Conceptual Design of a Hybrid-Electric Regional Turboprop Aircraft

The Harmful Effects of the Rare-Earth Mining Industry: A Case Study of the Bayan Obo Rare-Earth Mine

A Thesis Prospectus
In STS 4500
Presented to
The Faculty of the
School of Engineering and Applied Science
University of Virginia
In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science in Aerospace Engineering

By
Alexander Poley
November 30, 2022

Technical Team Members:
James Caputo
Darius Espinoza
Jannik Grabner
Ryan Grant
Ryan Keller
Eun Park
Kangyi Peng
Alex Wang

On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

ADVISORS

Dr. Kent A. Wayland, Department of Engineering and Society

Dr. Jesse R. Quinlan, Department of Mechanical and Aerospace Engineering

Introduction

Carbon and pollutant emissions have become the target of global climate standards. Corporations, governments, and citizens alike are striving to limit their production of harmful emissions, by developing and searching for green technologies. This push has been especially present in the transportation sector. According to the International Energy Agency (IEA), the transportation sector emits roughly 37% of global carbon dioxide annually (International Energy Agency, 2022b). Further, 2% of total carbon emissions come from aviation (International Energy Agency, 2022a). Though this percentage seems small, we must remember the scale of global emissions. The aviation industry emitted 720 megatons of carbon dioxide in 2021. This may seem like a lot, but to further put this in perspective, the industry only gained back about one-third of the drop from prior to the coronavirus pandemic. Given these statistics and background, the transportation sector has been the target for technological innovation and development. This fits with recent objectives of the American Institute of Aeronautics and Astronautics' (AIAA) Aircraft Design Challenges.

In recent years, the AIAA's Aircraft Design Challenge has focused on addressing environmental issues and concerns, and this year's challenge is no exception. The technical portion of this project will compete in this year's AIAA Aircraft Design Challenge, which features a request for proposals (RFP), calling for designs of a hybrid-electric, regional, turboprop aircraft, with an entry into service (EIS) date of 2035 (*Hybrid-electric*, 2022). The technical section of this report will explain what this project constitutes, and how a design will be reached. This endeavor will produce a conceptual design proposal for submission to the AIAA Aircraft Design Challenge. Ultimately, this design, as well as many electric designs, will require increased use of precious and environmentally-harmful materials and metals than their internal combustion counterparts. This leads to the science, technology, and society (STS) approach to this project.

In the STS portion of this project, a case study will be performed on a rare-earth metal mine in China. This mine, the Bayan Obo mine, is one of the largest producers of rare-earth materials. As is also seen with many other forms of mining, mining is very destructive to the surrounding land, and produces many hazardous by-products. Rare-earth mining is often even worse for the land than coal mining and oil extraction, with similar or worse land effects, and many toxic and radioactive by-products (Lee & Wen, 2017). In order for a successful switch to electric technologies, rare-earth mining will need to become clean and sustainable. Reducing carbon and pollutant emissions must not come at the cost of environmental considerations. This project will highlight a representative environmental case with much current study and data, and help to examine the impact this has on the people and society as a whole. Overall, the push for cleaner technologies has led to the development of electric transportation, inspiring the AIAA's RFP for a hybrid-electric regional turboprop aircraft, which will require sustainable and clean extraction of valuable rare-earth metals to be successful.

Designing a Hybrid-Electric, Regional, Turboprop Aircraft

Keeping with the recent themes of the AIAA Design Challenge, this year's challenge features the design of a hybrid-electric, regional, turboprop aircraft. This challenge seeks to create conceptual designs for the next generation of aircraft, calling out the goal of minimizing direct aircraft emissions (*Hybrid-electric*, 2022). As the world becomes more interconnected, the demand for air travel continues to increase. Thus, the aviation industry, an already significant emissions contributor, will only continue to grow. This puts the aviation industry at the center of the sustainability movement.

Breaking down the long, descriptive title of hybrid-electric, regional, turboprop, we will start to examine the design. “Hybrid-electric” means that the aircraft must utilize two propulsion systems, one of a typical internal combustion architecture, and the other of an electric propulsion architecture. In other words, some amount of the aircraft’s propulsion must come from electricity. Outlined in the AIAA’s RFP, this aircraft must see a 20% reduction in block fuel burn for a 500 nautical mile (nmi) mission (*Hybrid-electric*, 2022). This central and challenging requirement reinforces the AIAA’s commitment to cleaner aviation. Block fuel burn is the amount or weight of fuel that is burned over a designed flight or mission. The use of the word “regional” refers to the shorter designed mission, as well as the passenger capacity. The intended use of this aircraft would be commuter flights, rather than cross-country or international. While the block fuel reduction calls out a 500 nmi mission, the aircraft must have a range greater than 1000 nmi. Further, the RFP also states that the aircraft must seat at least 46 passengers, with the goal of 50, not including pilots and crew. “Turboprop” means that the aircraft is propelled by engines that utilize propellers. Turboprop engines are typically used on smaller aircraft, as they are more efficient than their turbofan engine counterparts, which you have likely seen and flown on if you’ve ever flown commercially.

The design will be completed through an iterative design process. This design will almost exclusively lie in the conceptual design phase (Quinlan, 2022). The process will be as follows. First, the team must understand the requirements, by studying and defining them. This is completed by a system requirements review (SRR) presentation. Next, research must be completed on the state-of-the-art concepts, technologies, tools, and methods. Afterwards, brainstorming begins. This part includes coming up with many potential ideas, solutions, and technologies, for a preliminary down-select, promoting some ideas, and eliminating others. Then, aircraft design concepts are generated. This includes determining geometry of the aircraft, as well as creating an initial sizing of the aircraft. This step also yields another opportunity of down-selection. Then the aircraft is configured for all necessary systems. Aerodynamic performance data is gathered. Final sizing is also determined at this step. Lastly, the final design of the aircraft is decided upon, based on system level metrics generated by the process.

The product of this design process will be a conceptual design report, in the form of a proposal to meet the RFP. This conceptual design report will compete in the yearly AIAA Aircraft Design Competition.

Rare Earth Mining Impacts: A Case Study

How does the Bayan Obo mine impact its surrounding communities and environment?

In relation to the technical research, which aims at a more sustainable future of aviation, this STS project will address the problem of clean and sustainable rare-earth mining by examining the largest and most important rare-earth mine in the world, the Bayan Obo mine in Baotou, China. Since this mine is the largest producer of rare-earth metals, and historically a major environmental offender, it encapsulates a good case study for the rare-earth industry.

First off, what are rare-earth metals, and what are they used for? Rare-earth metals include 17 elements, most of which are in the lanthanide series (Connelly et al., 2005). Despite their name, rare-earth metals are actually relatively common in Earth's crust. These elements are generally in high demand and have many other uses. Pertaining specifically to electrification, rare-earth metals find their way into most modern electric motors, especially when high mechanical power is required. These metals are often used to create strong, permanent magnets in these motors, which drive the mechanical energy. They are often heavily used in electric car motors, which often require about 5-6 times as much rare-earth materials as their internal combustion counterparts (Lee & Wen, 2017). Large electric motors, several times the size of an electric car's, will be necessary for electric flight. Thus, the drastically-increasing necessity of rare-earth metals in future electric aircraft motors means cleanliness and sustainability is paramount to this transition, so as to not replace one harmful technology with another.

The mine's impact on the surrounding environment is especially intense and scarring. Rare-earth metals are mined in two different processes. The first involves removing layers of soils and transporting them to a leaching pond (Standaert, 2019). The second process inserts polyvinyl chloride (PVC) pipes into hills, and shoots a mixture of water and chemicals into them, and flushes out a slurry of earth that contains the rare-earth metals, water, dirt, acid, and other chemicals used in the process. This process, like the first, also transports the slurry to a leaching pond. A leaching pond is a manmade pond where acids and chemicals are use separate the valuable rare-earth metals from clay, rock, and dirt.

As one could imagine, these chemicals are highly toxic to humans and the environment, and can cause many problems. Injecting these chemicals into the hill allows them to penetrate the ground and seep into the soil, poisoning the ground to future use, and contaminating groundwater. Leaching ponds generally are required to use containment systems and liners, but in the event of an overflow, these chemicals are spilled into the surrounding ground. Waste products and by-products are often left in tailing ponds, which only serve to hold wastes, which still seep into the soil at alarming rates. Deposits of rare-earth metals are often found with radioactive elements, such as thorium. Therefore, waste from these mines is not only acidic and toxic, but also radioactive. When these ponds and wastes are not cleaned and removed when mining is finished, the land becomes increasing unusable and harmful to the health of surrounding humans, plants, and animals.

Mining in the Bayan Obo region began in 1958 (Bontron, 2012). At that time, Bayan Obo was a vast and fertile farming region. As resident Li Guirong describes the beauty and prosperity of the land, “Before the factories were built, there were fields here as far as the eye can see. In the place of this radioactive sludge, there were watermelons, aubergines, and tomatoes.” In 1958, the large tailing lake appeared, though its toxicity and effects were unbeknownst to the local villagers. The lake still lacks a proper lining (Kaiman, 2014). By the late 1980s, as Li describes, crops started to fail, and when they would produce fruit, they were often small or smelt terrible(Bontron, 2012). By then, many farmers began to let fields run wild, and to only grow wheat and corn. The local environmental protection agency performed a study proving that the new rare-earth industry was the cause of these and many problems. A former farmer, Lu Yongqing, was among the first to move from his farm, leaving when he could no longer provide for his family. Societally, his registration as a farmer on identification paperwork leads him, and likely many others, to be treated as second-class citizens. Now, the population of the farming region has been drastically reduced, by about a factor of ten, and many old houses fall to ruin.

Not only has this mining produced terrible impacts on the society in the region, but the impacts on health and wellness in the region are also severe. Many of the farmers report that, in the late 1980s and early 1990s, many of their animals also died due to toxic groundwater (Bontron, 2012; Kaiman, 2014). As there was no tap water in the region, the residents all drank and watered their animals from wells. Though the well water was not visibly contaminated, the residents attest to its awful smell. The residents also inhale solvent vapors and coal dust in the local air due to the factory pollution, which is clearly visible in the air. Local resident He Guixiang states that all families in the town are affected by illness, such as aching legs, diabetes, osteoporosis, and chest problems. Further, resident Wang Jianguo says that seven of his remaining neighbors have died of cancer. His own teeth have grown yellow and crooked, and his gums have blackened. Further, the toxic sludge creeps towards the nearby Yellow River, a major drinking water source for a large part of northern China, at a rate of 20-30 meters per year, which could have drastic implications.

As the impacts of such mining are severe, and often underregulated or not regulated at all, surrounding communities are severely impacted. This mining destroys any existing landscape, as well as contaminating the groundwater, and creating many other environmental hazards (Jouini et al., 2022; Pan & Li, 2016). How is this cleaned up? Who will clean it? Who will pay? This is the situation that China is left with. These problems have arisen out of the desire to bring the rare-earth industry, and its deep pockets, to countries and communities (Pan & Li, 2016). As a result, minimal regulation is more profitable and attractive. Governments must develop smart and effective regulation to protect their land, their citizens, and their environment (Shi et al., 2022). Further, mining companies must accept some level of responsibility for the shambles they have left. Ethics of mining must be considered by all involved parties.

As can be seen above, there are many actors and actants in this complex problem network. First, and most importantly, the local populations and communities have a stake in this problem, as the environmental problems affect their health and land. Second, mining companies have a responsibility to clean up the land, as they have made the mess and profited substantially off of it. Many of these companies are state-run, which leads to a couple different angles in which the Chinese government must be involved. The government needs to not only direct and run their corporations in a responsible way, but to provide for the health wellness of their citizens, and conserve their land. Other foreign governments and corporations have a stake in this as well, as nearly all of the world benefits from these rare-earth metals produced, and trades to receive them, at relatively cheap, though increasingly expensive elements. Corporations must be willing and able to pay a just amount for these resources, so that the costs of sustainable production can be reasonably offset. International governing bodies also have a stake, as the World Trade Organization (WTO) has made judgements on Chinese rare-earth metals, and regulates global trade.

This case study will be accomplished by research from two main types of sources: academic papers on the quantitative impacts of the problems, and first-hand accounts and journalism, to receive direct accounts of the problems cause by rare-earth mining at Bayan Obo. Further, similar rare-earth mines in China may be examined and compared to provide more context. Overall, this case study will seek to exemplify problems with the rare-earth mining industry, and to provide another note of consideration in the movement for electrification.

Conclusion

The movement towards electric technologies is inevitable, and ongoing. This movement is bringing about major changes to transportation, as well as many other elements of our daily lives. Accordingly, the American Institute of Aeronautics and Astronautics' request for proposals for a design of a hybrid-electric, regional, turboprop aircraft is aiding in a global push for a cleaner future in commercial aviation. Our participation in this design challenge, and development of our own design candidate, allows us to be at the forefront of this development, and to contribute in this step towards a reduction in direct, harmful emissions from the aviation industry. The push for electrification cannot be reckless, though, as industry must ensure that electric technologies are not causing more harm than good for the environment. One way this is seen is in the rare-earth mining industry, where mines scar and toxify the land in ways that have not been seen before. Efficient regulation and policy must catch up to the times, for the protection of peoples, lands, and environments. Sustainable aviation is coming, and it will be electric. Humanity has the duty to be a steward of the planet, to keep and protect it, which must be ensured, specifically by the sustainable production of rare-earth metals.

References

American Institute of Aeronautics and Astronautics (AIAA). (2022). *Hybrid-electric regional turboprop RFP*. American Institute of Aeronautics and Astronautics (AIAA).

Bontron, C. (2012, August 7). Rare-earth mining in China comes at a heavy cost for local villages. *The Guardian*. https://www.theguardian.com/environment/2012/aug/07/china-rare-earth-village-pollution

Connelly, N. G., Damhus, T., Hartshorn, R. M., & Hutton, A. T. (2005). *Nomenclature of Inorganic Chemistry IUPAC Recommendations 2005*. The Royal Society of Chemistry. https://old.iupac.org/publications/books/rbook/Red_Book_2005.pdf

International Energy Agency. (2022a). *Aviation – Analysis*. International Energy Agency (IEA). https://www.iea.org/reports/aviation

International Energy Agency. (2022b). *Transport – Topics*. Internation Energy Agency (IEA). https://www.iea.org/topics/transport

Jouini, M., Royer-Lavallée, A., Pabst, T., Chung, E., Kim, R., Cheong, Y.-W., & Neculita, C. M. (2022). Sustainable production of rare earth elements from mine waste and geoethics. *Minerals (2075-163X)*, *12*(7), N.PAG-N.PAG. https://doi.org/10.3390/min12070809

Kaiman, J. (2014, March 20). Rare earth mining in China: The bleak social and environmental costs. *The Guardian*. https://www.theguardian.com/sustainable-business/rare-earth-mining-china-social-environmental-costs

Lee, J. C. K., & Wen, Z. (2017). Rare earths from mines to metals: Comparing environmental impacts from China’s main production pathways. *Journal of Industrial Ecology*, *21*(5), 1277–1290. https://doi.org/10.1111/jiec.12491

Pan, Y., & Li, H. (2016). Investigating heavy metal pollution in mining brownfield and its policy implications: A case study of the bayan obo rare earth mine, inner mongolia, china. *Environmental Management*, *57*(4), 879–893. https://doi.org/10.1007/s00267-016-0658-6

Quinlan, J. R. (2022, September 1). *Aircraft design process II*. Aircraft Design I, University of Virginia, MEC 213.

Shi, Z., Yong, L., Liu, Z., Wang, Y., Sui, H., Mao, W., Zhang, L., Li, Y., Liu, J., Wei, S., & Song, Y. (2022). Risk assessment of rare earth elements in fruits and vegetables from mining areas in China. *Environmental Science & Pollution Research*, *29*(32), 48694–48703. https://doi.org/10.1007/s11356-022-19080-7

Standaert, M. (2019, July 2). *China Wrestles with the Toxic Aftermath of Rare Earth Mining*. Yale E360. https://e360.yale.edu/features/china-wrestles-with-the-toxic-aftermath-of-rare-earth-mining