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Foreword

International security is increasingly shaped by systems that were once treated as separate domains: nuclear deterrence, energy, technology, space, industrial capacity, and critical infrastructure. The contributions in this issue of the Illinois Journal of International Security reflect that changing landscape and the need to understand security not only through military power, but also through the technologies, resources, and institutions on which modern states depend.

Several of the articles focus on areas where technological capability and geopolitical competition now intersect most directly. The future of the United States–China nuclear relationship raises fundamental questions about deterrence, strategic stability, and the management of competition between two major powers. At the same time, the growing importance of technology to the U.S.–China relationship, particularly in the context of Taiwan, demonstrates how economic interdependence, industrial policy, and technological leadership have themselves become matters of national security.

Other contributions turn to the infrastructures that sustain national power over the longer term. Nuclear energy is examined both as an instrument of foreign policy and as a component of energy security, while the nuclear fuel supply chain is considered as a strategic system whose resilience has implications far beyond electricity generation. These questions are especially timely as governments reassess the security of energy supply, the concentration of critical industries, and the vulnerabilities created by dependence on foreign sources of fuel, materials, and technology.

Space presents another rapidly evolving dimension of the security environment. Once considered largely the domain of exploration and scientific cooperation, it has become indispensable to communications, navigation, intelligence, commerce, and military operations. As dependence on space-based infrastructure grows, so too does the importance of developing policies and institutions capable of managing competition and reducing the risk of conflict in that domain.

The issue also looks beyond immediate geopolitical pressures to a challenge measured on a very different timescale: the permanent disposal of nuclear waste. The study of material durability in the Beishan repository context is a reminder that security also involves stewardship. Some technological choices create responsibilities that extend far beyond a political cycle—or even a human lifetime—and require institutions capable of thinking in decades and centuries.

What connects these contributions is their attention to the material foundations of security. Nuclear arsenals, energy systems, semiconductor economies, satellites, fuel supplies, and waste repositories are all physical manifestations of political choices. Understanding their technical characteristics is essential to understanding the strategic options they create, the vulnerabilities they introduce, and the policies required to govern them responsibly.

The articles collected here offer different perspectives on these questions, but together they point toward a broader conclusion: the boundaries of international security continue to expand. Preparing for the challenges ahead will require scholars and policymakers who are comfortable working across those boundaries and who can connect technical knowledge with political, economic, and strategic judgment. It is in that spirit that we present this issue.

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Radioactive Waste: Risks, Management Methods, and Where to Next

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Radioactive waste is a byproduct of a variety of industries including power generation, manufacturing, and medical uses. Low-level and high-level radioactive wastes must be stored and disposed of in a safe manner to protect the local environment, local communities, and personnel handling the waste while maintaining structural integrity for upwards of millions of years. The objective of this paper is to review the current low-level radioactive waste treatment and disposal methods and provide recommendations as needed to prevent future capacity concerns. For high-level radioactive waste, the objective of this paper is to review proposed disposal strategies and provide recommendations to streamline United States adoption of a permanent waste solution. A literature review was conducted to compile key information about different disposal methods for both low-level and high-level wastes. Current low-level waste disposal methods were deemed adequate for permanent disposal of the radioactive waste and protecting the surrounding area from inadvertent releases of radioactive materials. The United States does not currently have a permanent disposal method in place for high-level radioactive waste. A previous attempt was made with the Yucca Mountain Waste Repository but failed. It is recommended that the United States require states within a nuclear waste compact to provide a list of potential low-level radioactive waste sites in case current ones begin to face capacity concerns. Additionally, the Nuclear Waste Policy Act must be extensively amended prior to implementation of any form of long-term high-level radioactive waste storage and disposal solution.

Keywords: Radioactive waste, low-level waste, high-level waste, waste management, disposal methods, Nuclear Waste Policy Act

1. Introduction

Nuclear science has enabled numerous advancements in modern society from carbon-free energy production to breakthrough discoveries in the health and sciences sector. Nuclear energy is regarded as one of the most efficient and most reliable sources of power generation (Darda et al., 2021). Despite the accolades, the widespread deployment and embracement of nuclear technologies within the United States is hindered by the current lack of a standardized long-term radioactive waste disposal system. With license extensions for existing reactors and the construction of new reactors, such as Vogtle Units 3 & 4, the inventory of spent nuclear fuel (SNF) will continue to grow, despite the lack of a strategy to dispose of the waste that would be generated. At its core, a robust radioactive waste management plan must minimize harmful radiation to the surrounding flora and fauna as much as possible for as long as possible. The objective of this paper is to review the technologies available for the disposal and storage of radioactive waste within the United States, provide recommendations for adoption of a long-term radioactive waste plan, and highlight gaps in current waste strategies that must be addressed prior to implementation.

2. Background

The most widely adopted method for classifying radioactive waste depends on both the activity level of the material and the length of the half-life. Figure 1 provides conceptual understanding of the relative scales for the six different classifications of radioactive waste and recommended disposal methods: exempt waste (EW), very short-lived waste (VSLW), very low-level waste (VLLW), low level waste (LLW), intermediate level waste (ILW), and high-level waste (HLW) (International Atomic Energy Agency, 2009; Sefanovsky et al., 2004).

Exempt waste contains a small enough concentration of radionuclides that disposal does not prompt additional radiation protections or regulations. This property allows for waste to cross borders easily for further recycling or storage. Very short-lived waste contains radionuclides with very short half-lives ($\leq$ 100 days), such as 192Ir or 99mTc from industrial and medical applications. This VSLW must be stored temporarily until the activity levels decrease to levels less than those required to manage waste as conventional or exempt waste. Very low-level waste is most commonly a result of the operation and decommissioning of nuclear facilities and does require additional provisions for radiation protection and safety. Low-level waste is a broad category and relies on explicit classification of the radionuclides present within the waste to determine appropriate shielding and handling techniques. Intermediate-level waste contains a large enough concentration of long-lived radionuclides such that it cannot be disposed of in the same fashion as VLLW and LLW. Finally, high-level waste contains such a large concentration of both long- and short-lived radionuclides that the highest degree of containment and isolation from the accessible environment is required for long term safety (International Atomic Energy Agency, 2009).

It is important to note that the classifications established by the International Atomic Energy

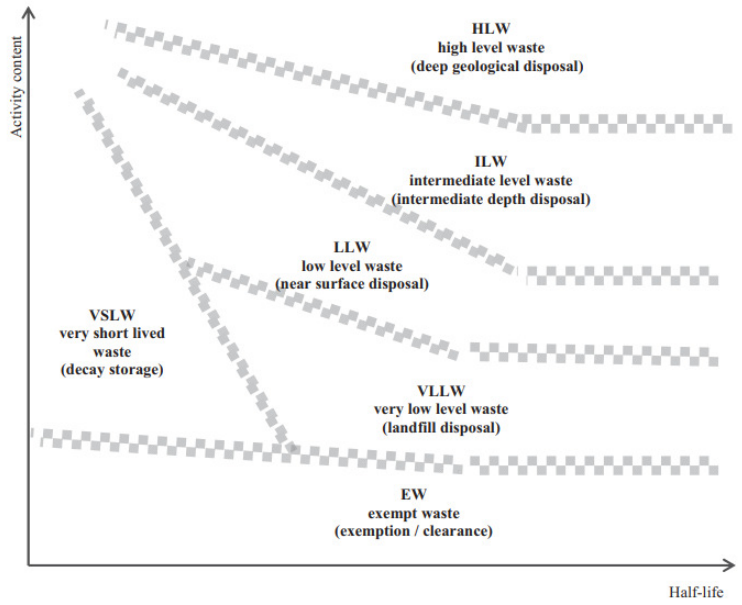


Figure 1: Conceptual illustration of the international waste classification scheme.

Agency (IAEA) were meant to provide a generalized framework to nuclear nations instead of strict regulations. Nuclear nations were expected to further develop this framework to fit their needs. Each class is not rigorously defined on a numeric scale to allow for specialized safety assessments for individual disposal sites. Within the United States, radioactive waste is classified into two major types: low-level waste and high-level waste. Low-level Radioactive Waste (LLRW) is further divided into four classes: Class A, Class B, Class C, and Greater Than Class C (GTCC). The United States Code of Federal Regulations (CFR) Title 10 Section 61.55 provides robust technical definitions for each classification. Table 1 summarizes these stipulations (Roy, 2021; 10 Code of Federal Regulations 61 §55).

Historical volumes and activities of Class A, B, and C waste are found in Figures 2(a) – (c) (United States Department of Energy, 2024).

It is important to note that activity data were not collected until 1996. Within the United States, high-level radioactive waste (HLW) is defined as "1.) irradiated nuclear reactor fuel, 2.) liquid wastes resulting from the operation of the first cycle solvent extraction system, or equivalent, and the concentrated wastes from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuel, and 3.) solids into which such liquid wastes have been converted" (10 Code of Federal Regulations 60 §2). The total amount of HLW from spent nuclear fuel alone is estimated at over 90,000 metric tons of initial uranium (MTiHM) or approximately 315,000 individual reactor fuel assemblies. With current construction projects and anticipated nuclear power plant license extensions, this number is anticipated to reach over 138,000 MTiHM or approximately 476,000 fuel assemblies by 2075 (Banerjee, Rigato, & Wilson, 2024). As of 2019, there were over 4,400 canisters of

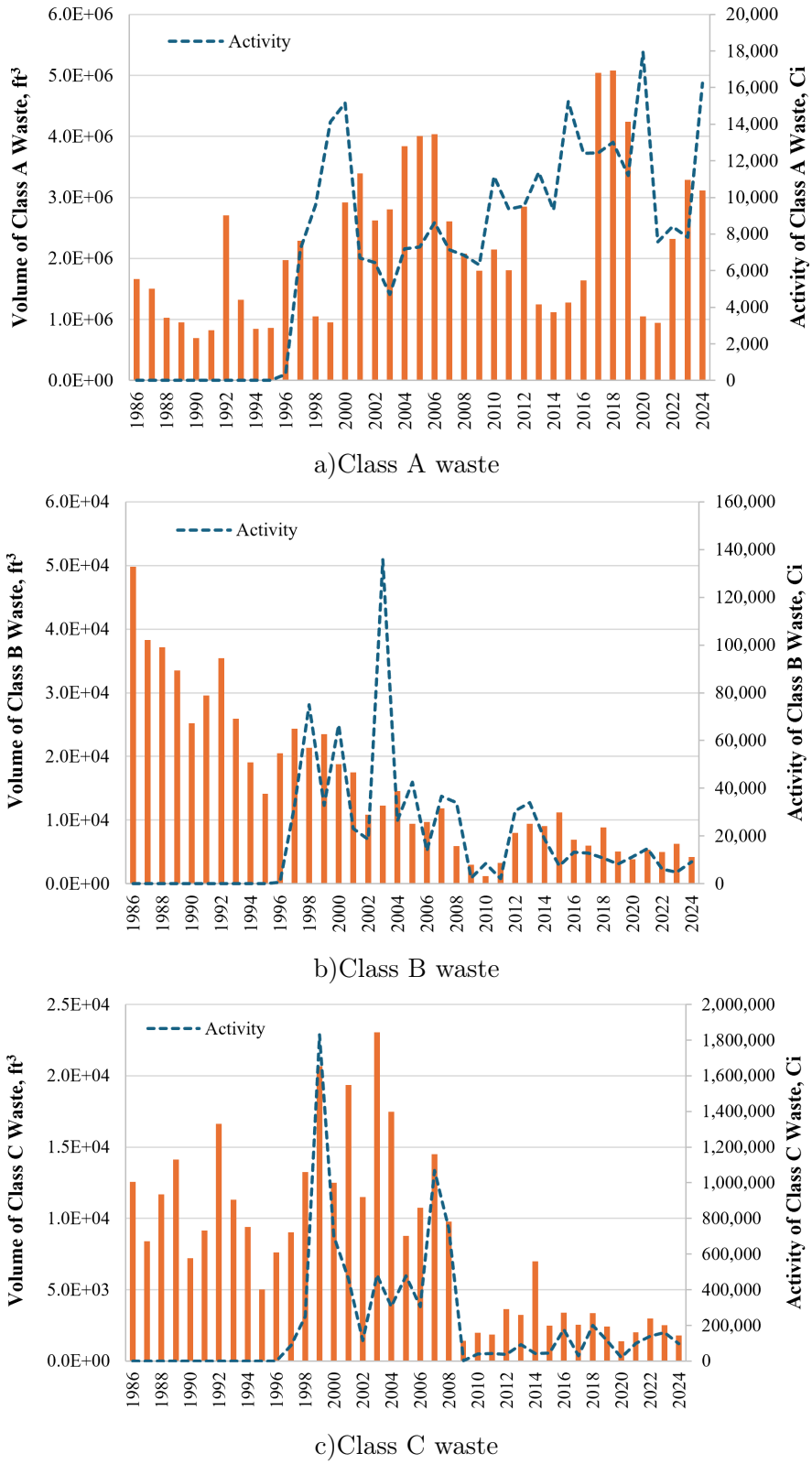


Figure 2: Historical volume in cubic feet and activity in Curies of Class A waste, Class B waste, and Class C waste within the United States.

Table 1: Summary of the LLRW classifications.

Class	Characteristics
Class A	• Smallest level • Specific activity: Near background – 700 Ci/m^3 • Not a threat to an intruder beyond 100 years • No specific waste stability requirements for disposal
Class B	• Specific activity: 0.04 – 700 Ci/m^3 • Not a threat to an intruder beyond 100 years • Waste containers must be stable for 300 years • Must be segregated from Class A wastes
Class C	• Specific activity: 44 – 7,000 Ci/m^3 • Not a threat to an intruder beyond 500 years • Waste containers must be stable for 300 years • Engineered barrier required • Must be segregated from Class A wastes
GTCC	• Poses a threat to an intruder beyond 500 years • Cannot be disposed of in same method as Class A, B, C wastes

reprocessed radioactive waste from commercial and non-commercial nuclear sources (Carter, 2020).

3. Results and Discussion

3.1. Risks of Radioactive Waste

Radioactive waste can pose a severe risk to the health of the environment and the health of personnel handling the waste. Significant doses of ionizing radiation generated by HLW damages genetic material in cells such as DNA and RNA. This damage can cause harmful cancers for humans and animals, leading to a significant decline in quality of life (Roy, 2021). Exposure to the environment can occur during the processing, packaging, and transportation of radioactive waste. Although the number of accidents during transportation of radioactive waste are small, radionuclides can still leach into soil or groundwater from damaged packaging (Laraia, 2015). It is beyond the scope of this manuscript to present a comprehensive review on transportation methods of radioactive material. Once within soil or groundwater, hazardous radionuclides with long half-lives can quickly reach communities, impacting food and water supplies. How quickly radionuclides move through soil is influenced by factors such as soil texture, pH, organic matter content, and moisture content. The ionic form of the radionuclides will also impact their transport, with some reacting with other ions within the soil to form stable compounds. Radionuclide contamination of soil can create a toxic environment for soil organisms, leading to impacts on soil fertility and food security for local com-

munities. Additionally, water security becomes threatened if radionuclides contaminate surrounding groundwater (Korede, Akinyemi, & Oshilalu, 2023). A large challenge for HLW disposal will be designing long-term engineering barriers that will prevent leaching of radionuclides into surrounding ecosystems.

3.2. LLRW Disposal within the United States

Nearly 98% of all radioactive waste globally can be categorized into LLW, VSLW, or VLLW (Darda et al., 2021). Disposal of LLRW has been practiced within the United States and on a global scale for decades. The management strategy had been well established and widely accepted. Any organic radioactive waste generated is incinerated while inorganic waste must be converted into a more durable form to prevent inadvertent radioactivity releases to the surrounding ecosystems (Stefanovsky et al., 2004). Disposal of LLRW within the United States often involves a form of pre-treatment to ensure thermodynamic stability followed by packaging and then transit to a final above ground or near-surface disposal facility. Depending on the activity and concentration of the radionuclides present in the waste, the final disposal location could be a landfill facility or require further engineering barriers (Darda et al., 2021). All licensing, operation, and enforcement details are governed by 10 CFR 61. As mentioned in Section 2 of this paper, LLRW can only be disposed of at above ground or near-surface disposal facilities if they are within one of three classes: Class A, Class B, or Class C. Regardless of classification, all LLRW intended for disposal must satisfy the following criteria outlined in Table 2 (10 Code of Federal Regulations 61§56). These requirements ensure the health and safety of personnel at disposal sites and facilitate safe handling practices.

Class A waste — unless mixed with other forms of waste — must be stored and disposed of in a segregated location away from Class B and Class C wastes. This restriction prevents overpressure and excessive compaction of waste containers that could cause subsidence of the surface above the disposal cells. Class B, because of its larger concentration of radionuclides, must meet stricter standards of stability compared to Class A waste prior to disposal. Class C waste must meet the most demanding standards of stability in addition to requiring additional engineering barriers to prevent inadvertent intrusions. Additionally, Class C waste requires deeper burial for additional protection to health, safety, and security (10 Code of Federal Regulations 61§55, 2025; Roy, 2021). It is not uncommon for Class C waste to be stored in near-surface disposal facilities that bury radioactive waste or operate out of caverns up to 50 meters below the ground level (Darda et al., 2021). During operation, above-ground disposal facilities must maintain a continuous monitoring system to track and store radionuclide concentrations. Security measures must remain in place to ensure adequate warning to surrounding communities of any unintended release of radionuclides before the particles cross the disposal site boundary (10 Code of Federal Regulations 61§53).

The United States currently has four licensed disposal sites for LLRW. Figure 3 is a map of the locations and the parent companies that operate the facilities (United States Nuclear Regulatory Commission, 2025).

Table 2: Criteria for LLRW disposal.

Waste Form Requirements	**Stability Requirements for Waste Forms**
• Not packaged for disposal in cardboard or fiberboard boxes • Liquid waste must be solidified or packaged in absorbent material • Solid waste containing liquid must contain as little freestanding and noncorrosive liquid as reasonably achievable • Waste must not be readily capable of detonation or explosive decomposition • Waste must not self-generate toxic gases or fumes • Waste must not be pyrophoric • Waste in gaseous form must be packaged at a pressure that does not exceed 1.5 atm at 20°C • Waste containing hazardous, biological, pathogenic, or infectious material must be treated to reduce the hazard to the maximum extent practicable	• Waste must have structural stability • Liquid waste must be converted until there is as little free-standing liquid as practicable • Void spaces within waste and between the waste and its package must be reduced as much as practicable



Figure 3: Location of licensed LLRW disposal facilities and parent companies Energy Solutions , US Ecology, and Waste Control Specialists (WCS).

All disposal sites except the Clive, UT Energy Solutions site process and dispose of all classes of LLRW. The Clive location only accepts and disposes of Class A LLRW. Because of closures of LLRW disposal sites prior to the start of the 2000s, a large influx of waste was arriving at the Barnwell and Richland sites. The reaction from the Washington and South Carolina governments prompted the passing of the Low-Level Radioactive Waste Policy Act in 1980 (amended in 1985) with the intention of increasing the number of LLRW sites within the US and allowing states to regulate their own radioactive waste disposal. The Act also encouraged the formation of "compacts" where states would dispose of LLRW at a common and shared site within the compact region. Despite this encouragement and compact formation, all siting efforts for new LLRW locations have been halted and only one LLRW disposal site has been successfully licensed and constructed (Roy, 2021).

3.3. Current HLW Disposal Methods

Akin to the rest of the globe, the United States does has not adopted a permanent solution for the disposal of HLW (recall that the US does not use the ILW classification proposed by the IAEA). Section 3.3 of this manuscript explores some of the current methods used within the US to temporarily store or convert HLW while Section 3.4 will cover proposed permanent disposal methods.

3.3.1. Wet-Pool and Dry-Cask Storage

Wet-pool storage is the first step of a two-step process when managing HLW in the form of SNF. Spent fuel assemblies from commercial reactors are moved to a secure location within the facility to a large pool filled with water. Water acts as both a coolant to dissipate the decay heat and a shield to prevent exposure incidents (Roy, 2021). Maintaining the water level and temperature within a spent fuel pool is a key security concern for managing SNF. The Fukushima—Daiichi accident in 2011 further emphasized the importance of maintaining robust back-up systems for wet-pool storage facilities and key equipment. Because of the risk for loss of coolant and make-up water to the fuel pool, fuel is transitioned to the second step of the two-step process — dry-cask storage — as quickly as possible (Rodríguez-Penalonga & Moratilla, 2017).

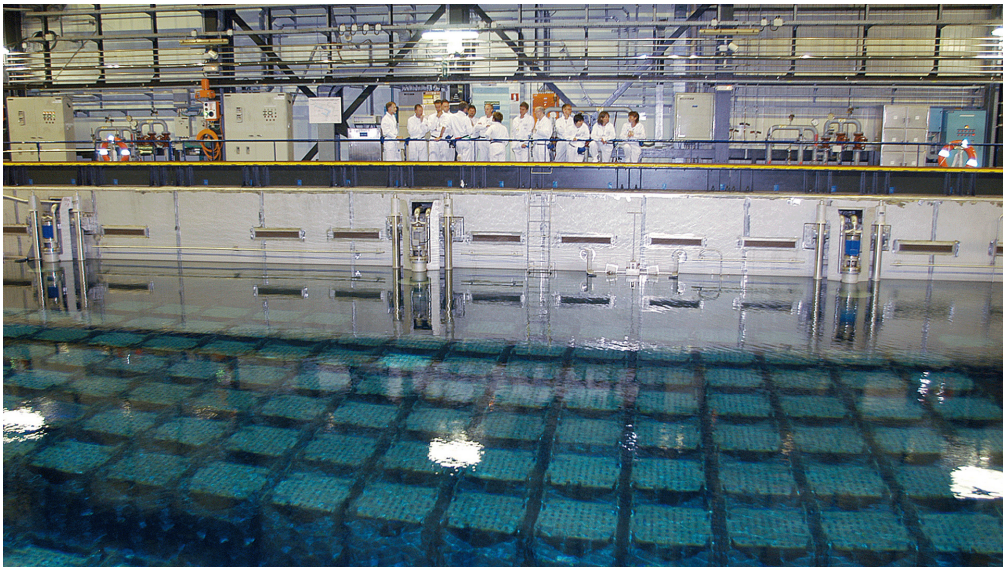


Figure 4: Photo of a spent nuclear fuel pool (Nuclear Energy Agency, 2010).

Dry-cask storage became an interim storage method for HLW in the United States because of the dwindling storage space remaining in spent fuel pools at commercial power plants and because there was not a long-term disposal site for HLW available. Spent nuclear fuel is placed into a multi-layered canister/cask system that can be designed for transportation to an alternative location for storage (Fig. 5a.) or one that can be designed strictly for storage of SNF (Fig. 5b.) (Roy, 2021).

Recent developments in dry-cask technology have seen the creation of "multi-use" casks that are designed for fuel transportation, storage, and long-term disposal once a HLW permanent disposal option arises. As long-term HLW storage sites continue to face an uphill battle within the United States, dry-cask storage is becoming a safe and attractive medium-term storage solution. However, dry casks are only licensed for 40 years in the United States and would not easily convert to a long-term permanent disposal option without a large regulatory effort (Darda et al., 2021).

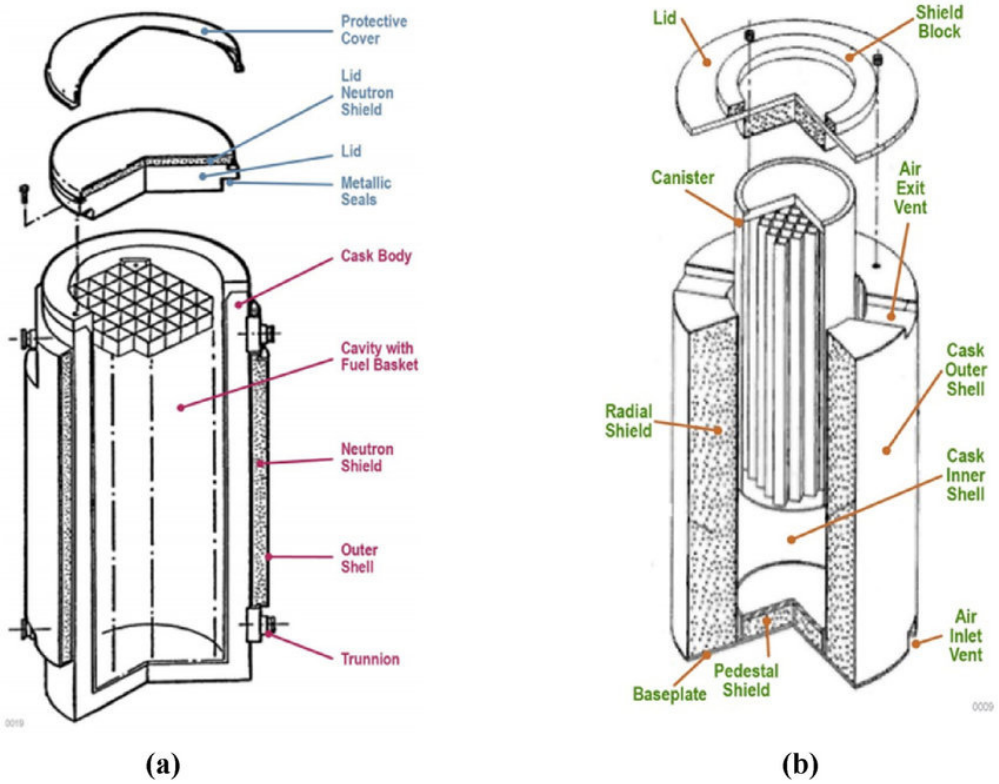


Figure 5: Cutaway views of vertical dry storage casks with bolted closure lid (a) and welded canister (b), each containing an internal basket for multiple spent fuel assemblies (Li & Liu, 2016).

3.3.2. SNF Reprocessing

Reprocessing involves chemical separation of the components SNF to recover valuable uranium (U), plutonium (Pu), and major actinides for reuse. The most widely used SNF reprocessing method on a global scale is the Plutonium Uranium Extraction (PUREX) process. PUREX involves a liquid—liquid extraction process that separates fission products from plutonium and uranium in used fuel. An acidic, aqueous phase is mixed with an organic phase to convert typically hydrophilic forms of uranium and plutonium into hydrophobic forms that can be easily extracted (see Fig. 6). Typically, the 4+ and 6+ oxidation states of metals — Pu4+ and U6+ in the form of (UO2)2+ — are extracted by the PUREX process (Roy, 2021). After extraction, the uranium can be recycled into reprocessed uranium fuel, and the plutonium can be recycled into mixed oxide (MOX) fuel or used for defense purposes.

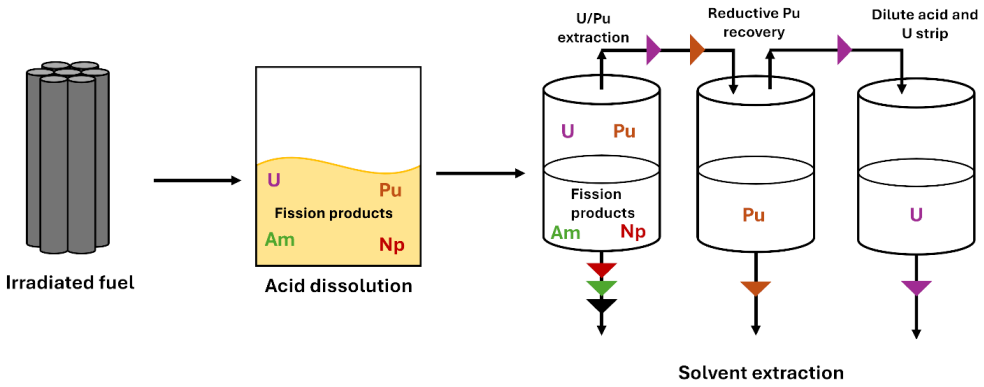


Figure 6: Simplified flow diagram of the PUREX process (Clark, Yang, & Shafer, 2018).

To avoid the separation of SNF into pure plutonium because of the high-proliferation risk, additional aqueous separation methods have been developed. For example, the Uranium Extraction (UREX) process does not extract plutonium independently and instead prioritizes the recovery of uranium and technetium while forcing the plutonium into a complex phase with neptunium. This property prevents further separation of Pu while reducing the heat load and radiotoxicity of the final HLW generated during the process (Rodríguez-Penalonga & Moratilla, 2017). The policy history of reprocessing SNF in the United States has been a tumultuous one. Reprocessing was originally leveraged during World War II as a means of generating plutonium for nuclear weapons. Beginning in the mid-1960s, the first commercial SNF reprocessing plant was licensed and operational until it was shut down in the 1970s for upgrades. Once the plant was shut down, operation never restarted. Three more reprocessing facilities for commercial SNF were subsequently constructed. However, these never reached operational status because of the proliferation risk and the low price of uranium disincentivizing fuel reprocessing. Further developments for commercial SNF reprocessing facilities have

continued to face delays or cancellations for identical reasoning (Roy, 2021; Rodríguez-Penalonga & Moratilla, 2017; Holt & Larson, 2025). In addition to the proliferation risk, commercial SNF reprocessing continues to be an economically unattractive means of addressing HLW when compared to long-term disposal methods. Research conducted by Bunn et al. in 2005 estimated that reprocessing commercial SNF would be more expensive than long-term disposal methods until the average price of uranium in $USD per pound of U exceeded $370 per kg U (approximately $167.83 per lb U). This is a price of uranium that has not been seen at all and was estimated to take several decades to reach (Fig. 7) (Bunn et al., 2005; Holt & Larson, 2025). The only time the price of uranium came close to this break-even value was in the early 2000s (Fig. 7).

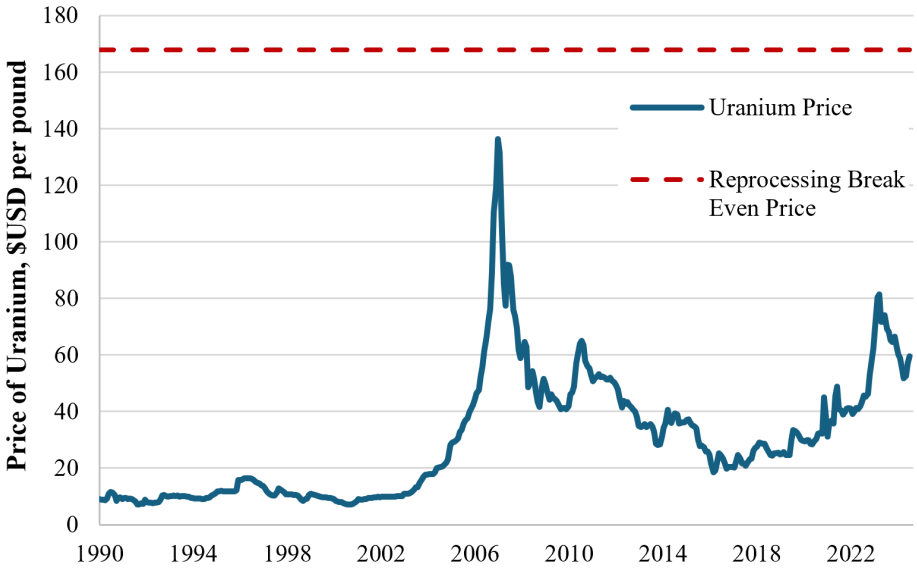


Figure 7: Historical global uranium price data compared to (Bunn et al., 2005) estimated break-even price of uranium in $USD per pound for SNF reprocessing to become economically incentivized (International Monetary Fund, ©IMF, 2025).

3.3.3. Pyroprocessing

Pyroprocessing is a non-aqueous alternative to aqueous extraction methods, such as PUREX. The core technique for pyroprocessing involves a high-temperature and an electrochemical, selective dissolution process. Fuel reprocessing using this method has a lower recovery efficiency, however it is more proliferation resistant and considerably reduces the final HLW volume for disposal (Roy, 2021; Rodríguez-Penalonga & Moratilla, 2017). All efforts in pyroprocessing are currently on a laboratory scale and research is on-going.

3.4. Proposed Permanent HLW Disposal Methods

Regardless of efforts for reprocessing or interim long-term storage for HLW, all forms of HLW will eventually need to be discarded in a repository that protects the environment and the public from exposure to radioactivity.

3.4.1. Permanent Geological Repository

A deep geological repository (DGR) is a large excavation within solid rock for the explicit purpose of storing radioactive waste (Roy, 2021). There is a strong consensus among all nuclear nations that a deep geological repository is the best option for the containment and isolation of HLW (Roy, 2021; Darda et al., 2021). The primary purpose of a DGR is to store highly radioactive waste long enough that the radioactivity levels decrease to safe levels and provide passive protection from the inadvertent release of radioactive materials. As designs have developed for the DGR, the concept of the multi-barrier safety system has been identified as a key component of the final design. A multi-barrier design is one in which there are multiple layers or engineering or geological barriers that prevent the radioactive materials within HLW from reaching areas that could cause harm to people or the environment (e.g. groundwater). The barriers are generalized as: the solid waste itself, the metal container around the waste, the overpack surrounding the container, the backfill surrounding the overpack, and the rocks that surrounding the final buried overpack (Roy, 2021).

One of the toughest challenges for deep geological repositories — excluding politics — is ensuring that the facility will remain a stable disposal site from upwards of tens of thousands to millions of years. High-level waste contains a variety of radionuclides with exceptionally long half-lives including iodine-129 (1.6E+7 years) and nobium-94 (2.0E+4 years) (Yang et al., 2004). Robust geological and environmental surveys must be conducted prior to site selection to verify the repository is equipped to handle such long half-life materials. Furthermore, design and operation of a geological repository can take one of two forms depending on the policy surrounding the site selection process and waste management. The first form is pure disposal of radioactive waste within a deep geological repository. This means that once the waste has been placed inside the repository, there are no systems in place to retrieve or move the waste. The second form is disposal with the option of retrieving the waste if desired. If spent nuclear fuel reprocessing becomes economically incentivized, there could be a push to retrieve highly radioactive waste for reuse. Additionally, if there are issues with the repository identified, the waste can be transported to another secure location to prevent accidental exposure to dangerous radionuclides. In the United States, the Nuclear Waste Policy Act of 1982 requires that all deep geological repositories for HLW be designed for disposal and retrieval (Roy, 2021).

Currently, the only deep geological repository in the United States licensed to dispose of HLW is the Waste Isolation Pilot Plant (WIPP) located in New Mexico (Darda et al., 2021). It is not open to the disposal of commercial SNF and only US Department of Energy (US DOE) facility-generated waste is accepted (Roy, 2021). There is no HLW storage and disposal facility available for com-

mercial spent nuclear fuel and other forms of HLW. There was only one facility deemed feasible for SNF and HLW storage and disposal within the United States: Yucca Mountain. Section 3.4.3 discusses in further detail the history and issues with this project that led to its ultimate cancellation.

3.4.2. Deep Borehole Disposal

Deep borehole disposal of radioactive waste is a proposed format of deep geological repository that involves drilling a single borehole deep into the ground (3—5 km), filling it with solidified waste, and then sealing the borehole with a mixture of bentonite clay and either asphalt or concrete (Fig. 8) (Brady et al., 2009).

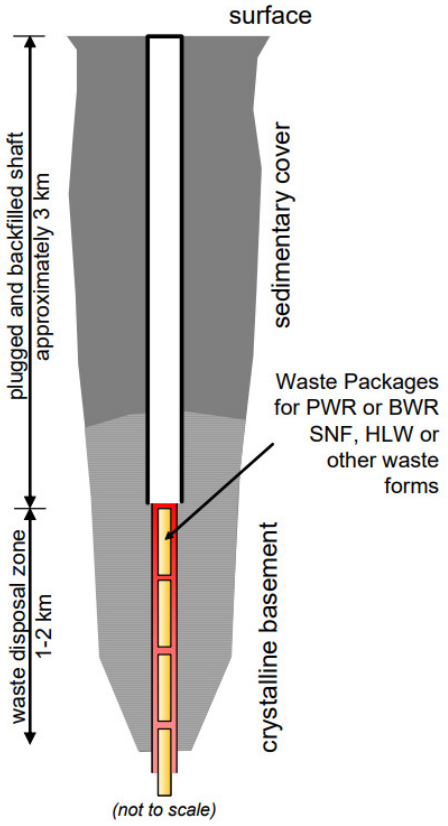


Figure 8: Deep borehole disposal schematic for spent nuclear fuel (Brady et al., 2009)

Deep boreholes are estimated to provide effective long-term storage because of the long pathways present that would hinder radionuclide transport, limited flow of fluids beneath the surface, insufficient upward ambient pressure to drive radionuclide migration, a favorable sub-surface chemical environment, and strong mechanical stability of the boreholes to prevent deformation. It was previously estimated in 2008 that one borehole would cost approximately $20 million dollars and approximately 110 days to construct (Brady et al., 2009). Without reprocessing or consolidation

of current HLW inventories, several hundred boreholes would be required. To implement the deep borehole disposal method, the Nuclear Waste Policy Act must be amended because it mandates that the Yucca Mountain Nuclear Waste Repository must be the first federally licensed waste disposal facility for HLW (Roy, 2021).

3.4.3. Yucca Mountain Waste Repository

The Yucca Mountain Waste Repository was one of five sites nominated by the then US Secretary of Energy as part of the requirements dictated by the Nuclear Waste Policy Act. In 1987, the Yucca Mountain site was decided by Congress to be the only site further evaluated and categorized as a permanent waste repository. Speculation exists as to why Congress only chose this site over the others, but a multitude of sources rely on bias to assert the claim that Yucca Mountain was chosen because of political short-cuts. In 1995, a large body of scientific evidence demonstrated that there was significant water movement within the fractures of the mountain, raising concerns for the transport of radionuclides. However, the site was not abandoned and performance assessments and environmental studies continued (Adams, 2010). Additional concerns of the oxidizing environment present in the volcanic tuff rock of the mountain, high-seismic activity, and recent volcanic activity forced the design of the repository to increasingly rely on engineered barriers rather than geological ones (Ewing & von Hippel, 2009). Proven falsification of geological data and models developed to predict Yucca Mountain site hydrology in 2005 generated further opposition to the progress of Yucca Mountain repository (Adams, 2010).

In 2008, the US DOE submitted a license application to the US NRC for the construction of the repository within Yucca Mountain. Strong opposition from the state of Nevada prompted the Obama administration to abandon the project and discontinue all funding (Roy, 2021). It has been estimated that final cost of the Yucca Mountain project sits at approximately $76 billion dollars in 2007 dollars (Ewing & von Hippel, 2009). At the time of writing, there have been no announcements from the current presidential administration to resume site exploration or funding for further Yucca Mountain repository development.

3.5. Barriers to Radioactive Waste Disposal

3.5.1. Policy Barriers

The current Nuclear Waste Policy Act (NWPA) as amended in 1987 currently encourages the adoption of a deep geological repository for long-term nuclear waste storage. The US Department of Energy was tasked with locating a desirable site, building the repository, and operating the final repository. The US Environmental Protection Agency (US EPA) was tasked with developing standards to protect the environment and surrounding communities while the US NRC was tasked with overseeing all licensing activities and ensuring the final repository satisfied requirements outlined by the EPA. Additionally, the NWPA only called for Yucca Mountain to proceed as the primary site

for disposal of radioactive waste despite the wording of the legislation prior to amending requiring the nomination of three sites for possible geological repository locations. Any second or third site identified in the site selection process would require authorization from the US Congress before any environmental assessment could proceed (Nuclear Waste Policy Act, 1987). The current language of the NWPA pigeonholes not only the state of Nevada, but also the NRC, EPA, and DOE into using Yucca Mountain as a viable site for long-term waste storage, despite mounting evidence against its viability. Additional siting activities are dissuaded because of the demanding amount of government approval required to begin the site selection process anew. This strict wording was a source of immense opposition to Yucca Mountain and eventually led to the cancellation of the project by the Obama administration (Rechard, Cotton, & Voegele, 2014).

Additionally, the NWPA amendments forced all regulations developed for HLW disposal and storage to become site specific rather than generic. The EPA could no longer develop non-site-specific guidelines and performance standards that ensured protection from hazardous radionuclides (Ewing & von Hippel, 2009). Instead, they were forced to create regulations for Yucca Mountain only. This set up the EPA for failure should the Yucca Mountain site become determined unsuitable for long-term waste disposal. Any additional sites that were selected would need completely new guidelines that would take more time and more approvals from within the US government.

Finally, the Nuclear Waste Fund established in 1982 by the original NWPA has suffered greatly since its inception and is ill-equipped to accommodate further funding of permanent geological repository work. In 1987, the US Office of Management and Budget (US OMB) eliminated the precedent of setting separate budget planning targets for the Nuclear Waste Fund and instead forced it to compete against other US DOE programs for discretionary spending. Fees collected from utilities by the Nuclear Waste Fund have been set to zero since 2014 because of ligation in the US Circuit Court of Appeals from the District of Columbia Circuit (United States Government Accountability Office, 2021). If fee collection were to resume today, the number of commercial nuclear power plants is less than in the 1980s. The funds would begin to recuperate, but it would take longer to reach a stable value in which the fund would be able to sustain efforts to find a suitable new geological repository site.

3.5.2. Social Barriers

Obtaining public support for a deep geological repository is arguably the most difficult portion of the process. The Yucca Mountain project failed to account for the opinions of the citizens of Nevada prior to final site selection (Rechard, Cotton, & Voegele, 2014). This generated vehement public opposition to the project immediately, which only compounded as issues began to arise with Yucca Mountain as a desirable long-term disposal site. Social issues and concerns with long-term nuclear waste repositories must be addressed completely and handled just as seriously as technical ones. Opposition to larger projects, such as deep geological repository construction, is often spurred on by lack of public involvement in decision processes. The concept of voluntarism — "expression of

interest in a community to participate in the search process for a suitable radioactive waste repository in their vicinity" — must be leveraged when the process of a long-term repository begins again in the United States (Di Nucci & Brunnengräber, 2017). This concept also means that communities must be given the opportunity to veto or rescind their consent from the site selection process within a reasonable amount of time. Successful examples of voluntarism and a consent-based repository siting search include the Onkalo repository in Finland and in Sweden (Di Nucci & Brunnengräber, 2017).

4. Conclusions and Recommendations

As nuclear energy continues to grow, so does the need for efficient and effective high-level and low-level waste disposal methods. The United States maintains a robust strategy for LLRW with the current four disposal sites. However, there are no concrete plans for additional sites in the future should the current ones become inundated. Despite formation of compacts, states are not currently obligated to put forth suitable locations for future LLRW disposal sites. It is recommended that the US government, through authority of the US DOE, US EPA, and US NRC, work with each of the compacts to identify potential LLRW sites and incentivize compacts to house LLRW disposal sites. This will prevent current disposal sites from potentially reaching a position of needing to turn away LLRW because of capacity concerns.

For long-term HLW disposal, deep geological repositories or deep boreholes are both sound technologies. However, before the United States can construct and operate either system, amendments must be made to the NWPA to remove the Yucca Mountain specific language and include the principle of voluntarism in site selection. Finland and Sweden are both excellent examples of where the United States can implement these policies while still selecting effective locations for long-term geological repositories. Additionally, it is recommended to further amend the NWPA to address funding gaps currently within the Nuclear Waste Fund. Deep geological repositories are technically sound, but without the support of surrounding communities in which the repository will be located, there is very little chance that the project will ever secure approval. The United States learned this once with Yucca Mountain and cannot afford to do it again.

References

Adams, M. (2010). Yucca Mountain—Nevada's Perspective. Idaho Law Review , 46 (2), 423–448. https://heinonline.org/HOL/Page?handle=hein.journals/idlr46&id=427&collection=journals&index=

Banerjee, K., Rigato, A., & Wilson, V. (2024). Spent Nuclear Fuel and Reprocessing Waste Inventory (No. PNNL-33938, Rev. 1.1). Pacific Northwest National Laboratory. https://curie.pnnl.gov/system/files/SNF%20and%20Rep%20Waste%20Inventory%20PNNL%2033938%20Rev.

%201.1_0.pdf

Brady, P. V., Arnold, B. W., Freeze, G. A., Swift, P. N., Bauer, S. J., Kanney, J. L., Rechard, R. P., & Stein, J. S. (2009). Deep borehole disposal of high-level radioactive waste. (Nos. SAND2009-4401, 985495; pp. SAND2009-4401, 985495). https://doi.org/10.2172/985495

Bunn, M., Holdren, J. P., Fetter, S., & Van Der Zwaan, B. (2005). The economics of reprocessing versus direct disposal of spent nuclear fuel. Nuclear Technology , 150 (3), 209–230. https://doi.org/10.13182/NT05-A3618

Carter, J. (2020). Spent nuclear fuel and reprocessing waste inventory (No. FCRD-NFST–2013-000263, 1670405; p. FCRD-NFST–2013-000263, 1670405). https://doi.org/10.2172/1670405

Clark, A. E., Yang, P., & Shafer, J. C. (2018). Coordination of actinides and the chemistry behind solvent extraction. In J. K. Gibson & W. A. Jong (Eds.), Experimental and Theoretical Approaches to Actinide Chemistry (1st ed., pp. 237–282). Wiley. https://doi.org/10.1002/9781119115557.ch5

Darda, S.A., Gabbar, H.A., Damideh, V. et al. (2021). A comprehensive review on radioactive waste cycle from generation to disposal. J Radioanal Nucl Chem 329 , 15–31. https://doi.org/10.1007/s10967-021-07764-2

Di Nucci, M. R., & Brunnengräber, A. (2017). In whose backyard? The wicked problem of siting nuclear waste repositories. European Policy Analysis , 3 (2), 295–323. https://doi.org/10.1002/epa2.1028

Disposal of high-level radioactive wastes in geologic repositories, 10 CFR 60 (2025). https://www.ecfr.gov/current/title-10/chapter-I/part-60

Ewing, R. C., & von Hippel, F. N. (2009). Energy. Nuclear waste management in the United States–starting over. Science (New York, N.Y.) , 325 (5937), 151–152. https://doi.org/10.1126/science.1174594

Holt, M., & Larson, L. N. (2025). Considerations for Reprocessing of Spent Nuclear Fuel . (CRS Report No. R48364). https://www.congress.gov/crs-product/R48364

International Monetary Fund (2025). Global price of Uranium [PURANUSDM]. ©IMF. Retrieved from FRED, Federal Reserve Bank of St. Louis on November 29, 2025, at https://fred.stlouisfed.org/series/PURANUSDM

Internationale Atomenergie-Organisation (IAEA) (Ed.). (2009). Classification of radioactive waste: General safety guide . International Atomic Energy Agency.

Laraia, M. (2015). Radioactive contamination and other environmental impacts of waste from nuclear and conventional power plants, medical and other industrial sources. In Environmental Remediation and Restoration of Contaminated Nuclear and Norm Sites (pp. 35–56). Elsevier. https://doi.org/10.1016/B978-1-78242-231-0.00002-8

Li, J., & Liu, Y. Y. (2016). Thermal modeling of a vertical dry storage cask for used nuclear fuel. Nuclear Engineering and Design , 301 , 74–88. https://doi.org/10.1016/j.nucengdes.2016.0

1.008

Licensing requirements for land disposal of radioactive waste, 10 CFR 61 (2025). https://www.ecfr.gov/current/title-10/chapter-I/part-61

Nuclear Energy Agency (2020). Spent Nuclear Fuel Pool [Photograph]. OECD Publishing . Accessed November 28, 2025, from https://oecd-nea.org/jcms/pl_47481/spent-nuclear-fuel-pool?details=true

Omoniyi Gbohunmi Korede, Oluwaferanmi O. Akinyemi, & Adeyemi Zaheed Oshilalu. (2023). Environmental and ecological impact of radioactive waste disposal. World Journal of Advanced Research and Reviews , 18 (2), 1419–1439. https://doi.org/10.30574/wjarr.2023.18.2.0728

Rempe, N. T. (2007). Permanent underground repositories for radioactive waste. Progress in Nuclear Energy , 49 (5), 365–374. https://doi.org/10.1016/j.pnucene.2007.04.002

Rechard, R. P., Cotton, T. A., & Voegele, M. D. (2014). Site selection and regulatory basis for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering & System Safety , 122 , 7–31. https://doi.org/10.1016/j.ress.2013.06.021

Rodríguez-Penalonga, L., & Moratilla Soria, B. Y. (2017). A review of the nuclear fuel cycle strategies and the spent nuclear fuel management technologies. Energies , 10 (8), 1235. https://doi.org/10.3390/en10081235

Roy, W. R. (2021). Radioactive waste management in the 21st century . World Scientific.

Stefanovsky, S. V., Yudintsev, S. V., Gieré, R., & Lumpkin, G. R. (2004). Nuclear waste forms. Geological Society, London, Special Publications , 236 (1), 37–63. https://doi.org/10.1144/GSL.SP.2004.236.01.04

United States Department of Energy (US DOE). (2024). Generator Data. Manifest Information Management System . Retrieved November 26, 2025, from https://mims.doe.gov/GeneratorData.aspx

United States Government Accountability Office. (2021). Commercial Spent Nuclear Fuel: Congressional Action Needed to Break Impasse and Develop a Permanent Disposal Solution (Report No. GAO-21-603). Retrieved December 1, 2025, from https://www.gao.gov/assets/gao-21-603.pdf

United States Nuclear Regulatory Commission. (2022). Regulation of radioactive materials |nuclear regulatory commission. Retrieved November 3, 2025, from https://www.nrc.gov/about-nrc/radiation/protects-you/reg-matls

United States Nuclear Regulatory Commission. (2025). Locations of low-level waste disposal facilities | nuclear regulatory commission. Retrieved November 28, 2025, from https://www.nrc.gov/waste/llw-disposal/licensing/locations

Yang, W. S., Kim, Y., Hill, R. N., Taiwo, T. A., & Khalil, H. S. (2004). Long-lived fission product transmutation studies. Nuclear Science and Engineering , 146 (3), 291–318. https://doi.or

g/10.13182/NSE04-A2411

Yano, K. H., Mao, K. S., Wharry, J. P., & Porterfield, D. M. (2018). Investing in a permanent and sustainable nuclear waste disposal solution. Progress in Nuclear Energy , 108 , 474–479. https://doi.org/10.1016/j.pnucene.2018.07.003

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Evaluating the Future of the United States-China Nuclear Weapons Relationship

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The current work examines the historical nuclear weapons relationship between the United States and China, and links the changes in nuclear policy to the current day. Since the inception of fundamental treaties like the Treaty on the Non-Proliferation of Nuclear Weapons that established the United States and China as nuclear weapons states, the roles of both nations have changed greatly in the international system. As the U.S. nuclear arsenal decreases and the Chinese nuclear arsenal increases, the relationship has begun to meet the definitions of a cold war. Through a discussion of each nations' security paradigms, unique positions in the international system, and multilateral commitments, possibilities for the future U.S.-China nuclear weapons relationship emerges.

Keywords: United States, China, nuclear weapons, nuclear policy, international relations, non-proliferation

Introduction

Historical US-China Nuclear Weapons Relationship

The United States and China have one of the world's most complex bilateral relationships. The respective nuclear weapons posture of both nations plays a fundamental role in the complexity of the relationship. Nuclear weapons conversations between the United States and China can be traced to the first Taiwan Strait Crisis in 1954 (Council on Foreign Relations, 2025). Tensions between the People's Republic of China (PRC) and the Republic of China (ROC) throughout the 1950s resulted in an armed conflict over specific islands in the Taiwan Strait that played a significant role in the Chinese Civil War (Office of the Historian, 2025). The United States intervened on behalf of the

ROC (Office of the Historian, 2025). The Eisenhower administration passed the "Formosa Resolution" in 1955 that gave President Eisenhower the complete authority to defend Taiwan and the other off-shore islands (Office of the Historian, 2025). During this time, the Eisenhower administration considered using nuclear weapons against the PRC (Council on Foreign Relations, 2025). Negotiations for the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) marks another instance of nuclear weapons altering the U.S.-China relationship. The NPT is considered to be one of the most successful arms control treaties in existence (Popp, 2016). The negotiations were prompted in part by the Chinese explosion of 1964, China's first nuclear test (Goldschmidt, 1980). This nuclear test was of an improvised device (Rodgers & Williams, 2025). The test occurred amidst U.S.-Sino tensions over an escalating crisis in Vietnam (Council on Foreign Relations, 2025).

In years prior to the test the United States monitored Chinese developments with angst (Goldschmidt, 1980). However, US analysts had conflicting reports and opinions about the potential dangers of the predicted activity (Goldschmidt, 1980). Both the Union of Soviet Socialist Republics (USSR) and the United States held a shared goal of preventing the PRC from acquiring an independent nuclear deterrent (Popp, 2016). The degradation of the Soviet Union's relationship with the PRC as a result of the Sino-Soviet split made it so that the PRC nuclearization was equally as worrying to the Soviet Union as it was to the United States. There existed concerns that the PRC's test could become a precedent for other nations with nuclear ambitions. This potential precedent promised to greatly upset the balance of power for the Soviet Union and United States. At one point the United States and the USSR considered colluding to halt the PRC's nuclear military progress with the use of force (Popp, 2016).

A year later in a declassified National Intelligence report, it was noted that China had TU-16 bombers that were capable of carrying a "bulky nuclear weapon" (Rodgers & Williams, 2025). Thus, the trepidation is rooted in the foundation of the US-China nuclear weapons relationship. The term "non-proliferation" did not formally appear until 1965 after this nuclear test (Goldschmidt, 1980).

In 1964, China declared its No First Use (NFU) policy, in which the nation pledges to never initiate nuclear warfare (Hautecouverture, 2025). China committed to only using nuclear weapons as a self-defense strategy (Hautecouverture, 2025). In a 2006 defense paper, China reiterated that its fundamental goal was to "deter other countries from using or threatening to use nuclear weapons against China (Hautecouverture, 2025). China remains firmly committed to the policy of NFU of nuclear weapons at any time and under any circumstances" (Information Office of the State Council of the People's Republic of China, 2006). Chinese promotion of this policy has continued to modern day with the submission of the working paper No-first-use of nuclear weapons initiative to the NPT Review Conference Preparatory Committee in 2024 (Hautecouverture, 2025). Additionally, another key part of China's official nuclear policy is the complete prohibition through total destruction of nuclear weapons (Zhang, 2012). The United States has refused to adopt a NFU policy (Bin & Hongzhen, 2009).

In the 1980s, China initiated a nuclear modernization program, aimed at developing mobile missiles (Bin & Hongzhen, 2009). The program included the expansion of underground facilities in order to shelter existing nuclear weapons from an enemy attack (China Power Team, 2019).

Operational Arsenal of China

Since 2020, China has continued to expand its nuclear modernization program (Kristensen et al., 2025). This includes developing three missile silo fields for intercontinental ballistic missiles (ICBMs), new variants of ICBMs, and new strategic delivery systems (Kristensen et al., 2025). Additionally, China recently re-assigned an operational nuclear mission to bombers with an air-launched ballistic missile that potentially had nuclear capability. China's nuclear expansion is "among the largest and most rapid modernization campaigns of the nine nuclear-armed states" (Kristensen et al., 2025, p. 1).

Table 1. Chinese nuclear forces, 2025.

Type	NATO designation	Number of launchers[a]	Year deployed	Range (kilometers)	Warheads x yield[b] (kilotons)	Warheads
Land-based ballistic missiles[c]						
Intermediate-range[d]						
DF-26	CSS-18	250[e]	2016	4,000	1 × 425	100[f]
Subtotal:		*250*				*100*
Intercontinental range						
DF-5A	CSS-4 Mod 2	6	1981	12,000	1 × 4.5 MT	6
DF-5B	CSS-4 Mod 3	12	2015	13,000	Up to 5 × 425	60
DF-5C	(CSS-4 Mod 4)	..	(2025)	13,000	1 × "multi-MT"	..
DF-27	?	..	(2026)	5,000–8,000	1 × ?	..
DF-31	CSS-10 Mod 1	..	2006	7,200	1 × 425	..[g]
DF-31A	CSS-10 Mod 2	24	2007	11,200	1 × 425	24
DF-31A	CSS-10 (silo)	320[h]	(2024)	11,200	1 × 425	30[h]
DF-31AG	(CSS-10 Mod 2)[i]	72	2018	11,200	1 × 425	72
DF-41	CSS-20 (mobile)	28	2020	12,000	Up to 3 × 425	84
DF-41	CSS-20 (silo)	..	..	12,000	Up to 3 × 425	..
Subtotal:		*462*				*276*
Total land-based		*712*				*376*
Submarine-launched ballistic missiles						
JL-2	CSS-N-14	0[j]	2016	7,000+	1 × 700	0
JL-3	CSS-N-20	6/72	2022[k]	9,000+	1 × 425	72
Aircraft[l]						
H-6N	B-6	20	2020	3,100+	1 × ALBM	20
H-20	?	..	(2030)	?	(ALCM?)	..
Subtotal		**804**				**468**
Warheads produced for incoming delivery systems						132[m]
Total						**600**[n]

Figure 1: Estimated Chinese nuclear stockpile in 2025 (Kristensen et al., 2025)

The Bulletin of Atomic Scientists estimates that China has a stockpile of approximately 600 nuclear warheads for delivery via land-based missiles, sea-based missiles, and bombers (Kristensen et al., 2025). Based on a 2024 Pentagon report, it is assumed that China's nuclear stockpile has surpassed 600 operational warheads since 2024 (Department of Defense, 2024). The Chinese nuclear stockpile is not operational in the same sense that U.S. and Russian nuclear stockpiles are (Kristensen et al., 2025). For the U.S. and Russian nuclear warheads, the warheads are deployed on operational missiles and bomber bases. In the case of Chinese warheads, storage is separate from launchers (Kristensen et al., 2025). This method is also known as de-mating the warheads from their delivery systems (Arms Control Association, 2019). By 2030, the Pentagon estimates that China will surpass 1,000 warheads. Many of these warheads will be deployed at "higher readiness levels" (Department

of Defense, 2024).

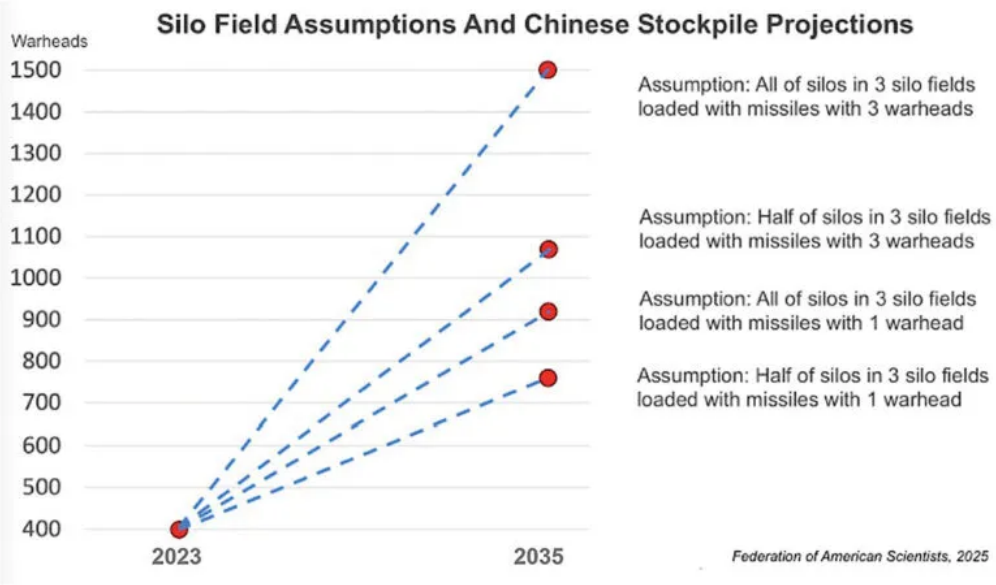


Figure 2: Chinese stockpile projections and silo field assumptions (Kristensen et al., 2025)

In previous projections, the Pentagon estimated that the Chinese would have 1,500 warheads by 2035 (Kristensen et al., 2025). This is reflective of the uncertainty in these projections. Uncertain factors include the number of missile silos China ultimately builds, how many silos will be loaded with missiles, how many warheads each missile will carry, how many bombers China can corporate, and how many warheads China can produce (Kristensen et al., 2025) . The more silos loaded, the greater the stockpile. The Pentagon projections apply the growth rate of new warheads from past periods to subsequent years (Kristensen et al., 2025).

Operational Arsenal of the US

According to the Department of Energy, the U.S. nuclear stockpile is at the smallest it has been since 1960 (Department of Energy, 2025). As visible in Figure 3, in the late 1960s the total warhead count sat at 31, 255. As of 2023, the U.S. nuclear stockpile sits at 3,748 warheads, amounting to a 88 percent reduction from the late 1960s peak (Department of Energy, 2025). The majority of the current stockpile was produced after the peak of the stockpile in the 1970s and 1980s (Department of Energy, 2025). At the time of assembly, the weapons were not designed to be long-lasting (Department of Energy, 2025). One hundred nuclear gravity bombs have been deployed to five NATO countries in order to extend the deterrence policy (Nuclear Threat Initiative, 2025). An estimated 1,500 nuclear warheads are currently awaiting dismantlement (Nuclear Threat Initiative, 2025).

The United States' total inventory is beyond agreed ceilings in the New START Agreement (Arms

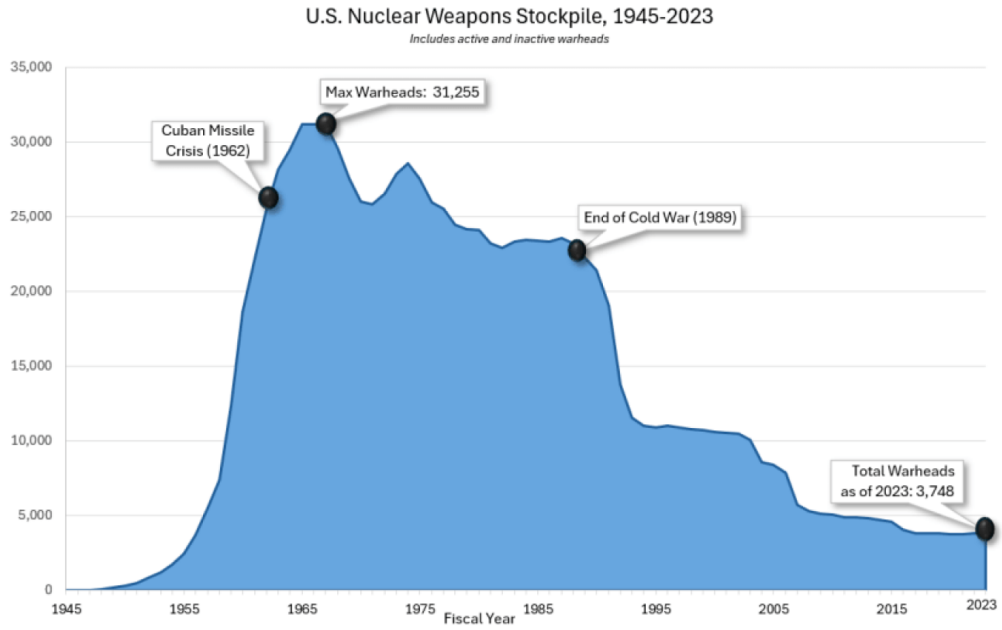


Figure 3: U.S. Nuclear Weapons Stockpile, 1945-2023 (Department of Energy, 2025)

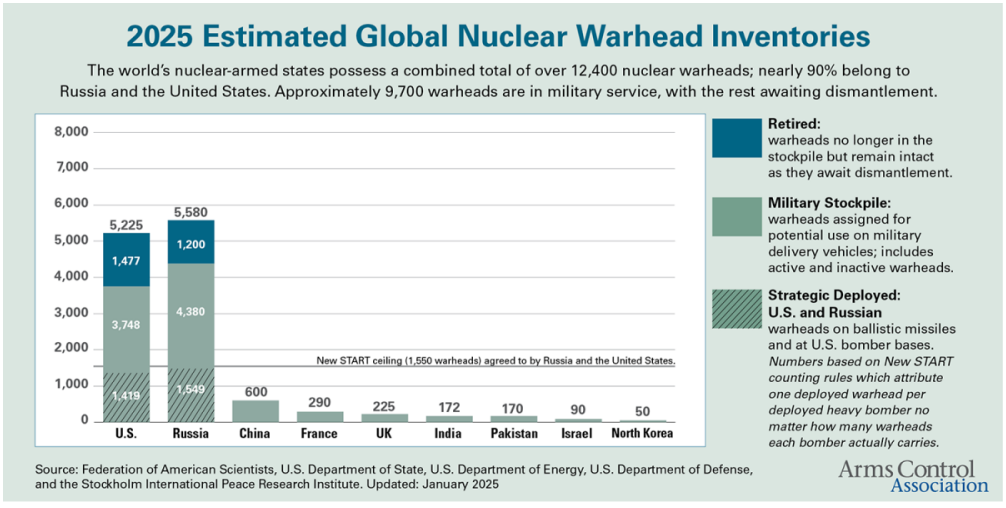


Figure 4: 2025 Estimated Global Nuclear Warhead Inventories (Arms Control Association, 2025)

Control Association, 2025). The New START Agreement replaced previous START treaties and was entered into force in 2011 (Arms Control Association, 2024). It continued a bipartisan process of reducing the U.S. and Russian strategic nuclear arsenals. The New START capped accountable deployed strategic nuclear warheads to 1,550, a 30% reduction compared to previous treaties (Arms Control Association, 2024). An extension of five years until 2026 was agreed to in 2021. However, in 2023 Russia announced it was suspending its START implementation (Arms Control Association, 2024).

China's Role in the NPT

China was not a member of the Eighteen Nation Disarmament Committee (ENDC), the body that ultimately created the NPT (Davenport, 2019). Despite a lack of formal involvement, China was considered to be an observer of note. China played a role in the process of negotiations. China argued that the treaty was discriminatory and made it clear to ENDC participants that Beijing would not sign the treaty as it stood in 1968 (Davenport, 2019). At the time of negotiations there existed a strong sense of abandonment among the ruling elite in China (Popp, 2016). Romania played a role in the overall influence of China in the NPT (Popp, 2016).

Romanian leadership during negotiations leveraged the Sino-Soviet split to distance themselves from the Warsaw Pact. Romania maintained relationships with both the Soviets and the PRC, which was a sign to the Soviets that they could no longer dictate Romanian foreign policy (Popp, 2016). Romania served as a de facto mediator between the PRC and the Soviet Union for a time. In 1964, Romania formulated a declaration in which all Communist parties were deemed equal to alleviate Sino-Soviet tensions (Popp, 2016). During a meeting in 1965 in which the Warsaw Pact members voted on a proposal for a nonproliferation treaty, the Romanians were the only nation to veto. They colluded with PRC officials (Popp, 2016).

During the process of negotiations of the NPT, intelligence operations, specifically disinformation operations were carried out by the Soviet Union (Nance, 2018). China was considered to be a target of a significant priority by Russian intelligence officers (Nance, 2018). China acceded to the NPT in 1992 (Ministry of Foreign Affairs People's Republic of China, 2025).

U.S. Role in the NPT

The United States played a key role in the negotiation process of the NPT. The United States led a western-bloc collection of nuclear weapon states (NWS) and non-nuclear weapon states (non-NWS). Drafts prior to the negotiations were created by the United States (Goldschmidt, 1980). Throughout negotiations, the United States served as the principal negotiator. The United States and the western-bloc pushed for strong verification measures as opposed to relying solely on national intelligence measures for compliance checks (Davenport, 2019). Ensuring the International Atomic Energy Agency (IAEA) could verify peaceful nuclear programs was a non-negotiable (Davenport,

2019).

Discussion

Perception of Power in the International System

The U.S. and China's status as a nuclear weapons state (NWS) is a privileged position in the international system. Non-NWS view nuclear weapons in a different light than NWS counterparts. A Zambian representative at the UN 78th Session of the First Committee (otherwise known as the Disarmament and International Security Committee) argued that nuclear weapons have no place in the modern world (UN Meetings Coverage and Press Releases, 2023). Despite the common justification by NWS that nuclear weapons serve as a deterrent, there is no guarantee of international security (UN Meetings Coverage and Press Releases, 2023). Other non-NWS national representatives conveyed similar perspectives, settling on the idea that the existence of nuclear weapons creates both temptation and the risk of use (UN Meetings Coverage and Press Releases, 2023). There are frequent calls for NWS to recall their requirements under the NPT and UN Charter, which extends to the eventual elimination of nuclear weapons (UN Meetings Coverage and Press Releases, 2023). Many non-NWS cite Article VI of the NPT, which requires the parties of the treaty to "pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament" (International Campaign to Abolish Nuclear Weapons, 2021).

The Chinese Ministry of Foreign Affairs asserts that China actively participates in the non-proliferation process at regional and international levels (Ministry of Foreign Affairs People's Republic of China, 2025). This participation includes signing the Comprehensive Nuclear Test Ban Treaty (CTBT) in 1996 (Ministry of Foreign Affairs People's Republic of China, 2025). Additionally, China was the first NWS to enter Additional Protocol arrangements with the IAEA into force (Ministry of Foreign Affairs People's Republic of China, 2025). However, non-NWS continue to call for not just signatures of these treaties but also ratification (UN Meetings Coverage and Press Releases, 2023). The Treaty on the Prohibition of Nuclear Weapons (TPNW) is a particular sore point, as neither the United States or China have become signatories (Treaty on the Prohibition of Nuclear Weapons, 2017).

For China, the political dimension of nuclear weapons have been emphasized by Chinese leaders (Kim et al., 2023). Many leaders have pushed the idea that nuclear weapons shape the international perceptions of China (Kim et al., 2023). Particularly with the United States, nuclear weapons are viewed as a method for the U.S. to accept a stable and peaceful relationship with China. Nuclear weapons have a broader political goal of fostering a good external environment for nations (Kim et al., 2023).

Differences in Thought Processes about Nuclear Weapons

Bin (2015) discussed the differences in Chinese and U.S. thinking on nuclear weapons. The differences in thought processes impact communication between Chinese and U.S. nuclear experts (Bin, 2015). The first dimension that differs is the security paradigms. For the United States, the basic paradigm is to identify and assess threats to national security. Typically a national security threat is an outside actor and enemy that can enact harm. The threat is measured by their capacity to harm and intentions. When attempting to implement a change in U.S. security policy, advocates for the change must establish an enemy that has the capacity and intention to harm (Bin, 2015). This paradigm is straightforward and accepted by other nations. The "indigenous Chinese security paradigm" emphasizes national security challenges rather than threats to national security (Bin, 2015). A national security challenge is a situation in which China is vulnerable to specific dangers. Typical phrasing in Chinese security documents includes "national security challenges" and "national security threats" (Bin, 2015). To establish Chinese policy on these threats, the government releases "white papers" (Bin, 2015). These white papers discuss defense policy and the national security threats as challenges, without creating or identifying a specific enemy (Bin, 2015). The location of national security threats is another differentiating factor. In the U.S. security paradigm, national security threats are almost exclusively located outside of the United States. In the Chinese security paradigm, there is more flexibility. Security threats can be inside the nation (Bin, 2015).

There exists a difference in understanding security concepts. One such issue is definitions of nuclear deterrence between the United States and China. Americans believe that nuclear deterrence is a defensive posture. Nuclear deterrence is forcing "an adversary to give up an action by threatening to use nuclear weapons" (Bin, 2015). Nuclear compellence is forcing the adversary to take an action. Deterrence and compellence are both considered to be coercion. If a coercive action changes the status quo it is compellence (Bin, 2015). If it does not change the status quo, it is deterrence. The Chinese criticize the offensive nature of deterrence instead. There are also various definitions for "security" and "safety" (Bin, 2015). In the English-speaking world, security and safety are concepts that are considered distinguishable (Bin, 2015). Safety concerns avoiding damage caused by accidents or natural disasters, whereas security is avoiding damage caused by human attacks. In China, the same assumptions do not hold. Safety and security are somewhat indistinguishable/integrated. When applied to nuclear policy, it results in the Chinese holistic philosophy of "comprehensive security theory" (Bin, 2015).

Changes in Chinese Nuclear Policy

Prior to the reform policy in 1978, Chinese citizens felt it was hypocritical to criticize the nuclear weapons programs of proliferator nations like India when China had its own nuclear weapons programs (Bin, 2015). The reform brought about a re-prioritization of national economic interests over national security interests. This impacts Chinese action in the international system. China became reluctant to join international sanctions and export control efforts that were against proliferation. In recent decades, views on economic and national security interests have become more balanced

(Bin, 2015).

Recent Aggressive U.S. Strategy

Bin and Hongzhen (2009) have noted three recent trends in the American nuclear posture that can change the U.S.-China nuclear relationship in favor of the United States. The first of these changes is a moving of nuclear submarines to the Pacific Ocean from other locations. Within the 2010s, the United States has shifted approximately 1,000 warheads to the Pacific Ocean, therefore making them much closer to any targets in China (Bin & Hongzhen, 2009). Bin and Hongyi argued that the shorter flight times for these missiles that are fired from submarines close to Chinese territory can decrease the mobility of China's new missiles.

Talmadge (2019) noted that the United States' core concerns in regards to China's nuclear arsenal is that improvements could reduce the United States' ability to limit damage in an all-out nuclear war with China. The United States' preference is for damage limitation, through the use of missile defense and counterforce measures (Talmadge, 2019). The intended goal with damage limitation is for China to worry that the United States would have a greater tolerance for bearing the risks of nuclear escalation when compared to China. The advocates for damage limitation believe that this approach could deter China from initiating conflict to begin with, including conflict that is less than the nuclear threshold (Talmadge, 2019).

Additionally, there has been a deployment of missile defenses and the development of space based radar (Bin & Hongzhen, 2009). Despite the aggressive strategy, Bin and Hongzhen believed that China could counteract these pressures with low-cost measures to protect "the effectiveness of its nuclear retaliatory capability" (Bin & Hongzhen, 2009). The counter measures include camouflage and dummy missiles.

Talmadge (2019) discussed the policies the United States should adopt to manage nuclear competition with China. Talmadge asserted that U.S. policymakers should acknowledge the trade-offs to a more competitive nuclear relationship with China (Talmadge, 2019). If the U.S. refuses to admit there is a mutual vulnerability in a stiff nuclear competition between the two nations, China becomes more likely to adopt an ambitious nuclear strategy (Talmadge, 2019).

Chinese Nuclear Program Modernization

Prior to 2019, China's nuclear posture was defined by three main characteristics: a retaliatory doctrine, a small nuclear arsenal, and strict civilian control of nuclear weapons use (Cunnigham, 2023). Despite general western skepticism of the NFU policy, most analysis concluded that China's nuclear forces existed to counter adversarial efforts to blackmail China with nuclear weapons in a traditional conflict (Cunnigham, 2023). Department of Defense planners are more concerned with China's dramatic expansion as opposed to Russian nuclear activities (Pifer, 2025). This significant expansion

changes its strategic capabilities. China now has an improved ability to retaliate following a nuclear attack (Cunnigham, 2023). Although it goes against long-standing policy, China also now has the option to threaten nuclear first use as coercive leverage in traditional conflicts (Cunnigham, 2023). This option undermines previous thought from western analysts that Chinese leaders would only use nuclear weapons in moments of desperation (Cunnigham, 2023). Instead, analysts and leaders face a new reality: China has greater agency and capacity to manipulate than ever before.

The factors driving China's modernization of its nuclear program are currently unknown and speculative (Cunnigham, 2023). Many Chinese nuclear policy experts did not anticipate the recent buildup and still struggle to understand the complete rationale (Zhao, 2024). Prior to the build-up, many experts argued that the Chinese nuclear deterrent remained credible and that only modest modernization was necessary to counter U.S. technological developments (Zhao, 2024). However, one potential driver is developments in U.S. capabilities (Cunnigham, 2023). In recent years, U.S. nuclear weapons have become more accurate (Zhao, 2024). Additionally, withdrawing from the Intermediate-Range Nuclear Forces (INF) Treaty in 2019 signaled an interest in deploying land-based missiles near China (Zhao, 2024). However, Chinese reactions have historically been less drastic in response to U.S. changes. Another possibility is a pursuit of a stronger nuclear field to enable non-nuclear escalation of conflict (Cunnigham, 2023).

The New START Treaty

The New Strategic Arms Reduction Treaty (New START) is built upon the original START treaties between the United States and the Soviet Union signed in 1991 and entered into force in 1994 (Center for Arms Control and Non-Proliferation, 2022). START I marked the first significant reduction in the U.S. and Soviet Union stockpiles. START I introduced limits for the number of deployed ICBMS (capped at 1,600) and the number of nuclear warheads on ICBMS, sea-launched ballistic missiles (SLBMs), and heavy bombers (at 6,000 total) (Center for Arms Control and Non-Proliferation, 2022). It introduced a ban on constructing new types of heavy ICBMS. START I expired in 2009. The New START treaty was signed in 2010 and entered into force in 2011 (Arms Control Association, 2024). It continued the process of reducing U.S. and Russian nuclear arsenals and was extended until 2026. Limits for nuclear warheads on ICBMS, SLBMs, and heavy bombers were set at 1,550 total, a 74 percent reduction from START I (Arms Control Association, 2024).

The Trump administration pushed for trilateral nuclear arms control conversations between the United States, Russia, and China in order to determine the future of the New START treaty (Arms Control Association, 2019). Some experts argue that a trilateral treaty is implausible and that waiting to act for the hope of China's participation would result in a loss of benefits from New START. In China's 2010 white paper on national security, it is clearly outlined that China believed the primary responsibility for nuclear disarmament rests on the shoulders of the United States and Russia (Arms Control Association, 2019). When the nations with the two largest nuclear arsenals take legally binding and irreversible action towards nuclear arsenal reduction, other NWS like China

intend to join in on other multilateral nuclear disarmament agreements (Arms Control Association, 2019).

Under New START rules, warheads are accountable only if they are deployed on long-range missiles, bombers, and submarines (Arms Control Association, 2019). China would be considered to have zero warheads deployed on long-range missiles.

As recently as August of 2025, the Chinese Foreign Ministry commented that it was unrealistic and unreasonable to expect China to participate in trilateral nuclear disarmament conversations with the United States and Russia (CBS, 2025). The spokesperson reiterated that because Russia and the United States possess the largest nuclear arsenals, combining nearly 90% of the world's nuclear weapons, that the primary responsibility for disarmament should rest on their shoulders (CBS, 2025). China favors disarmament in principle, but is currently unwilling to join invitations for nuclear arsenal reduction conversations.

Potential New Cold War

The last instance of an intense peer rivalry for the United States was during the Cold War with the Soviet Union (Kim et al., 2023). The U.S. guiding policy at the time was to check Soviet expansionism and Communism. There were two different economic worldviews, as the Soviets viewed capitalism as a direct threat to their socialist system. Moscow funded various left-wing revolutionary movements and the United States engaged in counter-movements and proxy battles resulting in destabilization of many regions globally. China's global position is not comparable to the Soviet Union (Kim et al., 2023). The U.S. and Chinese economies are increasingly intertwined after the post-Cold War era. Beijing has also taken a different approach than Moscow, as they do not seek to impose their political model on other nations (Kim et al., 2023). There is no existential threat posed by China to the U.S. and its way of life. China's continued growth is contingent on engagement with the outside world (Kim et al., 2023).

China seeks military superiority in its region (South and East China Seas and Taiwan) which poses a threat to the United States' alliance commitments (Kim et al., 2023). The relative strength of alliances in Sino-American competition is dependent on the region of the ally, the level of American commitment, and the relative level of shared interests (Bandow et al., 2025). Allies that are in the Indo-Pacific region aid more in deterring China as opposed to other regions (Bandow et al., 2025). Indo-Pacific nations can contribute greater to frontline defense through their own military power as well as hosting American military forces (Bandow et al., 2025). A threat posed to alliances that are strategically critical for maintaining deterrence will be taken seriously by U.S. officials.

While not identical to the previous Cold War conditions, the U.S.-China relationship meets the basic geopolitical definition of a cold war (Bandow et al., 2025). As defined by Bandow and colleagues (2025), a cold war is a "a state of political hostility between countries that unfolds across

all domains short of open, direct warfare." The particular challenge in this cold war is the inability to decouple from China, as doing so would come with a great economic cost. Not only is China a major trading partner with the United States, but also with 120 other nations, many of which are U.S. allies (Bandow et al., 2025). It is unlikely that the majority of these allies would fully join the United States against China. Chinese participation is necessary for tackling challenges like climate change and renewable energy transitions (Bandow et al., 2025). As a path forward, the U.S. and China must further sovereignty and non-aggression principles that are set forth in the UN Charter (Bandow et al., 2025).

A major barrier to managing crisis instability is who is responsible for causing the crisis liability (Kim et al., 2023). China's perception of hostile U.S. political intentions is a main contributor to disagreements (Kim et al., 2023). At the end of the first Trump administration, China reportedly became concerned that U.S. desperation to destabilize China would lead to a surprise military attack in 2020 (Kim et al., 2023). Many top Chinese military officials are of the opinion that China must leverage its nuclear power to contain any U.S. "war impulses against China" (Kim et al., 2023). This conviction that the U.S. is purposefully creating the crisis instability pushed China towards the belief that military risks are necessary (Kim et al., 2023). Ultimately, perceived political hostility will enhance "internal self-righteous thinking," leading decisionmakers to prioritize capability development over reduction measures (Kim et al., 2023). In managing a cold war, perception of political intentions will mean the difference between straightforward reduction measures that align with NPT commitments and escalation through capability development.

Conclusions

The United States and China have a complex nuclear weapons relationship that dates to the 1950s. It has consistently been interwoven with how both nations view the world and the ways in which they interact with other members of the international community. In recent years, the inventory of the respective operational arsenals have diverged. China appears to be growing its arsenal at a rapid pace, the United States has its smallest arsenal since the 1960s. While this divergence indicates nuclear policies still may be evolving, lack of ratification of multiple nuclear weapons treaties like the Comprehensive Test Ban Treaty (CTBT) and the Treaty on the Prohibition of Nuclear Weapons (TPNW) indicate that some underlying principles remain the same. Motivations for China's growing arsenal have been increasingly debated but remain largely unverifiable. U.S. technological developments, despite the lack of arsenal growth, could account for some of the Chinese concern and subsequent push to increase their arsenal. Aggressive U.S. political strategy is also noteworthy and could play a role in China's motivations for nuclear weapons growth.

China and the United States have different definitions for many facets of security, stability, and their positions NWS. Varying understandings of security paradigms can also contribute to a mismatch in priorities and strategy. There exists a need for mutual vulnerability on the part of both nations.

On the part of China, this need could require a greater willingness to engage in New START treaty discussions. Despite touting strong principles around disarmament, the reluctance to engage does not match these ideals.

The true future of the U.S.-China nuclear weapons relationship will rest in managing the ongoing cold war. The reasoning behind China's rapid modernization of its nuclear program needs to be further investigated. The continued growth of the Chinese arsenal will likely continue to be closely monitored. The current Trump administration needs to remain aware of how aggressive strategies are being perceived by Chinese leadership. Escalated competition between the U.S. and China will only lead to unbearable costs – particularly economic ones.

References

Arms Control Association. (2019, August 23). China's stance on nuclear arms control and New START. https://www.armscontrol.org/blog/2019-08-23/chinas-stance-nuclear-arms-control-new-start

Arms Control Association. (2024, December). New START at a glance. https://www.armscontrol.org/factsheets/new-start-glance

Arms Control Association. (2025, January). Nuclear weapons: Who has what at a glance. https://www.armscontrol.org/factsheets/nuclear-weapons-who-has-what-glance

Bandow, D., Blankenship, B., Solis, M., & Wright, T. (2025, May 15). Are America's alliances a source of strength or a burden as it competes with China? Brookings. https://www.brookings.edu/articles/are-americas-alliances-a-source-of-strength-or-a-burden-as-it-competes-with-china/

Bin, L., & Hongzhen N. (2009). China and nuclear arms control. Union of Concerned Scientists.

Bin, L. (2015). Chinese thinking on nuclear weapons. Arms Control Association. https://www.armscontrol.org/act/2015-12/features/chinese-thinking-nuclear-weapons

Center for Arms Control and Non-Proliferation. (2022, November 16). Strategic Arms Reduction Treaty (START I). https://armscontrolcenter.org/strategic-arms-reduction-treaty-start-i/

CBS. (2025, August 27). China rules out participating in denuclearization talks with U.S. and Russia, as suggested by Trump. https://www.cbsnews.com/news/china-rejects-trump-invite-nuclear-weapons-denuclearization-talks-us-russia/

China Power Team. (2019, December 10). How is China modernizing its nuclear forces? Center for Strategic and International Studies. https://chinapower.csis.org/china-nuclear-weapons/

Council on Foreign Relations (2025). 1949-2025, U.S.-China relations. https://www.cfr.org/timeline/us-china-relations

Cunnigham, F.S. (2023). The unknowns about China's nuclear modernization program. Arms Con-

trol Today, 53 (5), 6-14.

Davenport, K. (2019). Negotiating the NPT. In, The nuclear non-proliferation treaty (pp. 2.1-2.36) . Morgan & Claypool. 10.1088/978-1-68174-925-9

Department of Defense. (2024). Annual report to Congress: Military and security developments involving the People's Republic of China 2024. https://media.defense.gov/2024/Dec/18/2003615520/-1/-1/0/MILITARY-AND-SECURITY-DEVELOPMENTS-INVOLVING-THE-PEOPLES-REPUBLIC-OF-CHINA-2024.PDF

Department of Energy. (2025). The U.S. nuclear weapons stockpile. https://www.energy.gov/nnsa/us-nuclear-weapons-stockpile

Goldschmidt, B. (1980). Le complexe atomique. Editions Fayard.

Hautecouverture, B. (2025, April 4). Chinese no-first-use: A strategic signaling device, diplomatic tool, and dogmatic reality. Fondation pour la recherche stratégique. https://www.frstrategie.org/en/publications/notes/chinese-no-first-use-strategic-signaling-device-diplomatic-tool-and-dogmatic-reality-2025

International Campaign to Abolish Nuclear Weapons. (2021, April 7). Five ways the UK is undermining the NPT. https://www.icanw.org/five_ways_the_uk_is_undermining_the_npt

Information Office of the State Council of the People's Republic of China (2006, December 29). China's National Defense in 2006. https://nuke.fas.org/guide/china/doctrine/wp2006.html

Kim, P.M., Turpin, M., Nye Jr., J.S., Weiss, J.C., Jo, E.A., Hass, R., & Kimball, E. (2023, September 1). Should the US pursue a new Cold War with China? Brookings. https://www.brookings.edu/articles/should-the-us-pursue-a-new-cold-war-with-china/

Kristensen, H.M., Korda, M., Johns, E., & Knight, M. (2025). Chinese nuclear weapons, 2025. Bulletin of Atomic Scientists, 81 (2), 135-160. https://doi.org/10.1080/00963402.2025.2467011

Ministry of Foreign Affairs People's Republic of China. (2025, August 29). China's non-proliferation policy and measures. https://www.mfa.gov.cn/eng/wjb/zzjg_663340/jks_665232/kjlc_665236/fkswt_665240/202406/t20240606_11405135.html

Nance, M. (2018). Active measures. In, The plot to destroy democracy: How Putin and his spies are undermining America and dismantling the west (pp. 95-120) . Hachette Books.

Nuclear Threat Initiative. (2025). United States. https://www.nti.org/countries/united-states/#:~:text=The%20U.S.%20has%20one%20of%20the%20world's,bases%20in%20Montana%2C%20North%20Dakota%2C%20and%20Wyoming

Office of the Historian. (2025). The Taiwan Strait Crises: 1954-55 and 1958. https://history.state.gov/milestones/1953-1960/taiwan-strait-crises

Pifer, S. (2025, October 2). Responding to Putin's proposal to extend New START. Freeman Spogli Institute for International Studies. https://fsi.stanford.edu/news/responding-putins-proposal-extend-new-start

Popp, R. (2016). The long road to the NPT: From superpower collusion to global compromise (L. Horovitz, A. Wenger, Eds.). Routledge. 10.4324/9781315536576

Rodgers, J., & Williams, H. (2025, September 4). Parading China's nuclear arsenal out of the shadows. Center for Strategic and International Studies. https://www.csis.org/analysis/parading-chinas-nuclear-arsenal-out-shadows#:~:text=For%20the%20past%20five%20years,1%2C000%20nuclear%20weapons%20by%202030.

Talmadge, C. (2019, September). The U.S.-China nuclear relationship: Why competition is likely to intensify. Brookings. https://www.brookings.edu/articles/china-and-nuclear-weapons/

Treaty on the Prohibition of Nuclear Weapons, July 7, 2017, https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVI-9&chapter=26

UN Meetings Coverage and Press Releases. (2023, October 17). Existence of nuclear weapons creates temptation, risk of use, First Committee hears as it unpacks assumptions about complex path to peace. https://press.un.org/en/2023/gadis3720.doc.htm

Zhang, H. (2012, July 15). China's nuclear weapons modernization: Intentions, drivers, and trends. Harvard Kennedy School Belfer Center for Science and International Affairs. https://www.belfercenter.org/publication/chinas-nuclear-weapons-modernization-intentions-drivers-and-trends

Zhao, T. (2024, July 17). Political drivers of China's changing nuclear policy: Implications for U.S.-China nuclear relations and international security. Carnegie Endowment for International Peace. https://carnegieendowment.org/research/2024/07/china-nuclear-buildup-political-drivers-united-states-relationship-international-security?lang=en

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Nuclear Energy, Foreign Policy, and Energy Security

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Nuclear energy is experiencing unprecedented global interest, driven by its potential contributions to climate change mitigation and energy security. This paper examines the role of nuclear energy in providing energy security for countries that have either an established nuclear energy program or an emerging program, and analyzes how these considerations shape the foreign policies of the United States, Russia, and China. Russia and China have integrated nuclear energy technology and fuel exports into their foreign policies as tools of geopolitical influence. In contrast, the United States – despite its early leadership – has lacked a cohesive export strategy and allowed its industry to stagnate. Countries new to nuclear energy are increasingly seeking partnerships to introduce nuclear energy into their energy systems. Without United States participation, Russia and China are positioned to fill this demand, potentially reshaping global geopolitics. Comprehensive reform of the Nuclear Regulatory Commission and revised federal policy are essential to revitalize the United States nuclear industry and restore its role in the global market.

Keywords: Nuclear energy, foreign policy, energy security, geopolitics, United States, Russia, China

Introduction

The global energy landscape is changing. New technologies such as renewable energy have been introduced to combat climate change, while geopolitical tensions are prompting countries to reduce reliance on unstable energy supplies. At the same time, developing economies are seeking secure energy production technologies to support growth and improve quality of life. Two key forces shaping the global energy landscape are climate change and energy security — meaning the stability and reliability of energy systems.

Nuclear energy is an energy production technology that can help mitigate climate change and im-

prove energy security. Nuclear power has been deployed for commercial energy production since the 1950s. It is not a new energy technology like modern solar or wind, but it has experienced renewed interest because of shifts in the global energy landscape. It is recognized as a clean, secure energy source that can help mitigate climate change while providing reliable energy for both economic growth and the everyday needs of societies. As such, countries with and without civil nuclear energy experience are investigating its potential for their energy systems.

Like many other energy supplies and technologies, nuclear energy infrastructure and associated fuel exports can be leveraged by world powers as instruments of foreign policy. Two major world powers – Russia and China – have strategically included nuclear energy in their foreign policies. Another major world power – the United States – included nuclear energy in its foreign policy in the industry's early decades, but has failed to systematically incorporate it in modern foreign policy. This lack of direction disadvantages the United States relative to the other major world powers. Despite this, the United States remains an international standard-bearer for nuclear safety, regulation, and oversight practices. To retain this ability to ensure robust international enforcement of the Nuclear Non-Proliferation Treaty, the United States must participate in the global market. Comprehensive policy and regulatory reform are needed to enable the United States commercial nuclear industry to compete globally. Given that realignment of national leadership within the international nuclear energy industry has global consequences, the world stands to benefit from the United States' return to the global nuclear energy market.

Nuclear Energy in Context

Commercial nuclear power began in the United States and Russia in the 1950s. The industries grew quickly, and in 2023 nuclear energy represented 18.6% of electricity production in the United States (U.S. Energy Information Administration, 2024). Nuclear reactor construction in the United States slowed dramatically after the Three Mile Island accident in 1979 and the Chernobyl disaster in 1986, with few new reactors approved for construction after 1977 (World Nuclear Association, 2025b; Teräväinen et al., 2011). France, however, expanded its nuclear power program from 4% of its electricity production in 1970 to 78% in 2006 (Teräväinen et al., 2011).

Following the Fukushima reactor accident in 2011, it seemed nuclear energy would experience additional global decline. Indeed, Germany resolved to permanently close all its nuclear reactors and Japan quickly shut down all nuclear reactors. Both countries turned to fossil fuels to replace the power produced by the closed nuclear power plants. However, interest in nuclear energy is growing in developing economies, driven by the promise of low-carbon electricity and improved energy security (Holgate & Saha, 2018). At the same time, countries with established nuclear industries are re-evaluating nuclear energy's role in their energy systems as concerns about climate change and energy reliability intensify.

In 2023, the United States saw its first newly approved reactor since the late 1970s begin operation at Plant Vogtle in Georgia (U.S. Department of Energy, 2023b), a milestone that both highlights the country's long stagnation and signals its tentative re-entry into nuclear energy development. Similar trends are visible elsewhere: Japan, for example, has restarted reactors after years of shutdowns (World Nuclear Association, 2025b), while other nations are exploring new projects. Together, these developments illustrate a global trend of re-invigorating nuclear power to confront climate change and energy security challenges.

This renewed interest is reflected in international projections and agreements. In 2013, the International Atomic Energy Agency (IAEA) projected that global nuclear power plant capacity could increase by 100 to 768 GW in 2050, up from about 373 GW in 2012 (IAEA, 2013). In the 2015 Paris Agreement, countries committed to reducing greenhouse gas emissions, and ten countries – representing 40% of global energy demand – included nuclear energy in their climate pledges (Holgate & Saha, 2018). At the United Nations World Climate Action Summit of the 28th Conference of the Parties (COP28), attending countries recognized nuclear energy's value as a source of sizeable baseload capacity, comparable to fossil fuels but without carbon emissions, while also highlighting its energy security benefits. Nuclear energy was identified as a key tool for limiting warming to 1.5°C, with analysis showing capacity must triple by 2050 to reach net-zero emissions. At COP28, twenty countries signed an agreement to triple nuclear energy production by 2050 (U.S. Department of Energy, 2023a). Developing countries, expected to be disproportionately affected by climate change, are also turning to nuclear energy to support economic growth and expand reliable energy access (Holgate & Saha, 2018). Taken as a whole, these international commitments signal nuclear energy's repositioning as a central tool for climate mitigation and energy security.

Nuclear Power and Energy Security

Energy security is a cornerstone of modern energy policy, reflecting an energy system's resilience to disturbances and its ability to recover without major interruptions to supply or price (Jun et al., 2009; Kosai & Unesaki, 2024). Strong energy security minimizes disruptions for consumers and critical systems, ensuring reliable electricity when it is needed most. Energy security can be described by multiple interrelated factors that contribute to the resilience of an energy system. One factor of energy security is the number of energy suppliers because multiple supply paths minimize disruption when interruptions occur. Another factor is the diversity of energy sources. Relying on multiple forms of electricity generation – such as natural gas, nuclear, and solar – protects against failures that affect a single type. For example, a global shortage of natural gas would disrupt production everywhere, but diverse sources minimize disruption.

Energy security is also strengthened by increased domestic production and the ability to stockpile fuel. Domestic production gives countries greater control over their energy production and reduces the influence of international tensions on supply. Stockpiling further mitigates the impact of global

disruptions by providing time to reestablish supply paths before reserves are depleted (Ćwiek-Karpowicz, 2012). Energy security can be assessed through several indicators, including the share of the total supply provided by each energy type, the proportion of energy supply that is imported and the diversity of those imports, and the ratio of energy production to a country's population and gross domestic product (GDP). Beyond these structural indicators, a societal indicator that is more important to nuclear energy than other energy sources is public opinion. Negative perception can limit utilization and expansion of nuclear energy, making it an important element of nuclear energy security (Kosai & Unesaki, 2020).

These factors and measures illustrate the importance of energy security in ensuring societal and economic stability and shaping geopolitical dynamics. Reliable energy supplies are essential for economic stability, societal wellbeing, and supporting economic and social development in emerging regions (Committee for Economic Development, 1976; Holgate & Saha, 2018; Jun et al., 2009). As energy demands increase globally with rapid economic development, energy security is becoming a pressing challenge in rapidly growing regions. Geopolitical dynamics strongly influence energy security, as shifting alliances and international tensions can undermine energy security (Jun et al., 2009).

A key benefit of nuclear energy for energy security is the high-energy density of the fuel. As a result, nuclear power plants require relatively infrequent refueling when compared to other baseload energy options such as coal, oil, and natural gas. The high-energy density enables nuclear fuel to be stockpiled more extensively than fossil fuels and thus reduces its susceptibility to market price fluctuations, supply disruptions, or global geopolitical issues (Hebda & Mišík, 2024). This combination of energy density and stockpiling capability is a distinct contribution of nuclear energy to energy security.

However, nuclear energy also introduces unique risks, particularly the potential proliferation of weapons-grade material. Implementation of proliferation-resistant technologies and robust surveillance systems to monitor nuclear material globally can mitigate the risk of theft or sabotage (Committee for Economic Development, 1976). Importantly, the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), which has been in effect since 1970, requires non-nuclear-weapons states that are party to the treaty to file reports and allow International Atomic Energy Agency (IAEA) inspectors into facilities to validate materials are not being used for weapons purposes. Additionally, some small modular reactor (SMR) technologies have improved proliferation resistance and can thus mitigate proliferation concerns in countries with new nuclear energy programs (Holgate & Saha, 2018). These measures demonstrate that while nuclear energy has unique risks, strong international safeguards systems exist to mitigate them.

Nuclear energy is a valuable part of an energy system because it provides baseload energy supply without carbon emissions – offering an alternative to emissions-heavy fossil fuels. For example, following the Fukushima Daiichi reactor accident, Japan shuttered many nuclear power plants and turned to liquefied natural gas (LNG) and oil imports to meet its energy production needs. In the

four years following, carbon dioxide emissions and consumers' energy prices increased. Germany made a similar decision to close all of its nuclear plants. It aimed to replace nuclear plants with renewable energy sources, but ultimately increased reliance on coal to meet the energy demand. This decision increased Germany's carbon dioxide emissions and energy prices (Holgate & Saha, 2018). These cases demonstrate that removing nuclear from an energy mix can undermine climate goals and energy security by increasing reliance on fossil fuels.

Enhancing energy security inevitably involves costs. However, different energy sources have different costs of energy security, reflecting their distinct risks. For example, fossil fuels generally have greater probabilities of supply disruption compared to nuclear energy, and thus impose a larger cost to mitigate this risk. A study of South Korea's energy system found that nuclear energy had the least cost of energy security, reflecting the small probability of disruption and limited price volatility (Jun et al., 2009). This study indicates that while all energy sources have energy security costs, nuclear energy's are comparatively less. Energy security and climate change are central concerns in energy policy and have driven renewed interest in the potential contribution of nuclear energy to mitigate these concerns. For these reasons and others, international interest – from countries with prior nuclear energy experience to countries without any experience – is predicted to grow in coming decades. As a result, nuclear energy is likely to play an increasingly important role in global energy strategies.

Global Nuclear Programs: Interests and Trajectories

International interest in new nuclear power projects has grown in recent years, spanning both countries with experience in nuclear energy and countries that are new to the technology. The World Nuclear Association estimates more than 30 nations operate nuclear power plants and at least 20 are considering initiating nuclear power programs (Burns, 2019). The renewed interest can be attributed in part to global issues such as the 2008 economic crisis, the 2015-2016 oil price collapse, and the 2022 invasion of Ukraine (Burns, 2019; Hebda & Mišík, 2024). Several countries including the United States, Russia, China, France, Canada, and South Korea have established nuclear energy technology. Countries and regions in various stages of pursuing new nuclear energy projects include Poland, Hungary, Czechia, Slovakia, Finland, Turkey, the United Kingdom, and West African countries (Birikorang et al., 2026; Hebda & Mišík, 2024; Teräväinen et al., 2011).

Energy security is a common driver of nuclear energy expansion, alongside decarbonization, economic development, and cost stability amid volatile fossil fuel markets (Committee for Economic Development, 1976; Holgate & Saha, 2018; Jun et al., 2009). These drivers have fueled renewed global momentum behind nuclear energy projects. The Visegrad Countries, a collection of former Soviet states encompassing Poland, Hungary, Czechia, and Slovakia, have both extensive nuclear energy experience and interest in expanding the industry. Nuclear energy is an important energy source in three of the countries, providing 44% of Hungary's electricity, 60% of Slovakia's, and 37% of Czechia's. Poland does not have its own nuclear power plants and has historically relied heav-

ily on domestic coal production to power its energy grid. Energy security is an important reason the four countries are interested in expanding their nuclear power capacity. In their view, nuclear energy is viewed as a stable baseload supply that can be generated domestically, with only infrequent fuel imports. Russia's invasion of Ukraine in 2022, which led to the European Union (EU) imposing economic sanctions that discouraged Russian fuel imports, further encouraged Poland and Czechia to minimize dependence on Russian fuel supplies. Poland simultaneously aims to reduce its carbon emissions by phasing out its coal power plants in favor of nuclear power plants (Hebda & Mišík, 2024). In addition to energy security concerns, Czechia is facing an aging fleet of nuclear and coal power plants requiring replacement (Betkowski, 2022; Ćwiek-Karpowicz, 2012; Hebda & Mišík, 2024) and has plans to work with Korea Hydro and Nuclear Power (KHNP) for new reactors (World Nuclear News, 2024). Hungary is also pursuing new nuclear reactors to support a stable and independent energy supply, but unlike its neighbors, is working with the Russian state-owned nuclear energy company Rosatom (Hebda & Mišík, 2024). Slovakia has new reactors under construction and is evaluating additional reactors with French and U.S. nuclear companies (American Nuclear Society, 2024).

France is one of a handful of countries with established nuclear energy programs. Following the oil crisis of 1973, the French government pursued a coordinated effort to expand the country's nuclear energy production. The government pursued this effort to minimize the impacts of such crises in the future and achieve the country's energy security goals (Teräväinen et al., 2011). At 78% of total electricity production, France has the largest share of nuclear energy in its energy mix of any country. With an aging fleet, France is evaluating the future nuclear energy in its energy mix (Hebda & Mišík, 2024).

Prior to the Chernobyl and Fukushima reactor accidents, Japan and Germany both operated nuclear power plants for electricity production. Following these incidents, Germany resolved to close all of its nuclear power plants and Japan significantly scaled back nuclear energy production (Ćwiek-Karpowicz, 2012). As nuclear plants closed, both Germany and Japan increased fossil fuel imports and consumption (Holgate & Saha, 2018; Ćwiek-Karpowicz, 2012). Germany became increasingly reliant on Russian imports of crude oil and natural gas, as well as domestic coal production (Ćwiek-Karpowicz, 2012). However, Japan did not commit to completely phasing out nuclear energy following the Fukushima incident and has instead begun restarting shuttered reactors and initiated construction of new reactors (World Nuclear Association, 2025a; Hebda & Mišík, 2024). The contrasting trajectories of Germany and Japan demonstrate how countries with similar concerns have pursued different policies, with Germany remaining committed to its nuclear energy phase-out while Japan shifts course to a new era of nuclear energy.

In 2015, the West African countries of Burkina Faso, Benin, Mali, Ghana, Niger, Senegal, and Nigeria formed a coalition to evaluate the deployment of nuclear energy in the region. These countries are interested in nuclear energy to power their growing economies because it is reliable, produces energy without carbon emissions, and provides energy security. The group evaluated the ability of several

modern (Generation IV) reactor designs to be operated safely in a region with weaker regulation and oversight systems, less advanced physical infrastructure, and limited nuclear energy expertise. SMRs produce less power than traditional large reactors, making them better suited to the smaller energy demands of developing countries. Additionally, some SMR designs in development have improved safeguards against proliferation and sabotage compared with established designs (Birikorang et al., 2026). For West Africa, SMRs represent a opportunity for secure, low-carbon energy tailored to regional needs and governance capabilities.

A number of countries and regions – countries with established commercial nuclear energy and countries with no nuclear energy experience – have demonstrated renewed interest nuclear energy to meet their energy goals. Among countries with operational nuclear power plants, a minority have the capability to manage the full nuclear life cycle domestically, from design to decommissioning. This lack of capability provides an opportunity for countries with this capability to export nuclear reactors, nuclear power plant components, and nuclear fuel, representing both an economic boon and an opportunity for geopolitical influence, particularly for major world powers.

Comparative Nuclear Energy Policies: United States, Russia, and China

World powers leverage economic influence to a greater extent than military might to gain influence over other countries or political organizations. Nuclear energy is one of the levers available to the major world powers with nuclear energy capability – the United States, Russia, and China – to grow ties with other countries (Jun et al., 2009). While other countries such as France, South Korea, and Canada have developed nuclear reactor technology, reactor exports have not historically been a significant element of their foreign policies as it has been for the three world powers. Exporting countries can establish partnerships to provide support and technological expertise, and export reactors to countries with developing programs. The renewed global interest in nuclear power provides an opportunity for the United States, Russia, and China to establish partnerships with nations seeking to invest in nuclear energy, thereby strengthening economic and geopolitical ties (Burns, 2019).

Energy exports are an important lever Russia uses to implement its foreign policy. The country utilizes natural gas supply dependencies as geopolitical leverage over importing countries. For example, in 2006, Russia cut off natural gas supplies to Ukraine after its presidential election. Russia halted supplies to the country again in 2009 (Holgate & Saha, 2018; Ćwiek-Karpowicz, 2012). Russia's invasion of Ukraine in 2022 further destabilized natural gas supplies in the European Union partly because of economic sanctions imposed on Russia. The European Union recognizes the threat to energy security posed by the reliance on Russia for fuel supplies and aims to reduce reliance. However, similar to fossil fuel resources, nuclear energy technology provided by Russia's state-owned nuclear energy corporation, Rosatom, is another method for Russia to exert its influence globally

(Holgate & Saha, 2018; Hebda & Mišík, 2024). Russia has nuclear energy agreements and contracts with several countries (Figure 1), and these agreements are an element of Russia's foreign policy, with goals to reshape the European Union's energy dependencies and alter the global balance of power. Agreements with Rosatom may require an importing country to source fuel for the nuclear power plants from Russia for a specified term or rely on Russia for operation of the power plants.

Hungary provides an example of the interrelation between nuclear energy technology exports and Russian influence. Russia has provided the technology for and helped fund new nuclear power plants in Hungary. Russia's support for Hungary's new reactors has strengthened ties with Prime Minister Viktor Orban, who has become a proponent within the European Union of strengthening relations with Russia (Holgate & Saha, 2018). Russia has partnerships in varying stages between broad agreements and formalized contracts with countries in Europe, Asia, Oceania, Africa, and South America, which extends Russian influence around the world. Russia's use of nuclear energy exports mirrors its broader energy strategy of leveraging supply dependencies for geopolitical influence.

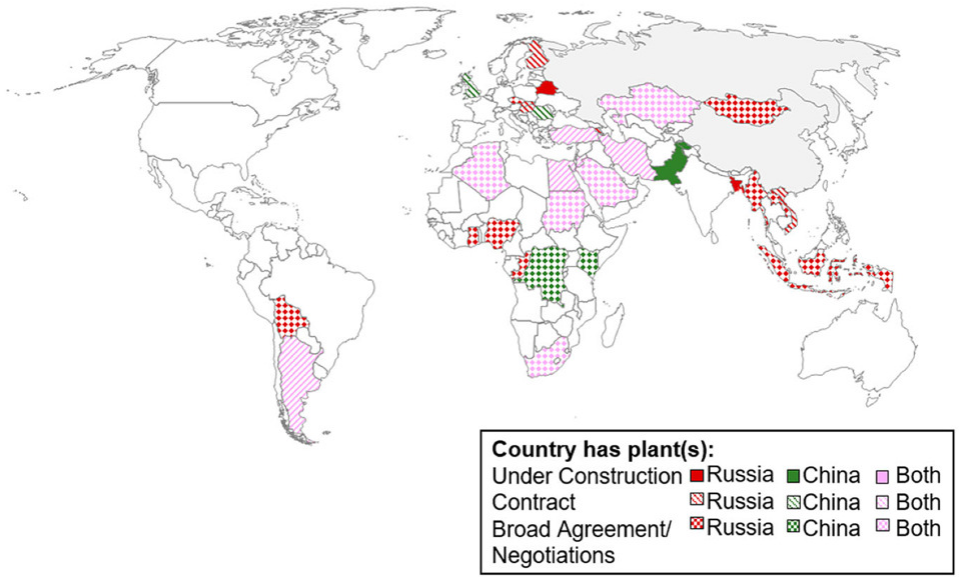


Figure 1: Geographic Distribution of Chinese and Russian Commercial Nuclear Exports.[1]

Although China's nuclear energy program developed more recently than those of Russia and the United States, it has significant potential. China has an established nuclear industry with technology deployed domestically and, like Russia, export agreements with other countries (Figure 1). China's

[1]Reprinted from "America Must Lead on Nuclear Energy to Maintain National Security," by L. S. H. Holgate & S. Saha, 2018, The Washington Quarterly, 41(2), p. 14. https://doi.org/10.1080/0163660X.2018.1484223. Copyright 2018 by the Center for Strategic and International Studies.

global development strategy, the Belt and Road Initiative, incorporates nuclear energy exports to strengthen ties with partner countries, particularly along the corridor from China through the Middle East to Europe. To date, China has exported nuclear reactors only to Pakistan, but there are 41 countries within the borders of the Belt and Road Initiative that have expressed interest in nuclear power. China has established relations with these countries, increasing the likelihood they turn to China for technology and help developing their nuclear energy programs. China extends loans and aid to make its nuclear exports more accessible to partner countries. China emphasizes research and development, attracting foreign firms – such as those in the United States – that face limits on testing designs domestically. Like Russia, China's exports have increased in recent years (Figure 2), and the country can be expected to use nuclear technology exports to exert geopolitical influence (Holgate & Saha, 2018). Nuclear energy exports have become a central element of China's Belt and Road strategy, positioning it as a potential competitor to Russia in global nuclear energy influence.

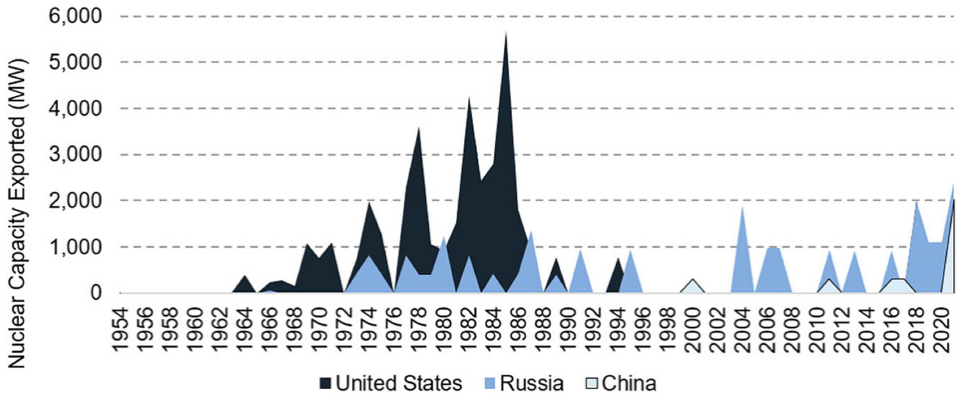


Figure 2: Global Nuclear Exports by Supplying Country (Russia, China, and the United States).[2]

The United States spearheaded the development of commercial nuclear energy in its early years, positioning itself as the industry's initial leader and, following President Eisenhower's "Atoms for Peace" speech in 1953, nuclear reactor exports became an important component of the United States' foreign policy. These exports simultaneously fostered long-term international relations and allowed the United States to establish international standards for safety and proliferation risk mitigation. Even as reactor exports waned (Figure 2), the United States continued to participate through nuclear cooperation agreements and fuel exports (Committee for Economic Development, 1976; World Nuclear Association, 2025b). By 2018, United States nuclear reactors represented only 13% of new construction globally, including domestic projects. However, the United States retains a distinct advantage that is attractive to potential customers – nearly seven decades of safe operation of its

[2]Reprinted from "America Must Lead on Nuclear Energy to Maintain National Security," by L. S. H. Holgate & S. Saha, 2018, The Washington Quarterly, 41(2), p. 12. https://doi.org/10.1080/0163660X.2018.1484223. Copyright 2018 by the Center for Strategic and International Studies.

domestic nuclear reactor fleet. The United States maintains a reputation for excellence in nuclear energy technology, safe operation, safeguards against bad actors, and robust regulation. This reputation can help the United States reenter the global market as a serious challenger to Russian and Chinese nuclear energy technology (Holgate & Saha, 2018). However, the United States' credibility depends on continued domestic deployment, which builds international trust in United States technology.

In addition to a slow pace of domestic nuclear reactor deployment, inconsistent federal funding support for research and development negatively affects the industry's competitive advantage over international players (World Nuclear Association, 2025b). United States nuclear technology companies and scientists have sometimes turned to Chinese funding, introducing a risk of intellectual property transfer. Partnerships with Chinese firms can erode United States firms' competitive advantage by providing China with access to United States firms' intellectual property and enabling exports reactor designs based on that technology (Holgate & Saha, 2018). Unlike Russia and China, the United States has not exported nuclear reactors since the 1990s (Figure 2), and reactor exports are no longer a central element of its foreign policy, even as cooperation agreements and fuel exports continue (World Nuclear Association, 2025b). This stance is in significant contrast to Russia and China's growth, highlighting that the United States effectively sidelined nuclear energy progress for decades. Recent policy changes – particularly the Inflation Reduction Act's tax credits for the existing fleet, research and development credits, and funding for new fuel research (Inflation Reduction Act of 2022, 2022) – signal renewed support. New Executive Orders in 2025 further highlight renewed federal interest in expanding United States nuclear energy.

The United States' lack of participation in the global market, which declined following the Chernobyl reactor accident (Figure 2), will not prevent expansion of nuclear energy globally. The International Atomic Energy Agency (IAEA) predicts that global nuclear energy demand will increase by 100 to 768 Gigawatts by 2050 when compared to 2012 (IAEA, 2013), and this demand will be filled by the United States' competitors if its technology is not an option. Russia and China are positioning to meet this demand while the United States is not (though that may have started to change in recent years). Russia and China's positioning represents a serious threat to the United States' national security interests if Russia and China remain unchallenged. Historically, the United States has used its global leadership in the industry to influence safety, security, and nonproliferation standards. The United States must participate in the global market to maintain this standard-bearer position and maintain the robust regulatory standards of the Nuclear Non-Proliferation Treaty (NPT). Russia and China have comparatively weak security standards and poor safety records (Holgate & Saha, 2018). If the United States does not increase its engagement, the global market may lack a strong leader to uphold standards for safety and safeguards (Burns, 2019).

Additionally, nuclear energy deployment in developing countries is an example of soft power, whereby the United States can gain influence in these by providing aid as opposed to exerting force. Supporting developing economies by providing nuclear energy technology is an opportunity for the United

States to support economic advancement and thus improve its reputation in these countries (Holgate & Saha, 2018; Jun et al., 2009). By providing secure nuclear energy partnerships, the United States can help nations reduce dependence on external aid, strengthening economic stability, autonomy, and resilience. However, if the United States' does not capitalize on the renewed global interest in nuclear energy and the opportunities to reenter the market, its global influence may decline (Holgate & Saha, 2018). The policies of Russia, China, and the United States illustrate divergent approaches to nuclear energy in foreign policies. Russia and China have expanded exports as tools of geopolitical strategy, with the United States has been conspicuously absent. The renewed global interest in nuclear energy presents an opportunity for the United States to reenter the market as a key competitor to Russia and China.

Recommendations for Advancing Nuclear Energy and Energy Security

In a landscape of increasing global nuclear energy demand, the policies of major nuclear energy suppliers are increasingly relevant. The United States' nuclear energy industry has declined partly because of increasingly burdensome regulatory requirements and neglect in energy policy. Policy changes can help boost its domestic nuclear industry and propel it back to a position of global leadership (Holgate & Saha, 2018). Russia has demonstrated a policy of extensive government support of the state-owned nuclear energy company, viewing nuclear energy technology export as an essential component of its foreign policy. China's nuclear energy industry similarly enjoys significant government support, and nuclear energy technology export is an important component of its "Belt and Road Initiative" foreign policy. The United States, however, has no cohesive plan for nuclear energy technology exports as an important component of its foreign policy. In this global balance, Russia and China stand to benefit economically and geopolitically from nuclear reactor exports.

Comprehensive reform of the United States Nuclear Regulatory Commission (NRC) to streamline safety reviews and permitting without compromising safety would be a significant benefit for the industry. Since the beginning of the commercial nuclear energy industry in the United States, regulations have become increasingly complex, creating barriers to innovation and deployment. Comprehensive reform can simultaneously improve safety by clarifying requirements and streamline the permitting process to encourage domestic innovation and new reactor projects. A healthy domestic industry is a prerequisite for exporting nuclear reactors, as it improves global trust in the technology. Simplifying federal governance of export agreements to expedite the establishment of export agreements would also improve the ability of United States companies to compete with firms in other countries that are able to reach such agreements more quickly. Additionally, Russia and China offer financing to importing countries, making their offers more financially attractive. Comparable financing mechanisms from the United States government would enhance international competitiveness of United States nuclear reactor technology (Holgate & Saha, 2018). Notably, in June 2025, the World Bank ended its ban on financing for nuclear energy projects (World Nuclear

Association, 2024). The development offers importing countries an alternative financing avenue beyond reliance on Russia or China. Finally, expanded investment in research and construction could help is essential to revitalizing the United States nuclear industry and restoring global leadership.

Conclusions

Nuclear energy may be entering a renaissance period of increased technological advancement and historic deployment of new nuclear reactors precedented only by the early days of the industry. This growth can be attributed in part to mounting concerns about the impacts of climate change and a desire for energy security. Nuclear energy is gaining momentum in countries with established nuclear power programs, in countries that scaled back following the Three Mile Island, Chernobyl, or Fukushima incidents, and in countries new to nuclear power. The foreign policies of Russia and China include nuclear energy as a lever to gain influence in countries to which they export nuclear reactors. Conversely, the United States, historically an important part of the international market and influential in shaping regulatory and oversight standards, has been conspicuously absent from the global nuclear energy market. In the early days of the United States' nuclear energy industry, nuclear reactor exports served as a diplomatic tool to strengthen ties with other countries. Today, nuclear energy is an afterthought in the U.S.'s foreign policy. As global demand for nuclear energy grows, Russia and China are better positioned to meet that demand than the United States, which risks shifting global geopolitics in favor of Russia and China. The United States has an opportunity to capitalize on the need to mitigate climate change while improving quality of life in developing countries and upholding the rigorous safeguards and safety standards it helped establish decades ago. If the United States does not step up, countries such as Russia and China will fill the void and international regulatory rigor may decline. The United States nuclear industry requires support of the federal government via comprehensive policy and regulatory reform and financial support to be competitive on the global stage. United States participation would reshape global balance of power and provide countries with access to clean, reliable nuclear energy from a supplier with decades of safe operating experience.

References

American Nuclear Society. (2024). EDF, JAVYS ink new nuclear pact for Slovakia. https://www.ans.org/news/article-5331/edf-javys-ink-new-nuclear-pact-for-slovakia/?utm

Betkowski, P. (2022). Energy security in Poland – transformation and role of nuclear energy. Eastern European Journal of Transnational Relations, 6 (2), 71–79. https://doi.org/10.15290/eejtr.2022.06.02.06

Birikorang, S. A., Mansung, Y., Marianno, C., Fuhrmann, M., & Adu, S. (2026). Choosing the right reactor technology: A key step to strengthen nuclear security in West Africa's nuclear energy plans. Annals of Nuclear Energy, 226, Article 111837. https://doi.org/10.1016/j.anucene.20

25.111837

Burns, M. G. (2019). Nuclear Energy Security: (Non-Renewable) Uranium, Plutonium, Thorium. In Managing Energy Security (1st ed., pp. 237–266). Routledge. https://doi.org/10.4324/9780429320071-8

Committee for Economic Development. (1976). Nuclear Energy and National Security: A Statement on National Policy. Committee for Economic Development.

Ćwiek-Karpowicz, J. (2012). Poland's energy security: between German nuclear phase-out and energy dependency from Russia. International Issues & Slovak Foreign Policy Affairs, 21 (1–2), 44–55.

Hebda, W., & Mišík, M. (2024). In Search of Energy Security: Nuclear Energy Development in the Visegrad Group Countries. Energies (Basel), 17 (21), 5390. https://doi.org/10.3390/en17215390

Holgate, L. S. H., & Saha, S. (2018). America Must Lead on Nuclear Energy to Maintain National Security. The Washington Quarterly, 41(2), 7–25. https://doi.org/10.1080/0163660X.2018.1484223

Inflation Reduction Act of 2022, Pub. L. No. 117169, 136 Stat. 1818 (2022).

International Atomic Energy Agency (IAEA). (2013). Energy, electricity and nuclear power estimates for the period up to 2050 (RDS-1/33). http://www-pub.iaea.org/MTCD/Publications/PDF/RDS-1-33_web.pdf.

Jun, E., Kim, W., & Chang, S. H. (2009). The analysis of security cost for different energy sources. Applied Energy, 86 (10), 1894–1901. https://doi.org/10.1016/j.apenergy.2008.11.028

Kosai, S., & Unesaki, H. (2020). Quantitative evaluation of security of nuclear energy supply: United States as a case study. Energy Strategy Reviews, 29, 100491. https://doi.org/10.1016/j.esr.2020.100491

Kosai, S., & Unesaki, H. (2024). Nuclear power, resilience, and energy security under a vulnerability-based approach. Cleaner Energy Systems, 7, Article 100107. https://doi.org/10.1016/j.cles.2024.100107

Teräväinen, T., Lehtonen, M., & Martiskainen, M. (2011). Climate change, energy security, and risk—debating nuclear new build in Finland, France and the UK. Energy Policy, 39 (6), 3434–3442. https://doi.org/10.1016/j.enpol.2011.03.041

U.S. Department of Energy. (2023a). At COP28, countries launch declaration to triple nuclear energy capacity by 2050, recognizing the key role of nuclear energy in reaching net zero. https://www.energy.gov/articles/cop28-countries-launch-declaration-triple-nuclear-energy-capacity-2050-recognizing-key

U.S. Department of Energy. (2023b). Plant Vogtle Unit 3 enters commercial operations, bringing carbon-free nuclear energy to millions. https://www.energy.gov/articles/plant-vogtle-unit-3-enters-commercial-operations-bringing-carbon-free-nuclear-energy-millions

U.S. Energy Information Administration. (2024). Electricity in the U.S. https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php

World Nuclear Association. (2024). World Bank shifts policy to fund nuclear energy projects. https://world-nuclear.org/news-and-media/press-statements/world-bank-shifts-policy-to-fund-nuclear-energy-projects?utm

World Nuclear Association. (2025a). Nuclear power in Japan. World Nuclear Association. https://www.world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power

World Nuclear Association. (2025b). Nuclear power in the USA. World Nuclear Association. https://www.world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power

World Nuclear News. (2024). KHNP sets out plans for USD 186bn Czech nuclear project. https://www.world-nuclear-news.org/articles/khnp-sets-out-plans-for-usd186bn-czech-nuclear-project?utm

Upon graduating from the University of Florida with a B.S. in Mechanical Engineering and a B.S. in Aerospace Engineering, Eva Prendergast joined the U.S. Navy as an officer in the Naval Nuclear Propulsion Program, where she worked to ensure the continued safety and reliability of the nuclear propulsion plants powering the Navy's submarine and aircraft carrier fleet, as well as the successful construction and testing of new nuclear power plants. Her time in the Navy ignited her passion for nuclear power and its ability to provide reliable, carbon-free energy. After completing her military service, Eva pursued a Master of Engineering in Energy Systems at the University of Illinois Urbana-Champaign. Upon graduation, she accepted a role as a manufacturing engineer at an advanced nuclear reactor technology company, where she works to support the successful manufacturing of the next generation of nuclear power plants aimed at decarbonizing the electrical grid.

Space Security and Policy in the Modern Era

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This paper provides an overview of the international laws, contradictions, and gaps of the governance of space exploration. With space exploration being a much more remote location, clarity of laws and treaties are of the utmost importance. Focusing on the constitution of outer space regulations, the Outer Space Treaty of 1967, the foundational international agreement regarding activity in outer space. Each article is summarized with emphasis on its core legal obligations. By outlining the treaty's central principles and their relevance to modern space operations, we can see where this treaty needs improvement to support the technological advances and safety of people traveling to space in the modern era.

Keywords: Space security, space policy, Outer Space Treaty of 1967, space exploration, international law

Introduction

Space Law encompasses the governance, rules, and restrictions surrounding activities conducted in outer space and on celestial bodies. Human activity is moving beyond earth, and international law has a need to evolve to accommodate spaceflight, human values, and manage the protection of shared resources. These laws are designed to encompass agreements between states and have principles regarding outer space to prevent future conflicts [UNOOSA 1967]. Much of the existing policy regarding spaceflight was developed reactively, with these treaties providing regulations for space travel, sovereignty, and the responsibilities of each party seeking to send objects into orbit. There are many other fields of law which are integrated into space law, which cover the unique and isolated areas like outer space.

During the first studies of outer space flight, the science was there, but policy was not. One scientist,

Theodore von Kármán, stated to a lawyer "you must tell us how to behave ourselves accordingly to law and safeguard our innocence," describing the need for legal institutions to catch up and support innovation [Rakić 2011]. A large number of policies were created through the Space Race to settle disagreements. These efforts culminated in a series of five foundational treaties intended to protect space for peaceful purposes and benefit all humankind. However, in the modern era of privatized spaceflight, advanced military capabilities, and increasing orbital congestion, gaps in these policies have become increasingly apparent.

These five treaties were the Outer Space Treaty of 1967, The Rescue Agreement of 1968, The Liability Convention of 1972, The Registration Convention of 1976, and the Moon Agreement of 1984 [UNODA 2025].

Background

The politics regarding the Space Race between the United States and Soviet Union have been a lurking issue from the Truman administration to the modern day. Post-World War II, the United States developed a major scientific intelligence program, Operation Paperclip. This endeavor brought over 1,600 German scientists to America to bolster technological advances such as rocketry, medicine, and synthetic fuels. This operation played a pivotal role in the Space Race and contributed to the successes of the Apollo missions.

The United States was not the only country developing space travel. After World War II, the widespread fear of nuclear weapons led people to worry that attacks could even be launched from outer space. In the early part of the Cold War, the Russian satellite Sputnik-1 was launched as the first artificial satellite. This directly caused the United States Congress to develop the Space Act and the National Aeronautics and Space Administration. From these events, five treaties of international space law were put into place to "stress the notion that outer space, the activities carried out in outer space and whatever benefits might be accrued from outer space should be devoted to enhancing the well-being of all countries and humankind, with an emphasis on promoting international cooperation" [UNODA 2025].

Treaties Regarding Outer Space

The first declaration of peace in space travel was the "Outer Space Treaty" of 1967, governing the actions in outer space and on celestial bodies. This treaty was initially signed by the USA, UK, and Soviet Union – this treaty is open to all spacefaring nations, and as of 2025, 117 countries have signed this treaty. The Outer Space Treaty, often described as the constitution of space law, consists of seventeen articles governing activities in outer space, many of which have been challenged by the evolution of spacefaring technology. The conditions of this treaty included "the prevention

of harmful interference with space activities and the environment", working with a previous treatise confirming "all space exploration will be done with good intentions and is equally open to all States that comply with international law" [UNOOSA 1967].

The Outer Space Treaty functions as the 'constitution' of space law, though many terms are broad and becoming increasingly difficult to apply to modern technology and ideals. Each article is foundational to space law and the legality of actions in outer space. Table 1 lists each article and provides a brief description.

Many of the articles are focused on the ratification and states participation in the treaty, although the main articles that are under consideration throughout this paper are the first eleven articles. Those articles intended to protect the sanctity in the Cold War Era Space Race which have become outdated with the modern evolution of technology.

The rescue agreement was a proposal made stating "States shall take all possible steps to rescue and assist astronauts in distress" [UNOOSA 1968]. In 1968, when this proposal was drafted, it was unlikely that lawmakers anticipated how relevant it would become in modern society with the growing likelihood of space tourism [Cates 2021]. This has been a revisited topic because of the gap in this agreement reflecting Americas lack policy for conducting in space rescues [David 2021].

The Liability Convention of 1972 states in article II & III, "A launching State shall be absolutely liable to pay compensation for damage caused by its space object on the surface of the earth or to aircraft in flight. . . . liable only if the damage is due to its fault or the fault of persons for whom it is responsible". This convention covers the care of reckless space satellite launching and international damage to space objects. The convention does not cover any penalties for leaving debris in space, which is becoming an increasing concern with the push towards future space travel [UNOOSA 1971].

Building upon the previous governances, the Registration Convention set a precedent for all information regarding space explorations must be documented and addressed issues of undocumented objects that were launched or will be in orbit [UNOOSA 1974]. With an increase in dead satellites on or near geostationary orbit, the litter from these satellites pose a threat to other working satellites. This convention keeps tabs on the satellites launched by each country to keep track of every launch and manage the possibility of mass junk and avoid hazards from space debris.

Lastly, after the moon landings occurred, the Moon Agreement was developed. This treaty was to ensure "those bodies should be used exclusively for peaceful purposes, that their environments should not be disrupted" [UNOOSA 1984]. There have been many countries to ratify this treaty over the restrictions of resource use, which is becoming an increasing concern with the ideas of asteroid mining becoming feasible for resources.

Table 1: List and short description of Articles from Outer Space Treaty of 1967 [UNOOSA 1967].

Article	Topic	Condensed Description
I	Freedom of Exploration	Space is free for use and exploration by all States; activities must benefit all nations.
II	Non-appropriation	States cannot claim sovereignty over outer space or celestial bodies.
III	International Law	Space activities must follow international law and the UN Charter.
IV	Peaceful Purposes	Bans nuclear weapons/WMDs in space; celestial bodies used only for peaceful purposes.
V	Astronaut Assistance	Astronauts are "envoys of mankind"; States must aid those in distress.
VI	State Responsibility	States are responsible for both governmental and private space activities; must authorize and supervise them.
VII	Liability	Launching States are internationally liable for damage caused by their space objects.
VIII	Jurisdiction	States retain jurisdiction and control over objects they launch and register.
IX	Harmful Contamination	States must avoid harmful contamination and consult others if interference is possible.
X	Observation of Launches	States should consider inviting other States to observe launches for transparency.
XI	Information Sharing	States should inform the UN and public about space activities "to the greatest extent feasible."
XII	Inspection Rights	Installations on celestial bodies must be open to inspection with reasonable notice.
XIII	International Organizations	Treaty applies when States act through international organizations; responsibility is shared.
XIV	Ratification	Outlines ratification and accession procedures.
XV	Amendments	States may propose amendments which require majority approval.
XVI	Withdrawal	States may withdraw with a one-year notice.

Gaps in Policy

Despite the significance of the five initial treaties supporting space exploration, they are no longer adequate to support the technological advancements of the modern day and the realities of the 21st century. In the modern day, these need a large number of revisions and updates. From the improvement in technology to potentially send tourists to space to the potential of illegal weaponized satellites, some of the older doctrines have gaps which need to be filled.

Privatized Space Travel

As of 2021, fully privatized spaceflights have occurred with companies such as SpaceX and Blue Origin; under the Outer Space Treaty, private companies require only authorization from their respective governments. From this there could be potential loopholes such as labor laws and lack of care about safety concerns especially because it is an isolated area [Nezvold 2022].

As more prevalent space travel occurs, jobs will become needed and available in orbit. With more privatized space travel occurring, people who go into space will be either pilots or paying passengers. Because of the distance between an outer space workplace and the ground — with no easy way to travel between the two — there is the possibility of a poor workplace environment being isolated from the rest of the world. The extended distance and lack of rapid communication lead to poorly monitoring the workplace and the enforcement of labor laws near impossible. With the flexibility and vagueness of the rules of outer space travel, it raises the question of how much the Outer Space Treaty of 1967 will protect workers and citizens.

Private companies can launch with "authorization" from the government and "continued supervision", but there is no stipulation on how much supervision is occurring. In addition, this policy mentions there shall be no detriment to space or celestial bodies but there is no specification on the effects on earth in these policies.

Orbital Resources

Another ambiguity in the Outer Space Treaty is its failure to define what it means for space activities to benefit all peoples. Without a clear legal definition, countries may prioritize their own populations and national interests rather than the broader interests of humanity.

Secondly, there are debates on the distribution of the resource of space. There is only a finite amount of orbital space around the earth, and it is currently being claimed on a first-come, first-serve basis – many by the countries which initially started the Space Race. In Figure 1, we can see that the United States have cumulatively launched the most satellites. Secondly, there are no limits on the number of objects that may be launched by each country, raising questions about where such

boundaries should be drawn.

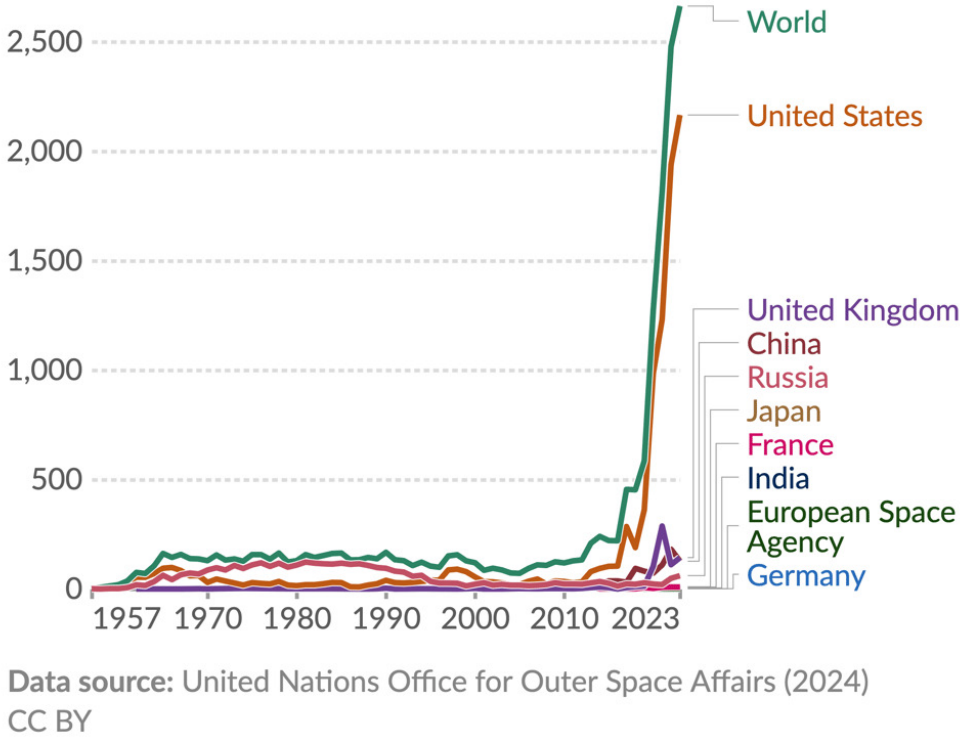


Figure 1: Annual number of objects launched into space by country up to 2023 [Mathieu 2024].

The distribution of the resource benefits of orbital space and celestial bodies needs to be allocated rather than first-come, first-serve. In the OST, exploration and use of outer space should be used for the benefits of all countries. Earth's limited resource of orbital resource has been dominated by space exploration states such as USA, Russia, and China. For launching rockets, a locational benefit to launching geostationary satellites is launching along the equator.

The lack of discussion on the sovereignty of orbital space prompted a meeting of equatorial countries, known as the Bogota Declaration, to further discuss the considerations of locations along the equator as a natural resource. Orbital space in the geostationary orbital path falls above the equator. The Bogota Declaration was a declaration from most countries along the equator to have sovereignty of the orbital space above these countries. This was one of the few challenges to the Outer Space Treaty by not having all space be unclaimed by any state or be governed by the "common heritage of mankind." This declaration claimed that the orbital space above the equatorial countries was a natural resource, and claiming this resource as part of their sovereign territory. This declaration was not supported by the wider international countries and was seen to violate the OST. Support for this declaration was abandoned. This declaration was one of the first steps into addressing the problem of geostationary orbit becoming a known limited resource and the problems with this being

first come first serve supporting the main spacefaring countries.

In the past 20 years, there have been multiple advances to space technology, and it begins to blur the lines of legality from the main five treaties. In 2015, there was the Commercial Space Launch Competitiveness Act which legalized space mining and was the start of introducing legislation in other countries to legalize extraterrestrial resources. This creates controversy regarding the legality of using celestial bodies for profit. Such activities could breach the Moon Agreement, which states that celestial bodies should not be disrupted and must be used exclusively for peaceful purposes.

Iridium-Cosmos Collision

In February of 2009, the American satellite Iridium 33 and Russian satellite Cosmos 2251 collided mid-orbit above northern Asia, (Figure 2). This event was the first major collision to happened between two full-body satellites.

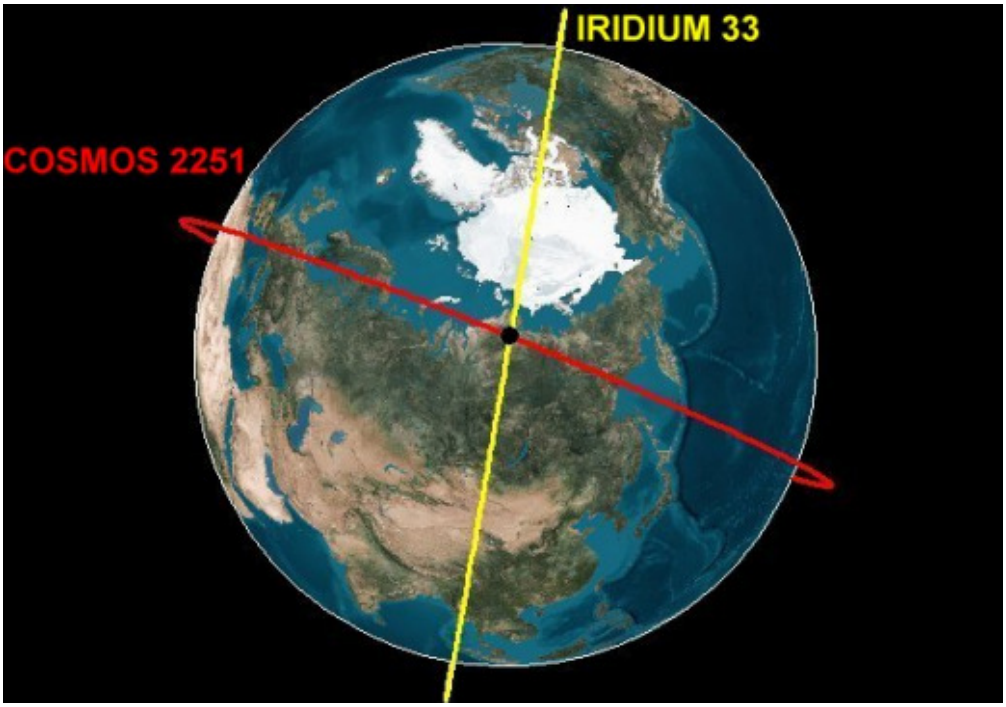


Figure 2: The orbits of Iridium 33 and Cosmos 2251 at the time of the collision, as viewed directly above the collision point (black dot). Earth and orbit imagery by Analytical Graphics Inc. [Earl 2012].

This collision scattered several hundred, if not thousands, of pieces of debris into orbit causing a major threat to other satellites still to this day. Satellite collisions occur in orbit at extreme velocities, with objects weighing hundreds of kilograms colliding at approximately 26 times the speed of sound,

or around 33,000 kilometers per hour. The resulting spread of debris from each satellite is shown in Figure 3. There is a large threat of debris and multiple maneuvers of the National Aeronautics and Space Administration NASA satellites to avoid debris from this incident [NASA, 2019].

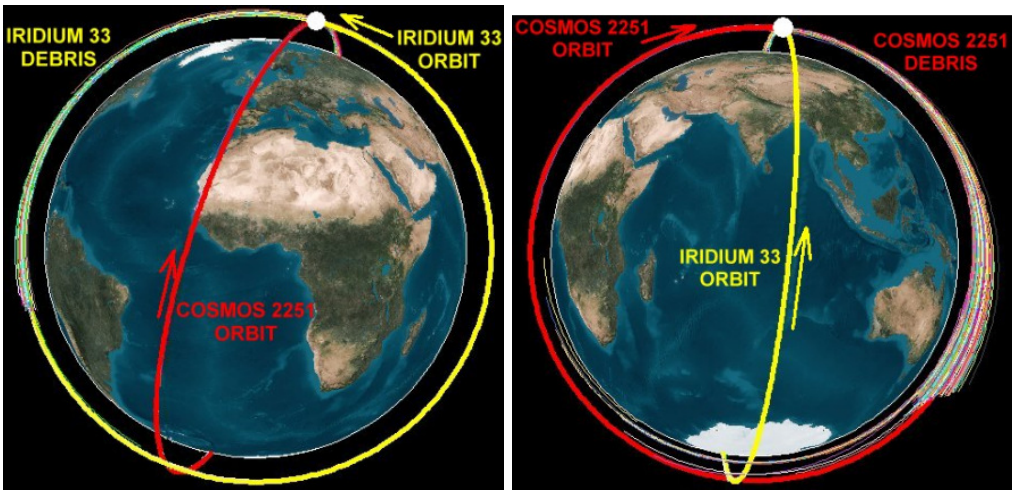


Figure 3: Debris orbital paths post collision of Iridium 33 (left) and Cosmos 2251 (right) Earth and orbit imagery by Analytical Graphics Inc. [Earl 2012].

Each of the satellites needed to be accounted for through the liability on responsibility of each of the countries. Through the registration convention, all satellites are registered in orbit to avoid collisions. There have been multiple, intentional-collision tests conducted for antisatellite missions and multiple high-speed collisions with particles of debris. This has been the only unintentional full-scale satellite collision to modern day. To avoid future collisions, satellite maneuvering has become common. For example, a near-collision occurred between an ESA satellite and a Starlink satellite, requiring ESA to adjust its orbit to prevent impact [Foust, 2019]. There have been many studies calculating risk and probability of satellite collision, one article provides and example of this with the Starlink satellite as the model [Tao, 2022].

Militarization of Space

Militarization of space is currently in the form of informational satellites. Numerous military satellites support intelligence, communication, and early warning systems; these assets would likely be primary targets for antisatellite weaponry. With the development of antisatellite weapons (ASAT) in the US space force, the blurry line for outer space being a free space is constantly being challenged. The Outer Space Treaty permits military observation in space, but does not allow any weaponry deemed a weapon of mass destruction.

Artemis Accords

Modern policy updates have been in the form of The Artemis Accords. In 2020, the accords were proposed by the United States National Aeronautics and Space Administration (NASA), to other states to set principles for space exploration, including but not limited to, transparency, resource extraction, and "safety zones". This presents itself as an operational version of the Outer Space Treaty regarding civil exploration of the moon, Mars, and other celestial objects. The primary provision this treaty upheld was consistency with Article XI, emphasizing transparency and the sharing of scientific information. It also specifies registration responsibilities, expanding upon the framework established by the Registration Convention.

This treaty seems good in practice but was criticized for being "too centered on American and commercial interests"[Boley 2020]. It was also condemned by Russia, the main contender of space exploration, for creating an international law that favors the US. This complaint ties into the major five treaties of outer space and celestial bodies are for the good of the world. Critics also complain that this treaty distinctly states that there is claim to resources extracted from celestial objects, contradicting the Outer Space Treaty forbidding the claim of a natural planetary body.

Several gaps and grey areas exist in current space policy coverage. For many states, this is allows loopholes to exploit the five overarching policies which govern outer space and celestial bodies. Potential methods of remedying these flaws would be to have collective meetings of countries focused on space travel to rewrite and update these policies. Now that most of these countries are focusing on space travel, updating defense budgets for orbital defense measures has been a major concern amongst countries at tension and increasing these tensions.

Policy Reform

With the need for policy reformation from a time when space exploration was far less advanced and space activity was mainly government focused, there needs to be active change in the policy to update for the modern times. Today, commercial actors, private companies, pedestrian passengers, and national security all play a large role. Many of the previously written doctrines contain gaps, ambiguities, and outdated assumptions regarding the innovations to space exploration. Private corporations are the main sources of space exploration, launching thousands of rockets and satellites annually and have the ability to fly with commercial passengers. With the initial laws supporting the space travel from the state side, they are no longer adequate for privatized travel.

One of the many critical areas for policy revision is in environmental protection. This area was overlooked in the initial treaties, only referring to it as harmful contamination for the context of celestial bodies and not of the earth itself. With a large number of launches happening, there is the concern of the environmental impacts from emission, debris, and atmospheric pollution. Modern policy must address all forms of environmental impact. While regulations exist for activities on Earth, policies

remain unclear for operations between orbit and Earth. Working to make standards for rockets, SpaceX has been developing reusable rockets and liquid oxygen oxidizers which reduce much of the damaging impacts from ammonia based fuels and discarding rockets into the ocean. Developing policy to standardize these methods would be the next step in constructing an environmental standard.

Supervision of privatized companies under the Outer Space Treaty only mention baseline requirements such as authorization and supervision. There is no definition of the supervision which is the main focus for reform. Providing adequate details to what supervision entails would have private companies either be a separate entity or tie in with government agencies like NASA. Private companies still have many laws they need to follow such as Occupational Safety and Health Act, and Fair Labor Standards Act, but these are not specialized for space exploration, and it would be good to further expand this topic before loopholes in government policy are exploited by space faring companies. Furthermore, clear, internationally agreed-upon guidelines are needed to ensure that commercial spaceflight is conducted safely and ethically.

Security concerns referring to the increasing rate of Anti-satellite weapons and space militarization are another point for reformation of space law. There has been the banning of nuclear weapons in space by the Outer Space Treaty, and Partial Test Ban Treaty, these do not cover the threats to a private traveler's safety or any manmade satellite. From ASAT tests, the product left long lasting orbital hazards. Updating regulations for ASAT devices and other potential forms of weaponry would promote a peaceful area and disincentivize orbital weapons. With the sovereignty of outer space being joint between all states, there should be regulations against any sort of interspace conflict.

Given these challenges, the United Nations Office for Outer Space Affairs (UNOOSA) will likely need to coordinate a comprehensive review or rewriting of the primary treaties. A reconstruction process of these treaties will need to be established rather than proceeding with an amendment process. There are many realities in the 21st century that need to be accounted for to maintain the original spirit of using outer space as a domain. Establishing clearer regulatory frameworks, environmental protections, and equitable access mechanisms will be essential to ensuring that space remains safe, sustainable, and accessible for future generations.

In summary, the main concerns of the Outer Space Treaty for modern day space exploration are in articles I, II, IV, VI, and VII - freedom of exploration and use (I), Non-appropriation (II), Peaceful purposes (IV), Responsibility (VI), and Liability (VII). Many of the reasons for each of the concerns were condensed in Table 2.

In Article I, the main focus is intentionally broad to promote innovation and development, but this creates some disparity in definition of 'use'. The article never defines use as a topic which leaves states to interpret 'use' in a variety of manners. Without clearer definitions, disputes over resources could potentially lead to conflicts over entitlement issues between countries. Any modern governance update must specify what kinds of uses are permitted and what regulatory or benefit-sharing

mechanisms apply.

Article II is the prohibition of any state claiming sovereignty over any part of space. This was intended to prevent territorial annexation like colonial-land grabs. States have argued that non-appropriation do not allow claim of sovereign territory but does not necessarily ban the extraction and ownership of resources taken from celestial bodies. This was contested through the Bogota Declaration, in which equatorial countries claimed geostationary orbit as a resource; however, the declaration was rejected for contradicting the prohibition on sovereignty claims in outer space. Modern framework needs to cover if a resource is allowed to be claimed from celestial bodies given the implications of modern technology to drill resources from asteroids.

Article IV covers nuclear weapons and other weapons of mass destruction into space, as well as summarizing peaceful purpose of outer space. This was mainly aimed at prohibiting all forms of nuclear technology in space to prevent competition. This forbids some forms of weaponry but does not ban conventional weapons. States have interpreted "peaceful" as meaning "non-aggressive", but allow military satellites for reconnaissance, communications, and navigation. The article needs to be solidified to create a uniform interpretation of the article to account for the technology of military intelligence satellites in orbit. Testing of ASATs need to be addressed through a revision of the Outer Space Treaty, especially debris-generating tests which are greatly harmful to all satellites in orbit.

The responsibility article, VI, makes States internationally responsible for national activities in outer space, whether carried out by governmental or non-governmental entities. Article VI includes authorizing and supervising non-government activities. Now that a majority of space travel has become privatized, there is an increasing problem of the lack of definition behind the word 'supervision'. A key component of reform should be to clarify where states must impose detailed restrictions, such as minimum standards, on private companies, thereby reducing future legal grey areas. In the near future, when more pedestrians have access to space travel, there is a legal safety net to prevent tourists from becoming a part of this grey area.

Lastly, in Article VII, it establishes that States are internationally liable for damage caused by their space objects. With a mass of floating debris with few available ways to clean it up, there is little to no way to determine the cause of debris, leading to no one able to take responsibility for damage to other satellites. Having regulations to avoid debris is a good step in other articles, where there needs to be methods to more accurately determine sources of damage as well as consideration of insurance. Debris-remediation programs, reducing the concentration of debris would be a great start to reducing the number of potential claims as well.

Table 2: Table of Outer Space Treaty (OST) principles and the overall gaps between OST and modern era.

OST Principle (1967)	Intended Purpose at Time of Drafting	Modern Interpretation	Current Challenges / Gaps
Non-appropriation of outer space (Article II)	Prevent territorial claims, avoid Cold War land grabs on the Moon/planets.	States cannot claim land in space, but can engage in exploration and "use."	Space mining laws reinterpret "use" as property ownership. No clarity on resource rights or boundaries.
Use of space for peaceful purposes (Article IV)	Prevent nuclear weapons or military bases in space.	Military satellites allowed, only WMD explicitly banned.	ASAT tests, jamming, cyberattacks, and dual-use satellites blur lines. No ban on rocket propulsion weapons.
Freedom of exploration and use for all states (Article I)	Ensure equal access for all nations regardless of technological capability.	Any nation can launch satellites and explore celestial bodies.	Massive inequality: U.S., China, and Russia dominate orbital slots. Developing countries have little access to orbital territory.
Avoid harmful contamination (Articles IX)	Prevent biological contamination of planets and Earth return. Primarily scientific concern.	Interpreted broadly to mean environmental protection and debris mitigation.	Treaty never envisioned mass rocket pollution from launches, large debris fields. No enforceable debris rules.
Authorization & continuing supervision of non-state actors (Article VI)	Governments responsible for private companies' actions in space.	Companies need launch authorization and minimal oversight.	No global standard for supervision. Loopholes for safety, labor rights, and environmental impacts.
International responsibility and liability (Articles VI–VII)	Assign responsibility if a state's satellite causes damage.	States are liable even for private launches.	Debris collisions (Iridium–Cosmos) and anonymous debris sources complicate causality. Mild to no penalties for creating debris.
Cooperation and mutual assistance (Article IX)	Encourage states to consult each other when activities may cause interference.	"Consultation" is often symbolic or ignored.	No enforcement mechanism: ASAT tests happen without meaningful international dialogue.
Space as the "province of all mankind" (Article I)	Ensure collective benefit and prohibit exclusive claims.	Often used as a symbolic principle, open to interpretation.	First-come-first-served orbit allocation and resource extraction undermine equitable access for developing states.

Conclusions

Over the years since the Space Race to the modern day, there have been active measures to protect and govern outer space and celestial bodies. In modern times, some of these preventive measures are being challenged, leading to some grey areas and loopholes being exploited. The changes in the interpretation of the OST is mainly the result of emerging advanced technology, and the governing agreements being made without knowing how much technology would advance in 50 years.

There are many ways to prevent potential conflicts in policy, including meeting and being proactive with other countries to develop updates for these laws. The laws governing space are being challenged, and there is the potential to work together for changes. Otherwise, the grey areas of outer space policies will cause conflict. Continued international engagement and responsible state behavior are therefore essential to uphold the treaty's purpose and ensure sustainable use of the space environment.

References

Boley, A., & Byers, M. (2020). U.S. policy puts the safe development of space at risk. Science, 370(6513), 174–175. https://doi.org/10.1126/science.abd3402

Breaking Ground Trust. (2022). Pioneering resource regimes for the Moon. Breaking Ground. https://breakingground.space/

Cates, A. (2021, July 29). The In-Space Rescue Capability Gap | Aerospace Center for Space Policy and Strategy. Aerospace.org. https://csps.aerospace.org/papers/space-rescue-capability-gap

Cates, A. (2025, May 8). Novel Workshop Spotlights Need for In-Space Rescue Capabilities | The Aerospace Corporation. Aerospace Corporation. https://aerospace.org/article/novel-workshop-spotlights-need-space-rescue-capabilities

David, L. (2021, September 15). Humanity needs a space-rescue capability, report stresses. Space.com. https://www.space.com/space-rescue-capability-needed-report

Foust, J. (2019, September 3). ESA spacecraft dodges potential collision with Starlink satellite. SpaceNews. https://spacenews.com/esa-spacecraft-dodges-potential-collision-with-starlink-satellite/

International Space Exploration Coordination Group (ISECG). (2024). GLOBAL EXPLORATION ROADMAP. https://www.globalspaceexploration.org/wp-content/isecg/GER2024.pdf

Jakhu, R., & Freeland, S. (2022). McGill MANUAL on International Law Applicable to Military Uses of Outer Space Volume I -Rules Co-Editors. https://www.mcgill.ca/milamos/files/milamos/mcgill_manual_volume_i_-_rules_final_0.pdf

Mathieu, E. (2024). A record number of objects went into space in 2023. Our World in Data. https://ourworldindata.org/data-insights/a-record-number-of-objects-went-into-space-in-2023

Michael, E. (2012). IRIDIUM 33 and COSMOS 2251: AN HISTORIC COLLISION. http://www.castor2.ca/08_Papers/collision.pdf

NASA. (2009). The Collision of Iridium 33 and Cosmos 2251: The Shape of Things to Come 60th International Astronautical Congress Daejeon, Republic of Korea. https://ntrs.nasa.gov/api/citations/20100002023/downloads/20100002023.pdf

Nesvold, E. (2022, November 14). Closing the Gaps: Space Policy Considerations Beyond Security and Economy. Georgetown Journal of International Affairs. https://gjia.georgetown.edu/2022/11/14/closing-the-gaps-space-policy-considerations-beyond-security-and-economy/

Rakic, S. (2025). View of IS THE REVISION OF THE OUTER SPACE TREATY NECESSARY? - A THEORETICAL APPROACH. Bg.ac.rs. https://epub.ius.bg.ac.rs/index.php/eudaimonia/article/view/34/23

Tao, H., Che, X., Zhu, Q., & Li, X. (2022). Satellite In-Orbit Secondary Collision Risk Assessment. International Journal of Aerospace Engineering, 2022, 1–18. https://doi.org/10.1155/2022/6358188

United Nations Office for Disarmament Affairs (UNODA) Treaties. (1963). Partial Test Ban Treaty. Treaties.unoda.org. https://treaties.unoda.org/t/test_ban

United Nations Office for Outer Space Affairs (UNOOSA). (1966). The Outer Space Treaty. UNOOSA. https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html

United Nations Office for Outer Space Affairs (UNOOSA). (1967). Rescue Agreement. Www.unoosa.org. https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introrescueagreement.html

United Nations Office for Outer Space Affairs (UNOOSA). (1971). Liability Convention. Www.unoosa.org. https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introliability-convention.html

United Nations Office for Outer Space Affairs (UNOOSA). (1974). Registration Convention. Unoosa.org. https://www.unoosa.org/oosa/sk/ourwork/spacelaw/treaties/introregistration-convention.html

United Nations Office for Outer Space Affairs (UNOOSA). (1979). Moon Agreement. Www.unoosa.org. https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/intromoon-agreement.html

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Wired Across the Ocean: How the Development of the Chinese and American Technology Economy Is Affecting the Current Conflict in Taiwan

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Taiwan has become a tense flashpoint between the relationship between the United States and China. One such factor that has led to the importance of this geopolitical flashpoint is the relationship between China and the United States' technology sectors of their respective economies. This paper is meant to explore the development of each nation's technological sector, and how said development has led to the current tension in Taiwan, as each nation competes for one of the most valuable resources of the 21st century.

Keywords: Taiwan, United States, China, technology sector, geopolitics, technology economy, international relations

Introduction

Thucydides' trap is being sprung in the South China Sea. As was said in the 19th century, "Britannia rules the waves". However, the story of the 20th and early 21st century was "America rules the waves". Since the ending of World War II, and especially after the decline and collapse of the Soviet Union, the world hegemon has been set on the shoulders of the United States. World finance, trade, and power has run through either New York City or Washington D.C. for the last 75 years, if not longer. However, throughout the past decade there has been a reshuffling of the world order, as nations that once were incomparable in power to the United States are rapidly catching up. The most obvious nation that fits this category would be the People's Republic of China. Beginning

with Mao Zedong's rise to power in 1949, and extending throughout the decline of Maoism and the rise of "Socialism with Chinese Characteristics" in the new millennium, China's economy and military power has been nearly eye-to-eye with the United States. China's GDP only follows the United States' by 6 trillion dollars, while its military manpower by sheer numbers almost doubles the United States (World Bank Open Data, World Population Review). Thucydides' Trap, coined by American professor Graham T. Allison, refers to a power struggle where an established power feels threatened by a new emerging power, which makes war between the two powers much more likely. He reasoned that this power structure will make America and China eventually come into a conflict in the Pacific (Allison). However a future conflict between the Americans and Chinese may play out is up for debate and impossible to predict. However, given recent tension and political maneuvering around the island nation of Taiwan, one can use interesting historical analysis and the economic context of the island nation of Taiwan to gain insight on why Taiwan is so important to both nations, outside of the political implications. Simply put, both the Americans and Chinese rely much on their technological economies for their respective power structures, and both desire Taiwan's output of technological necessities to keep those economies running.

Taiwanese Tech

Since the conclusion of the Chinese Civil War, the island of Taiwan has given a home to the Republic of China, a government that consists of Chinese Nationalists that were forced off the Chinese mainland by the Chinese Communist Party. For much of the Cold War, the island was subject to much pressure by the Chinese Communist Party, with Mao Zedong threatening to invade the island on multiple occasions, with the United States' "Containment Policy" of Communism being the only thing stopping him. The island always lived under threat of a Chinese invasion for the entirety of the Cold War, but the death of Mao did put the tensions to a bit of a rest. However, Taiwan went through a period of rapid industrial growth throughout the 1980s and 1990s dubbed the "Taiwanese Miracle".

Joining the "Asian Tigers" of Hong Kong, South Korea, and Singapore the Taiwanese economy became a major player on the global stage. Taiwan specifically focused on technological innovation, slowly molding itself into a sort of "Silicon Valley" nested off the coast of Mainland Asia. Companies from across the planet began to move production to Taiwan, and they held a solid base in international markets. The Gross National Product of Taiwan soared, moving from the same level of most sub-saharan African nations in the 1950s to rivaling those of Western European nations and Japan by the 2010s. Currently, Taiwan fits into the global market as a foundation of the global tech market. 92% of the world's leading computer chip manufacturing takes place on the island of Taiwan, with many other major motherboard and laptop manufacturing joining that (Fried, 2021). Therefore, it is obvious how this island is of major importance to anybody who seeks to dominate the world technology economy. Both the United States and its powerful Silicon Valley market, as well as the CCP's massive investment in state-owned enterprises that focus on technology shows just how much these nations care about the technology market. However, it is important to discuss

how these two nations got to the point where they are facing off over an island.

Chinese Tech Market: From Mao to Xi

The Chinese tech market has followed much of the rest of the nation throughout its history following the victory of the Communists in the Chinese Civil War. Immediately following the Communist victory, Mao attempted to rebuild the Chinese economy on the Soviet model, following what Stalin did in the USSR in the 20s and 30s. This meant bureaucracies led by party ideologues and highly centralized planning. This continued for most of the Great Leap Forward, as the nation rapidly industrialized, moving on from its mostly agrarian society to one focused on industry. However, much of the technological innovation that would have been possible in a rapid period of industrialization was hampered by the Cultural Revolution. The issue was that in Maoist ideology, many intellectuals and innovators that could have led this period of technological innovation were seen as "bourgeois" elements of capitalist decadence. Therefore, many intellectuals were either severely repressed or sent to work the fields in rural areas, leading to little technological progress. Universities turned into Red Guard breeding grounds as the nation was locked in ideological turmoil until the death of Mao in 1976.

When Deng Xiaoping took control after Mao's death, he implemented the Four Modernizations, which were certain goals that were meant to bring China out of the stagnation it faced during the height of the Cultural Revolution. One of those Four Modernizations was science and technology. This came along with a general decentralizing of the Soviet-style centralized economic system in the 1970s and 80s known as the Chinese Economic Reform. Rather than being specifically controlled by the Chinese Communist Party, certain industries (such as science and technology) began to come under the control of state-owned enterprises, which acted as corporations similar to ones seen in capitalist western nations (although, always under supervision of the CCP). In 1995, the State Council of the People's Republic of China issued the "Decision on Accelerating S&T Development", which outlined their plans for this sector of the Chinese economy. In this statement, the Chinese Government outlined its desire to increase the size of the technological sector of China's economy, grow the amount of Chinese workers in this sector of the economy, as well as dedicating funds of the Chinese government to achieve these results (US Embassy - China, 1996). This had been the case for the Chinese economy for much of the 1990s and 2000s, with the 2010s seeing a massive rise in spending in research and development, with Chinese spending in this sector rapidly approaching the American standard (Yau, 2021). However, much of this rapid success has been taken hold of by the Chinese Communist Party, especially with the rise of Xi Jinping and "Han Nationalism".

Xi Jinping, as undisputed leader of China, has brought China on a new path. Rather than focusing on a traditional Marxist-Leninist ideology like Mao, or bringing China into the modern world like Deng Xiaoping, Xi has turned China into a very nationalistic state. This phenomena is known as Han nationalism, which has dominated much of China's foreign policy decisions, from the Belt-

and-Road Initiative to its actions in Tibet. A perfect example of this type of nationalism is seen in the Chinese media's rhetoric on the COVID pandemic, which emphasizes the "western decadence" which led to an unorganized response in places like Italy and the United States, while the Chinese government fostered a collective, immediate response to the pandemic (The Economist, 2022). However, much of this nationalism is beginning to become extended to the world of economics, as this "Han Nationalism" is actually extended to something called "Techno-Nationalism", which brings this sentiment to the Chinese tech market.

Breakdown of co-dependence

Since Nixon's visit with Mao in the early 1970s, the Chinese and American economies have been very much tied at the hip. However, since these two nations are beginning to rub up against each other's strategic plans, they are beginning to decouple. China has seen the writing on the wall, and has realized that it is in their best interest to become technologically self-sufficient. Therefore, what "techno-nationalism" is in a realistic sense is the Chinese government's mercantilist policies to realize this. This is seen in many Chinese foreign policy decisions such as the questionably legal transfer of technology and intellectual property from foreign companies operating in China (Bilgan & Loh, 2021). This is designed to bolster China's ability to sustain its own technological progress without the influence of its strategic opponents. Noted by Alan Wolff, "What Beijing has decided to do is to move China from an imitation to an innovative stage of production... from "Made in China" to 'Made by China'" (Wolff, 2007). This, of course, naturally brings them at not only strategic odds with the West, but ideological odds, as this type of nationalist, mercantilist thinking brings them at odds with the West's neoliberalism. The West values free markets over all, and this ideological conflict is already bearing fruit. Nowhere else is this most seen in the U.S. President Donald Trump's "trade war" with China, as he himself cited China's mercantilist policies with China for his actions (Bilgin & Loh 2021). This "tough on China" attitude by U.S. leadership spans both parties, as President Joe Biden has continued this rhetoric. Therefore, this nationalist fervor to become technologically reliant on themselves by China has naturally brought the United States closer to an enemy as a friend. This being said, this would not be possible without the development of the American tech sector's mindset.

The American Tech Market: From Military Tech to the budding of "Silicon Valley"

After the Second World War, the United States was unrivaled in its potential for technological and economic growth. Most of its logical rivals (the traditional powers of Europe, the USSR, and China) were reeling from the effects of the war, and since the U.S. homeland was only marginally physically affected by the war, they were in the best position to fill the void. There was also a logical need to technologically advance, as tensions with the Soviet Union would drive the need to always be one

step ahead of the Communists. This led to a massive boom in technological innovation, much of it being first concocted as military technology (Friedberg, 1996). It must be remembered that things like the modern computer, jet engines, and many other "modern" inventions were first derived to be used in a military sense around this time. Nowhere else is this most seen in the United States' use of Nazi scientists such as Werner von Braun in the Space Race, as well as the development of one of the first computers, ENIAC. ENIAC was first designed to assist artillery firing calculations during the Second World War, as well as the feasibility of the thermonuclear bomb in the Cold War (Computer History Museum). However, this only set the stage for the development of the modern American tech market in California.

Coming from humble beginnings as a site for United States Navy radio research, the Santa Clara valley in California would grow into the center of the American technological world. The geographical proximity to U.S. military research facilities, as well as the prestigious Stanford University naturally made the times' best innovators flock to this area. This included men like William Shockley, the father of the modern transistor, as well as other inventors of computer technology. Given that many of these innovations were using the element Silicon, this gave the valley its nickname. Following its military legacy, the Pentagon set up one of four original nodes that consisted of ARPANET at Stanford, which would go on to become the basis of the modern Internet (Leyden, 2019). With this foundation as an area of massive technological innovation being solidified in the 1960s and 70s, the American tech market became centered in California.

Given the incredible value that this new technology had, and the potential it had (and would end up fulfilling) to change the world, people looking to make incredible amounts of money flocked to the area. This would bring the emergence of "venture capitalists", or people looking to help fund start-ups that could potentially pay off big time. Many future titans of industry such as Apple's Steve Jobs began their companies in this environment (Elgan, 2011). Given this perfect mix of hobbyists looking to change the world, military technology being advanced with the Cold War, and plenty of rich people looking to become wealthy off of innovation, the American tech economy began to experience explosive growth in the 1980s and 1990s. Prior to the dot.com crash of the Early 2000s, the American tech market was growing at a rate that can only be compared to the dawn of the automobile in the early 20th century, or the railroad in the 19th century. Given the collapse of the Soviet Union around this time, there was nobody on Earth who could come close to the domination that American companies such as Apple, IBM, Google, or Microsoft had. Even to the modern day, the "Big Five" (Google, Amazon, Meta, Microsoft, and Apple) have a total valuation of over $3 trillion, putting their valuation above the GDP of the United Kingdom (Sen, 2017). This would be the case for decades, but only until recently.

There should be an asterisk when understanding the modern U.S.-China economic rivalry. It should always be remembered that technically these two nations' economies are incredibly intertwined, nearly to the point where they cannot exist without the other. However, given Chinese mercantilism and American tariffs, this may not be the case forever. This position, however, is not just

in reaction to Chinese actions. The Americans have shown a discrete interest in slowing Chinese technological growth. Returning to the American "trade war", President Donald Trump issued strict limits to Chinese investment in American tech companies, as well as tariffs worth $50 billion in 2018 (Mishra, 2023). These tariffs specifically targeted Chinese imports that were a part of the "Made in China 2025" initiative, showing a discrete interest in keeping China from overtaking the American market (McBride & Chatzky, 2019). Therefore, when understanding how both markets came to be on this collision course with one another, one can understand how Taiwan finds itself between a rock and a hard place.

The Dragon and the Eagle

It is here, in the context of the established technological leader of the world being challenged by explosive and aggressive growth of a rival, which makes the American and Chinese rivalry so potentially dangerous. Whether it be the Greek Philosopher's given example of Athens and Sparta, the Roman example of Rome and Carthage, or Britain and Germany in the prelude to World War I, an established rival having its hegemony challenged more often than not is a pretext to a major conflict. However, in the context of the United States and China, the path to this conflict, if it were to ever take place, would likely be sparked by the intersection between Taiwan and its tech market. However, even the nations' two competing tech markets have to be understood under the broader context of Chinese-American politics.

China and the United States have gone through eras of being outright opponents to being neutral trading partners. Since the Chinese Communist Party took over in 1949, the nation was put under the same blanket as the Soviet Union and the rest of the "Iron Curtain". They were simply another communist nation that needed to be contained. However, there was a key development that made the Chinese become much warmer to the Americans, and that was the Sino-Soviet split. This was an ideological dispute that arose between Mao Zedong and the Soviet Union after the death of Josef Stalin. Simply put, Mao had felt that after the death of Stalin, the Soviet Union had been straying from the original goals of establishing Communism, and this led to the USSR and China becoming hostile to one another (Royal Air Force Museum). This came to the point where China saw the United States as less of a threat than the Soviet Union. Therefore, after negotiations between China and the United States, President Richard Nixon visited the country in 1972 to open up trade between China and the United States. This led to a period where China and the United States became dependent on each other.

Throughout the 1980s and 1990s, China provided the Americans with mountains of cheap goods, while America allowed Deng Xiaoping's export-led economic ideology to thrive. This would morph into a deeper relationship, as China would buy hordes of US Treasury Bonds, giving the US Dollar the foundation it needed to keep its budget deficits reliable (Roach, 2015). This codependency would exist throughout the beginning of the 21st century, but the internal politics of the United States

began to shift.

Populism began to rise in the United States after the 2008 housing crisis, and after a few failed movements like the Tea Party and the Occupy Wall Street movements, someone finally was able to take it by the horns. That man was famous businessman Donald Trump, and his economically populist rhetoric won him the presidency in 2016. A sticking campaign talking point in the Trump campaign was how China was "beating" America by bad trade deals. This rhetoric continued into his presidency, arguably leading to the aforementioned "trade war", as by manipulating its own currency (Imbert, 2019). This was the catalyst, from the American perspective, that led to the trade war, and much of that trade war was done in the technology sector. However, this war of economics has the potential to become a war of missiles and bombs.

Sabre-rattling in the South China Sea

Taiwan finds itself in a perfect scenario to be the powder-keg that ignites a major conflict. Not only do they serve as a complete antithesis to China's self-image as being the only government that is recognized as "China", but they could be a massive resource to China's tech market, as they serve as the world reservoir for computer chips. Especially in the modern context of the world computer chip shortage, these highly valuable resources are becoming more and more scarce (J.P. Morgan Research). China sees Taiwan as being an illegitimate mockery of its communist rule, as they house the losing side of the Chinese Civil War. China, for a long time, has attempted to encroach on the island of Taiwan, by both interfering in the island's politics, as well as publicly shaming those who recognize the small nation. However, both China and the United States rely on Taiwan to supply crucial chips to their technology sectors, and if China were to outright invade the island, the United States would defend them militarily. The United States has already pledged to defend the island in the event of an attack, and has shown to be strengthening diplomatic ties due to recent visits by American political officials such as Nancy Pelosi, the Speaker of the House. China has also shown to not be backing down from military action in the South China Sea, as military drills and exercises are becoming more and more common. This includes things like planes crossing into Taiwanese airspace, and ship and troop maneuvers on the Chinese mainland closest to Taiwan (Wu, 2023). Therefore, due to rising tensions, as well as economic and political context previously discussed, a major conflict emerging from the South China Sea may be imminent.

Conclusion

In the modern world, technology is king. All things run through the internet, or on devices. Whether it be military technology, computers for trading money and materials, or technology we put in our cars and household appliances, everything has computer chips in it. However, such a commodity is an extremely strong source of national pride. If a nation can provide its citizens and companies

with its own homemade computers, they not only can become very powerful due to their production increasing, but can also not rely as much on the outside world. This is the case with China, as they are attempting to become self-reliant on computer technology. However, China's explosive growth in this sector has angered the traditional tech center of the world, the United States. They want to keep China as a customer, as well as make sure they never become too big for the United States to handle. Therefore, the two are becoming natural enemies. However, the island of Taiwan serves as a crucial ally for both China and the United States, as not only does it serve as an important geographical and political point for both nations, the computer chips in Taiwan can keep both the Chinese and American tech markets thriving for decades. Therefore, this is how the island of Taiwan finds itself as the potential battleground for the world's next major conflict.

Not all instances of "Thucydides Trap" have led to major conflicts. For example, the "Cold War" between the United States and the Soviet Union was a decent example of this phenomena, and there were only minor proxy wars and political tensions that ended when one side collapsed. However, it can be argued that we see a similar state of "Cold War" between the Chinese and the Americans. Only time will tell if it will ever go "hot".

References

Allison, G. Thucydides Trap: An Overview. Belfer Center for Science and International Affairs. https://www.belfercenter.org/thucydides-trap/overview-thucydides-trap.

Bilgan, C. and Loh, A. (6 October, 2021) Techno-Nationalism: China's Bid for Global Technological Leadership. London School of Economics. https://blogs.lse.ac.uk/cff/2021/09/28/techno-nationalism-chinas-bid-for-global-technological-leadership/

Computer History Museum. ENIAC. Retrieved May 11, 2023, from https://www.computerhistory.org/revolution/birth-of-the-computer/4/78

Elgan, M (5 October, 2011) What Steve Jobs Means to Silicon Valley. Cult of Mac. https://www.cultofmac.com/121169/what-steve-jobs-means-to-silicon-valley/.

Fried, I (9 April, 2021) Why Threats to Taiwan Are a Nightmare for Tech. Axios. https://www.axios.com/2021/04/09/threats-to-taiwan-nightmare-tech.

Friedberg, A. (Winter, 1996) Science, the Cold War, and the American State. Diplomatic History 20 (no. 1) pp. 107-18 https://doi.org/10.1111/j.1467-7709.1996.tb00254.x.

Imbert, F (5 August, 2019) Trump Accuses China of 'currency Manipulation' as Yuan Drops to Lowest Level in More than a Decade. CNBC. https://www.cnbc.com/2019/08/05/trump-accuses-china-of-currency-manipulation-as-yuan-drops-to-new-low.html.

J.P. Morgan Research. (18 April, 2023) How Long Will the Chip Shortage Last? J.P. Morgan. https://www.jpmorgan.com/insights/research/supply-chain-chip-shortage.

Leyden, J (29 October, 2019) Arpanet Anniversary: The Internet's First Transmission Was Sent 50

Years Ago Today. The Daily Swig. https://portswigger.net/daily-swig/arpanet-anniversary-the-internets-first-transmission-was-sent-50-years-ago-today#:~:text=ARPANET%20initially%20connected%20four%20independent,and%20the%20University%20of%20Utah.

McBride, J and Chatzky, A (13 May, 2019) Is 'made in China 2025' a Threat to Global Trade? Council on Foreign Relations. https://www.cfr.org/backgrounder/made-china-2025-threat-global-trade.

Mishra, V. (9 March, 2023) The Great U.S.-China Tech Decoupling: Perils of Techno-Nationalism. Observer Research Foundation. https://www.orfonline.org/expert-speak/the-great-u-s-china-tech-decoupling/.

US Embassy - China.. (November, 1996) Decision on Accelerating S&T Development. US Embassy - China. https://web.archive.org/web/20010304135120/http://www.usembassy-china.org.cn/english/sandt/stdec2.htm.

Roach, S. (29 September, 2015) Are the US and China Trapped in Economic Codependency? World Economic Forum. https://www.weforum.org/agenda/2015/09/are-the-us-and-china-trapped-in-economic-codependency/#:~:text=Codependency%20between%20America%20and%20China,in%20a%20marriage%20of%20convenience.

Royal Air Force Museum, Sino-Soviet Split Retrieved May 11, 2023, from https://www.nationalcoldwarexhibition.org/schools-colleges/national-curriculum/detente/sino-soviet-split.aspx.

Sen, C. (15 November, 2017) The 'big Five' Could Destroy the Tech Ecosystem. Bloomberg. https://www.bloomberg.com/opinion/articles/2017-11-15/the-big-five-could-destroy-the-tech-ecosystem.

The Economist (13 July, 2022). Xi Jinping Has Nurtured an Ugly Form of Chinese Nationalism. https://www.economist.com/china/2022/07/13/xi-jinping-has-nurtured-an-ugly-form-of-chinese-nationalism.

Wolff, A (Spring, 2007) China's Drive Toward Innovation. Issues in Science and Technology 23 (no. 3) pp. 54-62.

World Bank Open Data. GDP (Current US$) World Bank. Retrieved May 11, 2023, from https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?most_recent_value_desc=true

World Population Review. Military Size by Country 2023 Retrieved May 11, 2023. https://worldpopulationreview.com/country-rankings/military-size-by-country.

Wu, H (10 April, 2023) China Military 'ready to Fight' after Drills near Taiwan. AP News. https://apnews.com/article/china-military-taiwan-us-7549c646a377f1f199d2cda983573279.

Yau, E. (May, 2021) The Rise of China Tech . FTSE Russell. https://www.ftserussell.com/blogs/rise-china-tech.

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The Role of the Nuclear Fuel Supply Chain in Energy Security

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Nuclear energy accounts for nine percent of the United States' total electrical energy generation and is increasing as governments and companies progress toward decreasing the use of fossil fuel energy sources. As with any energy source, the acquisition of fuel, the economy of producing energy, and the resulting waste products are all points of concern for national security. A comprehensive analysis of the acquisition, economy, and safety of nuclear energy was performed to understand the role nuclear energy in the national security interests of the United States. Several sources were consulted for this study, including the World Nuclear Association, the U.S. Departments of Energy, the U.S. Nuclear Regulatory Commission, and various academic resources to name a few. The result of this study was a consolidation of information on uranium fuel cycles, the economics of uranium resource trading, and the use of alternative fuels other than uranium-235 nuclides. It was concluded that the concerns of national security for nuclear energy were considerable, but manageable with the current fields of research and development.

Keywords: Nuclear energy, nuclear fuel supply chain, energy security, national security, uranium fuel cycle

1. Introduction

Electrical energy is one of the most important resources for a sovereign nation. A country's government and citizens require electricity for a functioning modern society. Water, food, and shelter all require electricity to be effective. Fuel resources for electrical energy generation have impacts on a country's economy, security, and the life of its citizens (U.S. Department of Energy, 2025). Ensuring that the United States is not fully reliant on another country for fuel is in the best interest of the government. If another country were to have full control over the United Sates fuel supply, that country could extort the U.S. and its people by having control over the economy and public health.

According to the U.S. Energy Information Administration (EIA, 2024a), 74% of the total energy consumed was through petroleum and natural gas, and only nine percent was nuclear energy as of 2023. Also in 2023, the EIA concluded that the U.S. was a net exporter of petroleum resources with 1.64 million barrels-per-day exported (U.S. Energy Information Agency, 2024b). Canada, a close ally with the U.S., was the largest source of imports of petroleum to the U.S. – at 3.62 million barrels-per-day. Nuclear fission mainly uses uranium compounds as a source of fuel. The U.S. imported 32 million pounds of triuranium octoxide (U_3O_8) which was 99% of the supply in 2023 according to the EIA (Johnson, 2025). Canada, Australia, Russia, Kazakhstan, and Uzbekistan were the primary sources of the imported compound.

Nuclear energy can be split into two major categories, fission and fusion. Fusion energy is the process of combing two isotopes of light elements such as hydrogen, helium, and lithium to form heavier elements. Fusion energy is not yet a reliable source of energy, and is still a field of active research to produce net positive energy. As such, fusion is beyond the scope of this study. Nuclear fission, on the other hand, has been utilized as a source of electrical energy generation since the early 1950's and continues to increase in importance as countries and corporations tend toward decreasing carbon-dioxide emissions. Fission works by colliding a neutron with uranium, an element with 92 protons. The fission reaction produces heat which is transferred to a coolant. That coolant, most often water, either directly turns a turbine or is used in a heat exchanger to heat more water which then turns a turbine. The fission also produces additional neutrons that collide with other surrounding uranium to create a self-sustaining chain reaction. This process is the basis for most nuclear reactors and will be the focus of this study.

Uranium-235 (U-235) is the isotope of uranium most used in commercial nuclear fission. U-235 is considered fissile, meaning that it readily undergoes fission, but makes up 0.7% of natural uranium (World Nuclear Association, 2025a). U-238 makes up the remainder of the natural uranium supply and is not fissile under the same conditions as U-235. Natural uranium is mined from deposits that can occur at various depths underground. The depth of the deposit determines the technique used for extracting the uranium. The U_3O_8 imported into the U.S. is the result of mining and milling of a natural uranium deposit. This uranium oxide compound is enriched until it reaches a uranium dioxide (UO_2) compound that is between 3.5 and 5% U-235. This uranium dioxide is fuel-grade uranium and is sufficient for commercial energy production. Uranium dioxide enriched to greater than 90% U-235 is considered weapons-grade uranium and the regulation of weapons-grade uranium is called non-proliferation. Depleted uranium is the remaining uranium dioxide that is less than 0.7% U-235.

Decades of research into nuclear fuels have revealed that U-235 is not the only viable fuel source. To fully understand how different fuels can be used, it is important to understand neutron temperature. Neutron temperature refers to categories that neutrons can be placed into depending on the kinetic energy of the neutron. U-235 is fissile with thermal neutrons at 20℃ which have a kinetic energy of about 0.025 electron-volts (eV) according to Oregon State University (2004). Two other important

categories for nuclear fission are fast neutrons at about 10-20 MeV and slow neutrons between 0.01 and 0.1 mega-electron-volts. Fast neutrons can be used in place of thermal neutrons and can be used to fission U-238. This type of fission increases the fuel efficiency of uranium because it can use depleted uranium supplies. Thorium, specifically thorium-232 (Th-232) is another alternative fuel that can be used in place of U-235.

This paper will focus on the study of nuclear fission and how the fuel cycle, primarily comprised of U-235, is important to the overall security of the United States government and its people. The life cycle of nuclear fuel begins with mining, then enrichment, usage, and finally waste removal. The specifics of these stages depend on the exact element and isotope used. The life cycle of U-235 will be explored followed by comparisons to alternative fuels such as U-238 and Th-232.

2. Mining and Milling

Uranium, like coal, is a solid mineral that must be mined. The method used for mining uranium usually depends on the depth that the uranium ore deposit is found at (Li and Yao, 2024). Ore deposits near the surface are mined using open-pit mining. Deposits deeper than the threshold for open-pit mining use an underground mining technique. The final extraction technique, in situ leaching (ISL) can be used depending on the depth and type of rock that contains the ore (Li and Yao, 2024). ISL also has various sub-methods that can be leveraged depending on the situation including: acid leaching, alkaline leaching, neutral leaching, and bioleaching.

2.1. Open-pit and Underground Mining

Open-pit mining is utilized for ore deposits that are relatively shallow. The exact depth that allows for open-pit mining depends on the rock and geology. In open-pit mining, the top soil and overburden layers above the ore are removed such that the ore is exposed to the surface and can be removed directly (Li and Yao, 2024). Underground mining, on the other hand, is for deeper deposits where removing layers would not be possible or economical. During underground mining, miners descend to various levels with tunnels exposed to ore deposits (Li and Yao, 2024). The ore deposits are then extracted and brought to the surface for processing.

2.2. In Situ Leaching

In situ leaching is the process of injecting a uranium ore deposit with a leaching solution and extracting the solution for further processing (Li and Yao, 2024). The leachate solution and uranium ore solution are fluids that have properties more like petroleum and natural gas. As such, the extraction techniques for the uranium solution are like other fluids. This also means that ISL has the same problems as other fluid extractions including groundwater pollution and leaking. Despite these concerns, Li and Yao (2024) claimed that ISL is more sustainable and economical when it can be used in place of open-pit and underground mining. Mudd and Diesendorf (2007) claimed that no matter what the technique, as more uranium is discovered and mining techniques improve, the

economics will improve. Fig. 1 from the U.S. Nuclear Regulatory Commission portrays a cartoon example of a simple in situ leaching process with a short description.

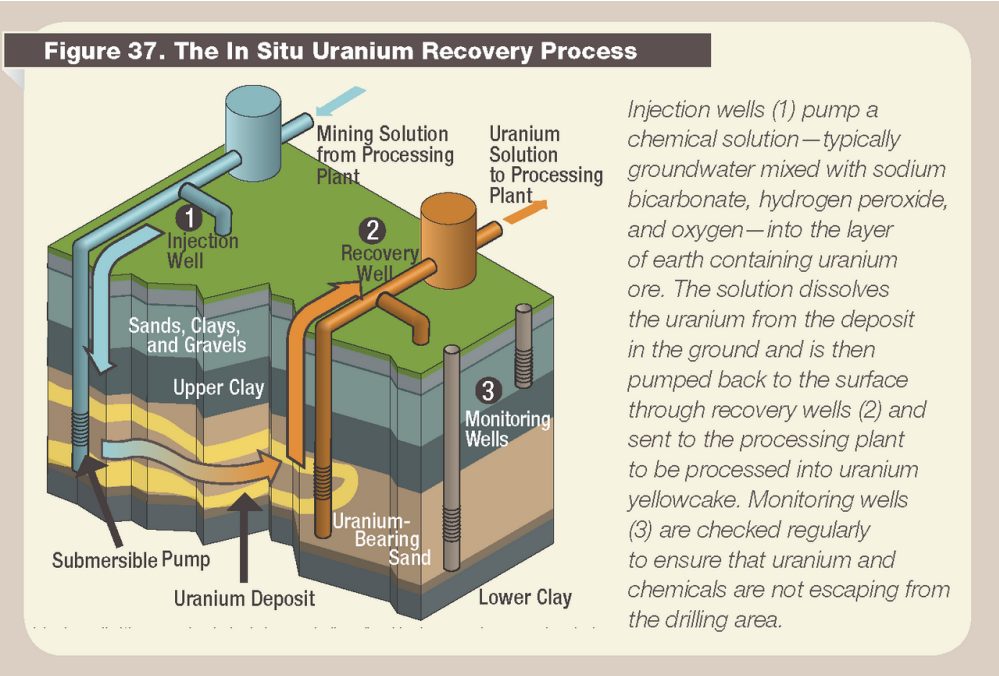


Figure 1: An example of in situ leaching with a blue injection well and an orange recovery well.[a]

[a]Information Digest, 2013–2014 (NUREG-1350, Volume 25) Section 4, Nuclear Materials http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1350/

There are four major types of ISL that are used depending on the composition of the material that the uranium ore is located. Acid leaching uses primarily strong acids that dissolve the uranium ore and can be very effective, especially for uranium that is readily oxidized. However, acid leaching is not useful when the deposit has carbonate content greater than 8% (Li and Yao, 2024). Alkaline leaching is used when the carbonate content is greater than 8% and there is a relatively small concentration of pyrite. Alkaline leaching is also less corrosive and has less impurities, but comes at the cost of greater energy requirements. Neutral leaching maintains a pH between about 7 and 8 and leverages the formation of uranyl ions for less environmental impact compared to the previous two techniques. Finally, bioleaching is considered more sustainable and economical than the previous techniques, but is used when there is relatively large pyrite and sulfide content in the deposit (Li and Yao, 2024). Open-pit and underground mining and ISL are the methods of retrieving unrefined uranium from ore deposits underground. Once the ore is extracted it needs to be extracted from the ore rock or solution before it can be refined into a useful fuel source.

2.3. Milling

Milling is the process of separating the ore from the rock that was mined with the ore. The mill is typically near the mine or between a group of mines because the ore cannot be sold before it has been milled. The mill crushes the rock of any solid ore, leaches it with sulfuric acid or a strong alkaline solution. The uranium is then precipitated, and is dried (World Nuclear Association, 2025a). The dried U_3O_8, called yellowcake, is sold and is about 80% uranium compared to about a 0.1% in the original ore. U_3O_8 is the material imported into the U.S. and other countries with the facilities for enrichment.

2.4. Mining Economics

Wang and Xing (2022) developed mathematical models and relationships between various factors that impact Global Uranium Resource Trade Networks (GURTNs). They concluded that trade relationships could be improved by natural uranium exporters increasing resources to better control their ability to influence the trade. Additionally, Wang and Xing suggested that China, another major consumer and producer of nuclear energy resources should increase trade participation to better improve domestic and international economy for uranium resources. The economics of uranium have an impact on the general global energy market (Mitreski and Lutey, 2024). As the importance of uranium increases for low-carbon-emission goals, the effect of the economics of uranium will also increase.

Uranium is a non-renewable resource, more like fossil fuels than other alternative energy sources. The efficiency of uranium mining and enrichment are major factors in the amount of usable uranium. New technologies for improving uranium usage will likely lead to increased energy prices for nuclear energy but innovation could be necessary if uranium supplies begin to deplete (Liebert and Englert, 2015). However, the demand for uranium is unpredictable because of the history of nuclear energy and the volatility of the energy market (Monnet et al., 2017). Improvements in alternative reactor types would also increase the supply of viable nuclear fuels.

3. Enrichment

The unenriched U_3O_8 imported into the U.S. contains the natural uranium isotope composition of about 0.7% U-235 and U-238 as the remainder. Enrichment is the process of increasing the U-235 concentration by separating out the U-238 isotopes in the uranium oxide compound. Fuel for nuclear reactors only needs to be between 3.5 and 5% U-235 to sustain the nuclear chain reaction necessary to continuously produce energy. The enrichment of uranium is regulated by international laws because at larger concentrations of U-235, it can become dangerous. Particularly at greater than 90% U-235 the compound is considered weapons-grade. Weapons-grade uranium is used in the development and creation of nuclear weapons. The U.S. and many other countries are part of non-proliferation efforts to monitor and prevent the manufacturing of weapons-grade uranium.

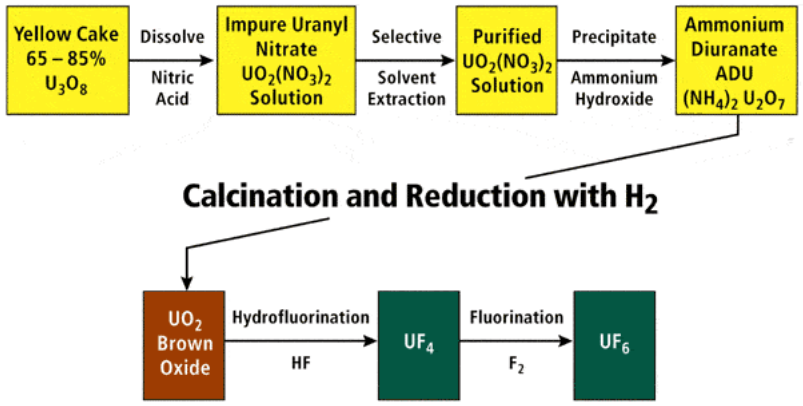


Figure 2: A flow chart showing the progression of chemical reactions used to convert U_3O_8 to UF_6 before enrichment (Source: US Nuclear Regulatory Commission).

According to the World Nuclear Association (2025a), for uranium to be enriched it must be in a gaseous form. Most of the uranium oxide compound reacts to form uranium hexafluoride (UF6) as a liquid and is made to solidify. Fig. 2 is from the U.S. Department of Energy and depicts a flow chart that shows the reactions used to convert U3O8 into UF6. The UF6 is shipped to the enrichment facility where it is separated into low-enriched uranium that is mostly U-235 and depleted uranium that increases in U-238 concentration without the U-235. There are multiple enrichment techniques but the most common utilizes the mass difference between the isotopes in centrifuges. The enriched UF6 is then converted into uranium dioxide. The UO2 masses are pressed and heated at over 1,400℃ to form pellets that are inserted into fuel rods.

3.1. U.S. Enrichment Facilities

The U.S. is the largest consumer of nuclear energy at about 782 terra-watthours (TWh) followed by China at about 418 TWh (World Nuclear Association, 2025b). Multiple U.S. government agencies agreed that domestic uranium mining and enrichment are priorities for the country's energy supply (U.S. Government Accountability Office, 2020). Currently Russia supplies about 20% to 30% of uranium enrichment to the U.S. and Europe (U.S. Department of Energy, 2025). The U.S. is currently looking to expand the domestic mining and enrichment capabilities for decreasing reliance on Russian supplies. As of now, there are two gas centrifuge uranium enrichment plants. These plants are in New Mexico and Ohio and are companies contracted by the U.S. government. Demand for nuclear energy is expected to increase and the need for domestic enrichment facilities will grow with demand for energy.

3.2. Non-Proliferation

In 1968 the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) was signed by 191 countries (International Atomic Energy Agency, 1970). In the treaty there are five nuclear-weapon States, including the U.S., that may maintain a nuclear weapons arsenal but may not assist in or encourage the development of nuclear weapons in non-nuclear-weapon States. The International Atomic Energy Agency (IAEA) and all countries that signed the NPT are tasked with maintaining the treaty and adhering to it. When a country gathers a uranium supply for enrichment, that country is observed to ensure that the uranium is used for civilian purposes and is not enriched to weapons-grade. There are many techniques for non-proliferation and the monitoring of international uranium resources. Oak Ridge National Laboratory is a major source of non-proliferation research in the United States. Non-proliferation is a direct national security concern that ensures that countries with uranium supplies do not build a nuclear arsenal and threaten nuclear war. One indirect source of non-proliferation is the increased demand for energy generation. Countries that have the capabilities to use uranium are predicted to use them more for nuclear energy generation rather than weapons manufacturing as the energy demands of the country increase (Zhangozhayeva et al., 2024).

4. Nuclear Fuel Waste

After uranium fuel is used in a nuclear reactor, it becomes spent fuel. The World Nuclear Association (2025a) estimateed that about 1% of the spent fuel is U-235, 1% plutonium, 95% U-238, and the remainder are miscellaneous fission products. Spent fuel can either be reprocessed and recycled or placed in long-term storage facilities. Nuclear waste products are radioactive and produce lethal doses of radiation at about 10,000 Rem per hour for about 10 years after being removed from the power plant whereas the average human has a fatal acute dose limit of about 500 Rem (U.S. Environmental Protection Agency, 2017; U.S. Nuclear Regulatory Commission, 2024). Nuclear energy is an attractive alternative to fossil fuels because it releases zero direct carbon-dioxide emissions which are known greenhouse-gas contributors. Greenhouse gases are gases produced by human activity that trap heat in the earth's atmosphere and leads to climate change.

While nuclear energy does not produce carbon dioxide, the lethality and lifetime of spent nuclear fuels are also harmful to life and the environment. The U.S. Nuclear Regulatory Commission (NRC, 2024) asserts that the uranium isotopes that absorb neutrons rather than fissioning are called transuranic wastes which take longer to decay compare to other fission products and are the major radioactive hazard after 1,000 years. Plutonium-239 (Pu-239), a possible product of radioactive decay of uranium, has a half-life of 24,000 years meaning that half of the radioactive Pu-239 isotope will have decayed after 24,000 years. Finding ways to recycle spent fuel to achieve greater yields before placing spent fuel in long-term storage is one solution for increasing the available nuclear fuel supply and ensuring that the fuel is not wasted before it enters long-term storage. Once the spent fuel is in long-term storage, governments must ensure that the fuel is secured and the spent fuel is not a danger to the health of people and the environment in the surrounding area for millennia.

4.1. Fuel Recycling

Reprocessing of spent nuclear fuel involves the separation of uranium and plutonium from other fission products that cannot be used as recycled nuclear fuel (U.S. Nuclear Regulatory Commission, 2024; World Nuclear Association, 2025a). The remaining U-235 is in greater concentration than natural uranium and can be further refined to be used again as a fissile material. The plutonium separated in the waste product can be used as an alternative fuel called mixed oxide (MOX) fuel. Remaining U-238 fuel is also not fissile under thermal neutron conditions but can also be considered an alternative fuel in a fast neutron reactor.

4.2. Waste Storage

Radioactive waste is produced in three major categories: low-, intermediate-, and high-level waste. Low-level waste has radioactive content that makes it dangerous to human health, but the radioactive content has shorter half-lives than the other two levels (European Nuclear Safety Regulators Group, 2025). Intermediate-level waste contains long-lived radioactive isotopes and must be stored underground and requires more containment than low-level waste. High-level waste generates heat and radioactivity that must be handled in specific manners and placed in facilities created specifically for high-level waste. Currently, high-level waste facilities are not permanent storage solutions as governments continue to use the spent fuel for a variety of purposes and do not want to lose access to potential radioactive resources (World Nuclear Association, 2025a). When permanent storage facilities are required, it is estimated that the fuel will be stored about 500 meters below the surface and will be sealed and made inaccessible. Current fields of research in nuclear waste storage focus on methods of nuclear fuel storage and ways to improve public reception of nuclear waste to increase the number of possible storage facilities.

Processing waste is just as important to national security as acquiring nuclear fuels. If nuclear waste is not properly stored and maintained, dangerous radioactive isotopes could contaminate groundwater, and affect the drinking water and agriculture of an area for hundreds of generations of people. Radioactive waste poses health concerns and public perception of nuclear energy hinges on governments properly securing their radioactive waste. Recycling spent fuel and using the Pu-239 and U-238 byproducts as alternative fuels are one way of decreasing the amount of waste and increasing the efficiency of the mining and enrichment processes.

5. Alternative Fuels

Because U-235 is the only fissile material in commercial nuclear reactors, the amount of waste produced to achieve fuel-grade uranium and produced from the usage of uranium for the amount mined is an area of concern for governments and nuclear energy companies. Increasing the number of viable fuel sources is one method of increasing the efficiency of nuclear fuel resources that has been researched for as long as nuclear power has been used. Three possible alternative fuels are U-238, Pu-239, and Th-232 which are not fissile under the same conditions as U-235. To achieve

fission with these alternative fuels, nuclear reactors that can utilize fast neutrons or coolants that are not water must be used.

5.1. Types of Nuclear Reactors

Most commercial nuclear reactors are known as Light-Water Reactors (LWRs). These reactors use water that has not been converted into heavy water – water that is dominated by hydrogen-2 (H-2) isotope, called deuterium. LWRs can also be split into two subcategories, Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs) (The Institution of Engineering and Technology, 2008). BWRs work by operating at near-atmospheric pressures that allow water to boil under the extreme heat of the nuclear reaction and directly turn a turbine to generate electricity. PWRs, on the other hand, operate at greater-than-atmospheric pressures that suppress the boiling of water and transfer heat to another water loop that is allowed to boil that then turns the turbine. Both LWR configurations are used commercially, but most reactors are PWRs. Fig. 3 shows an example of a PWR including the coolant water reservoir and connections to the power grid. The water in LWRs and the coolants used in alternative reactors also act as moderators that determine the energy of the neutrons. To maintain higher-than-thermal-energy neutrons, the coolant must not be a strong moderator and must be more thermally conductive than light water because reactions with slow and fast neutrons release more heat.

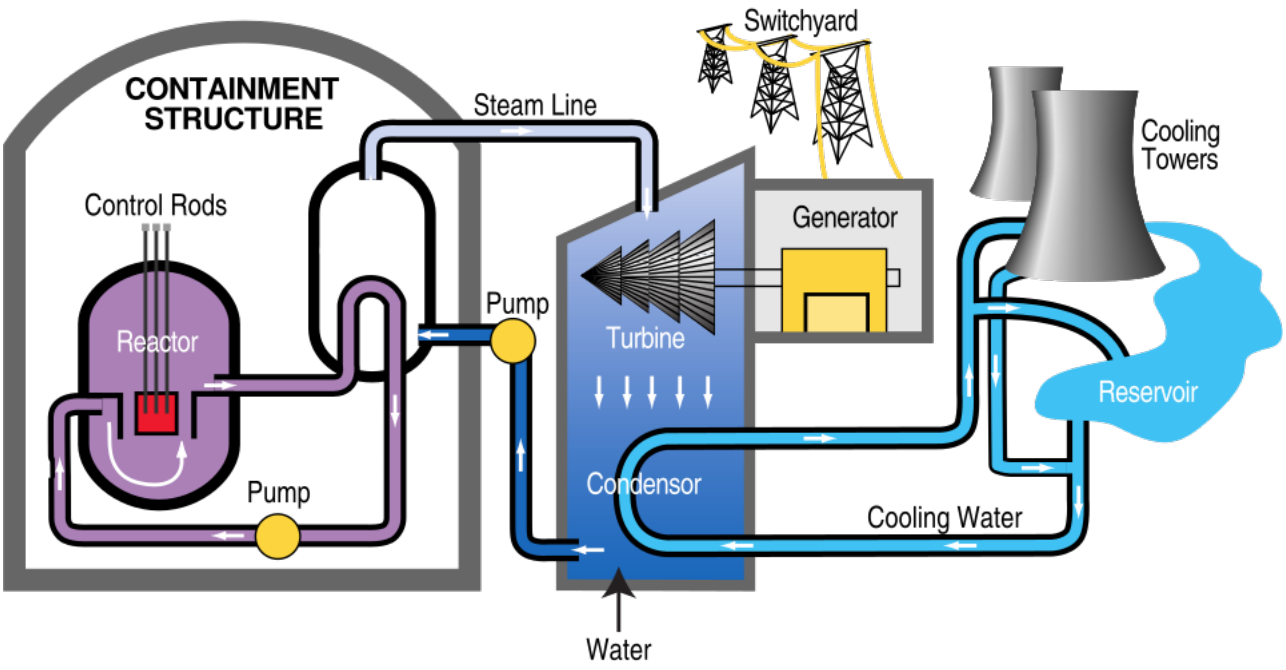


Figure 3: A depiction of a pressurized-water reactor with a coolant reservoir and connections to a power grid (Source: Tennessee Valley Authority).

Reactors that do not fall under the categories of LWRs are generally referred to as advanced reactors.

Advanced reactors include, but are not limited to, Gas-Cooled Fast Reactors (GFRs), Molten-Salt Reactors (MSRs), Heavy-Water Reactors (HWRs), Lead-Cooled Fast Reactors (LFRs), and Sodium-Cooled Fast Reactors (SFRs) (Generation IV International Forum, 2025). Each of these types of reactors use a different type of coolant that has different heat transfer and neutron moderation capabilities compared to the others. The differences between these reactors and the LWRs are what allow for the use of fuel other than U-235. Many of these reactors are still in a research and development stage and are not currently commercially viable.

5.2. U-238 and Pu-239

As stated previously, U-238 is non-fissile because it is a more stable isotope than U-235. However, when U-238 absorbs fast neutrons, it undergoes beta-decay which causes the isotope to gain an atomic number at the same mass (Encyclopedia Britannica, 1998):

$$^{238}\mathrm{U} + n \rightarrow ^{239}\mathrm{U} \tag{1}$$

$$^{239}\mathrm{U} \rightarrow ^{239}\mathrm{Np} + \beta^{-} \tag{2}$$

$$^{239}\mathrm{Np} \rightarrow ^{239}\mathrm{Pu} + \beta^{-} \tag{3}$$

Pu-239 and Pu-241 are both possible fissile materials produced by this reaction or a similar beta-decay process. The β^{-} particle is an electron that is released by the decay of the excess neutron into a proton. The original U-238 can undergo two stages of beta-decay after absorbing one or more neutrons to transmute into an isotope of neptunium and then a fissile plutonium isotope (World Nuclear Association, 2021). U-238 makes up 99.3% of the composition of the natural uranium supply. Fast neutron reactors have the capacity to increase the amount of usable uranium and reduce the necessity for expensive enrichment. GFRs, HWRs, LFRs, and SFRs are all reactors that are in development to support the use of fast neutrons for fission with U-238 nuclides. Reactors that can use U-238 must also support fission of Pu-239. Uranium-238 and Pu-239 are products of depleted uranium and spent U-235 fuel. Fast neutron reactors will increase the capacity to more of the products derived from each stage of the uranium fuel cycle.

If a reactor produces more fissile material than is initially used to begin, the nuclear reactions, the reactor is considered a breeder reactor (World Nuclear Association, 2021). Most reactor designs, even fast neutron reactors, are not considered breeder reactors because they consume more fissile material than they produce. Breeder reactors are another area of active development that have the potential to increase the efficiency and economy of nuclear fuels.

5.3. Th-232

Like U-238, Th-232 is not naturally fissile and must undergo a beta-decay process through protactinium-233 (Pa-233) to finally reach uranium-233 (U-233), an isotope of uranium that is fissile, but is not

found naturally (World Nuclear Association, 2024):

$$^{232}\text{Th} + n \rightarrow ^{233}\text{Th} \tag{4}$$

$$^{233}\text{Th} \rightarrow ^{233}\text{Pa} + \beta^- \tag{5}$$

$$^{233}\text{Pa} \rightarrow ^{233}\text{U} + \beta^- \tag{6}$$

Thorium is more abundant than uranium and only naturally occurs in the Th-232 form. Thorium can be used in various reactors including LWRs and MSRs. An example MSR can be seen in Fig. 4 and is shown to have several fluid loops and heat exchangers, showing the complexity of these advanced reactors. The Pa-233 can either be separated from the thorium and uranium to be reprocessed or – especially in MSRs – can be continuously decayed within the reactor without additional processing. Thorium reactors also have the potential to be breeding reactors, and can do so by using slow neutrons unlike the U-238 reactors which require fast neutrons. It is also possible to cause direct fission of Th-232 using fast neutron systems, however there is no relative advantage to doing when compared to the beta-decay process (World Nuclear Association, 2024).

The use of alternative fuels other than U-235 has the potential to improve the economic, public perception, and security of nuclear energy. According to the Generation IV International Forum (GIF), a global organization designed to support the development of a new generation of advanced nuclear reactors, new advanced reactors will reduce the long-term impact of nuclear waste, improve the safety of nuclear reactors by decreasing the likelihood and severity of reactor damage, and will support non-proliferation efforts by further discouraging the use of fuel resources for illegal weapons development. GIF also notes that these new reactors will have cost advantages, but will present economic risks when compared to traditional and previously established energy sources (Generation IV International Forum, 2025. The effectiveness and efficiency of traditional LWRs will ensure that LWRs are not fully replaced by advanced reactors, but the availability of alternative reactors for diversification of fuel and energy resources could be important to ensuring the security of the national nuclear energy supply.

6. Conclusions

Electricity generated by nuclear power plants is an increasingly attractive option for governments as countries move toward alternatives to fossil fuel generators. Nuclear energy has been used since at least the 1950s after the discovery of nuclear fission and the development of nuclear weapons. Since then, nuclear reactors of many types categorized by their coolants and neutron energies have been developed for a variety of applications and fuel cycles. The most common type of nuclear reactors are light-water reactors that use the uranium isotope U-235. As a fuel for power generation, U-235 is rare and expensive to acquire in usable quantities. It can be used in nuclear weapons by potentially dangerous governments or organizations. As such, nuclear energy poses significant challenges for nuclear security including economics, public health, and military concerns.

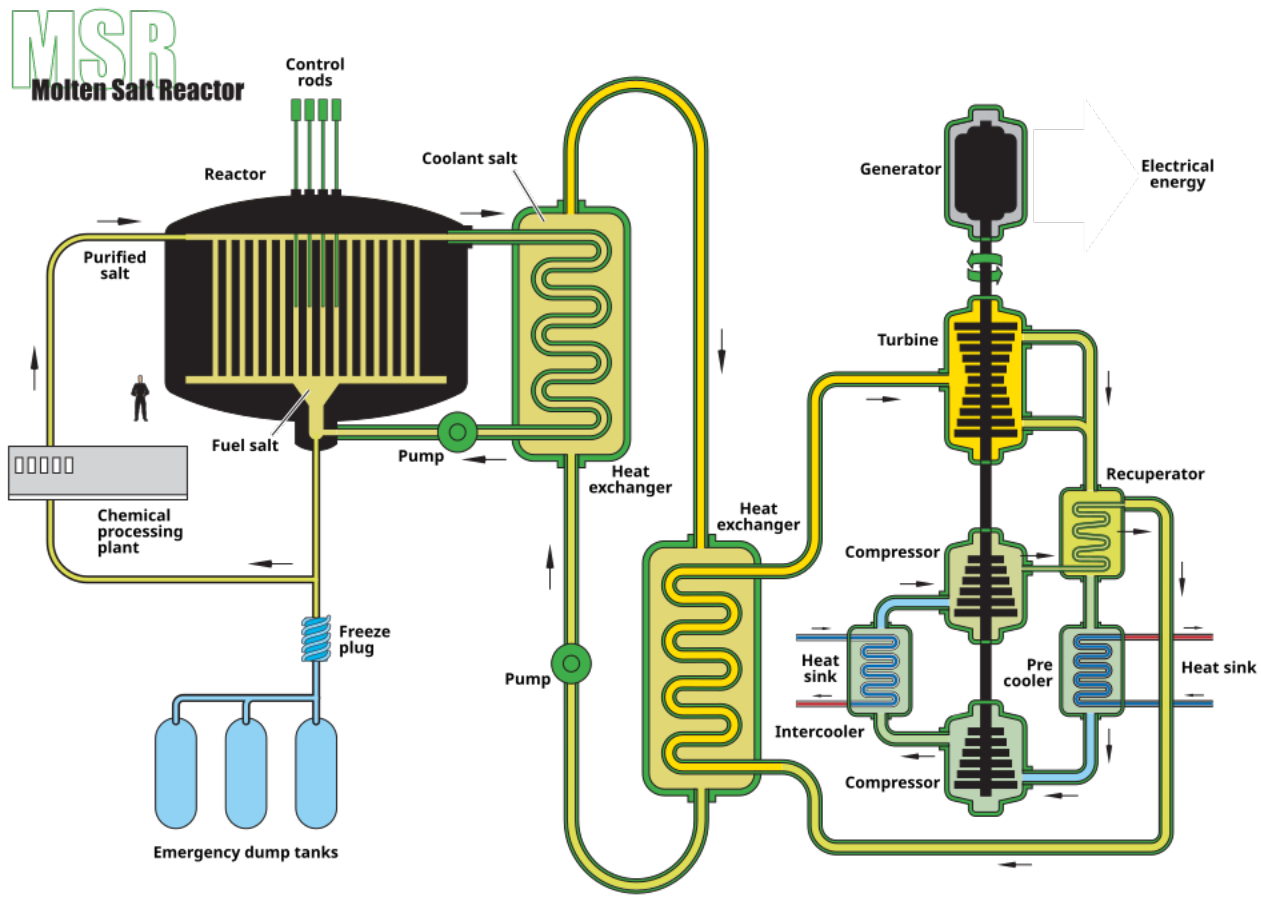


Figure 4: A molten salt reactor configuration with several fluid loops including two salt loops for the fuel mixture and coolant (Source: US Department of Energy Nuclear Energy Research Advisory Committee).

If the United States becomes reliant on nuclear energy as a primary source of energy, the concerns posed about the uranium fuel cycle will become more necessary to be addressed. Currently, the U.S. imports about 99% of its uranium fuel supply from various countries. The U.S. has enrichment facilities such that it only needs to import raw uranium. Maintaining positive relationships with the countries that uranium is imported from will be crucial to ensuring that uranium can be used as an energy generating fuel. Also keeping the diverse sources of uranium ensures that no one country could exploit the U.S. government to act against the interests of its populace.

The economics of uranium depend on the mining capabilities of the exporting countries, and the ability and willingness of those countries to continue making the uranium available. As demand for nuclear energy increases, it is predicted that the economy of the uranium trade will improve as more uranium is discovered, and new mining and enrichment technologies are developed. Another improvement to the economy of nuclear fuels could come in the form of alternative fuel sources. Uranium-238, Pu-239, and Th-232 are potential alternatives to U-235. The U.S. must continue to

focus on improving the economics of nuclear energy if the government is to rely on nuclear as a primary source of nuclear energy. Economy is another possible point of leverage that could be used to exploit governments and is a point of concern for national security.

Uranium-fuel waste is another major point of concern for the growth of reliance on nuclear energy. Spent uranium fuel is radioactive and harmful to human health, especially at fatal doses of radiation. Current solutions for storing spent fuel are temporary such that the waste can continue to be used in a variety of ways. However, spent fuel will eventually need to be stored permanently and without the ability to harm people or the environment. Methods are being developed for storage of nuclear fuel, and the current temporary solutions are generally considered to be safe.

Nuclear energy as an alternative to fossil fuels has historically, and continues to, face challenges because of the possible environmental and economic threats it poses. However, nuclear energy has the potential to improve national security and environmental health.

References

Encyclopedia Brittanica. (1998). Uranium Processing. Britannica. Retrieved December 1, 2025, from https://www.britannica.com/technology/uranium-processing/additional-info

European Nuclear Safety Regulators Group. (2025). Categorisation of radioactive waste | ENSREG. Retrieved December 1, 2025, from https://www.ensreg.eu/safe-management-spent-fuel-and-radioactive-waste/categorisation-radioactive-waste

Generation IV International Forum. (2025). Generation IV Goals, Technologies and GIF R&D Roadmap. GIF Portal.

Retrieved December 1, 2025, from https://www.gen-4.org/generation-iv-criteria-and-technologies

International Atomic Energy Agency. (1970). Treaty on the Non-Proliferation of Nuclear Weapons. Retrieved December 1, 2025, from https://www.iaea.org/sites/default/files/publications/documents/infcircs/1970/infcirc140.pdf

Johnson, S. (2025). U.S. nuclear generators import nearly all the uranium concentrate they use—U.S. Energy Information Administration (EIA).

Retrieved December 1, 2025, from https://www.eia.gov/todayinenergy/detail.php?id=64444

Li, G., & Yao, J. (2024). A Review of In Situ Leaching (ISL) for Uranium Mining. Mining, 4(1), 120–148. https://doi.org/10.3390/mining4010009

Mitreski, P. & Lutey, M. (2024). The Structural Importance of Uranium: Commodity Volatility and Sustainability. Journal of Business and Behavioral Science: Volume 36, 4-14.

Mudd, G.M. & Diesendorf, M. (2007). Sustainability of Uranium Mining and Milling: Toward Quantifying Resources and Eco-Efficiency. Environmental Science & Technology: Volume 42, 2624-2630.

Oregon State University. (2004). NE 581—Radiation Protection—OSU Extended Campus—Oregon State University. Retrieved December 1, 2025, from https://courses.ecampus.oregonstate.edu/ne581/five/neutrons.htm

The Institution of Engineering and Technology. (2008). Nuclear Reactor Types. Retrieved December 1, 2025, from https://www.theiet.org/media/8809/nuclear-reactor-types.pdf

U.S. Department of Energy. (2025). Uranium Enrichment, Explained. Energy.gov. Retrieved December 1, 2025, from https://www.energy.gov/ne/articles/uranium-enrichment-explained

U.S. Department of Energy. (2025). Energy Security. Energy.gov. Retrieved December 1, 2025, from https://www.energy.gov/topics/energy-security

U.S. Energy Information Administration. (2024a). U.S. energy facts explained—Consumption and production—U.S. Energy Information Administration (EIA).

Retrieved December 1, 2025, from https://www.eia.gov/energyexplained/us-energy-facts/

U.S. Energy Information Administration. (2024b). Frequently Asked Questions (FAQs)—U.S. Energy Information Administration (EIA). Retrieved December 1, 2025, from https://www.eia.gov/tools/faqs/faq.php?id=727&t=6

U.S. Environmental Protection Agency. (2017). Radiation Terms and Units [Overviews and Factsheets]. https://www.epa.gov/radiation/radiation-terms-and-units

U.S. Nuclear Regulatory Commission. (2024). Backgrounder on Radioactive Waste | Nuclear Regulatory Commission. Retrieved December 1, 2025, from https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/radwaste

Wang, Z. & Xing, W. (2022). Study on the Characteristics and Evolution Trends of Global Uranium Resource Trade from the Perspective of a Complex Network. Sustainability 2022, 14, 15295

World Nuclear Association (2017). Fast Neutron Reactors—World Nuclear Association. Retrieved December 1, 2025, from https://world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors

World Nuclear Association. (2024). Thorium—World Nuclear Association. Retrieved December 1, 2025, from https://world-nuclear.org/information-library/current-and-future-generation/thorium

World Nuclear Association. (2025a). Nuclear Fuel Cycle Overview—World Nuclear Association. Retrieved December 1, 2025, from https://world-nuclear.org/information-library/nuclear-fuel-cycle/introduction/nuclear-fuel-cycle-overview

World Nuclear Association. (2025b). Nuclear Power in the World Today—World Nuclear Association. Retrieved December 1, 2025, from https://world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today

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Material Durability in Permanent Nuclear Waste Disposal: The Beishan Case

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The permanent disposal of High-Level Waste presents a critical global security challenge because of the extreme longevity of radionuclides. Deep Geological Repositories (DGR) utilizing Engineered Barrier Systems are the accepted solution for isolating this waste from the biosphere. This paper highlights the suitability of the Beishan DGR in China, examining how its arid Gobi Desert climate and stable granite host rock provide optimal hydrogeological conditions for radionuclide retardation. The corrosion mechanisms of three candidate canister materials, carbon steel, copper, and titanium alloys, are evaluated within the geochemical environment in Beishan. While carbon steel and copper offer predictable behaviors, they face risks from hydrogen-induced cracking and localized corrosion, respectively. Titanium alloys demonstrate superior corrosion resistance through stable oxide film formation but remain susceptible to hydrogen embrittlement under long-term anoxic conditions. The successful implementation of the Beishan repository depends on validating these material performance through in-situ testing.

Keywords: High-level waste, deep geological repositories, Beishan, engineered barrier systems, corrosion, nuclear materials, canister materials

1. Introduction

Radioactive waste contains radioactive materials resulting from various nuclear activities. The management strategy for this waste is determined by its radiological characteristics: activity level, half-life, and decay heat generation. Radioactive waste is classified into three principal categories: (a) Low-Level Waste (LLW), contains small amounts of mostly short-lived radioactivity. LLW is generated widely and accounts for the largest proportion of waste volume. (b) Intermediate-Level Waste

Table 1: Classification and characteristics of radioactive waste categories.

Category	Volume %	Activity %	Decay Heat Requirement	Primary Sources
High-Level Waste (HLW)	<1%	≈95%	Requires Active Cooling (>2 kW/m^3)	Spent Nuclear Fuel, Vitrified Reprocessing Residues
Intermediate-Level Waste (ILW)	≈6%	≈4%	Negligible	Reactor operational waste, fuel element cladding
Low-Level Waste (LLW)	≈94%	≈1%	None	Protective clothing, tools, medical isotopes

(ILW), contains larger concentrations of radioactivity than LLW and generally requires some level of shielding for handling. (c) High-Level Waste (HLW), contains elevated radioactivity and significant heat generation resulting from decay. HLW contains most radiological hazards among the three categories. For example, HLW accounts for less than 1% of the total volume of radioactive waste produced, while it contains approximately 95% of the total radioactivity in UK ("Radioactive Waste," 2025). This extreme concentration of radiological hazard dictates the requirement for permanent, geological isolation. Table 1 compares different radioactive waste and their fractions approximately in the UK ("Radioactive Waste," 2025).

High-Level Waste originates from two sources: the direct use of fuel and the subsequent recycling of that fuel. The predominant source of HLW is Spent Nuclear Fuel (SNF), which is the "burned" uranium fuel removed from nuclear reactors. In the United States, commercial SNF remains stored near reactor sites pending the construction of permanent disposal facilities. Besides, some nuclear programs opt to recycle used nuclear fuel to recover reusable materials: uranium and plutonium. Reprocessing separates the spent fuel into these reusable elements and a highly concentrated residue. Additionally, nuclear weapons programs also generate significant radioactive waste that requires specialized disposal (Fernández-Arias et al., 2023).

HLW generates decay heat exceeding 2 kW/m^3, necessitating active cooling and substantial shielding for its immediate management. This thermal load is primarily generated by short-lived fission products, which also produce penetrating radiation capable of delivering fatal doses in a short period. In contrast, the long-term management challenge is dictated by transuranic elements like plutonium-239. Table 2 shows the key radionuclide half-lives and their radiological hazard timescale. These long-lived isotopes represent the dominant radioactive hazard that demands a permanent isolation strategy, such as deep geological disposal, capable of containing the material for tens to hundreds of thousands of years.

Table 2: Example of radionuclide half-lives and associated radiological hazard timescale.

Radionuclide	Half-Life (Years)	Primary Hazard Role
Curium-244	18	Short-term thermal load and gamma radiation
Cesium-137	30	Short-term thermal load and gamma radiation
Plutonium-239	24,000	Long-term radiotoxicity

The imperative for permanent disposal of HLW is rooted in ethical and security obligations spanning geological timescales. This imperative necessitates the use of a Deep Geological Repository (DGR) as an entirely passive isolation system, which requires no continuous human involvement to protect the biosphere and natural resources from long-term radiological contamination. The multi-barrier system is engineered to delay and limit the migration of long-lived radionuclides via groundwater transport for tens to hundreds of thousands of years. Moreover, this vast timeframe introduces a unique security challenge: ensuring that information about waste and its hazards is successfully conveyed across millennia, mitigating the risk of intentional intrusion by future societies that might otherwise view the repository as a tempting mining site (Tondel & Lindahl, 2019).

Several nations are actively developing DGR concepts, with advanced programs in countries like Finland, Sweden, Canada, Switzerland, and France. These global efforts explore a variety of host rock environments, including granite, shale, and salt formations. While the technical framework is mature, the ultimate success of international DGR projects, as demonstrated by the advanced status of Finland's program, depends critically on securing broad societal and political acceptance alongside technical competence, a requirement that has proven to be a deciding factor in the success or failure of national plans.

Engineered Barrier System (EBS) is a critical component of the DGR System to ensure the passive, long-term isolation of HLW. The EBS consists of several independent layers. At the core is the waste form, intended to minimize the release rate of radionuclides. This waste form is encased within a durable disposal canister, which provides robust physical containment for the initial period. Surrounding the canister is the buffer material, frequently compacted bentonite clay, which acts as a chemical and physical barrier by restricting water flow and swelling to self-seal minor fractures in the rock. Finally, specialized Backfill materials are used to seal the remaining tunnels and underground repository spaces. Figure 1 shows an example of EBS within a geological disposal system.

2. Deep Geological Repository development in Beishan, China

This section outlines the development of China's High-Level Waste disposal program, focusing on the establishment of the Underground Research Laboratory (URL) and the geological characteris-

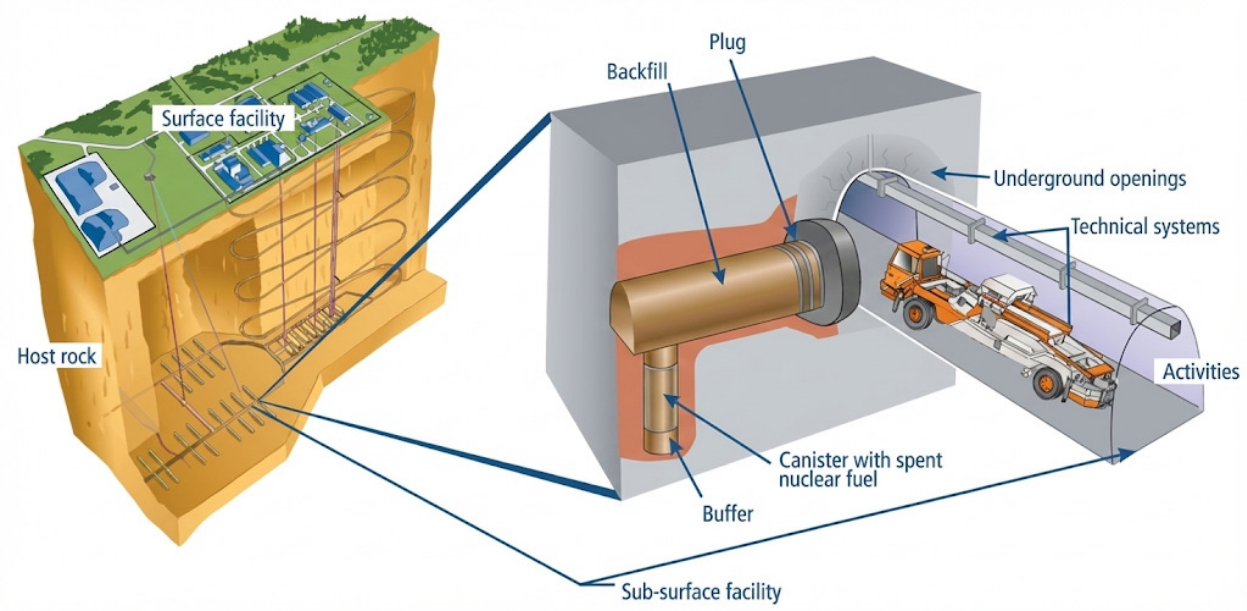


Figure 1: Example of an EBS within a geological disposal system (modifier from (Nuclear Energy Agency (NEA), Organization for Economic Co-operation and Development (OECD), 2012)).

tics that substantiate the selection of Beishan as the preferred site.

China's DGR program for HLW commenced research and development in 1985 with the objective of establishing a permanent disposal facility by 2050. The national strategy has identified the Beishan area in the Gobi Desert of Gansu Province (shown in Figure 2) as the preferred site, selecting hard granite as the host rock for the repository. The program is currently executing its second phase (2021–2040), which involves the construction and operation of the Beishan Underground Research Laboratory. This URL, a significant national undertaking with an investment exceeding 2.7 billion yuan, is planned to reach a depth of 560 meters and serves as the critical platform for validating the repository's safety and testing engineered barrier components. (The People's Republic of China, 2020)

The suitability of the Beishan site for permanent waste disposal is strongly underpinned by its unique geological and climatic context, which creates a stable environment for long-term material durability. The Beishan Underground Research Laboratory (URL) site is in Gobi Desert. This climate is characterized by annual average precipitation that is less than 80 mm, and intense evaporation rates (Wang et al., 2018), which fundamentally limits the potential for groundwater recharge. The hydrogeological conditions within the granite host rock are favorable. Site characterization data demonstrates limited permeability and slow groundwater movement. The host rock mass has a hydraulic conductivity ranging from 10^{-12} m/s to 10^{-10} m/s, leading to extremely limited permeability (An et al., 2025). This lack of permeability, combined with long-flow paths, results in slow groundwater seepage. This environment is expected to enhance the long-term durability of waste

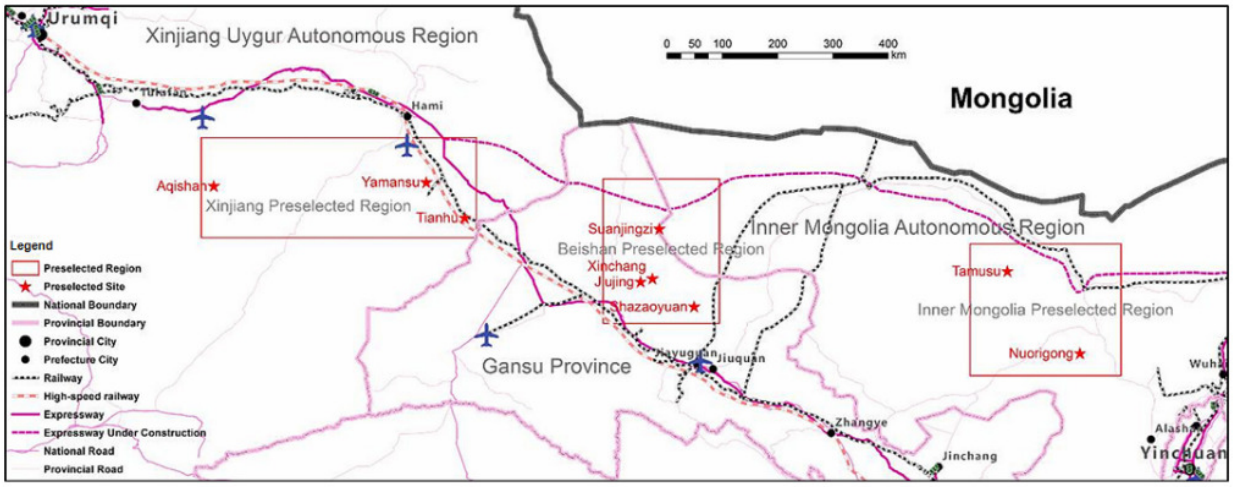


Figure 2: Distribution of the nine candidate URL sites, including Beishan, in northwestern China. (Wang et al., 2018)

canisters and effectively isolate waste by ensuring limited migration of potential radionuclides.

3. Key Material Degradation Mechanisms and Performance Predictions

This section evaluates the long-term durability of the EBS within Beishan repository. It first characterizes the critical environmental factors, including the hydrogeochemical conditions of the groundwater and the thermal-radiation effects resulting from HLW decay. Based on these environmental parameters, the corrosion mechanisms for three candidate canister materials, carbon steel, copper, and titanium alloys, are analyzed to assess their suitability for permanent isolation.

3.1. Geochemical Environment in Beishan

The chemical environment is dynamic and is the key to understanding the corrosion mechanisms. The natural Beishan groundwater is weakly alkaline (pH 8.22) and is a brine with elevated concentrations of Cl^- and SO_4^{2-} (Wei et al., 2021). Immediately after closure, trapped air and dissolved oxygen in the infiltrating groundwater create a short-term oxidizing period (Gras, 2002). Later, trapped oxygen is quickly depleted by container corrosion, mineral reactions, and microbial activity. The repository then transitions to a long-term reduction environment (Zhang et al., 2022).

3.2. Challenges from Radiation Effects and Thermal Effects

The decay heat from HLW can cause a significant temperature increases in the waste canister, in the bentonite buffer material, and in the surrounding host rock. This thermal effect requires consideration in repository design. The elevated temperatures will induce thermal expansion of the near-field materials, which generates thermal stress. This expansion could create tensile stress zones

and compromise the overall mechanical stability of the repository. Additionally, temperatures exceeding critical thresholds threaten material durability, leading to complex corrosion effects(Zhou et al., 2020).

The primary influence of radiation on container corrosion is the radiolysis of water which generates oxidizing species that would otherwise be absent in the repository environment. However, this effect depends on the dose rate. For carbon steel and copper, an acceleration in corrosion is only observed at dose rates >10–20 Gy/h (Muñoz et al., 2024). Repository designs often mitigate this effect through shielding.

3.3. Candidate Materials and Corrosion Mechanisms

The selection of canister material involves balancing performance, predictability, and cost. China's disposal program— similar to many international programs— has studied carbon steel, copper, and titanium alloys.

3.3.1. Carbon Steel

Carbon steel is widely considered a primary candidate for nuclear waste containers as a corrosion-allowance material. Its design life is achieved by engineering a thick wall sufficient to withstand predictable, slow metal loss over millennia rather than relying on complete corrosion resistance. The corrosion behavior of carbon steel is defined by the evolution of the repository environment. Immediately after repository closure, trapped air and dissolved oxygen in the infiltrating groundwater create an initial oxidizing environment. During this phase, corrosion is driven by oxygen reduction. The initial oxygen is rapidly consumed, in as little as one year (Yang et al., 2007). The environment then transitions to a stable, long-term reducing condition. In the long-term anoxic phase, corrosion is dominated by the slow reduction of water, which generates hydrogen gas (Zhang et al., 2019).

Several key factors governing this long-term behavior include formation of protective corrosion product layer, hydrogen embrittlement, and the effect of bentonite buffer. The formation of a protective corrosion product layer decreases long-term corrosion. At elevated temperatures above 60 °C, this layer is primarily magnetite (Fe_3O_4) (Zhang et al., 2019). Anaerobic corrosion is the primary source of hydrogen gas evolution. This hydrogen can be absorbed by steel, leading to hydrogen induced cracking . This cracking is considered a potential long-term failure mechanism (Zhang et al., 2022). The compacted bentonite buffer is beneficial in Beishan conditions. Electrochemical studies show that corrosion rates are slower in compacted bentonite in simulating Beishan conditions than in simulated groundwater alone, because the bentonite restricts ion mobility and oxidant transport (Zhang et al., 2019).

3.3.2. Copper

Copper is the reference canister material for the KBS-3 disposal concept in Sweden and Finland and is a primary candidate for China's Beishan DGR. It is chosen for its thermodynamic stability in the anoxic, reducing conditions of groundwater. However, the hydrogeochemical environment with chloride (Cl^-) and sulfide ($H\ S^-$) ions in Beishan raises challenges. During the initial aerobic phase, elevated Cl^- levels can destabilize the natural passivation of copper. Instead of forming a protective oxide film, chloride promotes dissolution by forming soluble complexes and porous corrosion, increasing the risk of localized pitting (Chae et al., 2023). In the long-term anoxic phase, sulfide is the main corrodent, and the corrosion process is governed by the transport of corrodents through the bentonite buffer rather than interfacial reaction rates (Hermansson & Eriksson, 1999).

3.3.3. Titanium

Titanium and its alloys are classified as passive materials. Unlike carbon steel, their design relies on kinetic stability to resist corrosion rather than on a thick wall designed to be consumed (Gras, 2002). An extremely stable, dense, adherent, and protective oxide film forms on titanium, giving excellent protection in a repository environment (Zhang et al., 2017). This film makes the general corrosion rate practically negligible and is significantly slower than that of carbon steel. A study simulating the Beishan environment estimated that the 1-million-year corrosion depth for carbon steel was 9058.2 mm, while for pure Ti (Ti grade 2) and a Ti-Pd alloy (Ti grade 16), it was only 38.7 mm and 38.6 mm, respectively (Zhang et al., 2019).

Although the general corrosion rate is negligible for titanium, two failure modes require assessment for long-term performance: crevice corrosion and hydrogen embrittlement (HE) (Muñoz et al., 2024). Crevice corrosion is the localized attack because of the presence of chloride ions and is the primary risk during the initial, short-term aerobic phase. This risk can be avoided or mitigated by alloying the titanium with palladium or ruthenium (Landolt et al., 2009; Schutz, 1996). Hydrogen embrittlement is considered the main potential long-term risk under anoxic conditions. After oxygen is consumed, the dominant cathodic reaction is the reduction of water, which produces hydrogen atoms. This hydrogen reacts with titanium to form brittle titanium hydrides within the metal lattice, causing a loss of ductility. Failure can occur if the absorbed hydrogen concentration exceeds critical hydrogen concentration. The risk of hydrogen embrittlement is pronounced at elevated temperatures, above 80°C, which accelerates hydrogen diffusion, and in very acidic ($pH < 3$) or very alkaline ($pH > 12$) environments (Zhang et al., 2022).

Other factors that may influence titanium performance include radiation and microbial influenced corrosion (MIC). The effect of radiation on titanium is dependent on the dose rate. At dose rates relevant to most repository designs (< 100 Gy/h), titanium is expected to remain passive (Wei et al., 2021). However, extremely intense dose rate of 5 kGy/h, can significantly accelerate corrosion rate (Wei et al., 2021). Radiation would not be the main concern because the radiation dose is generally less than the 100 Gy/h threshold. Additionally, titanium alloys are known to be immune

to MIC (King, 2020).

4. Conclusions

The permanent disposal of High-Level Waste is a critical global challenge necessitating robust isolation strategies because of the extreme longevity of radionuclides. This paper highlights the suitability of the Beishan Deep Geological Repository in China. The stable granite host rock and arid Gobi Desert climate provide excellent hydrogeological conditions to limit radionuclide migration. Central to the safety of the repository is the Engineered Barrier System and the selection of durable canister materials. Carbon steel offers a predictable corrosion behavior relying on gradual metal loss and protective film formation. However, hydrogen induced cracking remains a long-term concern. Copper is selected for its thermodynamic stability in reducing environments, yet the presence of chloride and sulfide ions in Beishan groundwater introduces risks of localized corrosion. Titanium and its alloys show outstanding corrosion resistance because of their passive oxide films, with hydrogen embrittlement as the potential long-term risks. The successful implementation of the Beishan repository depends on validating these material performance predictions through in-situ testing at the Beishan Underground Research Laboratory to ensure the protection of the biosphere for thousands of years.

References

An, Z., Di, Q., Fu, C., & Wang, Z. (2025). CSAMT-Driven Feasibility Assessment of Beishan Underground Research Laboratory. Sensors (Basel, Switzerland) , 25 (14), 4282. https://doi.org/10.3390/s25144282

Chae, N., Park, S., Seo, S., Foster, R. I., Ju, H., & Choi, S. (2023). Coupled mixed-potential and thermal-hydraulics model for long-term corrosion of copper canisters in deep geological repository. Npj Materials Degradation , 7 (1), 26. https://doi.org/10.1038/s41529-023-00345-6

Fernández-Arias, P., Vergara, D., Antón-Sancho, Á., Fernández-Arias, P., Vergara, D., & Antón-Sancho, Á. (2023). Global Review of International Nuclear Waste Management. Energies , 16 (17). https://doi.org/10.3390/en16176215

Gras, J.-M. (2002). Life prediction for HLW containers – issues related to long-term extrapolation of corrosion resistance. Comptes Rendus. Physique , 3 (7–8), 891–902. https://doi.org/10.1016/S1631-0705(02)01358-0

Hermansson, H.-P., & Eriksson, S. (1999). Corrosion of the Copper Canister in the Repository Environment (No. SKI Report 99:52). https://www.stralsakerhetsmyndigheten.se/contentassets/0b2a2b9566154b9b939f0be3161bdb18/9952-corrosion-of-the-copper-canister-in-the-repository-environment

King, F. (2020). Canister Materials for the Disposal of Nuclear Waste . In R. J. M. Konings & R. E. Stoller (Eds.), Comprehensive Nuclear Materials (Second Edition) (pp. 387–413). Elsevier. https://doi.org/10.1016/B978-0-12-803581-8.11764-3

Landolt, D., Davenport, A., Payer, J., & Shoesmith, D. (2009). A review of materials and corrosion issues regarding canisters for disposal of spent fuel and high-level waste in Opalinus clay . https://inis.iaea.org/records/8ccv0-2zn53

Muñoz, A. G., Abdelouas, A., Alonso, U., Fernández, A. M., Bernier-Latmani, R., Cherkouk, A., Gaggiano, R., Hesketh, J., Smart, N., Padovani, C., Mijnendonckx, K., Montoya, V., Idiart, A., Pont, A., Riba, O., Finck, N., Singh, A. R., King, F., & Diomidis, N. (2024). WP15 ConCorD state-of-the-art report (container corrosion under disposal conditions). Frontiers in Nuclear Engineering , 3 . https://doi.org/10.3389/fnuen.2024.1404739

Nuclear Energy Agency (NEA), Organization for Economic Co-operation and Development (OECD). (2012). Engineered Barriers and Geological Disposal .

Radioactive waste. (2025). In Wikipedia . https://en.wikipedia.org/w/index.php?title=Radioactive_waste&oldid=1324077903

Schutz, R. W. (1996). Ruthenium Enhanced Titanium Alloys: Minor Ruthenium Additions Produce Cost Effective Corrosion Resistant Commercial Titanium Alloys. Platinum Metals Review , 40 (2), 54–61. https://doi.org/10.1595/003214096X4025461

The People's Republic of China. (2020). Fifth National Report for the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management . International Atomic Energy Agency. https://www.iaea.org/sites/default/files/china-7rm_english.pdf

Tondel, M., & Lindahl, L. (2019). Intergenerational Ethical Issues and Communication Related to High-Level Nuclear Waste Repositories. Current Environmental Health Reports , 6 (4), 338–343. https://doi.org/10.1007/s40572-019-00257-1

Wang, J., Chen, L., Su, R., & Zhao, X. (2018). The Beishan underground research laboratory for geological disposal of high-level radioactive waste in China: Planning, site selection, site characterization and in situ tests. Journal of Rock Mechanics and Geotechnical Engineering , 10 (3), 411–435. https://doi.org/10.1016/j.jrmge.2018.03.002

Wei, X., Dong, J., & Ke, W. (2021). Progress on a corrosion study of low carbon steel for HLW container in a simulated geological disposal environment in China. Corrosion Communications , 1 , 10–17. https://doi.org/10.1016/j.corcom.2021.05.002

Yang, C., Samper, J., Molinero, J., & Bonilla, M. (2007). Modelling geochemical and microbial consumption of dissolved oxygen after backfilling a high level radiactive waste repository. Journal of Contaminant Hydrology , 93 (1–4), 130–148. https://doi.org/10.1016/j.jconhyd.2007.01.008

Zhang, Q., Jiang, Y., Zhang, B., Duan, J., Zhao, X., & Chen, J. (2022). Research progress on the hydrogen permeation behavior of the nuclear waste container–A mini review. Frontiers in Materials , 9 , 1058394. https://doi.org/10.3389/fmats.2022.1058394

Zhang, Q., Zheng, M., Huang, Y., Kunte, H. J., Wang, X., Liu, Y., & Zheng, C. (2019). Long term corrosion estimation of carbon steel, titanium and its alloy in backfill material of compacted

bentonite for nuclear waste repository. Scientific Reports , 9 , 3195. https://doi.org/10.1038/s41598-019-39751-9

Zhang, Q., Zheng, M., Huang, Y., Nishikata, A., Lu, D., Zhang, J., Wang, X., Wen, J., Li, Y., & Liu, Y. (2017). Corrosion behaviour of carbon steel, titanium and titanium alloy in simulated underground water in Beishan area preselected for nuclear waste repository in China. Corrosion Engineering, Science and Technology , 52 (6), 425–431. https://doi.org/10.1080/1478422X.2017.1319682

Zhou X., Sun D., & Lin Y. (2020). Canister spacing in a high level radioactive nuclear waste repository based on heat conduction. Chinese Journal of Geotechnical Engineering , 42 (11), 2069–2077. https://doi.org/10.11779/CJGE202011012