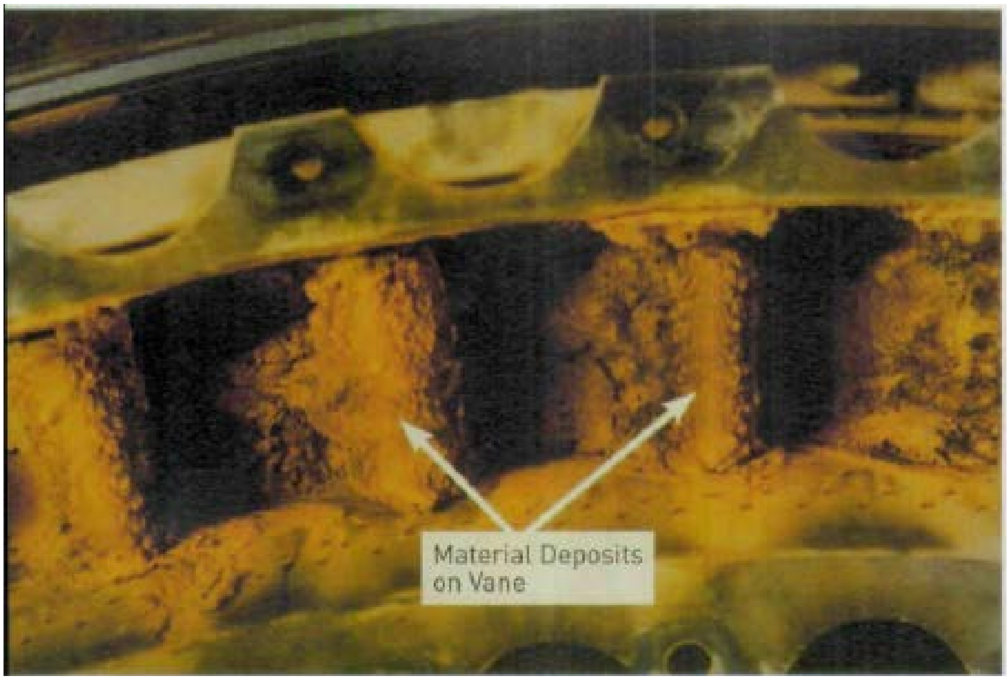

Figure 6: Material Deposits Located on Engine Vanes
(Langston, Asking for Trouble, 2010)

A Worldwide Threat

According to volcano experts, about 50 to 70 of the world's approximately 1,500 active volcanoes erupt each year (Langston, Asking for Trouble, 2010). A vast majority of these volcanoes are located near large population centers and within close proximity to critical transportation routes. As seen with the 2010 eruption of Eyjafjallajokull, a small disturbance can virtually bring air traffic over an entire continent to a standstill (Zizek, 2010). As with the variable nature of volcanoes, each eruption is different from the previous and these eruptions tend to vary in intensity, size and duration. In the past five centuries alone, it is estimated that 200,000 people have been killed by volcanoes globally, either directly as a result of the eruption or due to the ensuing famine when livestock, crops and farm land were affected (Tweed, 2012).

While the next eruption may not lead to mass casualties, the potential for disrupted international mobility is a real threat. As Eyjafjallajokull's 2010 eruption led to an unprecedented shutdown of air traffic in twenty-five European states, it greatest detriment was adversely impacting millions of passengers around the world and leading to billions in economic losses (Gruber, 2011). This same, unpredictable volcanic threat looms large in the Pacific region. Known as the Ring of Fire (Reference Figure 7 below), the 25,000 mile horseshoe is a complex string of volcanoes that stretch from the "southern tip of South America, up along the coast of North America, across the Bering Strait, down through Japan, and into New Zealand" (National Geographic, 2014).

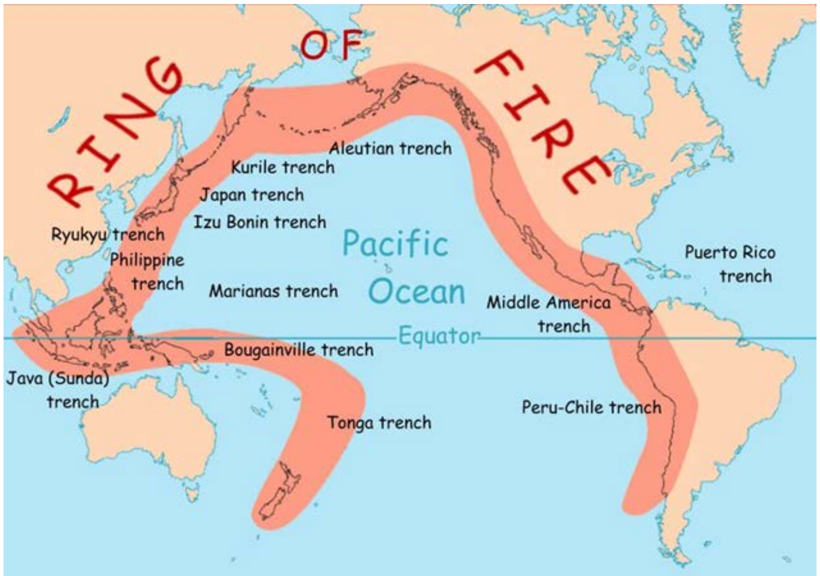

Figure 7: The Ring of Fire (National Geographic, 2014)

Classification of Volcanic Ash

Institutionally, the International Civil Aviation Organization (ICAO) is responsible for researching and mitigating the impact of volcanic ash on aviation. In 2004, the ICAO produced a *Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds*. Within the manual, the ICAO classified ash encounters based on selected criteria ranging from benign cabin odors to complete engine failure. This classification produces a severity index number, against which all incidents are measured (Reference Figure 8 below for the ICAO ash-encounter severity index).

Class	Selected criteria
0	Acrid sulphurous odour, electrostatic discharge
1	Light cabin dust, exhaust gas temperature fluctuations
2	Heavy cabin dust, abrasion damage, window frosting
3	Engine vibration, erroneous instrument readings (e.g., pitot-static system), damage to engine and electrical systems
4	Engine failure requiring in-flight restart
5	Engine failure or other damage leading to crash

Note: The pitot-static system is a system of pressure-sensitive instruments used to determine an aircraft's airspeed, altitude, etc.

Figure 8: ICAO Ash-Encounter Severity Index
(ICAO, 2004)

In the period 1953-2008, there were 126 aircraft encounters with ash clouds from 38 different volcanoes; all but three encounters occurred from 1975 onwards (Brooker, 2010)(Reference Figure 9 below). Remarkably, out of those 126 aircraft encounters, there were no recorded deaths related to the ingestion of volcanic ash.

Class	Incidents
0	21
1	10
2	51
3	17
4	10
5	0

Figure 9: Data on the 126 Aircraft Encounters (Brooker, 2010)

Analysts believe that the 21 Class 0 (i.e., acrid sulphurous odor, electrostatic discharge) encounters are quite misleading. They hypothesize the cause as being a combination of inaccurate reporting and inadequate data collection procedures. In only one of the ten Class 4 incidents was the ash not observable by the crew—this was a Gulf Stream survey aircraft rather than the long-range wide-body aircraft found in the other incidents (Brooker, 2010).

Volcanic Ash Mitigation

Despite the numerous encounters of aircraft and ash clouds over the years, surprisingly, there is little regulatory guidance on the acceptable levels of ash in which aircraft can safely operate. During an international symposium on the subject in 1991, the issue was raised (Przedpelski & Casadevall, 1994):

> Engine and (or) combustor tests should be sponsored by the Federal Aviation Administration (FAA) to establish threshold values for “safe” levels of ash concentration and the “safe” range of combustor temperature. This information, combined with updated dispersion and theoretical fallout models (and with improved cloud tracking) can establish when an ash cloud ceases to be a flight hazard.

However, when Eyjafjallajokull erupted in 2010, this same issue still remained unresolved. As a matter of fact, during the actual eruption in March of 2010, the issue was again addressed by analysts without gaining any significant traction. Experts at the international symposium in 2010 stated (WMO/ICAO, 2010):

> There continues to remain no definition of a "safe concentration" of ash for different aircraft, engine types or power settings. In order to give a reliable and justifiable "all clear" once a plume has dispersed enough to be undetectable, clear limits of ash content are required from both the manufacturers and aviation licensing authorities.

Interestingly enough, this revelation would come back to haunt the international community in the weeks that followed once the totality of Eyjafjallajokull's emissions were fully understood.

Without clear regulatory guidance or concrete scientific data on the concentration of ash permitted by particular engines, the only option for pilots is to avoid the hazard entirely. This inclination to completely avoid the threat is also in line with the design concept of the aircraft. While aircraft manufactures build airframes and engines to exact specifications, these provisions do not include flight through ash-laden environments. During the 55th Annual International Air Safety Seminar, specific guidance on encountering volcanic ash was discussed. Those present at the seminar determined that complete avoidance of volcanic ash by aircraft and the quick exit of an ash cloud, if encountered, are the only two courses of action for flight crews and dispatchers that guarantee flight safety (Guffanti & Miller, 2002). Today, avoidance is the most commonly used tactic, for civilian and military alike, to combat the effects of volcanic ash on aircraft operations.

Summary

This chapter provided a basic understanding of the history, timeline and dimensions of the Icelandic volcano Eyjafjallajokull. Next, the chapter discussed various aviation-related hazards, as well as other global volcanic hotspots. Also, pertinent information on the topics of eruption frequency and volcanic severity levels was discussed. The final portion of this review included the implications, past and present, of mobility system disruptions caused by volcanic activity and the lack of regulatory guidance concerning the mitigation of its effects.

III. Methodology

Chapter Overview

This chapter will determine the impact that the 2010 eruption of the Icelandic volcano Eyjafjallajokull had on AMC channel operations. Specifically, this methodology will produce the total number of channel missions affected by the eruption, the breakout and number of each aircraft type, the passengers and cargo disrupted and the average deviation per mission. There are numerous assumptions that need to be made in order for this methodology to fit appropriately. They will be stated in the assumptions section and are in addition to those listed previously in this document. The data set, from 2010, was provided by AMC/A9 and 618 TACC/XOND. It encompasses the duration of the entire eruption cycle and captures its impact on all AMC operations.

The Data Set

The data set, provided by AMC/A9 and 618 TACC/XOND on 26 February 2014, was a Microsoft® Excel spreadsheet named D-01-23-14-FCTask-5828-spreadsheet_v2.xlsx. It included 72,067 lines of data consisting of such information as *Key, FIRST_MISSION_ID, ITIN_NUM, MISSION_ID, MSN_CLASS, Aircraft Class, Aircraft Detail, Scheduled departure location, Actual departure location, Schedule take-off time, Actual Take-off Time, Departure Status, Delay Indicator, Primary Delay Code, Primary delay time (min), Delay Category, Delay Subcategory, Delay Description, Scheduled Arrival Location, Actual Arrival Location, Scheduled arrival time, Actual Arrival Time, Arrival Status, Pax Offloaded, Cargo Offloaded (stons), Pax Onloaded, Cargo Onloaded (stons), Leg Delayed, Mission Affected, Mission Changed, Went West* and *Ash Waiver Used*. The data set included all AMC missions that were executed from 25 March 2010 to 6 Jun 2010.

The data set had to be reduced in order to focus on the precise impact that the Icelandic volcano Eyjafjallajokull had on AMC channel missions. First, the researcher refined the data set by sorting by *Schedule take-off time* and eliminating all missions that fell outside the range of 0001Z on 14 April 10 to 0001Z on 28 May 10. This ensured that all missions executed between 14 April 10 and 27 May 10 were included in the updated data set. This range is significant as the second phase of the eruption began on April 14, 2010, generating ash plumes that blew east to Europe and resulted in a 20-80% decrease of airline flights for over a week (Wall & Flottau, 2010). As of late May the eruption continued, with occasional plumes that restricted air travel in parts of Europe (Smithsonian, 2014). This reduced the available lines of data to 53,333. Next, the researcher further refined the data set by sorting the 53,333 lines of data based on *MSN_CLASS*. Any line of data that was not classified as a channel mission was subsequently eliminated. This ensured that all channel missions executed between 14 April 10 and 27 May 10 were included in the updated data set. This reduced the lines of available data to 5,735. The researcher named the updated spreadsheet *AMC Channel Missions – 14 Apr – 27 May 2010*.

Identification of Affected Missions

The researcher classified affected missions as those missions that were rerouted, cancelled or delayed to avoid the impact of the impending ash cloud. In order to identify the affected missions, the researcher needed to further refine the data set. This step was accomplished by sorting the 5,735 lines of data by *Delay Category*. This technique also enabled the researcher to have visibility on the *Delay Subcategory* and *Delay Description* columns due to their close proximity within the spreadsheet. Next, using delay category information in conjunction with the delay description, the researcher identified which legs were rerouted, cancelled or delayed due to the 2010 eruption of Eyjafjallajokull. These delay categories and remarks were analyzed for any evidence of reroutes, cancellations or delays due to weather, airfield restrictions or air traffic control. Those missions that experienced reroutes, cancellations or delays due to management, coordination or maintenance were subsequently eliminated. Missions that did not contain a delay code or pertinent remark were assumed to have been executed without a reroute, cancellation or delay and were subsequently eliminated. If any individual mission leg was affected by the event, the researcher kept the entire mission and its subsequent or follow-on legs. This step was accomplished by highlighting the affected legs, sorting the spreadsheet by *FIRST_MISSION_ID* and grouping all individual mission legs together. This technique allowed for more detailed analysis later in the research effort. This further refined the data set to 954 lines containing all channel missions rerouted, cancelled or delayed by the event.

Within these 954 lines of data resided all of the missions that were affected by the eruption. However, these 954 entries are individual mission legs and not the missions themselves. It is also important to note that not all 954 data entries were affected by the volcanic activity; however, at least one individual mission leg under each mission number was affected. In order to determine the exact number of unique missions affected, the researcher used the assistance of the pivot table function within Microsoft®

Excel. By inserting a pivot table in the spreadsheet and designating *FIRST_MISSION_ID* as a row label, the researcher was able to identify how many unique mission numbers were affected (e.g., rerouted, cancelled or delayed).

Determination of Individual Mission Events Affected

As stated before, the spreadsheet contained all affected missions, but not all 954 individual entries or legs were affected by the blast. For example, a particular mission might have six legs, but only the third leg of the mission was affected by the ash hazard. The researcher had to further refine the data set to eliminate those individual mission legs that were not affected by the volcanic event. To accomplish this, the researcher had to first calculate the deviation between the *Schedule take-off time* and the *Actual Take-off Time*. This step was completed by inserting a column within the spreadsheet named *Delay Time* and programing in the following formula (Reference Equation 1 below) for all 954 lines of data.

$$\textbf{Actual Take-off Time}_{\textbf{Affected Leg}} - \textbf{Schedule Take-off Time}_{\textbf{Affected Leg}} = \textbf{Delay Time}$$

Equation 1: Delay Time

Following the delay time calculation of all 954 lines of data, the spreadsheet was sorted from the smallest to largest values. Those individual mission legs that took off early (e.g., demonstrated by a negative value) were eliminated as they were not impacted by the eruption. Those individual mission legs that departed with a difference of fourteen minutes or less were also eliminated as a delay is not recorded until the fifteenth minute.

The researcher had to be extremely careful during this step. With this methodology, missions that were cancelled showed an on-time takeoff due to data system limitations. As a matter of fact, cancelled missions showed zero delay as the scheduled take-off time is always the same as the actual take-off time within the system. For the purposes of determining individual mission leg disruptions, cancelled missions had to be accounted for as an aircraft was allocated to those particular mission events, and subsequently, was not used. In order to correct for this limitation and include these cancelled mission events, the data was sorted by *Departure Status* and searched for any evidence of cancellations. This step was done in concert with a careful cross-examination of the *Delay Time* column to verify the accuracy of the data. It is also important to note that some of these fields were incomplete or inaccurate and were subsequently eliminated in an effort to clean the data set. Similarly, any individual mission leg experiencing a reroute, cancellation or delay due to management, coordination or maintenance was also eliminated. Completion of these steps reduced the data set to 745 lines or individual mission legs that were affected by the event (e.g., rerouted, cancelled or delayed).

Determination of Number and Aircraft Type Affected

In order to determine the exact number and type of aircraft affected (e.g., rerouted, cancelled or delayed) by the eruption between 14 April 10 and 27 May 10, the researcher used a pivot table. By inserting a pivot table in the spreadsheet, designating *Aircraft Class* as a row label and *Aircraft Detail* as a value, the researcher was able to calculate the total number and type of affected aircraft. This number was predicated on the assumption that each individual mission leg was allocated one particular aircraft.

However, since it is common practice to assign one aircraft to a particular mission number, the researcher calculated the breakdown of aircraft class per each assigned mission. It is important to note that this number could not be higher than the total number of channel missions affected by the volcanic eruption. This was accomplished by inserting a pivot table in the spreadsheet and designating *FIRST_MISSION_ID* and *Aircraft Detail* as a row labels and *Aircraft Class* as a value. The researcher was then granted visibility of each aircraft type plotted against each unique affected mission number. While this step was not necessary for answering any of the investigative questions previously posed (e.g., could of excluded *Aircraft Detail*), this information could be considered useful for additional research.

Determination of Passengers and Cargo Affected

After isolating the 745 lines of data, the researcher was able to determine the total number of passengers and amount of cargo affected by the eruption (e.g., rerouted, cancelled or delayed). During this step, cancelled missions had to be accounted for as their passengers and cargo were considered frustrated. This process was completed by adding up the total number of passengers and short tons of cargo for each affected individual mission event. While this computation was completed in Microsoft® Excel, the following formulas can be used for the manual calculation of passengers and cargo on affected channel missions. Reference Equation 2 and Equation 3 below.

$$\sum_{a}^{b} Number\ of\ Affected\ Channel\ Passengers$$

Equation 2: Number of Affected Channel Passengers

Where a = first individual channel mission leg affected by the volcanic event and b = last individual channel mission leg affected by the volcanic event

$$\sum_{a}^{b} Amount\ of\ Affected\ Channel\ Cargo$$

Equation 3: Amount of Affected Channel Cargo

Where a = first individual channel mission leg affected by the volcanic event and b = last individual channel mission leg affected by the volcanic event

Determination of Mean Deviation Per Mission

In order to determine the mean deviation per mission, the researcher had to first calculate the individual delays for each mission affected by the eruption. The same methodology was used in determining which individual mission legs were affected by the event. This step was previously completed by inserting a column within the spreadsheet named *Delay Time* and programing in the following formula for all 745 lines of data. Reference Equation 4 below.

$$\textbf{Actual Take-off Time}_{\textbf{Affected Leg}} - \textbf{Schedule Take-off Time}_{\textbf{Affected Leg}} = \textbf{Delay Time}$$

Equation 4: Delay Time

Before calculating the mean deviation per mission or individual mission leg, the researcher needed to remove all cancelled events that were included in determining the total number of affected missions, legs, aircraft, passengers and cargo. In order to accomplish this step, the researcher sorted the 745 lines of data by *Departure Status* and searched for any evidence of mission cancellations. Those cancelled events were subsequently eliminated. The remaining data entries, 151 lines, were again checked for accuracy by sorting the spreadsheet by *Delay Time*, from the smallest to largest values. The researcher ensured that there were no delays listed less than fifteen minutes.

Once the 151 lines were checked for accuracy, the researcher calculated the mean deviation per individual mission leg by using the *AVERAGE* function in Microsoft® Excel. However, this step can be manually completed by using Equation 5 below.

$$\frac{\sum \textit{Delay of Individual Mission Legs}}{\textit{Total Number of Delayed Individual Mission Legs}} = \textbf{Mean Deviation of Individual Mission Leg}$$

Equation 5: Mean Deviation of Individual Mission Leg

Unfortunately, completion of this step does not factor into the calculation of the mean deviation per mission. It is important to note that simply taking the sum of all delayed individual mission legs and dividing by the previously calculated total affected mission number will produce erroneous results. The total affected mission number, calculated earlier in the methodology, included cancelled missions due to the simple fact that they were affected by the volcanic event. However, since cancelled missions were eliminated, the total number of affected missions also changed. Overlooking this fact will skew the data and make the mean deviation per mission appear lower than it actually is.

The researcher completed the mathematical computations in Microsoft® Excel using the logic found in Equation 6 below.

$$\frac{\sum \textit{Delay of Individual Mission Legs}}{\textit{Total Number of Updated Delayed Individual Missions}} = \textbf{Mean Deviation Per Affected Mission}$$

Equation 6: Mean Deviation Per Affected Mission

Assumptions

The following list of assumptions applies during the calculation of the total number of channel missions affected by the eruption, the breakdown and number of each affected aircraft type, the passengers and cargo disrupted and the average deviation per mission.

1. The definition of *affected mission* applies to those missions that were rerouted, cancelled or delayed.
2. A takeoff is classified as *late* as soon as the difference between the scheduled take-off and actual take-off time exceeds fourteen minutes.
3. Passengers and cargo on cancelled missions are considered frustrated, and subsequently, are defined as *affected* within this research.

4. Missing data fields or illogical entries are considered *erroneous* and are discounted.
5. Even though the effects of the Icelandic volcano Eyjafjallajokull were felt for months following its eruption, this research is based on the specific time period of *14 April 10 to 27 May 10*.
6. Each affected mission leg is viewed in *isolation*. This aided the researcher in painting a more accurate picture of the true mobility disruption. For example, a mission may have taken off and landed late on leg three of an eight leg mission. A subsequent takeoff (i.e., leg four) was delayed based on the delay from the third leg. In this research, both delays were accounted for, capturing the true effects reverberating throughout the mobility system.

Summary

This methodology was applied to calculate and analyze the effects that the Icelandic volcano Eyjafjallajokull had on AMC channel missions between 14 April 10 to 27 May 10. Painstakingly following its steps afforded the researcher the ability to calculate the total number of affected channel missions, as well as the total number of affected individual mission legs. In addition, this methodology allowed the researcher to determine the volcano's impact on aircraft, passengers and cargo. Finally, the logic found within this section enabled the researcher to compute both the mean mission and individual leg deviation experienced on AMC channel missions during this period of time.

IV. Analysis and Results

Chapter Overview

This chapter details the impact the 2010 eruption of Iceland's Eyjafjallajokull volcano had on AMC channel operations. Specifically, this chapter will address the total number of affected AMC channel missions (e.g., rerouted, cancelled or delayed), total number of affected individual channel mission events, total amount of disrupted passengers and cargo and the mean deviation of affected channel missions. Finally, the investigative questions posed at the beginning of this proposal will be answered. Calculating and analyzing these results will effectively describe the mobility disruption that reverberated throughout the system in late April through May of 2010.

Identification of Affected Missions

Excluding channel missions, there were 652 documented missions affected by the Eyjafjallajokull eruption between 14 April 10 and 27 May 10 (TACC/XOND, 2010). Based on this research, it was determined that there were 141 AMC channel missions that were negatively impacted by the events that transpired on 14 April 2010. When added to the 652 other missions (i.e., contingency, SAAM, other), there were a total of 793 AMC missions affected by the ash hazard produced by Eyjafjallajokull. Reference Table 1 below for a breakdown of the number and type of affected missions.

Table 1: Type and Number of Affected Missions

Mission Type	Missions Affected	% of Affected Missions
Channel	141	17.8%
Contingency	364	45.9%
SAAM	105	13.2%
Other	183	23.1%
Total	**793**	**100.0%**

The *other* category includes such missions as exercises, aerial refueling, support, training, coronet, airshows, deployments, transfers, rotators and guard missions.

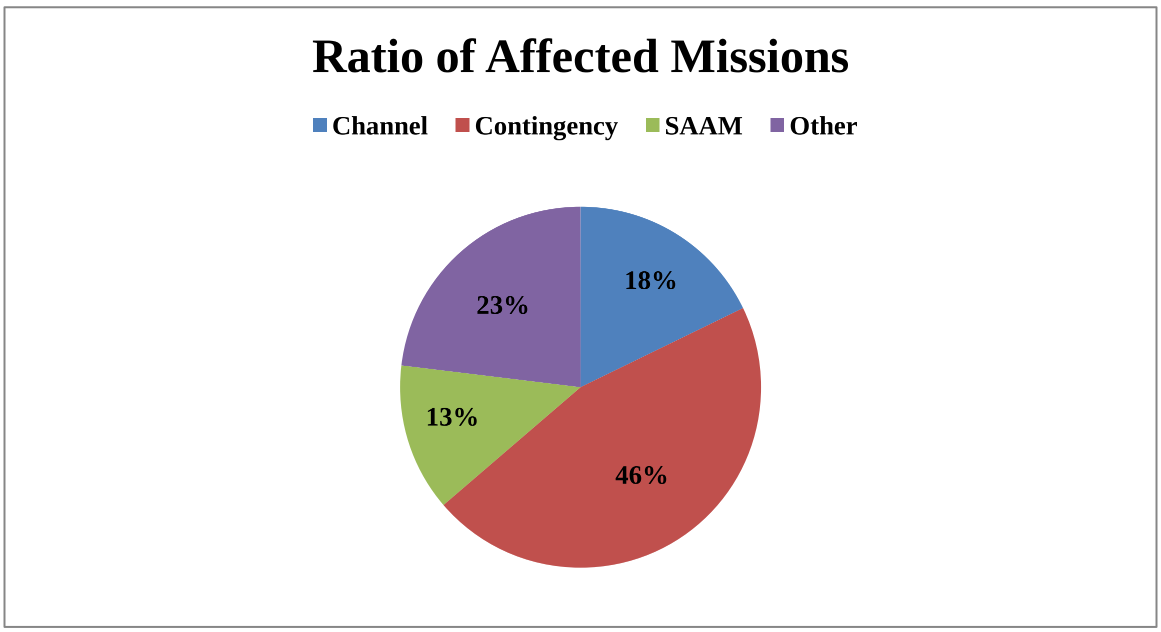

Figure 10: Ratio of Affected Missions

Since these categories individually consisted of such a small portion of the total percentage of affected missions, they were grouped together in the *other* category to illustrate the eruption's impact on their execution. Figure 10 above provides a visual representation of the ratio of affected missions by mission classification.

AMC channel missions made up 17.8% of all missions affected by the volcanic event in 2010. By comparison to all other AMC operations during that same period of time, the total number of missions affected by volcanic activity was relatively small. During the period of 14 April 10 to 27 May 2010, there were 20,416 AMC missions scheduled. The total amount of scheduled missions disrupted by the volcanic event was 3.9%. Table 2 below provides a breakdown of Eyjafjallajokull's impact on scheduled AMC missions.

Table 2: Percentage of All Scheduled Missions Affected

Mission Type	Missions Affected	Missions Scheduled	% Scheduled Missions Affected
Channel	141	1,422	9.9%
Contingency	364	4,844	7.5%
SAAM	105	570	18.4%
Other	183	13,580	1.3%
Total	**793**	**20,416**	**3.9%**

In order to gauge the magnitude of the disruption, the researcher overlaid the total number of missions affected on the total number of missions scheduled by mission classification. This visual representation demonstrates the scale of the disruption against all AMC operations during that specific time period. As it can be clearly seen, SAAM missions felt the greatest impact with 18.4% of all scheduled missions being affected by the volcanic hazard. This finding is in stark contrast with the total number of missions affected based strictly on mission classification. When analyzing the effects from a total mission impact perspective, contingencies had 364 affected missions whereas SAAM had only 105 affected missions. Figure 11 below illustrates this point and details the eruption's impact from a scheduling perspective.

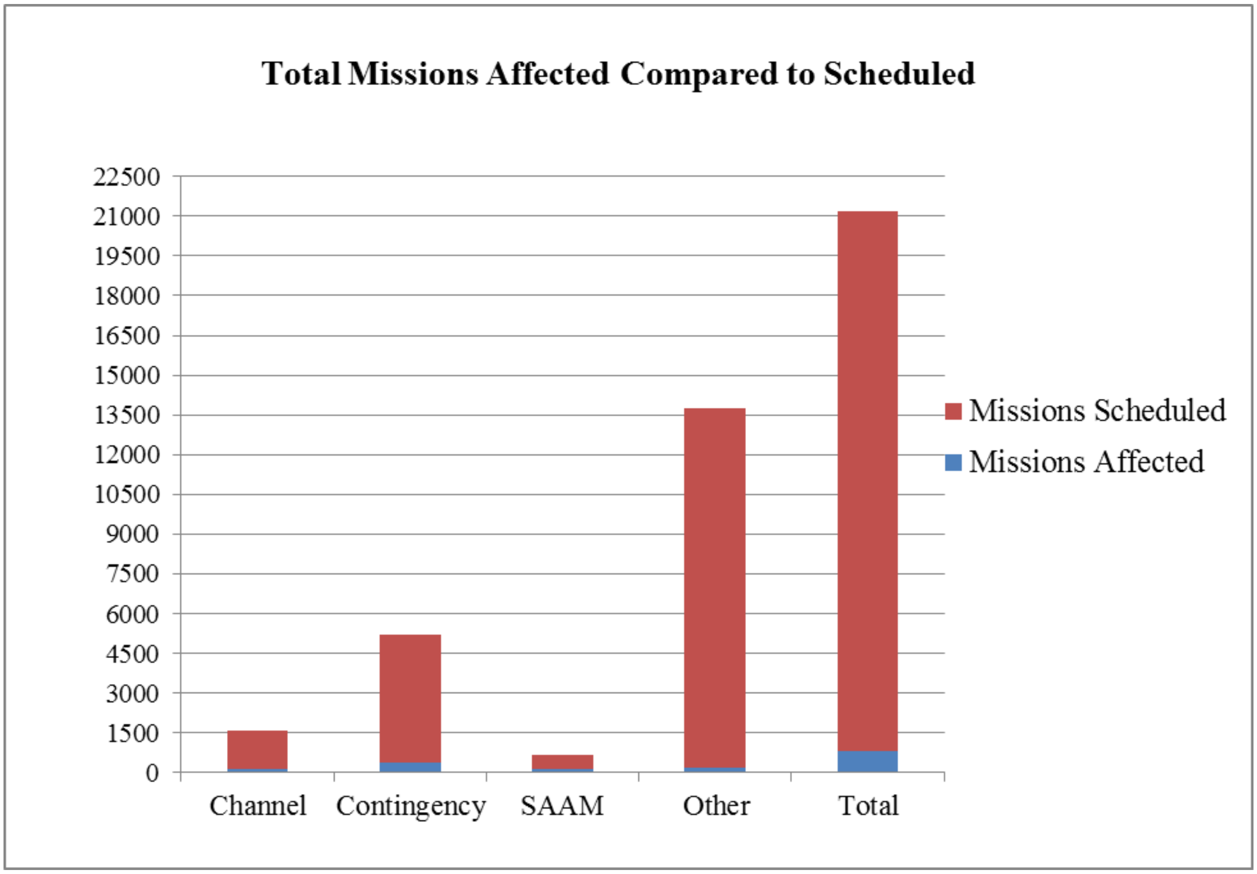

Figure 11: Total Missions Affected Compared to Scheduled

The researcher wanted to determine which day of the eruption cycle had the greatest impact on AMC channel missions. In order to accomplish this, the researcher annotated the number of missions impacted and the dates on which these impacts occurred. By plotting affected channel missions versus time, the researcher was able to pinpoint the exact day during the eruption cycle that had the greatest impact on AMC channel operations.

Eyjafjallajokull' s effect on AMC channel missions culminated on April 17, 2010. Through this research, it was determined this day had the greatest negative impact on AMC channel missions with 13 different disruptions. Table 3 below breaks down the total individual AMC channel mission disruptions per day and Figure 12 below provides a visual representation of the number of missions affected on any particular day between 14 April 2010 and 27 May 2010.

Table 3: Number of Affected Channel Missions By Date

Date	Number of Channel Missions Affected	Date	Number of Channel Missions Affected
14-Apr-10	6	6-May-10	0
15-Apr-10	9	7-May-10	4
16-Apr-10	7	8-May-10	4
17-Apr-10	13	9-May-10	5
18-Apr-10	5	10-May-10	3
19-Apr-10	12	11-May-10	4
20-Apr-10	9	12-May-10	10
21-Apr-10	12	13-May-10	1
22-Apr-10	6	14-May-10	3
23-Apr-10	5	15-May-10	0
24-Apr-10	2	16-May-10	3
25-Apr-10	2	17-May-10	2
26-Apr-10	1	18-May-10	0
27-Apr-10	1	19-May-10	0
28-Apr-10	1	20-May-10	0
29-Apr-10	0	21-May-10	0
30-Apr-10	0	22-May-10	1
1-May-10	1	23-May-10	0
2-May-10	1	24-May-10	0
3-May-10	0	25-May-10	0
4-May-10	3	26-May-10	0
5-May-10	5	27-May-10	0
	Total Number of Channel Missions Affected		**141**

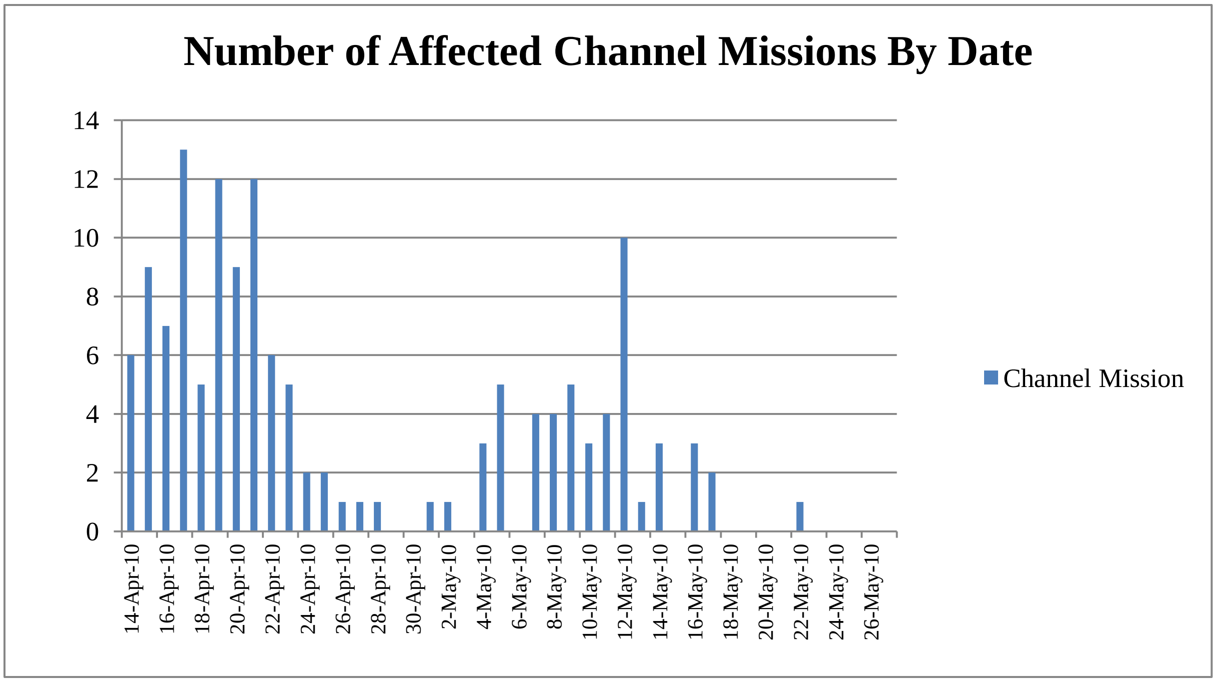

Figure 12: Number of Affected Channel Missions By Date

The researcher found that 745 individual channel mission events were affected by the volcanic event (e.g., rerouted, cancelled or delayed). Notably, 103 individual legs were cancelled and 642 individual legs departed late. It is paramount to understand that some of the recorded late departures were not a direct result of the volcanic eruption. A small portion of the departures were late due to the previous mission leg landing late or experiencing an in-flight diversion, and subsequently, delaying the follow-on mission departure. All of these data points were captured and examined in order to uncover the second and third-order effects of the volcanic event. Table 4 below breaks down affected individual channel legs by action and Figure 13 below provides a visual representation of the ratio of affected individual channel legs.

Table 4: Individual Channel Mission Events Affected

Action	Legs Affected	% of Affected Legs
Cancelled	103	13.8%
Departed Late	642	86.2%
Total	**745**	**100.0%**

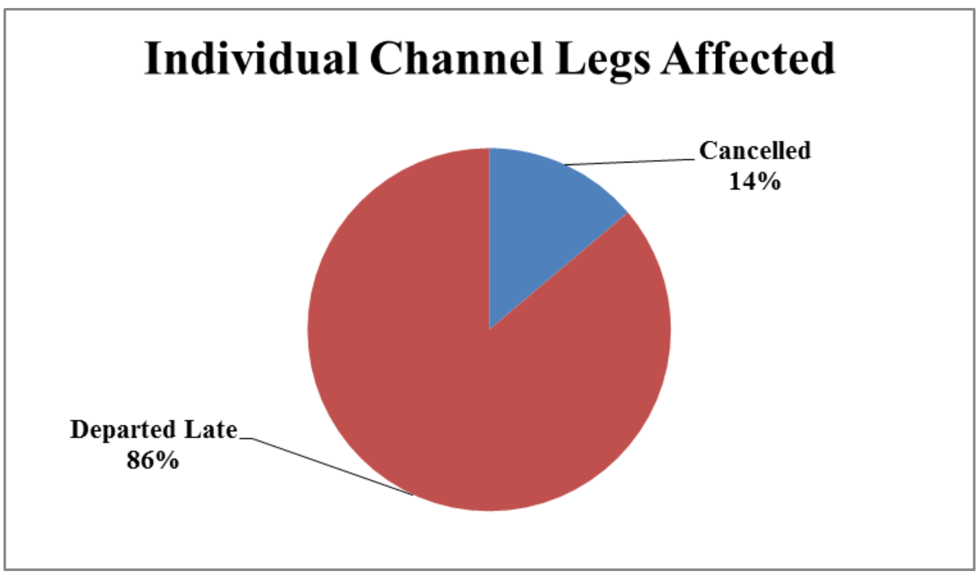

Figure 13: Individual Affected Channel Mission Events

Determination of Aircraft Type Affected

Since there were 141 AMC channel missions affected by the volcanic event, it was also assumed that 141 aircraft were also affected by this disruption. Essentially, AMC channel missions are assigned one aircraft per unique mission number. This assumption was validated by the following results. There were 141 individual aircraft disrupted by the volcanic activity, with C-17 aircraft feeling the greatest impact. The C-17 recorded 49 disruptions, commercial aircraft with 47 disruptions and the C-5 with 24 disruptions. However, this finding is not abnormal since a majority of channel missions are executed with C-17, C-5 and commercial aircraft. Table 5 below details the aircraft type and number of affected aircraft due to the volcanic activity. Figure 14 below provides a visual representation of both the number and type of affected aircraft.

Table 5: Breakdown of Affected Aircraft

Aircraft	Number Affected
C-5	24
C-17	49
C-130	9
KC-135	12
COMM	47
Total	**141**

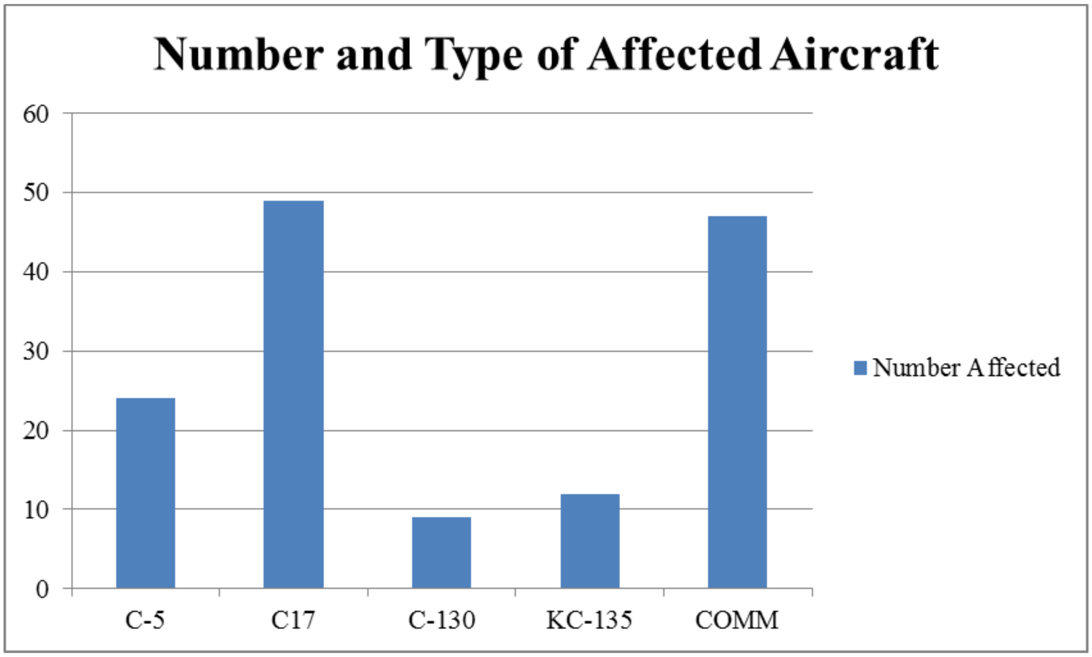

Figure 14: Number and Type of Affected Aircraft

Determination of Passengers and Cargo Affected

In total, the volcanic event disrupted 7,266 passengers and 9,133.4 short tons of cargo. This disruption was spread over a wide range of aircraft with the largest impact occurring within the commercial sector. The C-130 did not record any disrupted passengers or cargo during their nine affected channel missions. This can be explained as all nine missions were cancelled prior to execution; however, their missions were disrupted, and subsequently, were accounted for in the total affected AMC channel mission tally. Table 6 below lists the passengers and cargo frustrated by the disruption. Additionally, Figures 15 and 16 below provide a visual representation of the ratio of affected passengers and cargo per individual aircraft type respectively.

Table 6: Affected Passengers and Cargo

Aircraft	Passengers Affected	Cargo Affected (Stons)
C-5	731	2,956.1
C-17	659	1,414.8
C-130	0	0.0
KC-135	8	21.8
COMM	5,868	4,740.7
Total	**7,266**	**9,133.4**

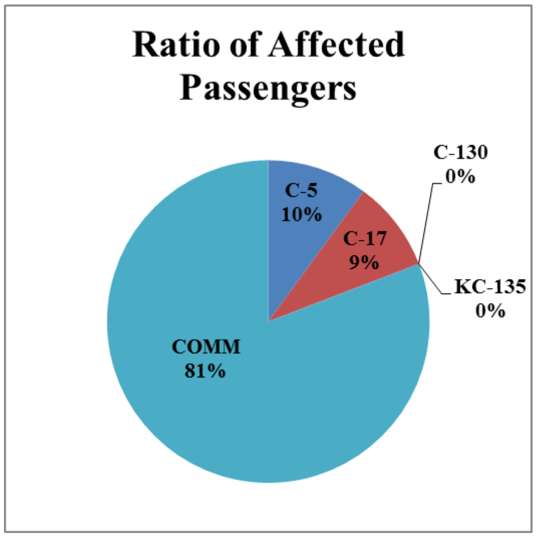

Figure 15: Ratio of Affected Passengers

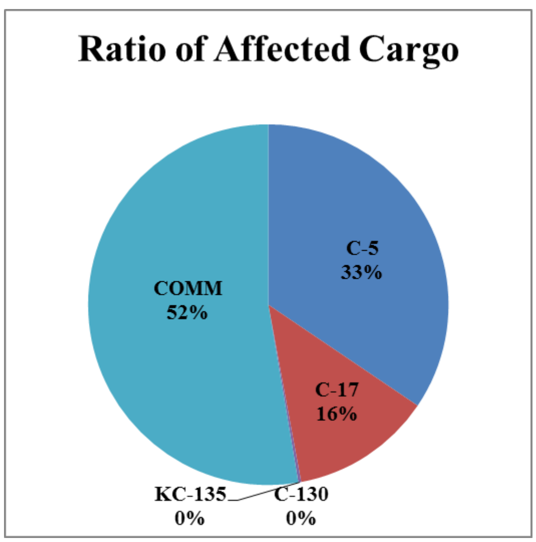

Figure 16: Ratio of Affected Cargo

The researcher also included a table below, Table 7, which illustrates the percentage of passengers and cargo affected per individual aircraft type. While these numbers coincide with the ratios depicted above, the tabular form provides an easy reference of both passenger and cargo disruption information in a side-by-side format.

Table 7: Percentage of Affected Passengers and Cargo By Aircraft Type

Aircraft	Passengers Affected	% of Affected Passengers	Cargo Affected	% of Affected Cargo
C-5	731	10.1%	2,956.1	32.4%
C-17	659	9.1%	1,414.8	15.5%
C-130	0	0.0%	0.0	0.0%
KC-135	8	0.1%	21.8	0.2%
COMM	5,868	80.8%	4,740.7	51.9%
Total	**7,266**	**100.0%**	**9,133.4**	**100.0%**

This research also sheds light on which particular aircraft model experienced the largest disruptions. The Boeing 767-300 experienced the largest impact on the passenger side with 3,300 stranded passengers and the Boeing 747-200 felt the greatest impact on the cargo side with 2,776.3 short tons of frustrated cargo. This is in agreement with a previous finding that commercial sector aircraft was the second largest affected aircraft category. Surprisingly, the C-17 had only 1,414.8 short tons of frustrated cargo with 49 affected aircraft. This contrast could be evidence of potential aircraft underutilization. Reference Table 8 below for affected passengers and cargo by aircraft model.

Table 8: Passengers and Cargo Affected By Aircraft Model

Aircraft	Passengers Affected	Cargo Affected
B74720	4	2,776.3
B74730	0	176.7
B74740	2	754.2
B76730	3,300	0.2
C005A	444	1,092.2
C005B	287	1,779.7
C005M	0	84.2
C017A	659	1,414.8
C130H	0	0.0
C130J	0	0.0
DC008	40	0.6
DC0103	2,498	0.0
KC135R	8	21.8
MD011F	24	1,032.7
Total	**7,266**	**9,133.4**

The researcher further refined the results and calculated the percentage of passengers and cargo affected per each individual aircraft model. As previously stated, while these numbers coincide with the ratios depicted above, the tabular form provides an easy reference of both passenger and cargo disruption information in a side-by-side format with reference to aircraft model. Reference Table 9 below for the percentages of affected passengers and cargo per aircraft model.

Table 9: Percentage of Passengers and Cargo Per Aircraft Model

Aircraft	Passengers Affected	% of Passengers Affected	Cargo Affected	% of Cargo Affected
B74720	4	0.1%	2,776.3	30.4%
B74730	0	0.0%	176.7	1.9%
B74740	2	0.0%	754.2	8.3%
B76730	3,300	45.4%	0.2	0.0%
C005A	444	6.1%	1,092.2	12.0%
C005B	287	3.9%	1,779.7	19.5%
C005M	0	0.0%	84.2	0.9%
C017A	659	9.1%	1,414.8	15.5%
C130H	0	0.0%	0.0	0.0%
C130J	0	0.0%	0.0	0.0%
DC008	40	0.6%	0.6	0.0%
DC0103	2,498	34.4%	0.0	0.0%
KC135R	8	0.1%	21.8	0.2%
MD011F	24	0.3%	1,032.7	11.3%
Total	**7,266**	**100.0%**	**9,133.4**	**100.0%**

Figures 17 and 18 below provide a graphical representation of both passengers and cargo affected by Eyjafjallajokull's 2010 eruption with reference to aircraft model. Again, these results were confirmed above in Table 9.

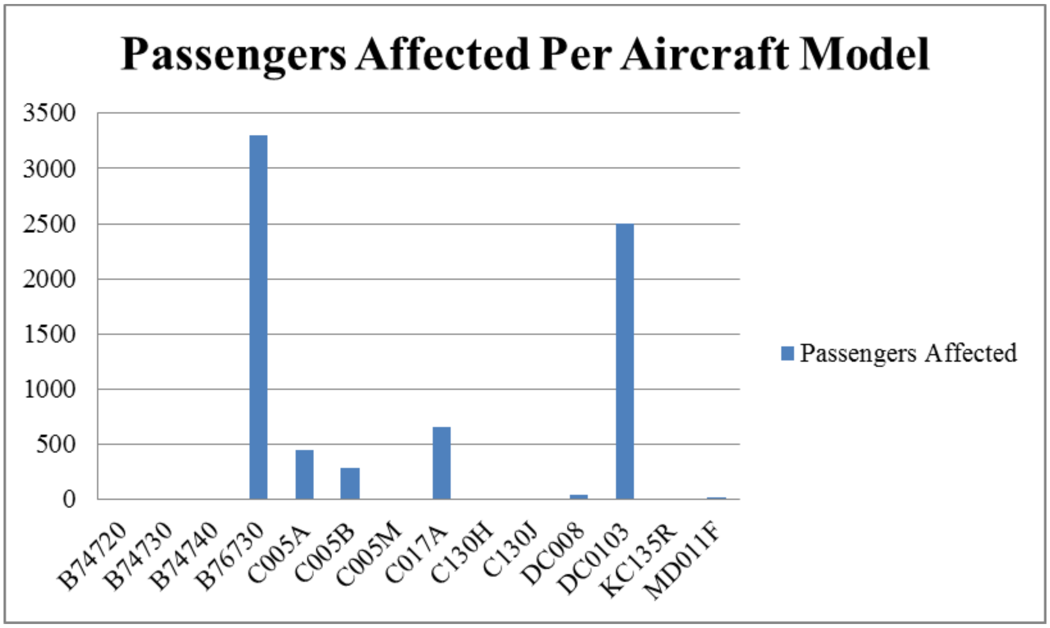

Figure 17: Passengers Affected Per Aircraft Model

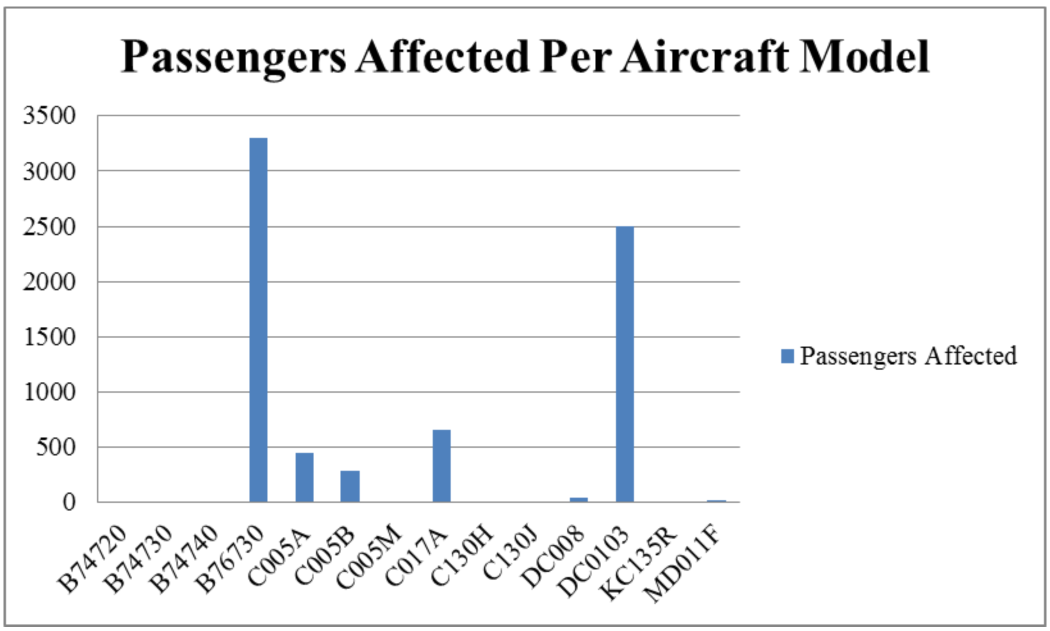

Figure 18: Cargo Affected Per Aircraft Model

Determination of Mean Deviation Per Mission

The mean AMC channel mission delay was 37 hours and 27 minutes. As stated in the methodology section, this figure does not include cancelled missions or those that were in delay less than fifteen minutes. This effectively reduced the number of affected missions to 113. The range of delay for those remaining missions was fifteen minutes to 3.41 days. When analyzing the data from an individual channel mission event perspective, the summation of each individual delay equated to 4,233 hours with an individual leg deviation of 28 hours and 13 minutes. These delay values spanned the date spectrum from 14 April 10 to 17 May 10, as those missions that were scheduled to execute from 18 May 10 to 27 May 10 were subsequently eliminated within the confines of the methodology. Table 10 below details the delay times in terms of the summation of individual mission events and the mean deviation of individual AMC channel missions. Table 10 also lists the updated mission count and the standard deviation.

Table 10: Updated Mission Count and Standard Deviation

Type of Delay	Time (Hours)
Summation of Individual Events	4233:02:00
Missions	113
Mean Mission Delay	37:27:38
Standard Deviation	25:20:42

Investigative Questions Answered

Investigative Question 1: How many AMC channel missions were disrupted due to the eruption of Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010?

During the eruption of Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010, there were 141 disrupted AMC channel missions. During that same period of time, there were a total of 793 AMC missions (e.g., contingency, SAAM, other) affected by the eruption. Hence, AMC channel missions accounted for 17.8% of all the affected AMC missions. Furthermore, there were 1,422 AMC channel missions scheduled between 14 April and 27 May 2010. With the disruption of 141 AMC channel missions, a total of 9.9% of all AMC channel operations were impacted during that time.

Investigative Question 2: How many individual AMC channel mission events were disrupted due to the eruption of Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010?

During the eruption of Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010, there were 745 disrupted individual channel mission events. Out of the 745 disrupted individual channel mission events, 103 or 13.8% were cancelled. The remaining 642 disrupted individual channel mission events, or 86.2%, departed late.

Investigative Questions 3: How many of each type of aircraft were disrupted due to the eruption of Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010?

During the eruption of Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010, there were a total of 141 disrupted channel aircraft. They included 24 C-5s, 49 C-17s, 9 C-130s, 12 KC-135s and 47 commercial aircraft.

Investigative Questions 4: How many passengers and how much cargo was disrupted due to the eruption of Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010?

During the eruption of Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010, there were 7,266 stranded passengers and 9,133.4 short tons of frustrated cargo on AMC channel missions.

Investigative Question 5: What was the mean mission deviation for AMC channel missions disrupted due to the eruption of Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010?

During the eruption of Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010, the mean mission deviation for affected AMC channel missions was 37 hours and 27 minutes. Reference Table 11 below for a summation of the individual channel event delays and for the mean channel mission deviation.

Table 11: Mean Mission Delay

Type of Delay	Time (Hours)
∑ Individual Channel Events	4233:02:00
Mission	37:27:38

Summary

This chapter presented the total number of AMC channel missions disrupted by Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010. Additionally, this chapter analyzed the volcano's impact on AMC channel aircraft, passengers and cargo during this same period of time. The chapter concluded with an analysis of the mean channel mission deviation caused by the ash hazard. Finally, the investigative questions posed at the beginning of this research proposal were reviewed and answered in their entirety.

V. Conclusions and Recommendations

Chapter Overview

Using data from AMC/A9 and 618 TACC/XOND, the objective of this research was to determine the total number of AMC channel missions disrupted by Iceland's Eyjafjallajokull volcano from 14 April to 27 May 2010. Additionally, the research aimed to determine the volcano's impact on AMC channel aircraft, passengers and cargo during that same period of time. The final goal of the research was to calculate the mean channel mission deviation caused by the ash hazard that blanketed the North Atlantic region. This chapter presents major conclusions, research significance and recommendations for future research.

Conclusions of Research and Recommendations for Action

Rapid global mobility provides the United States with an asymmetrical advantage; however, highly contested airspace or natural disasters may deter the United States from leveraging this unique capability. As seen with the unexpected eruption of Iceland's Eyjafjallajokull volcano, seemingly small, insignificant delays can reverberate throughout the entire mobility system. To a certain degree, AMC aircraft that cannot depart a field, subsequently, prevent another aircraft from arriving at that same location. AMC aircraft that arrive late due to an in-flight deviation, delay that aircraft's follow-on departure. When one spreads those intricacies across an entire mission set, these effects compound rather quickly. When Eyjafjallajokull' s ash concentration increased on 14 April 10, AMC channel operations were able to quickly adapt by cancelling unnecessary missions, rerouting necessary missions westward and delaying identified missions in place.

Understanding how disruptions affect the mobility system when natural disasters occur can help mitigate their impact quite considerably. For instance, understanding the impact that Iceland's Eyjafjallajokull volcano had on AMC channel missions from 14 April to 27 May 2010 can better prepare AMC for a subsequent eruption in the near future. Furthermore, this problem is not confined to the North Atlantic region. As the United States pivots toward the Pacific, it will have to contend with the looming threat of the Pacific Rim. The Pacific Rim region brings unique challenges and a litany of potential disruptions over a vast surface area. This problem becomes even more challenging considering the tyranny of distance and the fact that this region relies heavily on timely transportation modes. One advantage that AMC has in terms of these threats is the fixed nature of volcanoes. Volcanoes do not move or migrate and their positions are known. Two independent variables that exacerbate the problem are the uncertainty of when an eruption will occur and the severity of the event's impact on the entire mobility system.

With these two independent variables in mind, AMC can prepare contingency plans in the event that another eruption occurs. Throughout history, Iceland's Eyjafjallajokull volcano emitted a fairly consistent and sizeable ash hazard. Today, the size and concentration of this hazard can be estimated based on the time interval between eruptions and the scientific analysis of historical data. With those challenging estimations in hand, the problem is then reduced to only one variable—when will the next eruption occur? Furthermore, scientists today are developing models to better estimate the eruption interval and the duration of the eruption cycle. Armed with this information, AMC can develop plans to counteract potential mobility disruptions caused by volcanic activity. These plans, developed in and around the world's volcanoes, can be activated early on during an eruption cycle. Predetermined aircraft routes, suitable airfield locations and prioritized mission types can all be overlaid on historical ash patterns. This would preclude and could even eliminate a majority of the disruption experienced during the initial eruption. Eliminating the uncertainty created by the hazard will increase mission velocity and restore the unique advantages created by rapid global mobility.

Recommendations for Future Research

This research and its associated methodology can be applied to any eruption or natural disaster. One of the limitations of this research is its dependence on the analysis of historical data. This methodology is not forward looking; however, the insights gained from its implementation will increase the accuracy of future mobility disruption estimates. With that said, this methodology should be applied to other unique mission sets within AMC in order to accurately gauge the impact that either volcanoes or other natural disasters have on the entire mobility network.

In the future, analysts should focus on the disruption potential created by volcanoes whose eruption cycle is considered imminent. There are studies available that classify certain volcanoes as decade volcanoes—those that are prone to erupt at least once every ten years. Analyzing those volcanoes, their locations and their potential for creating mobility system disruptions would be considered a great starting point. Using that same logic, volcanoes that are in prime strategic locations (e.g., North Atlantic, Pacific region) should be studied for their impact to both ongoing operations, as well as potential future engagements. Arming decision makers with this knowledge increases the agility and speed of the mobility network.

Lastly, analyzing this problem through a fiscal lens would assist decision makers in determining the break point for investment in new and emerging anti-ash technologies. Cancelling or delaying critical missions is inefficient and inherently ineffective. By allocating a cost to the mobility system disruption caused by Iceland's Eyjafjallajokull volcano, leaders would be better positioned to justify additional investment in research and development. Using the methodology contained within this proposal starts that iterative process. For example, this research was able to determine the number of AMC channel missions affected by Eyjafjallajokull's eruption in 2010. This value can then be multiplied by a weighted cost (i.e., based on the ratio of aircraft type), similar to the cost per flying hour, to determine the total cost per affected channel mission. The total channel mission disruption cost can then be calculated by multiplying this value by the total number of channel missions affected by the eruption. This calculation would give leaders a better sense of the magnitude of the entire system disruption.

Summary

This chapter provided major conclusions based on the foundation of this research, as well as proposed recommendations for future research. Overall, AMC channel operations were negatively impacted by the unexpected eruption of Iceland's Eyjafjallajokull volcano. While the total number of affected missions was quite small, imagine the same scenario in the Pacific region where the availability of time-sensitive transportation is virtually non-existent. There is definitely a lesson to be learned from this case study—severe mobility system disruptions are just an eruption away.

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14. ABSTRACT
The basic foundation of airpower promotes unique capabilities and inherent advantages to achieve strategic, operational, and tactical objectives for the nation. Air mobility and its associated core competencies are seated appropriately under this airpower umbrella. Exploiting its inherent speed and tremendous range allows air mobility to become rapid global mobility. The core competency of rapid global mobility, the lifeblood of sustained combat operations, presents itself as one of the greatest military advantages in the world. Understanding the importance of rapid global mobility to the United States' National Security Strategy (NSS), and subsequent National Military Strategy (NMS), is paramount when analyzing the impact of its interruption. The eruption of the Icelandic volcano Eyjafjallajokull on April 14, 2010 significantly affected Air Mobility Command's (AMC) ability to execute rapid global mobility, and more specifically, its sustained channel network. The ash impediment created by the eruption perpetuated system disruptions that threatened the Air Force's ability to sustain combat operations abroad.

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