Nuclear Aviation Project

Kai Joy
Claire Lewis
Arnav Pradhan
Brennan Pratt
Madeline Tesch

Table of Contents

Abstract

Commitments to achieving zero net emissions by 2050 require large steps to be taken by those releasing large amounts of carbon dioxide into the atmosphere, most notably the aviation industry. The transportation industry remains the single largest producer of greenhouse gasses in the world which is why attention has shifted to aviation. Because of the consequences associated with hydrocarbon-based consumer propulsion, nuclear power has the potential to replace jet fuel in modern aircraft. Nuclear power boasts nearly no carbon emissions with the addition of uranium being an extremely energy dense resource. The proposed implementation of nuclear power enables the reduction of carbon emissions by replacing the heat due chemical combustion with heat generated by a fission reaction. This utilization of a nuclear-powered aircraft would be an enabling technology for long-distance, carbon-neutral transport for unmanned, cargo, and commercial aircraft. Placing a small reactor in the fuselage shows promise that nuclear powered aviation would be feasible in the commercial industry. The design would still pose significant technical challenges such as weight and safety of passengers. The analysis of this paper touches on the reactor, propulsion system, safety, fuel life cycle, and public policy that would be associated with a nuclear powered aircraft.

Introduction

As America attempts to decrease its environmental impact, there is a need to regulate aircraft greenhouse gas (GHG) emissions. As of 2020, "Aircraft remained the single largest GHG-emitting transportation source not yet subject to GHG standards in the U.S." [17]. As a result, aircraft have been a major contributor to environmental impacts internationally for years. Because of this, the International Air Transportation Association (IATA) has committed to a net zero carbon emission goal by 2050 [34].

The current design for our engine is based on the HTRE-3 engine that was designed by Oak Ridge National Laboratory and many others starting in 1951. Renewed interest in nuclear energy, the push for green energy in aircraft, and the ever developing nuclear industry, is cause to reconsider the possibility of nuclear powered aviation.

Why Nuclear?

Nuclear energy is a safe, clean, and reliable resource. With a low overall carbon footprint, it is estimated that nuclear energy could produce as low as 15 grams of carbon dioxide per kilowatt hour, making it an exceptional alternative energy source [61]. This makes nuclear competitive with renewable energy sources such as wind and solar, while providing an efficient and stable source of energy.

Despite the high entry cost of nuclear energy, the long term benefits make it worth pursuing. This economical advantage comes from uranium being inexpensive and energy dense. According to the World Nuclear Association (WNA), 8.9 kilograms of enriched uranium would cost around $1663 including raw materials and processing, however this price is only an estimate due to fluctuating market prices and enrichment techniques [73]. On the other hand, a barrel of Jet A-1 Fuel costs around $118 [36], [28]. The advantage comes from the longevity of the enriched uranium fuel source. Like the nuclear powered US naval vessels, the reactors could be designed to last up to 50 years with refueling taking place around every ten years [74]. That being said, nuclear submarines are very different from aircraft, and these numbers could not be guaranteed without proper testing and simulation. Looking at fuel price comparisons over the lifetime of the plane, the cost of uranium is a fraction of what it costs to use jet fuel. Around 200 kilograms of uranium is used in nuclear submarines which are designed to last fifty years [74]. While traditional fuel has the advantage in initial costs, this makes nuclear energy an economically competitive fuel source for either nuclear powered aircrafts or the creation of hydrogen fuel at airports.

Although there are other alternative energy sources that could provide a low carbon footprint, nuclear energy is more effective due to its power output and energy density. For example, Sustainable Aviation Fuel (SAF) is jet fuel mixed with up to 50% biofuels to maintain a low carbon footprint [64]. This would take "an estimated 1 billion dry tons of biomass" to meet the growing demand of the aviation industry and would require a significant amount of farmland [64]. Another alternative that was considered is biofuel. Biofuels face the same problems as SAF. For biofuels to be a viable low-carbon fuel source, it would require farmers across the country to switch to a low carbon system that prevents the use of their tractors, trucks, or other vital equipment in exchange for more expensive alternatives [5]. Biofuel would not be economically or spatially viable. With the shortcomings of the many other low carbon alternatives, nuclear energy will be the most viable solution to aviation's GHG emission problem.

Fuel Lifecycle

Fuel

The reactor will be run off of high assay low enriched uranium [30]. This means that the reactor will be powered by Uranium-235 (U-235) enriched to around 19-20% [30]. Anything more would result in greater power density, however, the high enriched uranium and the plutonium waste generated would contradict nonproliferation efforts.

There are multiple different radioactive materials such as U-235, thorium-232 (Th-232), or plutonium-239 (Pu-239) that could be used in this type of reactor. Using Pu-239 represents too great of a proliferation risk which excludes it from consideration. Th-232 could provide many potential benefits with the fuel theoretically being more efficient than U-235 reactors because they are able to use all available Th-232 in the reaction. U-235 only utilizes about one percent of its potential energy because plutonium is produced when the fuel is recycled which raises proliferation concerns. One ton of Th-232 is predicted to be able to produce the same amount of energy as 35 tons of U-235 and would generate significantly less waste [63]. However, even with these benefits, U-235 would still be a better alternative. U-235 reactors are easier to work with and more predictable than Th-232 fueled reactors because they have seen much more use on a global scale. Th-232 reactors are still extremely experimental and would likely cause enough problems to outweigh their benefits. For example, Th-232 by itself is not fissile, which means it cannot sustain a reaction without an outside source. A small amount of U-235 would still be required for reactor operation. This makes both the fuel cycle and reactor more complicated and therefore more prone to error. U-235 has been thoroughly tested in reactors all over the world and would be much more predictable in terms of problems that arise, fuel life cycle, and usable energy output.

Technologies that have been thoroughly tested are more likely to cause less problems once in use in commercial aircraft. U-235 will not only cause less problems for the reactor, but also the supply chain. The molten salt reactor (MSR) was chosen for a similar reason. During the original HTRE-3 experiment, a MSR was used which means the idea has been tested and run before. Technology that has been used for longer periods with low accident ratings will be best for this project. Being able to tell the general public that the technology used in the aircraft is safe and reliable will be key in the success of this project.

The heat energy needed to power four engines will require a large small modular reactor (SMR). A typical 737 engine requires at most about 50 megawatt-hour (MWh) to run effectively. That across four engines works out to around 200 megawatts (MW) of heat energy to power the engines. This means SMR technology will be required to maintain a low enough weight for the plane to fly. This 200 MW reactor will operate at around 1250˚ Celsius. The molten salt will flow throughout the whole system and transfer heat directly through the rods in the heat exchanger in the engine . This process and heat flow will keep the reactor cool enough to remain in safe operation during the whole flight.

Mining

The United States currently hosts one of the largest uranium deposits in the world [57]. Situated on the Colorado Plateau, the deposit is roughly 200 square miles and hosts over 1,200 mines that have produced uranium [57]. While this would be the ideal place for uranium mining it is important to note that much of the plateau is inside the Navajo Nation [41]. Since the mining boom at the end of the last world war the Navajo people have suffered many health effects from lack of regulations in the mine, and currently it is a topic of discussion of whether or not the government is responsible for some kind of reparation to the Navajo people [9]. Although since the 1960s many regulations have been implemented to increase worker safety and lower risk [9]. It is expected that by 2050 safety standards within the mines would be improved given the increased use of Nuclear power included in this project. The location of the Colorado Plateau is especially favorable for its close proximity to Nevada. Historically Nevada has been used for nuclear testing due to the large amount of government land in the state, today 48 million acres or 63% of the state [68].

Transportation

Most of the Uranium used in our proposed nuclear aircraft would be mined in the Colorado Plateau due to its advantageous position and abundant resources, and transported to an enrichment facility in Nevada in which laser separation would be used to enrich the uranium and check concentration for use in a nuclear engine [66]. There are currently no laser separation cities in the United States, but on May 12, 2008, the NRC approved research into laser separation and it is plausible that there will be laser separation cities operational in the future [66]. Nuclear material would be transported from the enrichment facility to the plane construction facility. Using casks, which are highly tested crash-resistant containers, the materials will be transported to Nevada by truck [75]. Trucks are currently the most popular method for transporting nuclear material over land because of the low cost [40]. By using a northern route from the plateau it is possible to avoid all high populated areas like Las Vegas when transporting nuclear material [25]. After the material is processed at the nuclear facility they will be processed into casks specially designed to be inserted into the reactor. This means that once the uranium has been enriched people will not be exposed to it.

Reactor Implementation

Many reactor designs and materials were considered for moderators, shielding, reflectors, and radiators while attempting to maintain the lightest possible load. The exact optimization of the reactor cannot be known without thorough research and testing. The following represents the best estimates and what the team considers to be the best design based on previous tests and modern research.

A spherical MSR was chosen for its high power density in comparison to other reactor types such as light water reactors and heat pipe reactors. Spherical reactors are best for this application because they offer the highest optimization for power density and also offer the least amount of neutron leakage. These specifications will allow for the smallest possible reactor which will in turn allow for more versatility in plane design and safety measures that can be taken. MSRs work by dissolving U-235 directly into a molten salt such as lithium tetrafluoroberyllate *(Li_2BeF_4)*, also known as FLiBe, where a fission chain reaction can take place generating the heat necessary to power the engines. Normally, this heat would be used to boil high pressure water, and then spin turbines to generate electricity. However, the heat will be transferred to a mediator which in turn will flow through the engines to heat the air inside of the jet engines. One problem that arises when using a MSR is that molten salt has very corrosive properties. This means that the lifespan will be severely decreased. However, using a thin layer of cladding material, such as Titanium-Zirconium-Molybdenum (TZM), can protect from the corrosive properties up to and over the temperatures at which the reactor will be operating [21].

To increase the efficiency of the reactor, it will utilize a reflector. Reflectors work by reflecting neutrons that pass through them back into the reactor, which allows them to once again partake in the fission reaction. This is essentially a thin shell around the outside of the reactor that acts sort of like a mirror for neutrons. Multiple reflectors were considered for the reactor including Lithium-7 Hydride and Beryllium Oxide. However, considering Beryllium Oxide is toxic to humans, Lithium-7 Hydride is the better choice [21]. Using a reflector could also be used as an added layer of safety by making the reflector necessary for the criticality of the reactor. This means if the plane were to crash, the reflector would shatter and cause the reactor to go subcritical and naturally shut itself down.

Shielding

The most crucial piece to getting a nuclear aircraft flying is demonstrating to the public that the aircraft is safe. In order to maintain a safe environment for passengers to ride alongside a SMR, there needs to be sufficient shielding. Radiation is when energy is given off in rays or particles that can or cannot be harmful [67]. Gamma rays and neutrons are dangerous byproducts of nuclear fission that are harmful to humans, so the shielding must provide ample protection from both [1]. The general rule for reducing gamma ray emissions to one billionth of their initial energy is to use 1.3 feet of lead [52]. Assuming placing the largest spherical reactor in the cargo bay of a 737 which would have a diameter of roughly 5 feet, it would require around 150 cubic feet of lead to completely encase the reactor. This would weigh around 115,000 lbs, which could be optimized. To prevent neutrons from reaching passengers, as according to Qi et al., shielding mainly consists of carbon, aluminum, and boron [62]. Polymers are typically the lightest, so to provide shielding on an aircraft, a polyethylene polymer will be used [54]. Due to its chemical stability, wide availability, and composition of two hydrogen and one carbon atoms, the material is an effective shielding material for neutrons [26]. The application of this material will be in the structure of the aircraft. Polyethylene will be coated around the outside of the reactor along with lead to protect the passengers. Overall, these two materials should provide assurance that the aircraft will remain safe in flight.

Storage

After the fuel has been used in an aircraft it will need to be stored and disposed of. Long term storage of used radioactive material is achieved with special casks that use concrete overpacks [59]. A front liner and concrete reinforced with rebar would be added to the base design of the cask as this ensures the damage from impacts is greatly reduced [59]. The casks would be monitored using muon tomography, which has the ability to detect both how long the material has been in storage and whether or not the fuel has been swapped out for another material [53]. After the used nuclear fuel is removed from the plane, the plane could then be repurposed, scrapped, fitted with a new reactor, or just refueled. If a plane is not in use it could also be stored without a reactor for long periods of time.

Disposal of Fuel

The fuel once removed from the reactor would be considered spent nuclear fuel (SNF). This fuel, though spent, can still be used for other reactors [39]. Partitioning and Transmitting of SNF has recently been accomplished on laboratory scale and it seems as though with continuing research it would be applicable on a commercial scale as well [39]. With this in mind the SNF would be transferred out of storage to a refining facility, which would refine the nuclear fuel and send it back to be reused in a reactor. Any fuel or byproducts that could not be further refined would be transported to a waste facility as High Level Waste [51]. Most likely the fuel would be stored in Palo Verde, a commercial SNF site with an operating reactor in southern Arizona, because of its location and facilities which allow recycling and disposal of fuel [49].

Plane Structure

Engine

The mechanical design is inspired by the schematics of the NB-36 Crusader. In the NB-36 Crusaders design, the engine works like a typical turbojet engine. A turbojet engine works by intaking air through an opening in the front, then compresses the air to increase the velocity of the air, heats up the air further and makes it faster by combusting the air with traditional jet fuel. This faster air then exits the aircraft as thrust while also turning a turbine that is connected to the compressors near the front of the plane engine [43]. In the case of the NB-36 as shown in ***Figure 1***, the NB-36 doesn't have a traditional combustion chamber. The combustion chamber is instead replaced with a heat exchanger. Hot molten liquid salt is pumped from the nuclear reactor to this heat exchanger, which is located behind the air compressors, where the combustion chamber is traditionally located. The heat exchanger heats up the already compressed air to create thrust to allow the plane to fly [12] [23].

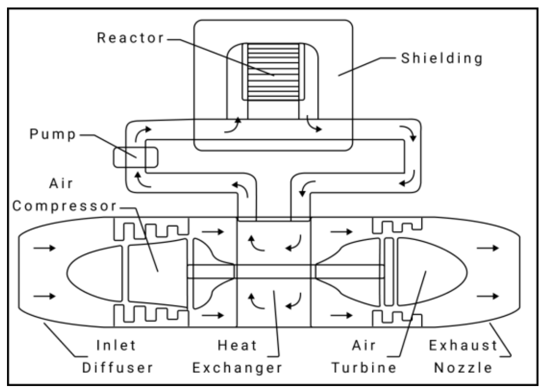

Figure 1: Blueprint of Thermal System

While the design is inspired by the NB-36, there are altered aspects to better match the efficiency and workings of today's aerospace industry. For example, one of the biggest changes is using a turbofan engine instead of a turbojet engine. Turbofan engines, while having more moving parts, are quieter and are typically used in commercial aircraft. Additionally, turbofan engines are able to provide higher thrusts at lower speeds. This is ideal for most planes as the average commercial and cargo aircraft flies at Mach 0.75 [42].

One of the biggest problems with the NB-36 and the HTRE was that the air that was expelled by the engine was radioactive, which is dangerous to people and the environment [12] [70]. The solution to this problem is to not directly heat the heat exchanger with molten liquid salt. Instead, in the HALEU reactor core, there will be molten salt going through the core and feeding into a heatsink. This heatsink will be located in a pipe with molten liquid lithium. The liquid lithium would then travel a pipe system to the heat exchanger in the engine, where another heatsink will exist. The compressed, faster moving air from the compressors will come into contact with the heat exchanger, getting heated up and becoming faster. The faster air will then come out the plane as the thrust and will also turn the turbine. The turbine will not only turn the compressors at the front of the engine, but will also be able to generate electrical energy for the rest of the plane to use for flight operations.

Because the reactor core is only capable of hitting a temperature of 1,200°C with modern-day technology, the aircraft will have four smaller sized engines, two on each wing, with each engine having its own pipe system. With advances in nuclear technology, materials technology, and engine design, the system will eventually be able to move away from a four-engine design to a simpler two engine design that is more in line with planes in today's aerospace industry.

Despite the decreased temperature and the smaller engines, the engines and their setup should still perform nominally compared to commercial passenger planes. For example, take the LEAP-1B, the engine present on the Boeing 737 MAX 8. The LEAP-1B is capable of producing a maximum takeoff thrust of

29,320 lbf, with it typically operating between 23,000 to 28,000 lbf [8]. However, it also operates at a temperature of 1,700° C. To counter this, the nuclear-powered aircraft will hold 4 nuclear engines that are operating in the range of 14,000 lbf to 18,000 lbf. The increased number of engines will allow it to be at a similar thrust range as the 737 MAX 8. The nuclear engines will also be smaller and lighter. The intake of the engines will be 15% smaller than the LEAP-1B, about 59 inches, and there is no complex combustion chamber, instead replaced with a simple heatsink [58].

Structure

Because of the risk of radiation from the nuclear reactor core, many changes were made to the structure of the aircraft. Traditionally, aircraft are built in four different segments: the fuselage, the left and right wings, and the rudder. These parts are each built separately, and are attached to the fuselage when they are finished. As a result, when a plane crashes, they are often split at the wings and the rudder 8. However, with the reactor-engine system, it was important to keep the molten liquid salts isolated from the outside because of the risk they pose to their surroundings.

As shown in ***Figure 2***, the structure of the plane was changed to protect the nuclear reactor upon impact and better protect passengers in the plane. In the proposed design, the plane is divided up differently in comparison to the transition design. Rather than having two distinct plane wings that were separated from each other, the plane wings will be kept together and will be connected through a section of the hull. This section of the hull would house the reactor core and shielding. The four unique pipe systems would run from the reactor core to its respective engine in this combined area. The whole system would be encased in a thick casing lead due to its ability to block gamma rays and absorb impact. A majority of the mass of the plane will be concentrated at the center of the aircraft, which is very similar to the mass distribution of current commercial aircraft. The reactor and a majority of the shielding will be located at the leading edge of the wing. This will allow for the center of gravity to be in front of the leading edge, which is integral to the stability of the aircraft [27]. Additionally, lots of testing will need to be done to figure out the ideal mass distribution during takeoff, flight, and landing. By combining the wing and the section of the hull, the maintenance of the whole engine-reactor system easier, better protect the passengers and crew on the plane, and keep the radioactive system enclosed upon impact.

Figure 2: Side View of Plane and Reactor

The fuselage will fit around this section, with the front and back side of the hull being used for cargo and landing gear. To help the center of gravity move more to the front of the plane and in front of the center of lift, the economy and first class cabins will be flipped. The weight distribution of the plane is critical because the shielding will be a substantial addition to the weight of the airplane to protect the passengers from the radiation of the reactor and to protect the reactor from being exposed in case of plane crashes. The total weight of the plane will also be heavier than the current systems that are currently available. The weight of the plane will be very similar to that of prior military planes in the 1950s and 1960s [43]. With that being said, the power density over fuel weight of nuclear energy and being a cleaner source of energy in comparison to the systems using hydrocarbon fuels are significant advantages to our proposed systems. Over time, shielding technology will improve with the creation of better alloys and composites that are not only lighter, but will be superior at blocking radiation. These alloys would not only make it much easier to address the design challenges associated with the heavy weight of nuclear reactors, but would allow planes to eventually use smaller engines to move a lighter plane.

Changes to the Industry

Despite the nuclear aircraft being very different from a traditional jet fuel powered aircraft, there aren't many changes needed to the industry to incorporate this fleet of aircraft. Because the size of the aircraft isn't changing, there will be minimal changes to airports. The biggest changes come with startup and shut off of the aircraft, which will take a longer time compared to jet fuel powered aircraft. With traditional aircraft, it takes as little as 20 minutes for the plane to get airborne from a cold start [29]. For nuclear powered aircraft, the plane would remain running and would take off without the need to restart the engine. When the plane is parked in the airport, the engine can be connected to a battery system within the airport to provide electricity to the airport facilities and if needed to the main electricity grids of the cities where the airport is located. Although this may require changes to the airport structures, it would be a remarkable advantage for our system to provide clean energy not only to the aviation industry, but also to the power generation industry.

The nuclear-powered aircraft will also run heavier than a traditional aircraft. To counteract this, runways need to be built to withstand the heavier weight of the plane and need to be longer to take into account the increased momentum of the aircraft. Many runways in the United States and around the world would need to be updated and retrofitted to allow the nuclear planes to take off and land from them [56].

Operations

Like traditional modern aircraft, the plane starts up the turbine with a rechargeable battery near the tail of the aircraft [29]. This startup is important to get the aircraft running since the engine needs to start the turbine up to take in air into the compressor and eventually the heat addition chamber and the turbine. For the HTRE-3, the Air Forces Nuclear Engine Project, they used jet fuel to start up the turbine. By using electricity for the startup, our proposed design would be more environmentally friendly and be in line with the rest of the aviation industry. This battery will be charged up during flight as the turbines in the engines will act as generators and will power the rest of the electrical operations for the plane, including lights, Wi-Fi, signage on the plane, food catering, the pilot controls for the plane, and emergency power if there are problems with the nuclear core during flight. In the event that there is an emergency the reactor will have an emergency shut down sequence that can be triggered manually by the pilot as well as remotely via an air traffic controller. This emergency procedure will drop control rods into the reactor core to quickly stop the fission reaction [50].

Safety

In the years between 2002 and 2021 there have been 21 crashes which resulted in hull loss of the plane, with 75% of these accidents occurring before 2011 [45]. Since 2011 there have been 4 crashes that resulted in hull loss of the plane [45]. Although these numbers show the risk of a crash is low, it is never none and because of this there are a myriad of safety procedures which need to be considered when designing a plane.

As a general safety consideration all workers who will interact with the plane daily, pilots, ground crew, and service personnel, will be educated on the proper procedures for working with nuclear material and on what to do if the reactor is damaged in any way. Currently the Code of federal regulations requires that pilots be educated on everything from meteorology to the point-of-no return [44]. This course work along with the training required for flight attendants would be expanded to include nuclear safety regulations such as safe distances from the reactor, the best ways to mitigate radiation exposure, emergency procedures in case the reactor shuts down, what to do in the case of a crash, and who to contact. The plane itself will also undergo safety checks and must pass them to be cleared to fly. For the first 6 years of production, cargo planes with a nuclear reactor will be checked every three months for material damage. After that, cargo planes will still be expected to receive inspections every six months. Once passenger planes begin to be implemented, they will also receive inspections every three months for the first five years of production, after that it will be reduced to every six months. In addition to the checks, an aviation nuclear reactor will only be licensed for three years. At the three-year mark, depending on the state of the materials, it can be given an extended license for two more years.

The reactor itself is housed in the hull of the plane around a reinforced structure, this ensures that in a crash the reactor will have the largest chance of surviving without unnecessary damage to its internal structure. Control rods, which are used in ground reactor emergency shutdown sequences, would also be mounted above the fission core within the plane. In the event of an emergency shut down sequence, the rods would be dropped into the fission core and would terminate the fission in seconds [50]. Breakage zones will be built into the reactor's design to ensure that in the event of a crash the reactor will break around the fuel cells keeping any and all nuclear waste encased within itself. A team will also be specially trained to deal with plane crashes. They will have the necessary training and knowledge to contain a spill once it has occurred.

While the plane is in service or turned off, the reactor will contain within it two cylindrical tubes that will house the liquid salt outside of the core ensuring that the reactor will not go critical outside of operating times. This will ensure the safety of airports and plane storage bunkers.

Over long term storage or disassembly the reactor waste will be removed and stored in ground casks. These casks will have a concrete overlay designed to withstand impacts as great as a launched missile [59]. They will be monitored against theft and age through muon tomography to ensure that the nuclear waste is stored safely and effectively until it is recycled or disposed of.

Human Factors

Environmental Considerations

When considering the environmental impact of modern aircraft, three main factors contribute to anthropogenic global warming: greenhouse gas emissions, contrails, and aviation-induced cirrus clouds [46] [11]. Since contrails are primarily formed from the additional water vapor that results from the combustion of kerosene fuels, coupled with typical jet fuels' propensity for direct greenhouse gas emissions, switching to a nuclear power source eliminates a large proportion of the environmental impact of aircraft [46] [18]. Extrapolating from the effect of SAF's to reduce soot emissions and ice particle expulsion compared to Jet-A1, a plane which has no combustion would completely reduce the apparent ice emissions that form contrail cirrus [69] [18]. As previously discussed, the generation of thrust within the engines comes from indirect heating, which means that there is a lack of fossil fuel combustion. Or essentially, a nuclear-powered plane would generate reasonably clean thrust. This is a substantial advantage of nuclear as a proposed alternative aviation fuel, as nearly 50-60% of estimated aviation pollution can be attributed to non-CO2 factors [37]. And then of course, with no carbon combustion, the remaining portion of the emissions are negligible, a huge improvement in comparison to the large amount of emissions produced by jet fueled planes as according to the US Energy Information Administration, every 21.5 gallons of jet fuel, 1 pound of CO2 is produced [64]. When specifically attempting to determine the most effective fuel source for the aviation industry that will limit the impact to the planet, nuclear is a clear frontrunner.

As for the most detrimental stage of the uranium life cycle, mining and milling perpetuate the most to climate effects, contributing to not only climate change but pollution of the environment [55]. The mining process is notably responsible for the creation of radioactive uranium dust as well as for the expulsion of radon gas, each of which pose a great threat to workers' health [55]. The domestication of the uranium mining process to the United States however, ensures that the Environmental Protection Agency can uphold the standards of a proper radiation protection program, which provide standards to guarantee worker protection [19]. Contrastingly, the milling process is volatile in its production of mill tailings as a byproduct of uranium refinement into yellowcake [16] [55]. These tailings are stored in surface reservoirs that can easily wash away contaminated slurry into nearby areas, but as a mitigation technique outlined by the Canadian Nuclear Safety Commission, the ponds can be covered and surrounded by trees and grasses to prevent this erosion [16] [33]. With the expansion of the uranium mining operations to match the potential of a nuclear based airline industry, there are improvements that can be made in the processing of nuclear material. These innovations will likely come with the implied growth in order to prevent factors such as increased background radiation and the release of radioactive gas and dust from mining that are the only remaining environmental impacts.

The last apparent environmental concern that comes from the operation of a nuclear-based aircraft is the dispersed radiation from the reactor. As discussed earlier, there will be a substantial amount of shielding surrounding the core reactor assembly which will limit the output of radionuclides to an acceptable range outlined by the WNA [72]. The four areas of the reactor that are unshielded will likely emit a negligible amount of radiation except in the case of taxiing, as radiation in the air will dissipate into the atmosphere. In this case, additional shielding will be supplied to airports mounted on wheels that can block the rays of radiation that endanger maintenance workers and round crew.

Political Constraints

America is striving to become a global leader in nuclear technology through advanced reactors and non-electric applications of nuclear energy. In the American Nuclear Infrastructure Act of 2021, section 202 concerns the creation of unique licensing requirements of nuclear reactors for non-electric applications through new policy or using a technology inclusive regulatory framework [2]. According to the Nuclear Energy Innovation and Modernization Act, the Nuclear Regulatory Commission (NRC) is expected to finalize the new framework by 2027 [47]. In the Nuclear Energy Innovation Capabilities Act of 2017, the Department of Energy (DOE) and NRC is working to develop and test the application of non-electrical nuclear energy and the commercial applications of advanced nuclear technology [48].

The American government funds advanced research by allocating budgets to different departments. A portion of the budget allocated to the DOE is focused on the Advanced Research Projects Agency (ARPA-E) [15]. ARPA-E's budget is increasing to a requested $650,200 in 2022 and will continue to increase in the future [13]. One of ARPA-E's new programs is Seeding Critical Advances for Leading Energy Technologies with Untapped Potential to support early development, high risk, environmentally friendly projects [60]. The DOE's Nuclear Energy department also provides a budget of $1,773,000 in 2023 for the purpose of supporting diverse civilian nuclear energy programs, assisting in a clean transition into nuclear energy through innovative research and development, and research into advanced reactors [14]. The Federal Aviation Administration's budget places money aside for the modernization of the aviation industry in a new Modernization Acceleration program and safety [65]. These sectors will be the primary funders of the MSR research and integration of the technology into industry respectively.

Public Opinion

The quote, "Closely intertwined with this technological enthusiasm, however, was also a strong strand of technological pessimism," can be applied to most technological advancements [35]. In the 19th Century, electricity was transferred through the city of New York by low hanging electrical wires that posed a dangerous threat to the citizens [35]. Despite the threat, New Yorkers continued to use and support electricity, as long as safety measures were being taken [35]. New technology consistently poses dangers to society, which causes society to be fearful of the technology, but ultimately accept the dangers when given proper safety precautions in exchange for the benefits, whether convenience or global health precautions.

Education is a critical part of gathering support for nuclear energy. According to the 2022 National Nuclear Energy Public Opinion Survey, 86% of people who felt very well informed about nuclear energy supported it whereas only 48% of people who felt not informed at all support nuclear energy [6]. The negative stigma surrounding nuclear energy can begin to be healed through educating the public. The American Nuclear Society has begun to do this, by partnering with the DOE and Discovery Education to provide free lesson plans to educators teaching between the third and twelfth grade [3]. By creating a positive learning environment around nuclear energy beginning in grade school, the public will begin to accept nuclear energy more readily prior to 2050.

Financial Considerations

Aircraft

Currently the cost of a 737 ranges from 99.7 to 134.9 million dollars depending on the model [7]. The maximum cost of one SMR reactor constructed on site is $5,576 per kWe^{-1} [24]. As stated above the reactor would need to generate about 200 MWh of energy. This will lead to an estimated total cost of 1.1 billion dollars for the reactors. The total overnight cost of a plane can then be estimated to 1.2 billion dollars per plane. In regards to the cost of the operation the plane, A 737, which flies an average of 55,000 flight hours in its lifetime and burns 850 gallons of jet fuel per flight hour, will burn through 188.9 million dollars worth of fuel in its lifetime [10] [20] [4]. However, the 737 has a much smaller tank than many commercial airplanes. A 747, for example, burns 5000 gallons of fuel per hour and flies a total of 165,000 flight hours in its lifetime [32] [31]. This means it burns a staggering 2.7 billion dollars worth of fuel in its lifetime [10]. By investing in a nuclear powered plane, the airline would trade the high, long term price of fuel for the high, short term initial price of an aircraft.

Fuel Lifecycle

The processing of uranium includes the cost of mining, milling, transport, enrichment, storage, and disposal. Fortunately, facilities for the mining, milling, storage, and disposal of uranium already exist in the States and therefore the construction cost of the facilities would not be considered here. The costs that should be considered are the cost of creation of an enrichment facility and the cost of transport. The cost of construction of a uranium enrichment facility using laser technology is about 1 billion dollars, one-fifth the cost of a facility using gaseous enrichment techniques, and would require 100 million dollars annually beyond that [38]. Transportation would occur through the use of casks and trucks. The cost of transport by cask costs about $15,600 per metric ton of heavy metal [75]. This all adds up to a capital cost of about $1.1 billion after adding allowances for inflation and at an estimation of 5 Metric tons disposed of per month this fuel life cycle would have an annual upkeep fee of about 100.9 million dollars. According to WNA's statistics 1 kg of uranium in 2017 would cost about $130 to buy and uranium costs about $400 dollars per kilogram of heavy metal to store in dry casks [76] [24]. Using these numbers, we can estimate the cost to refill the plane, which requires 8.9 kg, would amount to $4,717. Assuming this has a profit margin rolled in we can assume the cost to produce uranium would be slightly less than that.

Conclusion

Due to the fact that air traffic volume from 2006 will quadruple by 2050, the path to a low carbon aviation industry needs to begin now [71]. Research for the nuclear plane will begin in early October of 2023 when the 2024 fiscal year begins [22]. The research will primarily focus on the HALEU MSR being redesigned to fit the criteria needed to be met for an airplane. By 2040, there should be a proof of concept plane built. Starting in October of 2042 using the 2043 fiscal year budgets in the Federal Aviation Administration to begin the modernization of cargo airplanes. Two years later, in 2045, passenger airplanes will begin to be produced with nuclear reactors and be integrated into industry.

For all of this to be possible, legislation will need to start being changed beforehand. September of 2026, the American representatives should bring up the issue of aviation nuclear reactors to the International Atomic Energy Agency (IAEA) to allow America to develop an adequate argument prior and for the IAEA to have plenty of time to specify all requirements for this project to be approved. The NRC will begin working on the unique licensing requirements in 2030, specifically for an aviation based nuclear reactor. In addition to legislation specifically of advanced reactors, mining regulations for uranium in the Navajo nation should be completed by 2035, which will allow the previously explained fuel cycle to increase efficient HALEU uranium production prior 2042 for the first wave of cargo planes, and continue to do so as nuclear planes continue to become more popular. Then in 2050, there will be a fully integrated sector of the commercial and cargo aviation industry powered through HALEU MSRs.

References

[1] Abdelal, N., Alsabbagh, A., Al-Jarrah, M., Al-Jawarneh, F., Saleem, R.A. (2022, Oct. 8). *Effect of lead nanoparticles on the radiation shielding characteristics of carbon fiber/epoxy composites*. Journal of Reinforced Plastics and Composites. https://doi.org/10.1177/07316844221132738

[2] American Nuclear Infrastructure Act, S.2373, 117th Cong. (2021). https://www.congress.gov/bill/117th-congress/senate-bill/2373/text

[3] American Nuclear Society. (2021, August 17). *Energizing Our World. Navigating Nuclear.* https://www-ans-org.srv-proxy2.library.tamu.edu/nuclear/navigatingnuclear/

[4] Aviator. (2023, April 30). *How long does a commercial aircraft last*? . aviation related posts, aviation pioneers and aviation accidents. https://www.aviationfile.com/how-long-does-a-commercial-aircraft-last/#:~:text=Boeing%20estimates%20that%20their%20737,years%20or%2090%2C000%20flight%20hours

[5] Bioenergy Technologies Office. (n.d.). *Sustainable Aviation Fuels*. Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuels

[6] Bisconti A. S. (2022, June 3). *Record High Public Support for Nuclear Energy, 2022 National Nuclear Energy Public Opinion Survey Finds*. Bisconti Research, Inc. https://www.bisconti.com/blog/public-opinion-survey-finds

[7] Boeing. (2023). *About Boeing Commercial Airplanes.* https://www.boeing.com/company/about-bca/

[8] Brady, C. (1999). *Production.* The Boeing 737 Technical Site. http://www.b737.org.uk/production.htm

[9] Brugge D, Goble R. *The history of uranium mining and the Navajo people.* Am J Public Health. 2002 Sep;92(9):1410-9. doi: 10.2105/ajph.92.9.1410. PMID: 12197966; PMCID: PMC3222290.

[10] Bureau of Transportation Statistics. (2022, August 3). *U.S. airlines' June 2022 fuel consumption down 11.1% from pre-pandemic 2019; aviation fuel cost per gallon hits all time high. U.S. Airlines' June 2022 Fuel Consumption Down 11.1% from Pre-Pandemic 2019; Aviation Fuel Cost per Gallon Hits All Time High* | Bureau of Transportation Statistics. https://www.bts.gov/newsroom/us-airlines-june-2022-fuel-consumption-down-111-pre-pandemic-2019-aviation-fuel-cost

[11] Burkhardt, U., Kärcher, B. *Global radiative forcing from contrail cirrus.* Nature Clim Change 1, 54–58 (2011). https://doi.org/10.1038/nclimate1068

[12] Class Airliners & Vintage Pop Culture (2015). *Convair XB-36H "Crusader Progress Report - 1956* [Video]. Youtube. https://www.youtube.com/watch?v=PeXlWhxewfw

[13] Department of Energy, Advanced Research Projects Agency. (2023, March 3). *Energy Proposed Appropriation Language: FY 2024 Congressional Justification.* https://www.energy.gov/sites/default/files/2023-03/doe-fy-2024-budget-vol-2-arpa-e_0.pdf

[14] Department of Energy, Nuclear Energy. (2023, March 3). F*Y 2024 Congressional Justification.* https://www.energy.gov/sites/default/files/2023-03/doe-fy-2024-budget-vol-4-ne-v3.pdf

[15] Department of Energy, Office of the Chief Finanical Officer. (2023, March 3). *FY 2024 Budget Justification.* https://www.energy.gov/cfo/articles/fy-2024-budget-justification

[16] Dewar D, Harvey L, Vakil C. *Uranium mining and health*. Can Fam Physician. 2013 May;59(5):469-71. Erratum in: Can Fam Physician.2013 Jul;59(7):727. PMID: 23673579; PMCID: PMC3653646.

[17] Environmental Protection Agency. (2020). *EPA proposes airplane greenhouse gas emission standards.* United States Environmental Protection Agency, Office of Transportation and Air Quality.

[18] Environmental Protection Agency. Air and Radiation. (2000, September). *Aircraft Contrails Factsheet.* https://www.faa.gov/regulations_policies/policy_guidance/envir_policy/media/contrails.pdf

[19] Environmental Protection Agency. Radiation Protection. (2022, June 24). *EPA's Role in Radiation Protection*. https://www.epa.gov/radiation/epas-role-radiation-protection

[20] Epic Flight Academy. (2020, December 23). *Boeing 737-800*. Epic Flight Academy. https://epicflightacademy.com/boeing-737-800/

[21] F. Quinteros, P. Rubiolo, V. Ghetta, J. Giraud & N. Capellan (2023): *Design of a Fast Molten Salt Reactor for Space Nuclear Electric Propulsion, Nuclear Science and Engineering*, DOl: 10.1080/00295639.2023.2167470

[22] Federal Times Staff. (2022, Sep 20). *Happy New Year! Why the US Federal Fiscal Year Starts in October.* Federal Times Budget. https://www.federaltimes.com/management/budget/2022/09/20/why-the-us-federal-fiscal-year-2023-starts-in-october/

[23] Fraas, A.P., & Savolainen, A.W. (1954). O*RNL Aircraft Nuclear Power Plant Designs.* Oakridge National Laboratory. https://www.osti.gov/servlets/purl/12772844

[24] Geoffrey Rothwell, *Spent nuclear fuel storage: What are the relationships between size and cost of the alternatives?*, Energy Policy, Volume 150, 2021, 112126, ISSN 0301-4215, https://doi.org/10.1016/j.enpol.2020.112126.

[25] Google. (n.d.). [Google Maps directions to drive from the Colorado Plateau to Navada]. Retrieved may 14th, 2023, from Google. (n.d.). [Google Maps directions to drive from Colwood City Hall to Royal Roads University]. Retrieved December 4, 2019, from https://goo.gl/maps/BXdsUNzwHnzzeEes9

[26] Guetersloh, S., Zeitlin, C., Heilbronn, L., Miller, J., Komiyama, T., Fukumura, A., Iwata, Y., Murakami, T., & Bhattacharya, M. (2006). *Polyethylene as a radiation shielding standard in simulated cosmic-ray environments*. In Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms (Vol. 252, Issue 2, pp. 319–332). Elsevier BV. https://doi.org/10.1016/j.nimb.2006.08.019

[27] Hall, N. (2022, July 21). *Four Forces on an Airplane*. Glenn Research Center Beginners Guide to Aeronautics. https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/four-forces-on-an-airplane/

[28] Hansen, M.V. (n.d.). *Nuclear fuel cycle: World uranium resources.* IAEA Bulletin 23(2), 5. https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull23-2/23204891014.pdf

[29] Hayward, J., Singh, S. (2023, Apr 3). *How Do Pilots Start Jet Engines on Aircraft?.* Simply Flying. https://simpleflying.com/how-do-pilots-start-jet-engines-on-aircraft/

[30] High-Assay Low-Enriched Uranium - Centrus Energy Corp. (2022, February 16). *Centrus Energy Corp.* https://www.centrusenergy.com/what-we-do/nuclear-fuel/high-assay-low-enriched-uranium/#:~:text=of%20HALEU%20demand.-,What%20is%20HALEU%3F,fleet%20of%20light%20water%20reactors.

[31] Homer, T. (2023, March 8). *How much fuel does an international plane use for a trip?.* HowStuffWorks Science. https://science.howstuffworks.com/transport/flight/modern/question192.htm

[32] Flexport. (2023). *How are planes decommissioned, and how much value can be salvaged from their parts?.* https://www.flexport.com/blog/decommissioned-planes-salvage-value/#:~:text=On%20average%2C%20an%20aircraft%20is,before%20metal%20fatigue%20sets%20in

[33] Ilson G. Carvalho, Rosa Cidu, Luca Fanfani, Helmut Pitsch, Catherine Beaucaire, and Pierpaolo Zuddas. Environmental Science & Technology 2005 39 (22), 8646-8652. DOI: 10.1021/es0505494

[34] International Air Transport Association. (2023). O*ur Commitment to Fly Net Zero by 2050.* Programs & Policy. https://www.iata.org/en/programs/environment/flynetzero/

[35] J. P. Sullivan, *"Fearing electricity: overhead wire panic in New York City,"* in IEEE Technology and Society Magazine, vol. 14, no. 3, pp. 8-16, Fall 1995, doi: 10.1109/44.464629.

[36] Jet-A1-Fuel. (2023, Feb. 27). *Jet a1 price United States.* Jet-A1-Fuel.com. Retrieved on 2023, Feb. 27. https://jet-a1-fuel.com/price/united-states

[37] Lee, D. S. (2018, December). *The Current State of Scientific Understanding of the non-CO2 effects of Aviation on Climate*. Manchester Metropolitan University. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/813342/non-CO2-effects-report.pdf

[38] Los Alamos Science. (n.d.). *Sidebar 1: Economic Perspective for Uranium Enrichment T.* https://sgp.fas.org/othergov/doe/lanl/pubs/00416663.pdf

[39] Merk B, Litskevich D, Bankhead M, Taylor RJ. *An innovative way of thinking nuclear waste management - Neutron physics of a reactor directly operating on SNF. PLoS One.* 2017 Jul 27;12(7):e0180703. doi: 10.1371/journal.pone.0180703. PMID: 28749952; PMCID: PMC5531547.

[40] Mills, G.S., Neuhauser, K.S. *Urban Risks of Truck Transport of Radioactive Material.* Risk Anal 18, 781–785 (1998). https://doi.org/10.1023/B:RIAN.0000005923.25571.50

[41] Morales, L. (2016, April 10). *For the Navajo Nation, Uranium Mining's Deadly legacy lingers.* NPR. https://www.npr.org/sections/health-shots/2016/04/10/473547227/for-the-navajo-nation-uranium-minings-deadly-legacy-lingers

[42] NASA. (2021, May 13). *Turbofan engine.* NASA. https://www.grc.nasa.gov/www/k-12/airplane/Animation/turbtyp/etff.html

[43] NASA. (2021b, May 13). *Turbojet engines.* NASA. https://www.grc.nasa.gov/www/k-12/airplane/aturbj.html

[44] National Archives. (n.d.). *The Federal Register. Federal Registe*r :: Request Access. https://www.ecfr.gov/current/title-14/chapter-I/subchapter-H/part-142/subpart-C/section-142.54

[45] National Transport Safety Board. (n.d.). *US Civil Aviation Accident Statistics. Statistical reviews*. https://www.ntsb.gov/safety/Pages/research.aspx

[46] Noppel, F., & Singh, R. (2007). *Overview on contrail and cirrus cloud avoidance technology*. Journal of Aircraft, 44(5), 1721–1726. https://doi.org/10.2514/1.28655

[47] Nuclear Energy Innovation and Modernization Act, S.512, 115th Cong. (2019). https://www.congress.gov/bill/115th-congress/senate-bill/512?q=%7B%22search%22%3A%5B%22nuclear%22%5D%7D&s=10&r=28

[48] Nuclear Energy Innovation Capabilites Act, S.97, 115th Cong. (2017). https://www.congress.gov/bill/115th-congress/senate-bill/97?q=%7B%22search%22%3A%5B%22nuclear%22%5D%7D&s=10&r=29

[49] Nuclear Waste Storage Sites in the United States. (2020). *Congressional Research Service.* https://doi.org/https://sgp.fas.org/crs/nuke/IF11201.pdf

[50] Oak Ridge National Library. (2000, September)*. Scram!. "SCRAM!*" https://web.ornl.gov/info/reporter/no19/scram.htm

[51] Ojovan MI, Steinmetz HJ. *Approaches to Disposal of Nuclear Waste. Energies*. 2022; 15(20):7804. https://doi.org/10.3390/en15207804

[52] Palmieri, M. R. (n.d.). *Neutron Shielding for Small Modualar Reactor.* [Major Qualifying Project] Worchester Polytechnic Institute. https://web.wpi.edu/Pubs/E-project/Available/E-project-051820-060142/unrestricted/Neutron_Shielding_for_Small_Modular_Reactors_MQP_Palmieri_Final.pdf

[53] Poulson D, Bacon J, Durham M, Guardincerri E, Morris CL, Trellue HR. *Application of muon tomography to fuel cask monitoring*. Philos Trans A Math Phys Eng Sci. 2018 Dec 10;377(2137):20180052. doi: 10.1098/rsta.2018.0052. PMID: 30530532; PMCID: PMC6335304.

[54] Qi, Z., Yang, Z., Li, J., Guo, Y., Yang, G., Yu, Y., & Zhang, J. (2022). *The Advancement of Neutron-Shielding Materials for the Transportation and Storage of Spent Nuclear Fuel.* In Materials (Vol. 15, Issue 9, p. 3255). MDPI AG. https://doi.org/10.3390/ma15093255

[55] R. E. MacPherson, J. C. Amos & H. W. Savage (1960) *Development Testing of Liquid Metal and Molten Salt Heat Exchangers, Nuclear Science and Engineering*, 8:1, 14-20, DOI: 10.13182/NSE8-1-14

[56] Law Insider. (n.d.-a). *Runway weight bearing capacity definition.* https://www.lawinsider.com/dictionary/runway-weight-bearing-capacity

[57] S.M. Hall, B.S. Van Gosen, R.A. Zielinski, *Sandstone-hosted uranium deposits of the Colorado Plateau, USA,* Ore Geology Reviews,Volume 155, 2023, 105353, ISSN 0169-1368, https://doi.org/10.1016/j.oregeorev.2023.105353.

[58] Safran. (n.d.).*Leap-1B, a new-generation engine for the B737 Max.* Safran. https://www.safran-group.com/products-services/leap-1b-new-generation-engine-single-aisle-commercial-jets

[59] Sanghoon Lee, Sang-Soon Cho, Je-Eon Jeon, Ki-Young Kim, Ki-Seog Seo, *Impact Analysis And Tests Of Concrete Overpacks Of Spent Nuclear Fuel Storage Casks,* Nuclear Engineering and Technology, Volume 46, Issue 1, 2014, Pages 73-80, ISSN 1738-5733, https://doi.org/10.5516/NET.06.2013.005.

[60] SCALEUP Launch Pad. (2022). ARPA-E's Semi-Finalist. arpa-e. https://arpa-e.energy.gov/technologies/scaleup/scaleup-launch-pad

[61] Serin, E. (2022, Dec.). *What is the role of nuclear in the energy mix and in reducing greenhouse gas emissions?.* The London School of Economics and Political Science Explainer. https://www.lse.ac.uk/granthaminstitute/explainers/role-nuclear-power-energy-mix-reducing-greenhouse-gas-emissions/#:~:text=Nuclear%20power%20has%20a%20minimal,around%201%2C050%20gCO2%2FKWh

[62] Thibeault, S., Kang, J., Sauti, G., Park, C., Fay, C., & King, G. (2015). N*anomaterials for radiation shielding*. MRS Bulletin, 40(10), 836-841. doi:10.1557/mrs.2015.225

[63] Ting, H. (2015, Nov 12). *Thorium Energy Viability.* [Coursework] Stanford. http://large.stanford.edu/courses/2015/ph240/ting1/#:~:text=Benefits,-Thorium%20is%203&text=Thorium%20is%20safer%20and%20more,making%20it%20more%20environmentally%20friendly

[64] U.S. Department of Energy. (n.d.). *Biofuels Greenhouse Gas Emissions: Myths versus Facts*. [Infographic]. Energy.gov. https://www.energy.gov/sites/prod/files/edg/media/BiofuelsMythVFact.pdf

[65] U.S. Department of Transportation, Federal Aviation Administration. (2023). *Budget Estimates Fiscal Year 2024.* https://www.transportation.gov/sites/dot.gov/files/2023-03/FAA_FY_2024_President_Budget_508.pdf

[66] United States Nuclear Regulatory Commission. (2020, December 2). *Uranium enrichment.* NRC Web. https://www.nrc.gov/materials/fuel-cycle-fac/ur-enrichment.html

[67] United States Nuclear Regulatory Commission. (2020, Mar. 20). *Radiation Basics*. Retrieved on May 14th 2023, Feb. 2023. https://www.nrc.gov/about-nrc/radiation/health-effects/radiation-basics.html

[68] US Department of the Interior Bureau of Land Management. (n.d.). *About: History of BLM: History by region: Nevada: Bureau of Land Management.* Nevada. https://www.blm.gov/about/history/history-by-

region/nevada#:~:text=Today%2C%20Nevada%20contains%20forty%2Deight,carried%20out%20the%20Homestead%20Act.

[69] Voigt, C., Kleine, J., Sauer, D. et al. *Cleaner burning aviation fuels can reduce contrail cloudiness*. Commun Earth Environ 2, 114 (2021). https://doi.org/10.1038/s43247-021-00174-y

[70] Waid, J. (n.d.).*Manned Nuclear Aircraft Program*. Media.defense.gov. https://media.defense.gov/2021/Jun/21/2002745848/-1/-1/1/HN2_MANNED%20NUCLEAR%20AIRCRAFT%20PROPOLSION%20-%20WAID%2018%20JUN%2021.PDF

[71] Wilkerson, J. T., Jacobson, M. Z., Malwitz, A., Balasubramanian, S., Wayson, R., Fleming, G., Naiman, A. D., & Lele, S. K. (2010). *Analysis of emission data from global commercial aviation: 2004 and 2006. In Atmospheric Chemistry and Physics* (Vol. 10, Issue 13, pp. 6391–6408). Copernicus GmbH. https://doi.org/10.5194/acp-10-6391-2010

[72] World Nuclear Association. (2022, October). Focus. *Radiation and Health Effects*. https://world-nuclear.org/focus/fukushima-daiichi-accident/nuclear-radiation-and-health-effects.aspx

[73] World Nuclear Association (2022, Aug). *Economics of Nuclear Power*. Economic Aspect. https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx

[74] World Nuclear Association (2023, Feb). *Nuclear-Powered Ships*. Transport. https://world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-powered-ships.aspx

[75] World Nuclear Association. (2022, January). Transport of Radioactive Material. *Transport of Radioactive Material - World Nuclear Association.* https://world-nuclear.org/information-library/nuclear-fuel-cycle/transport-of-nuclear-materials/transport-of-radioactive-materials.aspx

[76] World Nuclear Association. (2023, April). Supply of Uranium. *Uranium Supplies: Supply of Uranium-World Nuclear Association.* https://world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/supply-of-uranium.aspx#:~:text=Identified%20resources%20recoverable%20(reasonably%20assured,is%207.918%20million%20tonnes%20U