CATEGORIZATION OF ADDITIVE MANUFACTURING TECHNIQUES FOR NUCLEAR NONPROLIFERATION THREAT ANALYSIS

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CATEGORIZATION OF ADDITIVE MANUFACTURING TECHNIQUES FOR NUCLEAR NONPROLIFERATION THREAT ANALYSIS

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You're gonna make it after all.

Sonny Curtis

For my parents, Tim and Susan, and my sister, Maddie.

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LIST OF ACRONYMS

3D Three-Dimensional

ABS Acrylonitrile butadiene styrene

AM Additive Manufacturing

ANPRM Advanced Notice of Proposed Rule making

BIS Bureau of Industry and Security

BJ Binder Jetting

CAD Computer-Aided Design

CBAM Composite-based additive manufacturing

CCL Commerce Control List

CFF Continuous Fiber Fabrication

CLIP Continuous Digital Light Processing

DDTC Directorate of Defense Trade Controls

DED Directed Energy Despotion

DLP Digital Light Processing

DMD Digital Micromirror Display

DMLS Direct Metal Laser Sintering

DOC Department of Commerce

DOD Drop on Demand

DOE Department of Energy

DOS Department of State

EAR Export Administration Regulations

EBM Electron Beam Melting

ECCN Export Control Classification Number

FDM Fused Deposition Modeling

FFF Fused Filament Fabrication

GATT General Agreement on Tariffs and Trade

HEA High Entropy Alloy

ISR In-Situ Recovery

ITAR International Traffic in Arms Regulations

LB-DED Laser-based Directed Energy Deposition

LOM Laminated Object Manufacturing

MHD Magneto-Hydro-Dynamic

MIT Massachusetts Institute of Technology

MJ Material Jetting

MJF MultiJet Fusion

MJP MultiJet Printing

MOX Mixed Oxided Fuel

MTCR Missile Technology Control Regime

NPJ NanoParticle Jetting

NQ nitroquanidine

NRC Nuclear Regulatory Commission

NSG Nuclear Suppliers Group

NTP Nuclear Thermal Propulsion

PC Polycarbonate

PEEK Polyetheretherketone

PLA Polylactic Acid

PP Polypropylene

RPDED Rapid-Plasma Directed Energy Deposition

SHS Self-Propagating High-Temperature Synthesis

SLA Stereolithography

SLCOM Sheet Lamination Composite Object Manufacturing

SLM Selective Laser Melting

SLS Selective Laser Sintering

Ti-DSS Titanium-Stabilized Duplex Stainless Steel

UV Ultraviolet

WA Wassenaar Arrangement

WDED Wire-based Directed Energy Deposition

SUMMARY

Additive manufacturing, or AM, is a rapidly developing technology that simplifies and automates the production of intricate objects. Recently, AM methods have been implemented in the domains of nuclear weapons and nuclear enrichment technologies. However, there are presently limited international or domestic regulations for AM's involvement in the nuclear sector, leading to unregulated proliferation pathways. Existing export regulations are broad in scope and do not account for the particular nuances of different AM techniques. It is crucial to scrutinize and assess the nuclear applications of AM methods to establish effective regulations and limitations for monitoring proliferation routes. This project involves identifying and assessing 31 of the most commonly employed AM methods based on their potential impact on the nuclear fuel cycle. Using this identification and classification system, export controls can be directed at nuclear proliferation threats posed by AM, without disrupting the entire industry and fuel cycle. Additionally, this comprehensive approach to regulating and monitoring proliferation channels would expose gaps in export regulations.

CHAPTER 1

INTRODUCTION

Since the 1940s, the nuclear industry has experienced a steady growth of emerging technologies that have been constructed to demonstrate its technical feasibility. Since the beginning, conventional manufacturing techniques, such as subtractive manufacturing, have been predominantly employed. However, recently, there has been a noticeably shift towards the utilization of advanced or additive manufacturing Additive Manufacturing (AM) techniques to produce complex and unique components.

This shift signals a trend within manufacturing which could have significant implications and consequences for the future of nuclear. Advanced or Additive manufacturing, AM, is a method of production where three-dimensional objects are created by building up layers of material, such as plastic, metal, or ceramic to create a finished product. [1] In theory, AM technology allows for greater design freedom for user and allows for the creation of complex geometries and thus makes it well suited for applications in industries such as aerospace, healthcare, and now the nuclear sector. The presented processes, as well as the current and project uses of AM int he nuclear industry, offer a prospective alternative route toward a state's or non-state actor's acquisition of sensitive nuclear technology.[2]

Additive Manufacturing leverages the substantial computational capabilities of contemporary computers to facilitate the rapid production of complex objects, surpassing conventional manufacturing methods. As a result, Additive Manufacturing technologies possess the ability to fabricate an increasing number of items that are subject to regulation under nuclear export controls.Therefore,AM likely presents a viable alternative to export-controlled manufacturing technologies, by enabling the widespread sharing of sensitive information in the form of build files via the Internet. Despite the existence of export controls for AM, they lack uniformity and prove challenging to enforce at a national or global level.Due to thelack of guidelines for governments and organizations, it becomes difficult to determine the extent to which AM techniques should be subject to regulatory controls, particularly in terms of complexity and detail. While export controls have a long history of protecting technologies, adapting, and implementing such controls in the digital age presents significant challenges.[3]

1.1 Additive Manufacturing

Advanced or Additive manufacturing can be thought of as a comprehensive manufacturing concept that encompasses various technologies beyond 3D printing. These technologies include rapid prototyping, direct digital manufacturing, and layered manufacturing. Early in the industry, research focused on rapid prototyping, which involved the visualization of parts before production. However, over time, the industry has evolved to the manufacturing of end-use parts for various industries. The process begins with a computer-aided design Computer-Aided Design (CAD) sketch, which is a digital model of a physical object that can be edited and manipulated. The additive manufacturing team then reads the data from the digital file and fabricates the part by adding material in successive layers. In comparison to traditional production techniques, many additive manufacturing techniques are designed to streamline the production process by eliminating intermediate steps such as tooling production, theoretically resulting in faster production of parts.[4]

1.1.1 Brief History of Additive Manufacturing

The advent of additive manufacturing can be traced back to 1980 when Dr. Hideo Kodama submitted the first patent for this technology. As a researcher at the Nagoya Municipal Industrial Research Institute, Dr. Kodama aimed to devise a system for producing photopolymer prototypes. This approach proposed the use of ultraviolet light (UV) to solidify a container of photopolymer material to manufacture a simple component layer by layer. However, due to funding constraints, the project was never completed. The next significant milestone took place in 1986 with the development of additive manufacturing with the invention of the first Stereolithography Stereolithography (SLA) device, a prototype technique that utilized lasers to achieve the first solidified layer. The following year, a researcher at the University of Texas, introduced a novel technique that used a laser to fuse powder into a solid structure, which would later evolve into a technique known as Selective Laser Sintering Selective Laser Sintering (SLS). The year 1989 marked the advent of a novel technique of additive manufacturing known as fused deposition modeling Fused Deposition Modeling (FDM). Which emplys the melting of a filament and depositing it layer-by-layer to create three-dimensional objects. In the early 2000s, additive manufacturing became increasingly utilized to produce functional products. By 2009, additive manufacturing had moved towards mass use and became available to hobbyists. [5]

1.1.2 The Modernization of Manufacturing Due to AM

For decades, conventional manufacturing techniques have been a ubiquitous feature of the industrial landscape. In the past, precursors to additive manufacturing methodologies necessitated the use of a substrate or mandrel as a means of imparting the requisite shape to the manufactured item. The machinery employed in this operation had to be meticulously engineered to operate within pre-determined technical specifications and was frequently limited to the production of a single type of product. In contrast to traditional AM techniques, contemporary additive manufacturing methods do not rely on a substrate or mandrel, thereby liberating the process from the constraints of geometry and automating the production of intricate objects, which could largely mitigate the need for specialized training. 3-D printing, an umbrella term encompassing several existing processes, represents the most associated technology with AM, and because of it's rapid expansion and evolution in recent years, has propelled AM into the category of a ”disruptive technology”. [6]

”Disruptive technologies” are technologies or industries that are emerging on an international level and could potentially upset the balance of power between nation states. These technologies could give control over powerful and new technologies to states or non-state actors, causing major chaos in global order, and impact warfare, and terrorism. To contend with the possibility of these technologies, states or non-state actors could establish new alliances or build new capabilities. Niche innovations often lead to disruptive technologies that challenge and change the established dominant technology. These new technologies are initially less efficient and capable but have a potential to alter the status quo by providing a unique solution to an existing challenge. Disruptive technology embodies significant and unexpected change. [6]

As additive manufacturing has grown, materials that were previously difficult or impossible to process using conventional manufacturing methods can now be utilized to fabricate intricate and customizable shapes using additive manufacturing. Notably, a diverse array of materials, including polymers, metals, alloys, carbon fibers, biological tissue, and superalloys, are now extensively used as feedstock in various AM processes. This increase gives designers and manufactures opportunities to create products with unique properties. For instance, the potential to create complex geometries with biological tissue as feedstock has enabled the creation of synthetic organs and other medical devices that can be tailored for individual patients [7]. The application of superalloys in AM has also facilitated the production of high-performance components for utilization in aerospace and other industries. Numerous universities and institutions have incorporated maker spaces, which house a variety of additive manufacturing machines that are made available for use by students. The rapid advancement of contemporary AM methods has led to a corresponding increase in the intricacy of AM products. As research institutions, laboratories, government organizations, colleges, and businesses continue to contribute to the evolution of AM technology, it is now even more vital to be vigilant and monitor the distribution of data and the spread of technical knowledge. [7]

CHAPTER 2

AN OVERVIEW OF THE URANIUM-BASED NUCLEAR FUEL CYCLE

The nuclear fuel cycle encompasses the creation of nuclear fuel from creation all the way to disposal.The cycle starts with the mining of natural uranium ore, which is then milled and chemically treated to extract the valuable uranium. Following extraction, the uranium is chemically converted into a form, such as uranium dioxide. Next, it undergoes enrichment which increases the concentration of U-235 in the uranium, and typically achieved through a gas diffusion or centrifugal process. Fuel fabrication follows enrichment, where the enriched uranium is transformed into pellets and loaded into fuel assemblies. Fuel assemblies are then loaded into a reactor and nuclear fission occurs within the core producing heat that is used to turn turbines to generate electricity. After use, spent fuel is highly radioactive and thus must undergo special handling in order to ensure that it is properly disposed of. While some countries reprocess spent fuel to extract remaining fuel materials, the practice is contentious due to proliferation concerns and the possibility of nuclear material falling into the wrong hands. Ultimately, spent fuel is either reprocessed, or stored in specialized facilities until an appropriate disposal solution is implemented. [8]

2.1 Uranium Mining

The mining of uranium, the first step in the nuclear fuel cycle, involves a range of methods, with open-pit mining, underground mining, and in-situ recovery In-Situ Recovery (ISR) being the most used. Open-pit mining is utilized when the uranium deposit is close to the earth's surface and involves the excavation of large holes in the ground to extract uranium. [9] When uranium deposits are located at great depths, underground mining is typically employed which necessitates the drilling of vertical shafts into the ground, followed by blasting the ore out below the surface and then transporting it to the processing plant.

An alternative method, In-situ recovery mining, is often used when uranium deposits are too deep to be extracted through traditional mining methods. Thus, a solution is injected into the ground, which then dissolves uranium ore. This uranium solution is then pumped back to the surface for extraction. Once the uranium ore has been extracted from the solution, it's transported to a processing plant for processing, refinement, and enrichment.

[10]

2.2 Uranium Milling

The uranium milling process typically begins by crushing uranium ore into small fragments using crushers or grinders. From there, the ore is ground ball mills or rod mills into fine particles. The ground ore is then mixed with water and chemical reagents to begin the process of separating the uranium ore and to ultimately extract the uranium from the ore using a chemical leaching process. Next, this ore slurry is mixed with typically a strong acid, such as sulfuric acid, to dissolve the uranium and then processed through a solvent extraction circuit, to separates the uranium from other elements in the solution. [11]

In the next step, the slurry is treated with a stripping solution, which is typically an acid or ammonia, to remove the uranium. This stripped solution, contains uranium and other impurities and is then precipitated using chemical agents which react with the uranium to form a solid precipitate. The precipitate is then separated from the solution and washed to remove any remaining impurities and the uranium precipitate is dried and heated to form uranium oxide, commonly known as yellowcake. [11]

2.3 Uranium Enrichment

The next step of the nuclear fuel cyce is uranium enrichment, which is the process of increasing the concentration of uranium-235 in natural uranium which is necessary to create fuel that can be used in nuclear reactors. The oldest and a common method of uranium enrichment is gas diffusion, which involves passing uranium hexflouride gas through porous barriers. This results in the lighter isotope, uranium-235, being able to pass through the barrier more easily than the heavier isotopes in natural uranium would.

Another common method of uranium enrichment uses gas centrifuges to spin the uranium hexafluoride at high speeds in a cylindrical container.This force then causes the lighter isotope, U-235 to move towards the center of the container, while heavier isotopes move towards the outer edge, increasing the concentration of U-235. \cite{olander1981theory}

Currently, the most advanced method to enrich uranium is through laser enrichment which uses lasers to selectively ionize uranium atoms based on the composition to gradually increase the enrichment. Theoretically, this is the most efficient and is requires less energy consumption, however it is not widely used due to high costs. \cite{krass1977laser}Once the uranium is enriched to a given level, it can be converted into a suitable form for use as nuclear fuel, such as uranium pellets for fuel rod assemblies.

2.4 Fuel Fabrication

Nuclear fuel fabrication is a complicated process that creates fuel rods that designed to produce energy in nuclear reactors. These fuel rods are typically composed of cylindrical pellets that contain fissile material, typically enriched uranium dioxide or mixed oxide Mixed Oxided Fuel (MOX) fuel. To start, the enriched uranium is ground into a powder form, which is then blended with binding agents and other substances to form a homogeneous mixture. This powder blend is then compressed into pellets, which have a typical diameter and length of 1/2 inch, utilizing a hydraulic press to a desired density and hardness. [12]

These pellets are then sintered in a furnace, which renders them harder and more durable while removing any remaining volatile compounds and are then inserted into elongated, slender tubes constructed of zirconium alloy, known as fuel rods. Multiple fuel rods are then packaged together to form a fuel assembly, which is loaded into the reactor core. [12]

2.5 Power Reactors

The fuel rods that were processed and packaged into a fuel assembly are then carefully arranged in a specific pattern inside the reactor core.This arrangement is carefully selected to ensure optimal efficiency and safety during reactor operation by allowing for efficient heat transfer, while also ensuring that the fuel remains contained within the reactor. \cite{ho2019review}

When the reactor is operating, neutrons are produced through nuclear fission; the uranium isotopes in the fuel are hit with neutrons, which cause them to split apart into two smaller isotopes and release a large amount of energy and neutrons, which can collide with other uranium atoms and cause a chain reaction of fissions.

In order to control the chain reaction and prevent it from getting out of control, reactor operators rely on control mechanisms within the reactor. Control rods, which are made of materials such as boron or cadmium that have a high neutron absorption cross section, can be inserted or removed from the reactor core to adjust the rate of the chain reaction. Additionally, burnable poisons can be added to the coolant system of the reactor in order to control the number of fission reactions. Power reactors operate at steady state, and are monitored by multiple redundant safety systems and sensors to ensure the safe and efficient operation of the reactor. [13]

2.6 Nuclear Reprocessing

The initial phase of nuclear reprocessing commences with the extraction of spent fuel from the reactor. This spent fuel comprises a blend of uranium, plutonium, and assorted radioactive isotopes, residing in cooling pools until relocation to a reprocessing facility becomes feasible.

When the spent fuel reaches the reprocessing facility it undergoes an initial chemical procedure known as dissolution which involves dissolving the fuel in acid, resulting in a solution that contains the different fissile and non-fissile components of the fuel. The first stage of the separation process entails separating fissile material from non-fissile material in the solution. Subsequent separation steps are executed to isolate uranium and plutonium from other fissile materials. The residual radioactive waste, typically existing in either liquid or solid form, is then treated to diminish both its volume and radioactivity. [14]

2.7 Disposal

Disposing of nuclear waste is long-term storage faciliaties requies a detailed analysis of any factor that could affect the long-term stability of the facility. It is important for all aspects related to the repository to be considered by the community and the nuclear industry, such as the geographic location of the repository and whether it si likely to be affected by natural events such as earthquakes or volcano eruptions. Once a site has been selected, the disposal process typically involves placing the waste in containers that are designed to prevent the release of radioactive materials. The containers are then placed in a series of engineered barriers, which can include backfill material, seals, and other materials designed to prevent the migration of water and other fluids into the repository.Over time the span of millions of years, the waste will undergo radioactive decay and ultimately become less radioactive. However, even after thousands of years, the waste can still pose a hazard to people and the environment, so the repository must be designed to isolate the waste for the entire duration of its hazard. Currently, there is no long-term nuclear waste storage facility within the United States, and the majority of spent nuclear fuel is kept in spent fuel pools at the nuclear reactor facility. [15]

CHAPTER 3

AN OVERVIEW OF ADDITIVE MANUFACTURING TECHNOLOGIES

3.1 Binder Jetting

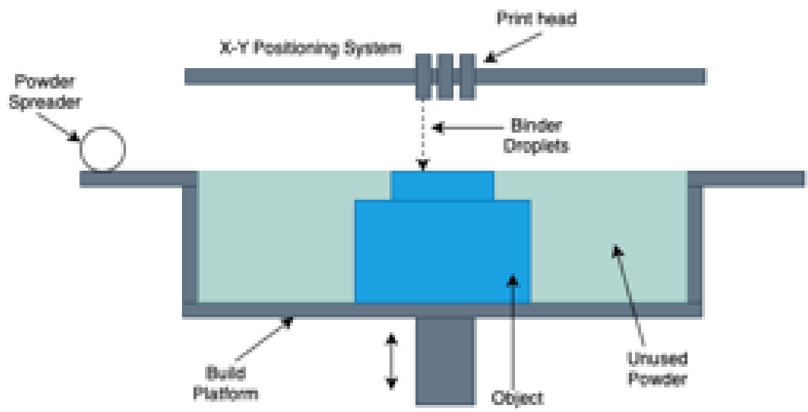

Figure 3.1: Binder Jetting Block Diagram

Binder Jetting Binder Jetting (BJ) is an additive manufacturing process that prints a binder into a powder bed to create a part, with the remaining material being a powder. It features parallel nozzles for rapid patterning and can be scaled by increasing printer nozzles for cost-effectiveness. Post-processing involves removing unbound powder and infiltrating the part for improved strength. Parts are self-supporting in the powder bed, and assemblies of parts and kinematic joints can be fabricated. Low-cost BJ machines use plaster-based or polymer powders, while metal powders can be used for functional prototypes or production. BJ can also fabricate molds and cores for sand casting.[16]

3.1.1 Metal Binder

The process of metal binder jetting entails the initial formation of metallic parts, followed by post-processing for densification. In the case of metal binder jetting, the printed parts remain in a fragile green state, necessitating further post-processing for strengthening purposes, such as sintering and infiltration. A fundamental challenge in fabricating metal parts through this technique is achieving densities equivalent to those of conventional powder metallurgy \gls{pm} processes. This challenge arises from the low packing densities commonly exhibited by binder jetted parts, owing to the absence of compacting forces during printing. Because of this it is difficult to manufacture highly dense parts, as these parts have the tendency to shrink during the sintering process. This can make it difficult to precisely control the amount of shrinkage that occurs, which could negatively impact dimensional tolerances. \cite{gibson2021binder} Printing metal parts using binder jetting technology necessitates several post-processing steps, as the parts initially printed are in a green state, possessing low mechanical properties and often appearing weak and brittle.This post-processing stage is meant to strength the parts through curing, sintering, and infiltration finishing methods. As the name suggests, metal binder jetting uses primarily metal materials such as various types of stainless steel, titanium, aluminium, cobalt, and copper. The type of material that is used is based on the application and by considering factors such as tensile strength, chemical resistance, and thermal conductivity.[17]

3.1.2 Furan Binder

Furan is a highly volatile and flammable liquid that has common applications as the starting material for the synthesis of various organic compounds. Furan is a heterocyclic organic compound with a five-membered ring containing four carbon atoms and one oxygen atom. [16]Furan resin is utilized in the binder jetting additive manufacturing process as a binding agent for the fabrication of sand molds and cores. Furan resin is mixed with sand particles to create a mold or core that is held together by the cured resin. During the binder jetting process, the furan resin is jetted onto the sand particles in precise patterns according to the desired part geometry. Once the binder jetting process is complete, the mold or core is cured in an oven to harden the resin and provide sufficient strength to withstand the casting process. Furan resin in binder jetting is often used to create complicated molds with high accuracy and low cost, which has made a common method in foundry applications. Furan binders can also be used in the manufacturing of composite materials and have been utilized to produce printed circuit boards and other electronic components. [18]

3.1.3 Phenolic Binder

Phenolic is a thermosetting resin that is widely used in the production of composite materials. Phenolic results from the reaction between phenol and formaldehyde which gives it the properties of having high-temperature and chemical resistance. The curing of phenolic resin can be achieved either at room temperature or through heating, producing a final product with high strength, stiffness, and dimensional stability. Phenolic binders are frequently utilized in binder jetting additive manufacturing due to their ability to form highly stable and robust green parts. [18]Typically, phenolic binders consist of a combination of phenol and formaldehyde mixed with metal powders and jetted onto a build platform. The green parts are subsequently sintered to achieve the final product. The use of phenolic binders is particularly well-suited for producing ceramic and metal-ceramic composite parts due to their ability to resist oxidation during sintering and high-temperature stability. In various industries, including aerospace, automotive, and biomedical, phenolic binder systems are used in the production of foundry molds for metal casting processes due to their high strength and thermal stability. Phenolic binders have also been used to manufacture ceramic parts like cutting tools and tiles and been investigated to produce composite materials, such as carbon fiber-reinforced composites utilized in aerospace and automotive applications. [16]

3.1.4 Silicate Binder

Silicate binders stand out as an inorganic binding solution commonly employed in additive manufacturing methods like binder jetting. This binder is crafted by blending a silicate solution, usually sodium or potassium silicate, with a hardening agent, typically an acid.

The resulting mixture proves effective in uniting metal or ceramic powders, resulting in green parts characterized by commendable dimensional accuracy and stability [19]

What makes silicate binders noteworthy is their unique characteristic of not necessitating a high-temperature curing process; they can solidify at room temperature. Beyond their economic appeal, silicate binders contribute to the final part's strength and stiffness, coupled with excellent chemical and thermal stability.Silicate binders are used across a diverse group of industries, such as aerospace, automotive, and biomedical due to the high strength and precision of the green parts produced. . [16]

3.1.5 Aqueous-Based Binder

Aqueous-based binders are typically composed of a water-based solution, these binders incorporate a blend of organic and inorganic compounds. The organic component comprises polymers or resins, which are primarily responsible for conferring binding attributes to the formulation, while the inorganic compounds act as additives to enhance the properties of the resultant product. [18]

Aqueous-based binders are a widely adopted binder category in binder jetting additive manufacturing due to their eco-friendliness and the ease of removal from the green part by either evaporation or thermal decomposition. This feature is particularly advantageous for intricate or fragile parts that may be adversely affected during binder removal.

The use of aqueous-based binders in binder jetting can result in high-resolution parts with favorable mechanical properties and thus expansive industrial applications. [20]

3.2 Material Extrusion

Material extrusion involves the use of a continuous filament composed of either thermoplastic or composite material to construct parts. This filament is fed through a heated extruding nozzle and deposited onto the build platform layer by layer. This technique is widely available, which makes it the preferred additive manufacturing process for general consumers

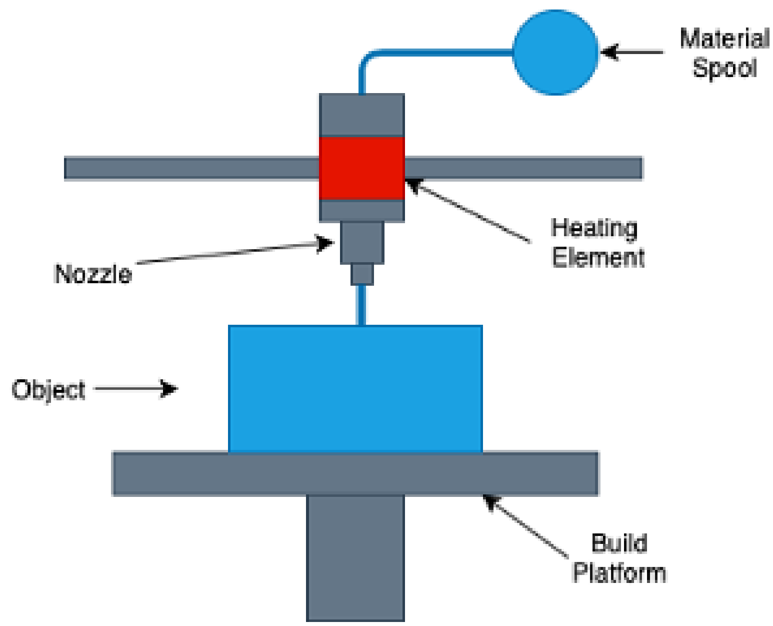

Figure 3.2: Material Extrusion Block Diagram

and hobbyists. The most commonly used materials for material extrusion include thermoplastics, Acrylonitrile butadiene styrene Acrylonitrile butadiene styrene (ABS), Polylactic Acid Polylactic Acid (PLA), Polypropylene Polypropylene (PP), Polyetheretherketone Polyetheretherketone (PEEK), Nylon, or Polycarbonate Polycarbonate (PC). [21]

3.2.1 Continuous Fiber Fabrication

Continuous Fiber Fabrication Continuous Fiber Fabrication (CFF) utilizes dual print nozzles, where one nozzle dispenses plastic filament to build the internal and outer shell of the part, while the other nozzle deposits composite fiber, which is often made from materials such as Kevlar, fiberglass, or carbon, on each layer resulting in printed objects that exhibit higher strength than traditional material extrusion techniques. [22]

There are currently two methods that are based on continuous fiber fabrication: Isotropic Fiber fill and Concentric Fiberfill. The former requires arranging the layers in a unidirectional pattern, similar to how traditional laminated composites are built, and placing 180-degree turns at the part's edges to prevent bending in the XY plane. On the other hand, the concentric fiberfill involves tracing a specified number of shells within the walls of the part to fortify them, which prevents the part from bending around the Z-axis. [21]

3.2.2 Fused Deposition Modeling

Fused deposition modeling FDM 3D printing, also known as fused filament fabrication Fused Filament Fabrication (FFF), employs two linearly sliding extruding nozzles, a linearly sliding build platform, and supports for plastic filament spools. The printer is outfitted with a thermoplastic filament spool for both the model and support extruders. Typically, the build platform is heated to a higher temperature and maintained at that temperature to regulate the cooling of the extruded material. Upon heating the extruders, the nozzle commences the process of pushing and melting the filament into a thin ribbon, roughly the size of a human hair, once the nozzle reaches the desired temperature. The extrusion head gantry, as well as the build platform, operates on a three-axis system, enabling the nozzle tip to move in three spatial directions. The extruder then proceeds to deposit the material layer by layer in predefined areas to facilitate cooling and solidification. Occasionally, cooling fans attached to the extrusion head assist in the cooling process of the material. [21]

Fused Deposition Modeling is frequently subdivided into distinct techniques according to the specific material employed, such as Acrylonitrile butadiene styrene, Polylactic Acid, Polypropylene, Polyetheretherketone, Nylon, or Polycarbonate. The selection of material significantly influences the build's strength, type, and applications and therefore, these variations are often treated as distinct techniques. [23]

Acrylonitrile butadiene styrene

ABS is a polymer known for having high impact resistance, rigidity, and resistance to abrasion, strain, and impact. It maintains good impact resistance even at low temperatures. It also exhibits high dimensional stability and a smooth, polished finish. \cite{montero2001material}

Polylactic Acid

PLA is a type of thermoplastic that is derived from renewable sources, such as cornstarch or sugarcane. [24]It is known for being hobbyist-friendly and possesses higher stiffness in comparison to materials like ABS and nylon. However, PLA does exhibit limitations when exposed to high temperatures or significant stress. [21]

Polypropylene

Polypropylene, a widely used thermoplastic, possesses an ordered molecular structure with distinct melting points that govern its crystallinity and orientation. Furthermore, it exhibits high fatigue resistance, allowing it to maintain its structural integrity even after being subjected to extensive torsional stress, rendering it suitable for hinge manufacturing. Additionally, it serves as an effective electrical insulator. Polypropylene poses challenges in practical applications. Its inert surface makes bonding difficult, and it exhibits high flammability, susceptibility to UV damage, and oxidation. Polypropylene is not commonly used in additive manufacturing, primarily due to its challenging printing properties, including the requirement for meticulous temperature control. [25]

Polyetheretherketone

PEEK is a polymer synthesized via the step-growth polymerization process, where each polymerization step doubles the length of the polymer chain. This material exhibits outstanding properties, including exceptional electrical and heat resistance, as well as wear and fatigue resistance. Furthermore, PEEK possesses creep-resistant properties, allowing it to retain its shape even under challenging conditions such as high temperatures and mechanical stress. Additionally, PEEK's toughness is accompanied by its light weight and ease of fabrication. [21]

PEEK in its pure, unfilled form is a highly durable material. However, PEEK is frequently reinforced with carbon or glass fibers to enhance its toughness. Glass-filled PEEK, for instance, offers greater stiffness than unfilled PEEK and is frequently used in the oil and gas sector to mitigate the negative effects of steam, chemicals, and high temperatures.

One of the limitations of glass-filled PEEK is its propensity to wear down mating parts. In contrast, carbon-filled PEEK displays improved compressive strength and a reduced expansion rate, resulting in superior wear resistance and load-bearing capabilities. Additionally, carbon-filled PEEK has greater thermal conductivity, which enhances its longevity and performance. [26]

Nylon

Nylon is a synthetic polymer that characterized by the presence of repeating units linked by amide bonds. Its texture exhibits a resemblance to silk, and it is a thermoplastic material that is derived from petroleum. The incorporation of various additives into nylon polymers can lead to a diverse range of material properties. Nylon has widespread uses in fabric and fibers for clothing, flooring, and reinforcement of rubber, as well as its application in molded parts for electrical equipment, automobiles, and food packaging. [21]

Nylon is suspecitable to moisture damage, which means that it must be manufactured in a vacuum or under high-temperature conditions and stored in air-tight containers. The potential for shrinkage in certain nylon parts can also render it less precise compared to ABS. Among the various types of nylon suitable for additive manufacturing, Taulman 618, Taulman 645, and Bridge Nylon are the most widely employed.[27]

Polycarbonate

Polycarbonates belong to a group of thermoplastic polymers that are characterized by the presence of carbonate groups in their chemical composition. Their usage in engineering is primarily due to their high strength and durability, with certain grades also exhibiting optical transparency. Their ease of moldability, workability, and thermoformability make them highly versatile and their ability to combine with flame retardant materials without significant degradation make them a preferred choice for applications that require robust, impact-resistant surfaces. [21]

3.3 Sheet Deposition

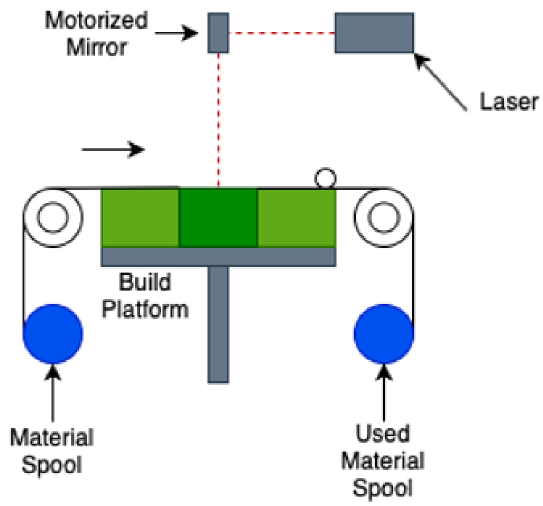

Figure 3.3: Sheet Deposition Block Diagram

Sheet deposition additive manufacturing is a method of additive manufacturing that involves using sheets of materials, such as plastic or metal, to construct 3D objects by sequentially adding layers. We begin this process by heating up a flat piece of material using a heat source, such as a laser, to achieve its melting or softening point. The heat source is then directed to specific regions of the sheet, which selectively melts and fuses the material to build up the object layer by layer.[28]

The development of sheet deposition additive manufacturing can be traced back to the early 1990s when researchers at the Massachusetts Institute of Technology Massachusetts Institute of Technology (MIT) initially began investigating the use of sheet materials for 3D printing. This research paved the way for the creation of a process known as Laminated Object Manufacturing Laminated Object Manufacturing (LOM), which relied on paper or similar sheets to construct 3D objects. Despite this early progress, the adoption of the technique utilizing plastic or metal sheets was not widespread until several years later when companies developed variations of this technology, driving its widespread usage across industries. [29]

3.3.1 Sheet Lamination Composite Object Manufacturing

Sheet Lamination Composite Object Manufacturing Sheet Lamination Composite Object Manufacturing (SLCOM) is a layer-based additive manufacturing process that involves the bonding of stacked composite sheets to produce three-dimensional Three-Dimensional (3D) objects. Based on the method of sheet deposition, SLCOM requires heat and pressure to melt a polymer matrix and activate the adhesive to build up uniform parts between the laters. The temperature profile during the bonding process plays a crucial role in achieving a consistent bond, as it affects the polymer's viscosity, flowability, and adhesive activation.

3.3.2 Composite-Based Additive Manufacturing

Composite-based additive manufacturing Composite-based additive manufacturing (CBAM) is an advanced manufacturing process that involves the deposition of composite material layers and their joining using an adhesive. A continuous fiber-reinforced tape, typically comprising carbon or glass fibers embedded in a polymer matrix, is delivered onto a build surface using a specialized nozzle in the CBAM process. The deposition of the tape requires heating to its softening point, which permits the material to flow and conform to the build surface's shape. The fundamental physics underlying the CBAM process encompasses the thermal properties of the composite material and adhesive, the melt viscosity of the polymer matrix, and the flow behavior of the fiber tape. The CBAM process temperature profile is crucial for achieving a uniform bond between layers. The nozzle temperature and heating rate influence the polymer matrix's viscosity, flow characteristics, and adhesive activation. The quality and strength of the final part are influenced by the pressure exerted by the nozzle and the tape deposition speed. [30]

3.4 Powder Bed Fusion

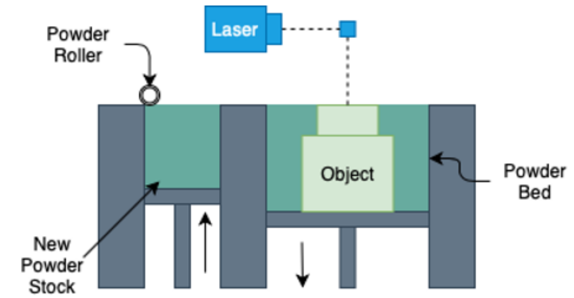

Figure 3.4: Powder Bed Fusion Block Diagram

Powder bed fusion is a type of additive manufacturing technique that uses a powder bed as the raw material. The process involves spreading a thin layer of powdered material, such as metal, plastic, or ceramic, onto a build platform. A high-powered laser or electron beam then selectively melts the powder according to the 3D digital model design, layer by layer, until the final object is formed.

The beams are focused on a small spot on the powder bed, where they deposit energy into the material, causing it to melt and fuse. The melting and solidification of the powder material create thermal gradients within the material, which can cause residual stresses and distortions in the final part. To control these effects, the process parameters, such as laser power, scanning speed, and layer thickness, must be carefully optimized to achieve the desired part properties.

Powder bed fusion AM is often used to manufacture complex, high-precision parts with intricate geometries that would be difficult or impossible to produce using traditional manufacturing techniques. [31]

3.4.1 Selective Laser Sintering

Selective laser sintering SLS uses a high-powered laser to precisely fuse powdered materials, such as polymers, into a solid object. SLS is frequently utilized for the fabrication of complex geometries and involves the spreading of a thin layer of powdered material over a build platform, where a laser beam then selectively scans and melts the powder, fusing the particles together based on a digital model. Once a layer is complete, the build platform is lowered by one layer thickness, and a new layer of material is deposited on top of the previous layer. This process then repeats until the final part is complete. A notable feature of SLS is the fact that it does not require support structure during printing. The powder is able to act as a self-supporting bed for the manufactured part, which means that the sintering of the powder material requires precise control of the laser's power, speed, and beam size. [31]

3.4.2 Selective Laser Melting

Selective laser melting Selective Laser Melting (SLM) is similar to selective laser sintering, however SLM uses a higher power laser to fully melt the material powder, to produce dense and homogeneous parts with complex geometries. After a layer of the material powder, typically a metal powder, is spread over a build platform, the laser selectively melts the powder, causing it to bond to the later below. After which, the build platform is lowered, and the process is repeat until the final part is complete. [31]

3.4.3 Direct Metal Laser Sintering

Direct Metal Laser Sintering Direct Metal Laser Sintering (DMLS) is another technique that shares many similarities with SLS. DMLS uses a high-power laser to selectively sinter and fuse metallic powders, layer by layer, into the desired object. The biggest difference between Unlike SLS, DMLS exclusively uses metal powders instead of polymers. Some consider DMLS to be a sub-category of SLS, however it is widely considered it's only category as it does not follow the exact same process as SLS. DMLS is often used for rapid prototyping and small-batch production. It is often used in the production of highly customized metal parts that require high strength and complex geometries. [32]

3.4.4 Self-Propagating High-Temperature Synthesis

Self-Propagating High-Temperature Synthesis Self-Propagating High-Temperature Synthesis (SHS)involves heating a mixture of metal and non-metal or metal oxide powders, until it reaches an ignition temperature and the exothermic reaction becomes self-sustaining, which spreads throughout the powder mixture.

The speed of the reaction depends heavily on the system's temperature and pressure, the chemical makeup of the reactants, and the size of the objects involved. As a result of this reaction, the mixture melts and solidifies into the desired product. [31]

Some specific applications of SHS are the production of ceramics, synthesis of intermetallic compounds, fabrication of nanomaterials, and production of reactive materials. Currently, SHS is used to produce ceramics with high hardness, wear resistance, high thermal stability, and nanomaterials with high reactivity and high surface area.[32]

3.4.5 Electron Beam Melting

Electron Beam Melting Electron Beam Melting (EBM) requires the use of an accelerated electron beam that is selectively applied to a bed of, typically, metal powder.The electron beam is produced by a cathode and is accelerated towards the powder bed by an electric field. The beam is focused onto the powder bed using electromagnetic lenses, which control the spot size and intensity of the beam. When the beam interacts with the powder, the accelerated electrons transfer kinetic energy to the material, which causes the atoms in the material to become excited and ionize and produce thermal energy. The material then melts and fuses together. EBM is often performed in a vacuum environment to prevent oxidation and contamination of the metal powder and allows for a higher precision electron beam as it interacts with the metal powder. [32] The intensity must be carefully controlled to ensure that the powder is melted and fused without being vaporized or overheated.

3.4.6 MultiJet Fusion

MultiJet Fusion Printing MultiJet Fusion (MJF) operates on similar principles to a standard inkjet printer. In this process, a thin layer of material powder is spread across a build platform and an inkjet print head applies a layer of a chemical fusing agent onto the powder bed. This is then followed by an infrared heating source. The fusing agent then absorbs the infrared energy and transfers that energy into the powder bed through chemical and thermal energy, which causes the powder to fuse. In order to obtain an accurate build, it is imperative that the fusing agent is distributed in just the right amount and location, otherwise it can affect the final properties of the part. The fusing agent is also crucial for the process, as it must be able to absorb the infrared energy and transfer it to the powder bed to achieve fusion.The infrared heating source is must also be carefully controlled to ensure that the temperature of the powder bed is raised to the melting point of the material without causing excessive heating or melting of adjacent layers. [31]

3.5 Directed Energy Deposition

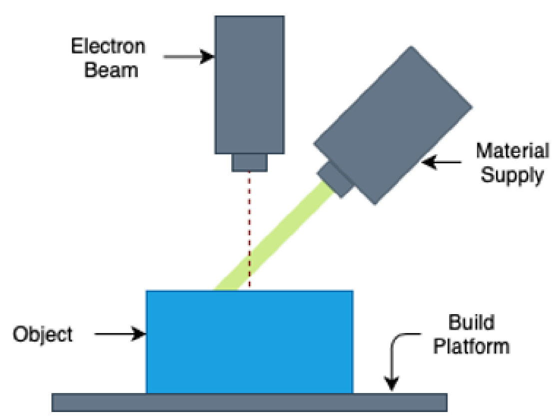

Figure 3.5: Directed Energy Deposition Block Diagram

Directed Energy Deposition Directed Energy Despotion (DED) is a technique that utilizes a high-energy source, such as a laser or an electron beam, to melt and fuse metallic powders or wires onto a substrate. During the DED process, the energy beam is precisely directed to the targeted area, causing the metal particles to melt and solidify, thus creating a new layer. The process is repeated layer by layer until the final component is formed. DED allows for the production of large, complex metal parts with high accuracy and precision. [33]

DED involves the interactions between the energy beam and the metal particles, the laser or electron beam generates heat that is absorbed by the metal particles, causing them to reach their melting point and become liquid. The melt pool's shape and size are influenced by several factors, such as the beam's power and intensity, the powder or wire feed rate, and the distance between the energy source and the substrate. The solidification behavior of the melt pool is also influenced by these parameters, which affect the cooling rate and the resulting microstructure of the metal part. [34]

3.5.1 Laser-Based Direct Energy Deposition

Laser-based Direct Energy Deposition Laser-based Directed Energy Deposition (LB-DED) involves the use of a high-powered laser beam to melt and fuse metal powders or wires onto a substrate. The principles of this process are dependent on the material being deposited absorbing the laser energy, which heats it up quickly and melts it. Short pulses of laser energy are applied to the surface, minimizing heat transmission to the surrounding material and lowering the possibility of the part becoming distorted or warped.

During the LB-DED process, the laser beam is focused onto the substrate, causing the metal powder or wire to melt and fuse with the underlying material. The laser energy is carefully controlled to achieve the desired melt pool size and shape, which is critical to achieving a strong and consistent bond between the deposited material and the substrate. The interaction of the laser beam with the metal wire or powder is another aspect of the process' physics that may have an impact on the material's quality after it is deposited. [34] Materials with high melting points and good heat conductivity, like titanium, aluminum, stainless steel, and alloys based on nickel, are frequently used in laser-based DED. . [33]

3.5.2 Electron-Beam Based Direct Energy Deposition

Electron-Beam Based Direct Energy Deposition is a method that uses a beam of accelerated electrons to melt and bond the material layer by layer to build up an item. When electrons make contact with the build object, there is a transference of kinetic energy to the atoms of the material, which cause them to become excited and ionize. This ionization generates thermal energy, which leads to the material melting and depositing onto the build object. The electron beam's energy, focus, and the beam current determine the size of the melt pool and the amount of energy that is deposited. Additionally, some electron-beam based DED involves controlling the beam's deflection and shaping through the use of magnetic fields, which give increase precision on build item geometry and material micro-structure. [34]

3.5.3 Rapid Plasma Direct Energy Deposition

In Rapid Plasma Direct Energy Deposition (Rapid-Plasma Directed Energy Deposition (RPDED)), a high-voltage electrical current ionizes an inert gas, such as argon, to produce a plasma arc. This plasma arc is focused into a beam and then used to melt the material into a molten pool. From here, feedstock is added to the pool, where it cools and then fuses with the molten substrate material. The layer is then rapidly cooled, which results in a fine micro-structure of the deposited material. The plasma beam is at such a high temperature that it is able to overcome the high melting points of most metals and alloys, which allows for a wide range of materials to be used and results in a fine-grained micro-structure. [33]

3.5.4 Wire-Based Direct Energy Deposition

Wire-based direct energy deposition Wire-based Directed Energy Deposition (WDED) is a process that uses a wire as the feedstock material. The wire is melted by a heat source, typically a laser or an electron beam, and the molten material is deposited onto a substrate to build up a part layer by layer. When the laser or electron beam is directed at the wire, the heat generated causes the wire to melt and form a molten pool. As the wire is fed into the pool, it begins to solidify and form a new layer. The heat input from the laser or electron beam also causes the existing layer to fuse with the newly deposited material, creating a strong bond between the layers.[33]

Wire-based direct energy deposition can process a variety of metallic materials, including titanium, stainless steel, aluminum, nickel, and copper-based alloys. These materials are preferred due to their high thermal conductivity and high melting points.

3.6 Material Jetting

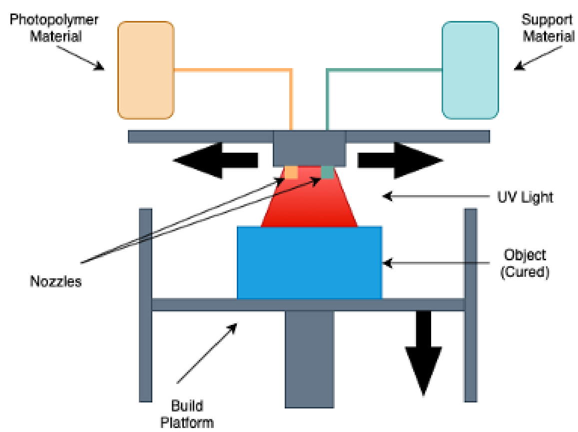

Figure 3.6: Material Jetting Block Diagram

Material Jetting Material Jetting (MJ) is an entire category of AM techniques that share similiarities with how standard inkjet printers operate. MJ techniques use printheads to dispense droplets of photosensitive material, which then solidies under ultraviolet Ultraviolet (UV) light and building a part layer-by-layer.

is an additive manufacturing technique that shares similarities with 2D printers. The process entails the use of a printhead, akin to those used for standard inkjet printing, which often dispenses droplets of a photosensitive material. In some techniques, this material solidifies under ultraviolet UV light, thereby building the part in a layer-by-layer fashion. The materials utilized in MJ are typically thermoset photopolymers, specifically acrylics, which are in a liquid state. Due to the thermoset property, printed objects cannot be melted or reshaped once cured by heat. [35]

3.6.1 Drop on Demand

In the Drop on Demand Drop on Demand (DOD) method, precise droplets are expelled from a nozzle in a controlled manner, resulting in a highly accurate printed component. DOD printing can be actuated through various mechanisms, including pneumatic, piezo-electric, and Magneto-Hydro-Dynamic Magneto-Hydro-Dynamic (MHD) actuators. The first two methods are limited in droplet size, droplet generation frequency, or for use with low melting point materials.MHD technique has been extensively studied and has been shown to overcome the droplet generation frequency limitations present in other DOD methods. [36]

3.6.2 Nanoparticle Jetting

NanoParticle Jetting NanoParticle Jetting (NPJ) involves ejecting a liquid comprising suspended metal or ceramic nanoparticles while simultaneously discharging a support material onto a heated bed. The temperature of the bed causes the liquid to vaporize upon ejection and the suspended particles are able to adhere in all directions. This results in a 3D object that contains minimal bonding agents. NPJ often uses a combination of 316L stainless steel, zirconia, and alumina that are loaded into the machine. The produced green parts then undergo sintering in an oven to eliminate leftover bonding agent.

is a material-jetting technology that uses suspensions of powdered material to build up parts. NPJ jetting involves ejecting a liquid comprising suspended metal or ceramic nanoparticles to create a part while concurrently discharging a support material. The procedure is carried out in a heated bed maintained at 250°C, causing the liquid to vaporize upon ejection, thereby enabling the particles to adhere in all directions. As a result, the final 3D object contains minimal bonding agents in its body and supports. [36]

The NanoParticle Jetting process involves using 316L stainless steel and two ceramic materials, zirconia, and alumina. These materials are loaded into the machine via a cartridge, eliminating the need for any processing or handling. Following printing, NPJ parts will still contain a minor quantity of bonding agent and could include support structures. However, the support material is soluble in water and can be dissolved by placing the object in a water bath. Next, the parts undergo sintering in an oven to eliminate the remaining bonding agent. [35]

3.6.3 MultiJet Printing

The MultiJet Printing MultiJet Printing (MJP) technique employs piezo printhead technology to sequentially deposit photocurable plastic resin or casting wax materials in layers. MJP is widely applied to create parts, patterns, and molds with exceptional feature precision to cater to diverse industrial needs. These printers with high resolution are cost-effective to procure and utilize and leverage a meltable or dissolvable support material to streamline post-processing. [35]

3.6.4 PolyJet Printing

PolyJet printers comprise a build platform, an elevator, a carriage, UV lights, and jetting print heads. To initiate the printing process, photopolymer resin is poured into the material container and heated until it reaches the desired viscosity. The printing process begins with the carriage moving across the X-axis of the build platform, while the print heads selectively jet the resin as droplets onto the platform. The UV lights promptly cure the droplets, resulting in a solid layer. PolyJet printers feature multiple print heads that enable printing different materials simultaneously, which is particularly useful for applications such as parts requiring support. Once a layer is complete, the build platform moves down one layer in height, and the process continues until the part is finished. PolyJet printers support a broad range of materials, including bio-resins. [36]

3.7 Vat Photopolymerization

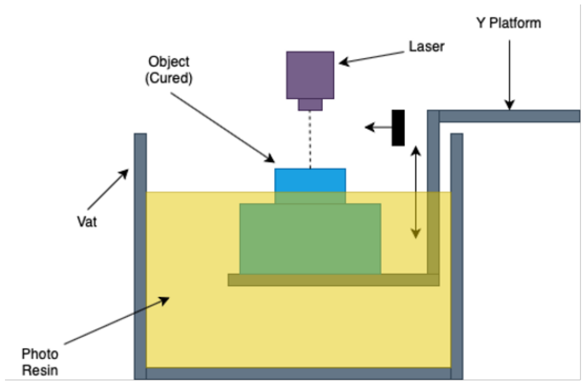

Figure 3.7: Vat Photopolymerization Block Diagram

Vat photopolymerization is a highly specialized technique that involves the use of a photopolymer, a type of light-curable resin, which is exposed to visible or UV light in a vat. The interaction between the photons and the photopolymer triggers a polymerization reaction, resulting in the formation of polymer chains and crosslinks that solidify the resin. [37]

The photopolymer used in this process is composed of monomers, oligomers, and photoinitiators. Monomers are molecules that react with other monomers to form a three-dimensional network, while oligomers consist of repeating units from monomers. Photoinitiators are compounds that produce radicals when exposed to UV light. These radicals react with monomers or oligomers to initiate polymer chain growth. It is important to note that the chain-forming process is irreversible, meaning that prototypes cannot be reverted to their liquid form.[38]

3.7.1 Stereolithography

Stereolithography SLA printing is a prevalent method for fabricating 3-dimensional objects using photopolymer resin. This technique involves focusing an ultraviolet laser onto a vat of photopolymer resin, whereby the laser draws a pre-programmed design or shape onto the surface of the resin.

To fabricate the object, the build platform is lowered incrementally, with a blade recoating the top of the tank with resin for each layer. This process is repeated until the object is complete. However, post-processing is necessary to remove wet resin from the completed parts, which requires washing with a solvent. [38]

In contrast, an inverted stereolithography machine initiates a print by lowering the build platform to the bottom of the resin-filled vat, after which it moves upward by a single layer height. The UV laser writes the bottom-most layer of the desired part through the transparent vat bottom. The vat is then flexed and peeled to detach the hardened material from the bottom of the vat and attach it to the rising build platform. The process is repeated for each subsequent layer. [37]

3.7.2 Digital Light Processing

Digital Light Processing Digital Light Processing (DLP) is a similar process to stereolithography from the perspective that it concerns a 3D printing process that works with photopolymers. The major difference, however, is the light source used to cure the resin. DLP uses a more conventional light source, such as an arc lamp with a liquid crystal display panel, which is applied to the entire surface of the vat of photopolymer resin in a single pass, generally making it faster than SLA.

In the DLP printing process, a filtered light source illuminates a digital micromirror display Digital Micromirror Display (DMD) and a focusing lens. The DMD, composed of tiny mirrors in a matrix attached to a semiconductor chip, projects an entire layer of the 3D model at once onto the resin. DLP printers are faster than SLA printers because they cure every coordinate in a layer simultaneously. However, the digital projection in DLP printers is pixelated, resulting in less detailed prints. The lens focuses the light reflecting off the DMD to correctly place the layer onto the build platform in the desired size and orientation. The printer is housed in an orange protective casing to prevent outside light interference. [38]

3.7.3 Continuous Digital Light Processing

In Continuous Digital Light Processing Continuous Digital Light Processing (CLIP), liquid photopolymer resin is selectively exposed to a UV light source and is solidified into parts. Despite initial appearances, CLIP is unique from SLA and DLP as it is a continuous process that “grows” parts, removing the discrete steps of previous printing methods. CLIP’s innovation lies in its oxygen-permeable membrane that creates a dead zone underneath the part (known as a persistent liquid interface), allowing for continuous curing as the part is drawn out of the resin. Instead of using a layer-by-layer approach, CLIP uses a digital projector and various microcontrollers to project an ever-changing picture of a 3D model, streamlining the print into a layer-less design.

The projector is an essential component in the printing process that provides a crucial curing light source. Typically positioned below the resin vat, it projects a series of ultraviolet images through the vat and onto the build platform, generating a layer-less print through a continuous sequence of cross-sectional images, distinct from SLA/DLP light sources. Like DLP designs, these light engines have a fixed resolution, are digitally projected, and emit a layer’s worth of light at once. However, the CLIP process differentiates itself by blurring the layers together and removing the voxelated effect. [37]

CHAPTER 4
POLICY CONSIDERATIONS

4.1 US Domestic Policies

4.1.1 US Domestic Policies Regulating Additive Manufacturing Technologies

The widespread use of additive manufacturing technologies poses a unique challenge to US national security, requiring the development and maintenance of specialized infrastructure. At present, the US government has adopted a cautious ”wait and see” approach, monitoring technological developments closely and taking action to address security concerns only when necessary. The overarching goal of domestic policy regulating additive manufacturing technologies is to foster the growth of the US additive manufacturing industrial base while upholding national security standards. However, the policy implications of achieving this goal are far from straightforward.

The US Department of Defense (DoD) has recognized additive manufacturing as a strategically significant technology with important military applications. Industry experts have stressed the need to embed cybersecurity capabilities within the technology’s design files, materials, and machines. Moreover, the growing availability of hobbyist 3-D printers has complicated traditional regulatory regimes, potentially leaving gaps in legal protections. As additive manufacturing technology advances and becomes more widely used, hobbyist machines may be capable of producing increasingly complex and potentially dangerous items. [39]

In the interest of national security, certain policymakers and military officials have adopted a protectionist stance that some have termed ”Fortress America,” advocating for the imposition of restrictive export controls and licensing requirements on additive manufacturing technology. However, this position has encountered significant pushback from industry leaders who contend that such controls incorrectly presuppose a US monopoly on the technology and may stifle the growth of domestic companies. In place of strict export controls, these leaders are urging the government to engage in a nuanced assessment of the trade-offs involved in addressing potential national security risks. [40]

To this end, industry leaders are promoting a national dialogue about government intervention in additive manufacturing, intending to create clearly defined objectives and limitations through a consensus-building process. Such a process, they argue, will avoid the pitfalls of unilateral government action while ensuring that the US additive manufacturing industry is equipped to meet the demands of national security without compromising on growth potential. [41]

Additive manufacturing technologies fall under the purview of the Export Administration Regulations Export Administration Regulations (EAR) of the US Department of Commerce's Bureau of Industry and Security (BIS). In October 2020, BIS released updates to the Export Control Classification Number Export Control Classification Number (ECCN), which governs a specific class of computer-controlled CNC machines. The updated rule requires an assessment of multi-axis CNC capability and additive manufacturing technologies based on the technical criteria outlined in the ECCN. [42]

The BIS first identified additive manufacturing as an area of growing concern in 2018, when it issued an Advanced Notice of Proposed Rulemaking Advanced Notice of Proposed Rule making (ANPRM) seeking feedback on criteria for identifying emerging technologies. In 2021, the BIS withdrew a proposed rule that would have imposed export controls on additive manufacturing equipment used for printing ”energetic materials” and related software and technology. The BIS defines energetic materials as substances or mixtures that react chemically to release the energy required for their intended application, with sub classes including explosives, pyrotechnics, and propellants. The proposed rule sought to amend the Commerce Control List Commerce Control List (CCL) and add changes to this emerging technology, which the US has proposed for inclusion in the Wassenaar

Arrangement List of Dual-Use Goods and Technologies and Munitions List Wassenaar Arrangement (WA), administered by the Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies. No formal rules have been proposed since the withdrawal of this measure. [42]

4.1.2 US Domestic Policies Regulating the Export of Nuclear Technology

the Export Administration Regulations of the Commerce Department's Bureau of Industry and Security Bureau of Industry and Security (BIS), and the International Traffic in Arms Regulations International Traffic in Arms Regulations (ITAR) of the State Department's Directorate of Defense Trade Controls Directorate of Defense Trade Controls (DDTC) are the two largest bodies of export regulations in the United States. However, a small yet crucial slice of nuclear export activity falls under the jurisdiction of the Nuclear Regulatory Commission Nuclear Regulatory Commission (NRC) and the Department of Energy Department of Energy (DOE). [43]

The DoE has a long-standing responsibility for authorizing the transfer of unclassified nuclear technology to foreign nuclear energy activities within the United States or abroad. As per the Atomic Energy Act of 1954 , the production or development of special nuclear material outside the territorial boundaries of the United States is restricted to those individuals who have obtained explicit authorization from the Secretary of Energy, with the additional requirement of concurrence from the Department of State Department of State (DOS), and consultation with the Departments of Defense DOD and Commerce Department of Commerce (DOC), along with the Nuclear Regulatory Commission NRC. The DoE instituted a requirement that pertains to the transfer of technology and assistance in specific nuclear fuel-cycle activities, commercial nuclear power plants, and research and test reactors. Covered transfers may comprise physical documents or electronic media transfers, electronic transmissions, or the conveyance of knowledge and expertise. [44] the Code of Federal Regulations, the Secretary has issued broad permission for specific types of activities that have been deemed non-detrimental to the interests of the United States. This permission includes the transfer or provision of technology and assistance to the ”generally authorized destinations”. Transfers of sensitive nuclear technologies and transfers to countries not listed in Appendix A require specific authorization from the Secretary of Energy. In 2015, the regulation was updated to provide expanded general authorizations and an affirmative list of destinations that are generally authorized to receive transfers of non-sensitive nuclear technology. In December of 2022, the Secretary of Energy signed a Final Rule establishing procedures for the imposition of civil penalties for violations provisions of the Atomic Energy Act of 1954, as amended, The Final Rule also reflects the review and consideration of comments received from the public in response to the Notice of Proposed Rulemaking that DOE issued in October of 2019. [43]

The Nuclear Regulatory Commission regulates major hardware, components, and nuclear material. These include nuclear reactors and their components, plants for uranium and lithium isotope separation, reprocessing of nuclear fuel, fabrication of nuclear fuel elements, conversion of uranium and plutonium, production of heavy water and deuterium, and special nuclear material production using certain systems. NRC regulations apply to all persons in the United States, unless the equipment or material is otherwise under the jurisdiction of the EAR or ITAR, or is an in-bond shipment transiting the U.S. The NRC provides licenses for equipment and materials used in the nuclear industry. The licenses include a ”Specific License” that requires approval for exporting nuclear equipment or materials based on an application filed with the NRC. The approval is subject to review by various executive branch departments. The ”General License” is another option that exempts the exporter from obtaining specific approval if the prerequisites for a specific list of destination countries are satisfied. There are five general licenses currently available from the NRC, each covering a different type of nuclear material. To transfer certain nuclear equipment or material which includes special nuclear material produced using equipment, source material, or special nuclear material that has obligations to the United States under a cooperation agreement, approval must be obtained from the Department of Energy. This applies to situations where the equipment or material is being transferred to a new destination. However, if the transfer is authorized by the NRC under a specific or general license or an exemption from licensing requirements, then approval from the Department of Energy is not required. [45]

4.1.3 US Domestic Export Controls on Materials

The United States maintains strict export control regulations on various materials and technologies that could pose a threat to national security or be used for military purposes. Among these regulations are those about certain high-strength materials, including maraging steel, aluminum alloys, boron or boron alloys, guanidine nitrate, nitroguanidine, ceramic powder of titanium diboride, and fibrous or filamentary materials. [46]

Under section 7 of the US Export Administration Regulations, maraging steel capable of ultimate tensile strength of 2050 MPa or more is subject to export controls. This means that a license is required for the export of such steel to certain destinations or end-users, especially those with a history of military or weapons-related activities.[47]

Similarly, aluminum alloys with an ultimate tensile strength of 460 MPa or more are subject to export controls under section 7 of the EAR. This is because such alloys can be used in the production of high-performance aerospace components, missile structures, and other military hardware.

Boron and boron alloys with a particle size of 60 μm or less are under US export control regulations if they have a purity of 85% by weight or more, or if they are boron alloys with a boron content of 85% by weight or more. Along with this, Guanidine nitrate (CAS 506-93-4) and nitroguanidine nitroquanidine (NQ) (CAS 556-88-7) are also subject to export control regulations. [47]

Fibrous or filamentary materials with a specific modulus of more than 3.18 × 106 m and a specific tensile strength greater than 76.2 × 103 m are also subject to export controls under section 7 of the EAR. This includes materials consisting of a metal or carbon matrix, as well as carbon fibrous or filamentary materials meeting specific modulus and specific tensile strength requirements.

In the case of carbon fibrous or filamentary materials, a specific modulus exceeding 10.15 × 106 m and a specific tensile strength exceeding 17.7 × 104 m are required to trigger export controls under section 7(b)(1) of the EAR. These materials are used in various military applications, including aerospace structures, missile components, and protective gear.[48]

It should be noted that the metals or alloys specified by 1C011.b also refer to metals or alloys encapsulated in aluminum, magnesium, zirconium, or beryllium. Additionally, ”precursor materials” that are ”specially designed” for the ”production” of materials controlled by 1C007.c are subject to export controls. Finally, metal alloys made from powder or particulate material controlled by 1C002.c, such as nickel, niobium, titanium, aluminum, and magnesium, are also subject to export controls. [47]

4.2 International Policies

4.2.1 International Policies Regulating Additive Manufacturing

International discussions on how to regulate the spread of AM technology have been taking place within the Missile Technology Control Regime Missile Technology Control Regime (MTCR), the Wassenaar Arrangement, and the Nuclear Suppliers Group Nuclear Suppliers Group (NSG) since 2014. Conversations have centered around implementing controls on the export of AM machines, controls on the machines used in the AM process, and controls on the transfer of build files. Currently, the only multilateral export control, that contains language regarding AM is the Wassenaar Arrangement. In 2016, the WA’s list of dual-use goods was amended to add “directional-solidification or single-crystal additive manufacturing equipment” to produce gas-turbine engine blades, vanes, and tip shrouds, as well as associated software. However, this amendment introduced controls for a very specific set of applications on a specific AM technique, and thus only ensured coverage of technologies for the specific purpose. While there is a distinct lack of controls for complete AM machines, many high-risk proliferation AM machines are mounted with high-powered lasers. Control lists already cover several categories of lasers and their components, but the technical definitions do not yet apply specifically to the lasers used in metal AM machines. [49]

In 2014, an amendment to the MTCR was proposed by Australia to introduce specific controls on AM technology, with a focus on ”machine tools for ’additive manufacturing’” that process certain materials in a controlled environment. In 2016, France put forward a proposal to the NSG to regulate AM machines that have a controlled atmosphere, a build chamber with one dimension larger than 20 centimeters, and use LBM or EBM powder bed techniques. Both proposals were ultimately rejected by the MTCR. However, the issue of AM was considered important and qualified as a topic of interest to be discussed in future meetings of the WA, following a subsequent proposal from Australia. Additive manufacturing machines that process metals, alloys, or ceramics, which are widely considered to be the most proliferation-sensitive, necessitate the feeding of these materials into the machine in a powdered form with specific characteristics. These characteristics are often distinct from the binding or fusing technique utilized by the machine. [50] existing roster of dual-use commodities and technologies maintained by the WA encompasses a vast array of special metals and alloys. Nevertheless, the presently regulated powders are delimited by criteria that pertain to the distinct chemical and physical characteristics required by conventional manufacturing methods, and these specifications are not aligned with the requisite properties for AM utilization. [49] MTCR and NSG control lists contain provisions for maraging steels that possess certain characteristics, although they do not include these steels in powder form as a specific category. Conversely, the WA currently lacks control measures for maraging steels. In 2015, France proposed adding maraging steel powders to the WA control list, which would entail restrictions on metal alloy powders and alloyed materials that possess specific particle sizes and compositions and have alloying elements. Such a measure would also encompass powders utilized in AM. However, the proposal was not ratified. [51]

The transfer of build files is a crucial component of the additive manufacturing process, as they provide the specific information necessary for the AM machine to execute the desired task. The increasing reliance on information technology and automation, including the transfer of data and knowledge through digital means, poses significant challenges to export controls, not just for AM but for many goods and technologies that rely on information technology and transfer. The MTCR defines technology as specific information necessary for the development, production, or use of a product, including technical data and assistance, and states that transfers of technology associated with controlled goods are also regulated. However, there are varying interpretations and national practices as to what information qualifies as ”required” to develop or produce a controlled item, and no guidance has been provided by the MTCR or other multilateral export control regimes on how to apply and enforce controls concerning AM. [50] Effective implementation and enforcement of controls on digital transfers of information, including those related to additive manufacturing, poses a significant challenge for both companies and states. National licensing authorities are required to collaborate with the industry, promote effective internal compliance programs, and employ intelligence-gathering tools to detect violations. Similarly, companies must ensure the security of their build files and maintain comprehensive records of their exports. Moreover, the susceptibility of systems to vulnerability and potential malicious distribution underlines the importance of cybersecurity in the context of AM.

4.2.2 International Policies Regulating the Trade of Nuclear Technology

Despite the emergence of regional free trade areas, such as the European Union, the North American Free Trade Area, and the Asia-Pacific Economic Cooperation area, it remains the case that export controls on nuclear technology, reactor components, and radioactive materials are exercised exclusively at the national level. This situation is justified by the General Agreement on Tariffs and Trade General Agreement on Tariffs and Trade (GATT), which permits governments to safeguard their essential security interests by exempting fissionable materials and war-related implements from the treaty's obligations to eliminate barriers to international trade.[52] There is little indication that this arrangement will be altered in the foreseeable future, both suppliers and export control authorities have a role to play in facilitating legitimate trade in nuclear materials, components, technology, and safety-related information exchange. Strategic export controls are considered an indispensable component of governments' armory in preventing the acquisition of weapons of mass destruction by unauthorized entities. These measures serve to complement other non-proliferation and counter-terrorism strategies aimed at ensuring public safety against such catastrophic threats, as well as prosecuting the perpetrators. The implementation of strategic export control regimes involves a multifaceted approach, including the enactment of legislation to establish relevant competencies and enforcement processes, the regulation of controlled technologies, goods, services, and materials through a control list, export licensing, border control activities such as intelligence gathering, detection, inspection, and an interception, financial sanctions on designated parties, and public outreach to industry via public information campaigns.

After the NPT was implemented in 1970, a group of signatories formed an informal inter-governmental organization 1971 called the NPT Exporters Committee or Zangger Committee. The objective was to establish a consensus on the technologies, radioactive sources, and fissionable materials that should be covered by export controls. The committee aimed to provide a unified interpretation of Article III of the NPT, which mandates governments to regulate nuclear materials and certain other materials and equipment. The Zangger Committee concurred on a list of goods that "trigger" the need to introduce export controls and guarantees that the importing state adheres to IAEA safeguards.[53]

The Nuclear Suppliers Group was established in 1974 by several countries that adhere to the NPT intending to issue guidelines for safeguarding and controlling the international trade in nuclear and related dual-use technology, equipment, and materials. The guidelines originally consisted of a ”trigger list” and ”guidelines” which set out the circumstances under which nuclear exports could take place. However, as the international community became more aware of clandestine nuclear weapons development programs in certain countries, the NSG guidelines were revised in the early 1990s. The revised guidelines expanded the trigger list and added a ”dual-use list.” They also included the ”Non-Proliferation Principle,” which requires exporting countries to ensure that their exports do not contribute to nuclear weapons proliferation or pose a risk of nuclear terrorism. Under the NSG arrangements, countries can only export nuclear technologies, equipment, and materials to countries that have accepted full-scope safeguards applied by the IAEA to their nuclear facilities. The NSG guidelines are applied to both participating and non-participating states, and states can choose to adhere to them without participating in the NSG.[51]

Under the UN Security Council Resolution 1540, governments are obligated to create and enforce measures to prevent unauthorized entities and individuals from acquiring or utilizing nuclear weapons and sensitive materials and technology. In addition to the Zangger and NSG regimes, conventions for international cooperation, such as the amended Convention on the Physical Security of Nuclear Materials and the International Convention for the Suppression of Acts of Nuclear Terrorism, have been established for detecting, countering, and punishing acts of theft, smuggling, and unauthorized use of nuclear materials and technology. These conventions are meant to impose obligations on states to safeguard all radioactive and nuclear materials, return stolen materials and devices to the country of origin, prosecute, or extradite terrorist suspects, and aid in crises. [53]

Many countries have agreed to an Additional Protocol with the IAEA since 1997, which places additional reporting requirements on member states and strengthens the safeguards system. With an additional protocol in place, governments are required to provide information on the export of nuclear equipment and certain non-nuclear materials, and if requested, information on their nuclear imports. This is meant to encompass the entire fuel cycle of a given nation, however while uranium mines may be inspected by the IAEA under the terms of the Additional Protocol, they are not subject to the full safeguards applied to nuclear facilities.[51]

4.2.3 International Export Controls of Materials

The Special Materials and Related Equipment category, found in the Wassenaar Arrangement's List of Dual-Use Goods and Technologies, pertains specifically to materials and equipment that possess dual-use characteristics, i.e., having applications in both military and civilian fields.[49]

Among the materials included in this category are aramid fibers, boron fibers, and carbon fibers with tensile strength greater than 7 GPa, which are widely used in the manufacture of advanced composites for applications in the aerospace and missile industries. Furthermore, materials are used in the production of armor and other protective gear for military personnel and equipment, such as boron carbide, beryllium, depleted uranium, and certain types of ceramics, are also subject to export controls.

The Nuclear Suppliers Group aims to prevent nuclear proliferation by controlling the export of nuclear-related materials and technologies. One of the materials controlled by the NSG is aluminum alloys with ultimate tensile strength of 460 MPa or more at 293 K (20 °C) and are in the form of tubes or cylindrical solid forms with an outside diameter of more than 75 mm.[53]

It's worth noting that the phrase "capable of" includes aluminum alloys before or after heat treatment. This means that even if an aluminum alloy does not have the required strength at room temperature, it may still be controlled if it can be heat-treated to achieve the required strength.

Beryllium metal and alloys containing more than 50% beryllium by weight, beryllium compounds, manufactures thereof, and waste or a scrap of any of the foregoing are also controlled by the NSG. However, some specific products are excluded from control, such as metal windows for X-ray machines or for bore-hole logging devices, oxide shapes in fabricated or semi-fabricated forms specially designed for electronic parts or as substrates for electronic circuits, and beryl (silicate of beryllium and aluminum) in the form of emeralds or aquamarines.[53]

Another material controlled by the NSG is bismuth with a purity of 99.99% or greater by weight and containing less than 10 ppm by weight of silver. Boron enriched in the boron-10 (10B) isotope to greater than its natural isotopic abundance is also controlled, including elemental boron, compounds, mixtures containing boron, manufactures thereof, waste, or a scrap of any of the foregoing.

Finally, the NSG controls ”fibrous or filamentary materials,” including carbon or aramid ”fibrous filamentary materials” with specific characteristics of a specific modulus of 12.7 x 106 m or greater, or a specific tensile strength of 23.5 x 104 m or greater. Glass ”fibrous or filamentary materials” with a specific modulus of 3.18 x 106 m or greater and specific tensile strength of 7.62 x 104 m or greater are also controlled. However, some aramid ”fibrous or filamentary materials” are excluded from control if they have 0.25% or more by weight of an ester-based fiber surface modifier.

MTCR export controls play a significant role in limiting the spread of sensitive missile technology and materials to countries of concern. Among the materials controlled under the MTCR guidelines are saturated pyrolyzed (i.e., carbon-carbon) materials, fine grain recrystallized bulk graphite (with a bulk density of at least 1.72 g/cc measured at 15 degrees C and having a particle size of 100 × 10–6 m or less), pyrolytic, or fibrous reinforced graphite, ceramic composite materials (dielectric constant less than 6 at frequencies from 100 Hz to 10,000 MHz), and bulk machinable silicon-carbide reinforced unfired ceramic usable for nose tips. [50]

Additionally, tungsten, molybdenum, and alloys of these metals in the form of uniform spherical or atomized particles of 500-micrometer diameter or less with a purity of 97 percent or higher are typically used in the fabrication of rocket motor components such as heat shields, nozzle substrates, nozzle throats, and thrust vector control surfaces, and thus subject to controls.

Maraging steels, which are characterized by high nickel, very low carbon content, and the use of substitutional elements or precipitates to produce age-hardening, are also controlled under the MTCR guidelines. Specifically, maraging steels having an Ultimate Tensile Strength of 1.5×109 Pa or greater, measured at 20 degrees C, are subject to export controls.[50]

Finally, titanium-stabilized duplex stainless steel Titanium-Stabilized Duplex Stainless Steel (Ti-DSS) having certain characteristics is also controlled under the MTCR guidelines. Specifically, Ti-DSS containing 17.0 to 23.0 weight percent chromium and 4.5 to 7.0 weight percent nickel, and a ferritic-austenitic microstructure (also referred to as a two-phase microstructure) of which at least 10 percent is austenite by volume, according to ASTM E-1181-87 or national equivalents, is subject to export controls. [50]

CHAPTER 5
METHODOLOGY

In order to comprehensively understand the potential proliferation risks associated with AM processes in the nuclear fuel cycle, a rigorous methodology can be employed. This methodology aims to assess the likelihood of nuclear proliferation in specific steps of the fuel cycle by considering the likelihood of AM being utilized at different parts of the nuclear fuel cycle.

The assessment begins by developing specific criteria for each phase of the fuel cycle and reactor components. These criteria are evaluated on a numerical scale ranging from 1 to 5, where 1 indicates no anticipated usage or applications and 5 represents current applications of AM technology in the nuclear industry. The criteria encompass multiple aspects, including the manufacturing method, design, completed product quality and complexity, and existing or experimental uses of each AM technology.

5.1 Mining Methodology

In order to comprehensibly develop a framework for assessing the potential risks of using AM in uranium mining, it's essential to consider the technology's impact on the exploratory phase of mining. AM has the potential to significantly enhance exploration by constructing physical models of geological formations, providing geologists with a more accurate understanding of rock structure and composition. This improved knowledge leads to more precise resource estimation and identification of potential uranium deposits. Furthermore, AM enables the creation of specialized equipment and tools tailored to specific geological conditions, enhancing operational efficiency, and reducing the risk of equipment failure.

However, while considering the deployment of AM technology in uranium mining, it is important to account for the risk of nuclear proliferation. Among all stages in the nuclear fuel cycle, uranium mining has historically shown relatively low instances of illicit proliferation. A comprehensive study spanning from 1995 to 2016, conducted by the Global Terrorism Database, revealed that non-uranium mines worldwide experienced 135 instances of terrorist or insurgent attacks. Most of these attacks occurred in countries with active insurgencies, namely Colombia, Indonesia, India, and the Philippines.[54] While uranium mines are not inherently more or less susceptible to attack compared to other types of mines or foreign company processing facilities, they can be vulnerable in areas with active insurgencies due to various factors such as environmental concerns, labor issues, revenue disputes, and concerns about resource exploitation by foreign companies. In the case of Niger, the mining company Orano required government assistance to ensure the security of their uranium mine and convoy transportation of Uranium Oxide. [54]

5.2 Milling Methodology

To comprehensively evaluate the potential risks associated with the utilization of AM technology in uranium milling, a thorough analysis is essential to address nonproliferation concerns. Uranium milling occupies a critical position within the nuclear fuel cycle, as it encompasses the conversion of mined uranium ore into nuclear fuel. Nevertheless, the possibility of diversion of nuclear materials during the uranium milling process raises nonproliferation concerns that could potentially lead to the development of nuclear weapons.

Analysis of attacks on nuclear facilities reveals that incidents targeting conversion facilities are historically rare. Out of 80 recorded incidents between 1960 and 2014, only two involved pre-enriched uranium, both of which were thefts from Russian facilities in the early 1990s. In one instance, an individual attempted to smuggle 2.5 kilograms of uranium into Poland, believed to have originated from a facility in Udmurtia, Russia, with plans to steal more. In another case, three teenagers stole 9.5 kilograms of natural U-238 from Sarov, Russia, intending to sell it. A notable incident involving yellowcake diversion occurred in 1968, known as the Plumbat Affair, where 200 metric tons of U3O8 were diverted from Antwerp to Haifa, Israel, and then sent to the Dimona nuclear reactor. A dataset of 869 trafficking incidents from 1991 to 2016 indicates that theft, loss, and trafficking of nuclear material are relatively uncommon but more likely in countries with lower levels of security. [54]

The implementation of AM technology in uranium milling offers a promising solution by enabling the production of customized components that can mitigate nonproliferation risks. For instance, AM has the capability to fabricate durable and precise components for milling equipment that are less prone to wear and tear. Additionally, AM facilitates the creation of specialized components that can be easily monitored and tracked, allowing for unique identification of milling equipment components throughout the entire milling process, from initial processing to final disposal. [55]

5.3 Enrichment Methodology

It's important to consider its applications in the production of uranium enrichment equipment in order to assess possible risks that may emerge by utilizing AM in these processes. AM enables the efficient manufacturing of key components such as centrifuges and gas diffusion barriers, which raises concerns about nonproliferation. The confluence of AM and uranium enrichment technologies could potentially facilitate the clandestine production of highly enriched uranium by states or non-state actors lacking the necessary equipment or technology. Past incidents of nuclear proliferation linked to uranium enrichment highlight ongoing concerns regarding this technology's potential misuse in acquiring nuclear weapons or materials. The detection of illicit enrichment activities presents a formidable challenge, as they can be conducted in small-scale or concealed facilities that are difficult to monitor. [56]

In the early 2000s, it was revealed that North Korea had secretly been enriching uranium for weapons purposes using centrifuge equipment, with evidence of a connection to Pakistan's centrifuge program. The full extent of North Korea's uranium enrichment program remained uncertain, but by 2009, it was announced that tests had been successfully conducted, and the program was in its final stages. North Korea installed approximately 2,000 Pakistani P2-type centrifuges at the Yongbyon site, and while the purpose was unknown, North Korea claimed they were used to produce low-enriched uranium. The estimated capacity of the centrifuges doubled by 2015. [57] Iran, on the other hand, has significantly expanded its uranium enrichment activities since 2000, with multiple enrichment plants subject to international safeguards. The IAEA expressed concerns about Iran's lack of cooperation, transparency, and continued enhancement of its enrichment facilities, along with the construction of the Arak heavy water reactor. South Africa and Libya also had uranium enrichment capabilities, with South Africa having a large-scale plant for its nuclear power program, and Libya obtaining illicit technology from Pakistan for its early-stage enrichment program. [58]

5.4 Fuel Fabrication Methodology

The deployment of AM in nuclear fuel fabrication offers the potential to optimize fuel performance by enabling the production of fuel pellets in various shapes and sizes, enhancing reactor efficiency, and reducing fuel consumption. However, the unauthorized production of specialized fuel components using AM raises significant nonproliferation concerns.

One crucial aspect to consider is the handling of radioactive materials during the nuclear fuel fabrication process, which poses safety and security risks. These materials play a critical role in the manufacture of nuclear weapons, making it imperative to prevent their unauthorized access. The case of North Korea's illicit nuclear fuel fabrication facilities serves as a prominent example, demonstrating the potential for fuel fabrication technologies to be misused for the production of weapons-grade plutonium. The combination of AM and nuclear fuel fabrication technology raises concerns about non-state actors or states clandestinely producing advanced nuclear weapons through the exploitation of this technology. [59]

Examining previous incidents of proliferation, it is noteworthy that Iran has established a fuel manufacturing plant in Isfahan to support the IR-40 reactor and potentially the Bushehr facility. They have produced prototype and final natural uranium fuel assemblies, as well as fuel assemblies using enriched uranium. Additionally, Iran has produced a significant quantity of enriched uranium, raising concerns by the IAEA. Furthermore, Israel's Dimona nuclear reactor, operating without full international safeguards, has been subject to only limited inspections. [60]

5.5 Power Reactor Methodology

One of the primary concerns for AM use in nuclear power reactors is the potential diversion of nuclear material for unauthorized purposes, including the development of nuclear weapons or dirty bombs. The risk of sabotage or terrorist attacks on nuclear power plants must also be taken into account, as such incidents can have severe consequences and pose a threat to public safety.

The introduction of AM technology in nuclear power reactors brings additional risks. The production of substandard or defective components using AM could compromise the safety and security of the reactors. Moreover, the creation of specialized components through AM could potentially be exploited for the development of advanced nuclear weapons or other illicit activities.

Due to the hazardous nature of nuclear materials and their potential misuse, robust safety and security measures must be implemented in nuclear power plants to prevent unauthorized access or diversion.

Examining historical incidents, the operation of a small experimental power reactor in Yongbyon by North Korea raised concerns about plutonium production for weapons purposes. The IAEA has reported numerous incidents involving illicit trafficking and unauthorized activities related to nuclear and radioactive materials across multiple countries. Nuclear terrorism incidents, such as attacks on Pakistani nuclear facilities and burglaries at the Pelindaba research facility in South Africa, underscore the risks associated with nuclear materials. Suspicions have also been raised regarding Israel's Dimona nuclear plant and its potential involvement in the production of nuclear weapons. [60]

5.6 Reprocessing Methodology

The first criterion that must be considered when assessing proliferation risks associated with the utilization of AM in nuclear fuel processing involves evaluating the use of AM in the production of reprocessing equipment to ensure that the resulting components meet the required quality and safety standards. Non-destructive testing methods need to be applied to assess the composition and structural integrity of the components. The second criterion focuses on the potential risks of nuclear material diversion or accidents arising from substandard or defective equipment produced through AM. Evaluating the risks associated with using AM to fabricate specialized components and their potential exploitation in illicit activities, such as unauthorized extraction of nuclear material is critical. [61]

The third criterion addresses the impact of AM on the efficiency and effectiveness of nuclear fuel reprocessing. While AM has the potential to enhance the precision and complexity of components, there also needs to be a guarantee that it won't compromise safety or security in the reprocessing process. Compliance with international agreements and safeguards related to nonproliferation should be evaluated to ensure that the utilization of AM in nuclear fuel reprocessing adheres to nonproliferation standards and does not contribute to heightened risk. [61]

5.7 Nuclear Fuel Disposal Methodology

In order to establish a methodology for assessing proliferation risks associated with the utilization of AM in nuclear fuel disposal, there must be an evaluation on the use of AM in the production of canisters for storage and transportation of spent nuclear fuel, as well as equipment used in handling and disposal, to ensure that the canisters and equipment meet the required quality, safety, and regulatory standards to prevent nuclear material diversion or unauthorized access. Proper storage and disposal practices should be in place to mitigate the risks of nuclear material diversion or proliferation. Stringent safeguards and regulations should be implemented to prevent unauthorized access to spent nuclear fuel and the potential misuse of AM technology in this context.

Considering historical incidents, such as North Korea's suspected undisclosed storage sites and Iran's production of enriched uranium, there is substantial evidence that the potential for proliferation incidents still largely exists today, although the number of historical incidents remains low. [62]

CHAPTER 6

RESULTS

Using the specific criteria that were developed for each fuel cycle phase, techniques were evaluated on a numerical scale ranging from 1 to 5, with higher values indicating a larger presence in the nuclear industry. The numerical findings for each phase, with the highest risk approaches further analyzed to identify commonalities that may pose an unchecked proliferation danger. 31 AM techniques were investigated and ranked based on their perceived risk. The data collected was graphed from highest to lowest to quickly identify the techniques at the highest risk of being exploited. Techniques were categorized as high risk with a cumulative score of greater than or equal to 20, moderate risk with scores between 19 and 11, and low risk with scores of 10 or below. These findings provide critical insight into the proliferation risks associated with AM techniques and are essential for developing effective regulations and strategies to minimize the potential for nuclear proliferation.

6.1 Binder Jetting

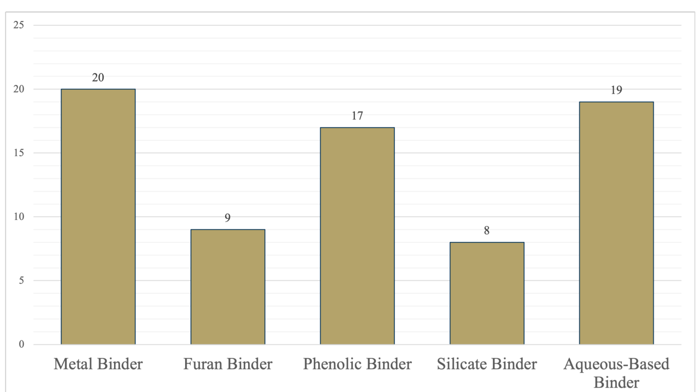

Figure 6.1: Total Values of Binder Jetting

6.1.1 Metal Binder

Table 6.1: Results of Metal Binder

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Metal Binder	4	2	3	4	3	2	2	20

Metal binder jetting is considered a high-risk technology due to its calculated value of 20. Currently, the technology is being tested in the mining industry, particularly in the production of complex tungsten carbide-cobalt (WC-Co) cutting tools and bits, with ongoing research aimed at establishing mainstream utilization. [63] metal binder jetting has the theoretical capacity to create parts used in milling uranium or related ore, its practical application in this field is not yet pursued.

Research is underway on the use of 315L stainless steel produced by binder jetting to create high-strength complex parts, such as those found in gas centrifuges utilized for uranium enrichment. However, the current focus is on analyzing the effects of process parameters of debinding and sintering on the material's microstructure, without practical applications in industry. [64]

Furthermore, binder jetting technology is being employed to produce molybdenum disks that are filled with uranium nitride microspheres for use in high-temperature reactors, such as those used in nuclear thermal propulsion Nuclear Thermal Propulsion (NTP) for deep space exploration. Metal binder jetting can also utilize the Ni-base superalloy, Inconel 718, which has been successfully used in high-temperature applications such as in the pressure vessels of nuclear reactors. Novel applications of metal binder jetting with Inconel 718 for advanced and nuclear reactors are currently being explored. [64]

6.1.2 Furan Binder

Table 6.2: Results of Furan Binder

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Furan Binder	1	1	1	2	1	2	1	9

Furan binder jetting is a technology that exhibits relatively low risk, with a value of 9. Furan, a volatile cyclic ether, finds widespread use in the production of various substances, including resins, agrochemicals, and pharmaceuticals.

However, furan binder jetting has not garnered significant research interest for use in industries such as mining, milling, enrichment, power reactors, or disposal due to its chemical composition. Additionally, components produced by furan binder jetting lack the mechanical strength required for use in these industries. [18]

Nonetheless, there is a possibility that furan binder jetting could be applied in the manufacture of nuclear fuel or spent fuel reprocessing, although this application remains limited. Current discussions revolve around using this technology to produce molds by combining silica sand and furan resin, an approach that shows promise to produce complex geometries.

6.1.3 Phenolic Binder

Table 6.3: Results of Phenolic Binder

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Phenolic Binder	2	2	3	3	3	2	2	17

Phenolic binder jetting is a promising technology that holds significant potential in various industries. With an intermediately-high risk classification, its unweighted value of 17 suggests that there are some inherent risks for this technology.

Phenolics, which are most commonly used in the manufacture of composites, possess desirable characteristics such as high-temperature stability and adhesion to different substrates. Consequently, phenolic binder jetting holds great potential in composite manufacturing processes, including filament winding, resin transfer molding, and compression molding.[65]

While not currently used in the mining or milling of uranium ore, phenolic binder jetting could find applications in the industry in the future, especially in the development of new composite materials that could withstand the harsh operating conditions of the mining and milling process.

Currently, phenolic binder jetting is being investigated as a hybrid method for the production of denser structures made from materials such as Inconel 718, graphite, or 316L stainless steel green parts. This process has shown promising results, producing high-strength parts with low binder content, signalling potential applications in enrichment technologies and power reactors. [65]

In addition to these potential applications, phenolic resin binders could also be used in the production of high-strength molds for fuel fabrication and reprocessing. While experimental work is still in its early stages, the possibility of using this technology to manufacture high-strength molds is an interesting prospect that could lead to more efficient and cost-effective fuel fabrication and reprocessing processes.

6.1.4 Silicate Binder

Table 6.4: Results of Silicate Binder

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Silicate Binder	1	1	1	1	2	1	1	8

Silicate binder jetting is classified as a low-risk technology, with a score of 8. As of the time of publication, no peer-reviewed scientific papers have explored the use of silicate binder jetting at any stage of the nuclear fuel cycle.

Silicates are widely employed as adhesives in the cement, ceramic, and glass industries. Silicate binder jetting is currently utilized to manufacture casting patterns, full-color decorative objects, jewelry, and various other applications. Although the use of silicate binder jetting may be possible for casting patterns and molds for parts in a reactor vessel, no research currently explores this possibility.[66]

Currently, the primary applications of silicate binder jetting remain in the domains of art, crafts, and decorative objects. However, given the versatility of silicates as adhesives and the ability of binder jetting technology to manufacture intricate shapes, it could be plausible that future research could explore the possibility of using this technology in nuclear fuel cycle applications.

6.1.5 Aqueous-Based Binder

Table 6.5: Results of Aqueous-Based Binder

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Aqueous Binder	3	2	3	4	3	2	2	19

Aqueous-based binder jetting employs water-based binders, and is considered to have a moderately-high risk. Thus, it has an unweighted score of 19 and a weighted score of 19.1. This technology has the potential to produce complex geometries with high accuracy and precision, making it suitable for various industries. In the nuclear industry, aqueous-based binder jetting has been identified as a potential technology due to its ability to fabricate high-density, high-strength, and thermally resistant parts required for uranium enrichment and power reactors.[67]

One of the primary advantages of this technology is that it allows for the use of multiple materials, which can be mixed and deposited layer-by-layer to create intricate structures. [68] The deposition process is computer-controlled, which enables high accuracy and precision. Additionally, the ability to incorporate aqueous-based binders that don't react with volatile materials makes it a safe and reliable option for nuclear fuel fabrication.

There are also some potential drawbacks to aqueous-based binder jetting. For example, the printed parts require post-processing to remove excess binders and achieve the desired mechanical properties. Moreover, this technology may not be suitable for producing large-scale components due to limitations in printing speed and size. However, despite these limitations, the potential benefits of aqueous-based binder jetting make it a promising technology for various applications, including nuclear fuel fabrication. [69]

6.2 Material Extrusion

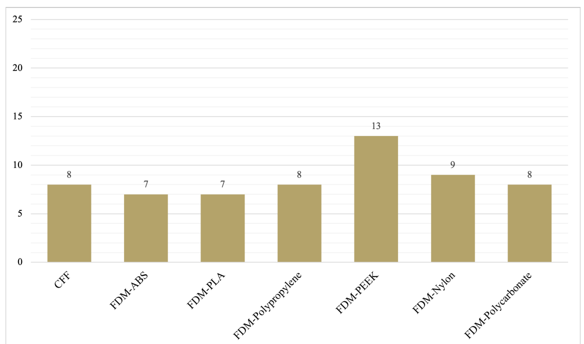

Figure 6.2: Total Values of Material Extrusion

6.2.1 Continuous Fiber Fabrication

Table 6.6: Results of Continuous Fiber Fabrication

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
CFF	2	1	1	1	1	1	1	8

Continuous fiber fabrication is a type of material extrusion additive manufacturing technology that uses thermoplastic filaments to create parts with an outer shell and an internal matrix. This technique is often considered low risk, as demonstrated by its calculated risk of 8 , making it an attractive option for many hobbyists. [70]

In the nuclear industry, CFF has only been utilized in the production of vehicle cabin filters for mining work cabins. However, the use of CFF-produced parts is currently limited by their lack of material strength and properties, rendering them unsuitable for use in critical applications such as enrichment, power reactors, fuel fabrication, reprocessing, or disposal. [71]

6.2.2 Fused Deposition Modeling

Fused deposition modeling is a widely utilized additive manufacturing process among hobbyists. This technique involves the deposition of various types of thermoplastic filaments onto a build platform.

Fused Deposition Modeling is frequently subdivided into distinct techniques according to the specific material employed, such as Acrylonitrile butadiene styrene, Polylactic Acid, Polypropylene, Polyetheretherketone, Nylon, or Polycarbonate. The selection of material significantly influences the build's strength, type, and applications and therefore, these variations are often treated as distinct techniques.

Acrylonitrile Butadiene Styrene

Table 6.7: Results of Acrylonitrile Butadiene Styrene

Technique	**Mining**	**Milling**	**Enrichment**	**Fuel Fab.**	**Power Reactors**	**Reprocessing**	**Disposal**	**Total**
ABS Plastic	1	1	1	1	1	1	1	7

Acrylonitrile Butadiene Styrene is the prevailing material utilized in Fused Deposition Modeling, owing to its low production cost and ease of handling. ABS plastic is conventionally utilized to create figurines and models for hobbyists and is not intended for high-performance applications. Consequently, the total numerical risk of ABS stands at 7. As such, there is no published literature exploring the use of ABS FDM for any nuclear applications. [72]

Table 6.8: Results of Polylactic Acid

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Polylactic Acid	1	1	1	1	1	1	1	7

Polylactic Acid

Polylactic acid is a hydrophobic polymer primarily employed in the biomedical sector for suture threads and drug delivery devices. PLA is acknowledged for its biodegradability and recyclability [73] In Fused Deposition Modeling, PLA would be categorized as a low-risk technology, given its value of 7. Despite these merits, PLA lacks the requisite material strength to be used in nuclear applications. Therefore, there is an absence of research aimed at assessing the suitability of PLA as a material for manufacturing nuclear components.

Polypropylene

Table 6.9: Results of Polypropylene

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Polypropylene	1	1	1	2	1	1	1	8

Polypropylene is an additional thermoplastic polymer that finds its applications in a multitude of consumer goods due to its high chemical resistance, increased heat tolerance, and marginal hardness. However, this material is unsuitable for nuclear applications as it lacks the necessary material strength required for such environments. With a value of 8, Polypropylene is considered to be a low-risk material. [71]

Polypropylene FDM has been utilized previously to create molds for various solid fuels. Although theoretically plausible, there is currently no experimental research conducted on its feasibility for nuclear fuel fabrication. Correspondingly, there has been minimal research carried out on the potential use of Polypropylene FDM in the nuclear fuel cycle.

Polyetheretherketone

Table 6.10: Results of Polyetheretherketone

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
PEEK	1	1	1	1	1	4	4	13

Polyetheretherketone is a semicrystalline thermoplastic renowned for its exceptional chemical and temperature-resistant properties. Its moderate-risk classification is attributed to its value of 13.

Despite the promising properties of PEEK, its potential applications in mining, milling, enrichment, or power reactors are currently not under extensive investigation. However, it has found applications in nuclear reprocessing, particularly in the fabrication of ceramic composites and polymers that exhibit excellent radiation resistance. PEEK is utilized in nuclear fuel reprocessing plants for this purpose, and further research may explore its potential uses in other areas of the nuclear fuel cycle. [74]

Nylon

Table 6.11: Results of Nylon

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Nylon	1	1	1	1	1	2	2	9

Nylon is a thermoplastic material composed of polyamides that exhibits a silk-like texture, making it an ideal candidate for various consumer goods. The low-risk classification of Nylon FDM is attributed to its total of 9.

There is a theoretical possibility that Nylon FDM can be applied to nuclear reprocessing and disposal. One example of such an application is the use of Nylon FDM to produce disposable filtration units for nuclear reprocessing and disposal facilities. Although commercial filtration units are currently available, several discussions are ongoing regarding the potential of Nylon FDM in this area. However, no other applications of Nylon FDM in nuclear reprocessing or disposal have been explored thus far. [75]

Polycarbonate

Table 6.12: Results of Polycarbonate

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Polycarbonate	1	1	1	2	1	1	1	8

Polycarbonate is a widely used thermoplastic that can be found in a variety of everyday consumer products, including eyeglasses. However, when considered for nuclear applications, polycarbonate FDM can be classified as a low-risk technique due to its total of 8.

While polycarbonate FDM has potential applications in the nuclear industry, the only theoretical use identified thus far is in the creation of molds for nuclear fuel fabrication. [71] No specific applications of polycarbonate FDM have been pursued in the nuclear industry, but future research may investigate the feasibility of polycarbonate FDM for other areas of the nuclear fuel cycle.

6.3 Sheet Deposition

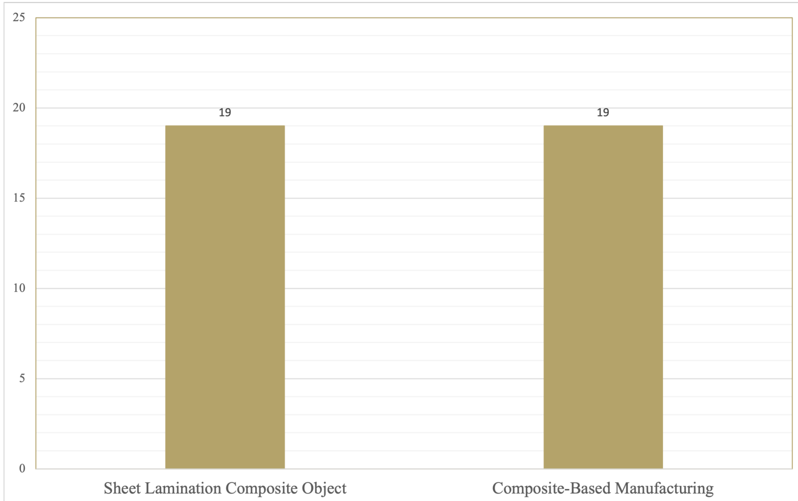

Figure 6.3: Total Values of Sheet Deposition

6.3.1 Selective Lamination Composite Object

Table 6.13: Results of Sheet Lamination Composite Object Manufacturing

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
SLCOM	3	3	3	2	3	3	2	19

Selective lamination composite object manufacturing is a manufacturing process that utilizes thermoplastics as the base material and woven fiber composites. SLCOM is categorized as a moderately-high risk technique with a calculated risk total of 19. Although not widely practiced, SLCOM has been used in the nuclear industry to create proof of concept parts, such as fuel elements, reflectors, and moderator components.[76]

Beyond nuclear applications, SLCOM has a diverse range of mainstream applications, particularly in the automotive and aerospace industries. This technique is highly suitable for the production of lightweight structural components that can provide excellent mechanical properties and durability. SLCOM can also be used to manufacture parts with complex geometries, making it a highly versatile technique. [77]

It is noteworthy that SLCOM has garnered increased attention in recent years, as it offers several advantages over traditional manufacturing methods. SLCOM reduces the cost and time required to produce complex parts, which makes it an efficient and desirable process.[76] The potential for high-quality, lightweight, and strong parts produced by SLCOM makes it a promising technique for various industries.

6.3.2 Composite-Based Manufacturing

Table 6.14: Results of Composite-Based Additive Manufacturing Technique

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
CBAM	2	2	2	2	3	3	2	16

Composite-based additive manufacturing is a novel technique with a large potential for high-performance part fabrication. It's categorized as a moderate-high risk technology with a total of 16. CBAM has the potential to revolutionize the manufacturing industry, particularly in the production of complex structures with exceptional mechanical properties. The technology is currently being investigated for its potential in nuclear applications, such as developing composite-based oxide fuel for nuclear power reactors [78] This research aims to improve thermal conductivity within the reactor and reduce waste. Additionally, CBAM is being explored for its applicability in fuel cladding and core structures for light water reactors and for the possibility of using CBAM to fabricate coatings for nuclear waste containment. [79]

6.4 Powder Bed Fusion

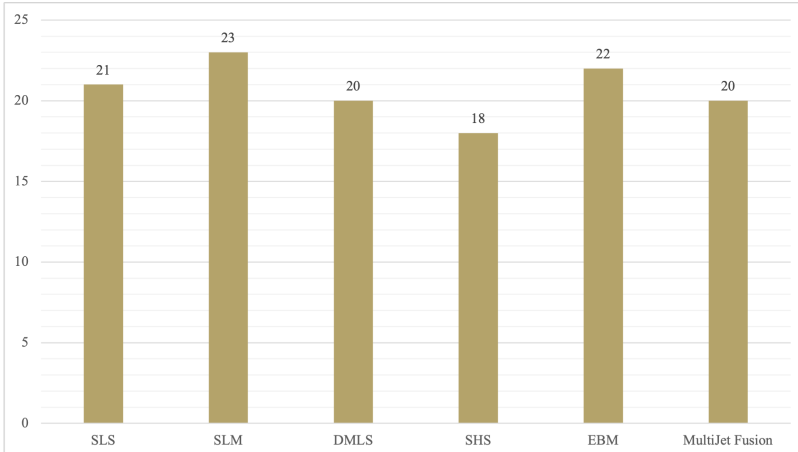

Figure 6.4: Values of Powder Bed Fusion

6.4.1 Selective Laser Sintering

Table 6.15: Results of Selective Laser Sintering

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Selective Laser Sintering	3	2	3	3	4	3	3	21

Selective laser sintering is a powder-based technology that uses high-powered lasers to selectively sinter the particles of a polymer powder, and is considered a high-risk technique as it has a value of 21.

One of its most prominent uses is in the production of small-scale nuclear components, such as fuel rods and cladding. SLS has the potential to produce parts with high resolution, tight tolerances, and intricate geometries, making it an attractive option for manufacturing nuclear components.[80]

SLS has also been used for creating prototype models of nuclear reactor components, allowing engineers to quickly and accurately test designs before committing to full-scale production. In addition, SLS has been used to create molds for casting nuclear components, such as fuel rods, which can reduce the time and cost of traditional manufacturing methods.[81]

Theoretical applications of SLS in the nuclear industry include the production of complex geometries for nuclear waste containment, as well as the production of replacement parts for aging nuclear infrastructure. As with any technology, the feasibility of these theoretical applications depends on factors such as material properties, part size, and regulatory considerations.[81]

6.4.2 Selective Laser Melting

Table 6.16: Results of Selective Laser Melting

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Selective Laser Melting	3	2	3	4	5	3	3	23

Selective laser melting is a powder-based additive manufacturing technique that utilizes a high-powered laser to selectively melt metal powder particles together to produce fully dense metal parts. This method is regarded as a high-risk technology, with an unweighted value of 23 and a weighted value of 23.7. One of the significant benefits of SLM is the ability to create complex geometries that would be difficult or impossible to achieve using traditional manufacturing techniques.

In the nuclear industry, SLM has the potential to create fully dense metal parts with high strength and heat resistance, making it suitable for the manufacturing of nuclear reactor components such as fuel cladding, control rods, and heat exchangers. SLM can also be used to produce radioactive sources for medical and industrial purposes. [82]

In addition, SLM has theoretical applications in the development of new materials for use in nuclear reactors. High entropy alloys High Entropy Alloy (HEA), for example, are complex alloys that contain multiple elements in nearly equal proportions, offering improved strength, ductility, and corrosion resistance compared to traditional alloys. SLM could be utilized to manufacture HEAs in intricate geometries, which would be difficult to produce using other manufacturing methods [83] The use of HEAs in nuclear applications could potentially lead to the development of safer and more efficient nuclear reactors.

6.4.3 Direct Metal Laser Sintering

Table 6.17: Results of Direct Metal Laser Sintering

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Direct Metal Laser Sintering	2	3	2	4	4	2	3	20

Direct metal laser sintering employs high-power laser beams to fully melt metal powder, resulting in intricate geometries and designs that are difficult or unfeasible to achieve via conventional manufacturing techniques. This additive manufacturing technology involves the layer-by-layer addition of material rather than the removal of material from a larger block [84] While DMLS is deemed a high-risk technique with a value of 20, it offers exceptional potential in the production of nuclear reactor components, including fuel and control rods, and heat exchangers, which must meet precise specifications and endure extreme temperatures, pressures, and radiation levels. DMLS can produce parts with exceptional accuracy, material properties, and geometries, improving reactor safety and performance.

DMLS has been extensively employed in fabricating nuclear fuel assemblies, including their bottom nozzles, using materials such as 316L stainless steel, titanium 6Al-4V, and Inconel 718. [85] The method also holds promise in creating high-density radiation shielding materials, which protect equipment and workers against the harmful effects of ionizing radiation.

6.4.4 Self-Propagating High-Temperature Synthesis

Table 6.18: Results of Self-Propagating High-Temperature Synthesis

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
SHS	4	2	2	2	3	2	3	18

Self-Propagating High-Temperature Synthesis is an advanced technology that utilizes a high-energy heat source, such as a laser or an electron beam, to selectively heat and fuse powders composed of reactive elements or compounds. This leads to an exothermic reaction between the powders and results in a self-propagating synthesis reaction, ultimately leading to the formation of a solid product [86] As a relatively new technology, SHS-AM is considered to be of moderate-high risk with a value of 18.

In the nuclear industry, SHS-AM has been employed in various applications, one of which is the fabrication of fuel pellets made from enriched uranium or plutonium. The production of fuel pellets with precise specifications is crucial to ensuring the safe and efficient operation of nuclear reactors. By utilizing SHS-AM, fuel pellets with higher density and improved homogeneity can be produced, which could enhance the energy output and lifespan of nuclear fuel.[87]

Another potential application of SHS-AM in the nuclear industry is the manufacturing of cladding materials for fuel rods, which are used to contain nuclear fuel in a reactor and, therefore, must withstand high temperatures and radiation levels. SHS-AM can produce cladding materials with improved corrosion resistance and mechanical properties, leading to enhanced safety and performance of fuel rods. [87]

6.4.5 Electron Beam Melting

The electron beam melting process involves the generation of an electron beam via an electron gun and its subsequent direction at a metal powder bed. Owing to its potential hazards, EBM is regarded as a high-risk technology with a value of 22. In the nuclear

Table 6.19: Results of Electron Beam Melting

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Electron Beam Melting	2	2	4	3	5	3	3	22

industry, EBM finds applications in the production of fuel pins for nuclear reactors, which require adherence to stringent performance and safety standards. Typically made of zirconium alloy, EBM can be leveraged to produce fuel pins that satisfy these requirements with high precision and accuracy. [88]

In addition, EBM is employed to manufacture components for nuclear fusion reactors, which rely on magnetic fields for plasma confinement and control, necessitating high-performance components that can endure extreme temperatures and radiation levels. Ongoing research focuses on the development of hierarchical structures for porous scaffolds using stainless steel 316L and Ti6AL4V. EBM exhibits several specific and current applications in the nuclear industry owing to its ability to produce fully dense, high-quality metal parts with exceptional mechanical properties. [88]

Additionally, EBM is utilized in the fabrication of parts for nuclear waste storage and transportation containers, which must withstand hostile environments and radiation levels while safely containing radioactive materials. [89]

6.4.6 MultiJet Fusion

Table 6.20: Results of MultiJet Fusion

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
MultiJet Fusion	2	2	4	4	4	2	2	20

The MultiJet fusion process entails the sequential deposition of a thin layer of powder material onto a build platform, followed by the selective fusion of powder particles through the controlled application of a liquid binding agent via an inkjet array. Given its high-risk nature, this technique has been assigned a value of 20.

In the nuclear industry, a specific and significant application of MJF technology is the production of ceramic nuclear fuels for use in nuclear power reactors. This advanced manufacturing technique facilitates the creation of fuel pellets with intricate geometries that can improve fuel performance by augmenting the surface area exposed to the reactor coolant. Moreover, the precise control over fuel pellet dimensions afforded by MJF is indispensable in ensuring their compatibility with the fuel assembly design of the reactor, thus enhancing safety and efficacy. [90]

In addition to its use in fission reactors, MJF has also shown great promise in the manufacturing of components for nuclear fusion reactors. Of note is its application in the production of high-quality permanent magnets for use in stellarator fusion reactors. [91] Furthermore, MJF can be leveraged to produce critical components for nuclear waste storage and transportation containers, which must endure harsh environments and high levels of radiation while safely containing radioactive materials.

6.5 Directed Energy Deposition

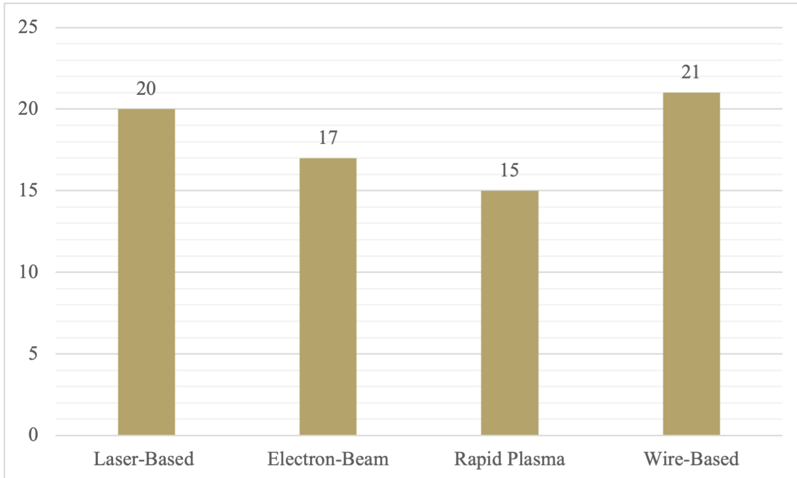

Figure 6.5: Values of Directed Energy Deposition

6.5.1 Laser-Based DED

Table 6.21: Results of Laser-Based Directed Energy Deposition

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Laser-Based DED	2	3	3	3	4	2	3	20

Laser-based directed energy deposition is a metal additive manufacturing technique that employs a high-power laser beam to melt and deposit material onto a substrate in a layer-by-layer manner. This technique has been assigned a total value of 20.

One of the most significant applications of this technique is in the manufacturing of nuclear fuel components, including fuel cladding tubes and fuel pins. [92] Laser-based DED also shows great promise in the production of large and complex metal parts used in nuclear reactors. For instance, the technology has been used to manufacture large structural components such as reactor pressure vessels, steam generators, and heat exchangers. [93]

Additionally, laser-based DED can be employed to produce nuclear waste storage and transportation containers that are robust enough to. Moreover, laser-based DED technology can be utilized in the repair and maintenance of nuclear components, such as damaged reactor components or corroded pipes.

6.5.2 Electron-Beam DED

Table 6.22: Results of Electron-Beam Directed Energy Deposition

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Electron-Beam DED	2	2	3	2	4	2	2	17

Electron-beam DED uses an electron beam to melt and deposit material onto a substrate in a layer-by-layer manner. Electron-beam DED is considered a moderately-high risk technique with a total of 17. One of the most significant applications of EBD in the nuclear industry is the repair and refurbishment of nuclear components. Nuclear components can experience wear and tear due to exposure to radiation, high-temperature, and corrosive environments. [94]

Moreover, EBD is used to produce fuel assembly components, such as end plates, guide tubes, and spacer grids. EBD is also used to manufacture parts for nuclear waste storage and transportation containers. EBD can produce fully dense and high-strength components, such as lids and bodies, that meet these requirements. Finally, researchers are exploring the use of EBD to manufacture novel materials for fuel cladding, which is the protective layer that surrounds nuclear fuel pellets. [95]

6.5.3 Rapid Plasma DED

Table 6.23: Results of Rapid Plasma Directed Energy Deposition

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Rapid Plasma DED	2	2	2	1	4	2	2	15

Rapid plasma deposition is a type of directed energy deposition technology that uses a plasma torch to heat and melt metal powders, which are then deposited layer by layer onto a substrate. It is considered a moderate-risk technology with a value of 15.[94]

One specific application of RPD in the nuclear industry is the repair and re-manufacture of turbine components for nuclear power plants. RPD is also being explored for the manufacture of advanced nuclear fuel cladding materials. Moreover, RPD can also be used to produce parts for nuclear waste storage and transportation containers. These containers must be able to withstand extreme environments and radiation levels while safely containing radioactive materials. RPD can produce fully dense, high-strength stainless steel and other metal parts that meet these requirements. [94]

6.5.4 Wire-Based DED

Table 6.24: Results of Wire-Based DED

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Wire-Based DED	3	3	4	3	4	2	2	21

Wire-based DED is an additive manufacturing technique that offers both versatility and cost-effectiveness in the production of complex metal parts. However, its high-risk nature is reflected in both its value of 21.

In the nuclear industry, wire-based DED finds applications in several areas. One significant application of wire-based DED is in the production of components for nuclear fusion reactors, where it has been used to create components for tokamak devices designed to confine hot plasma in a toroidal shape. Additionally, wire-based DED is used to manufacture high-strength stainless steel containers for the storage and transportation of radioactive materials. [96]

Wire-based DED is also valuable in the production of critical components for nuclear power plants, including reactor pressure vessels, steam generators, and pumps. These components require a high degree of precision and accuracy, which wire-based DED can provide. Furthermore, wire-based DED has been employed in the manufacturing of nuclear fuel cladding tubes, which are crucial components of a nuclear reactor. [96]

6.6 Material Jetting

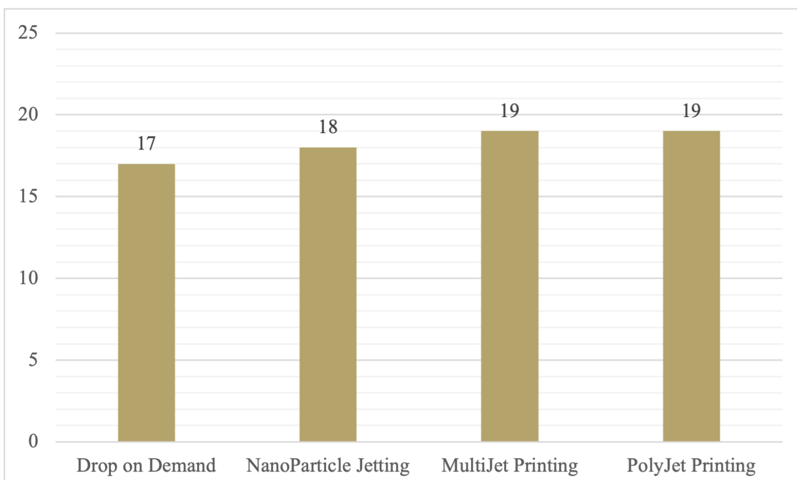

Figure 6.6: Total Values of Material Jetting

6.6.1 Drop on Demand

Table 6.25: Results of Drop on Demand

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Drop on Demand	2	2	1	4	4	2	2	17

Drop on Demand is a type of material jetting additive manufacturing process that involves depositing material droplets onto a build platform using a piezoelectric print-head. It has a value of 17, thus making it a moderately-high risk technique. Drop on Demand technology has found various applications in the nuclear industry. One of the key applications is in the production of nuclear fuel pellets. DoD can be used to create intricate and precise fuel pellet shapes that maximize the surface area exposed to the reactor coolant. This can enhance fuel performance and efficiency in nuclear reactors. Additionally, DoD can be used to manufacture miniature sensors for in-situ monitoring of reactor systems. These sensors can be used for real-time monitoring of reactor conditions, such as temperature, pressure, and radiation levels, to ensure safe and efficient operation of the reactor. Furthermore, DoD can also be used to produce customized nuclear-grade materials, including ceramics and metal alloys, for various nuclear applications. The precision and versatility of DoD technology make it a promising option for the manufacturing of complex nuclear components with tight tolerances and high-performance requirements. [97]

6.6.2 NanoParticle Jetting

Table 6.26: Results of NanoParticle Jetting

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
NanoParticle Jetting	2	2	2	4	4	2	2	18

NanoParticle Jetting is a type of material jetting additive manufacturing process that involves the use of nanoparticle-based ink to create high-resolution, complex parts. It has a value of 18, thus making it a moderately-high technique. One application of NPJ in the nuclear industry is the production of compact and efficient heat exchangers for use in nuclear power plants. Another application of NPJ in the nuclear industry is the production of radiation shielding components with optimized designs to provide efficient radiation attenuation. Additionally, NPJ can also be used for the manufacturing of nuclear instrumentation components with complex geometries, such as flow meters, pressure transmitters, and level sensors, that require high precision and accuracy. [90]

6.6.3 MultiJet Printing

Table 6.27: Results of MultiJet Printing

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
MultiJet Printing	4	2	2	3	4	2	2	19

MultiJet Printing, with a calculated risk value of 19, is a type of material jetting additive manufacturing process that utilizes an inkjet printhead to selectively jet droplets of photopolymer resin onto a build platform.

One such application is the production of custom-made molds and fixtures used in the casting of nuclear components. Another potential application of MJP is the production of small and intricate nuclear components, such as sensors and detectors. Additionally, MJP can be used to produce mock-up models of nuclear components for testing and validation purposes. MJP can also be utilized in the production of nuclear fuel assemblies. [90]

Furthermore, MJP has the potential to be used in the production of customized shielding materials for nuclear applications. Shielding materials are critical components that protect workers and the environment from harmful radiation. [90]

6.6.4 PolyJet Printing

Table 6.28: Results of PolyJet Printing

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
PolyJet Printing	3	2	3	3	4	2	2	19

PolyJet Printing, with a risk value of 19, is a type of material jetting additive manufacturing process that involves jetting photopolymer droplets onto a build platform. PolyJet Printing has been utilized to create models and prototypes of complex components and assemblies for nuclear reactors, as well as to produce molds and fixtures to produce parts. PolyJet Printing can also be used in the creation of custom radiation shielding and dosimetry devices, as it allows to production complex geometries with high accuracy and resolution. Additionally, PolyJet Printing has been applied in the development of advanced sensors for nuclear applications, including temperature and radiation sensors, which can be used for monitoring and control purposes in nuclear reactors and other nuclear facilities.[90]

6.7 Vat Photopolymerization

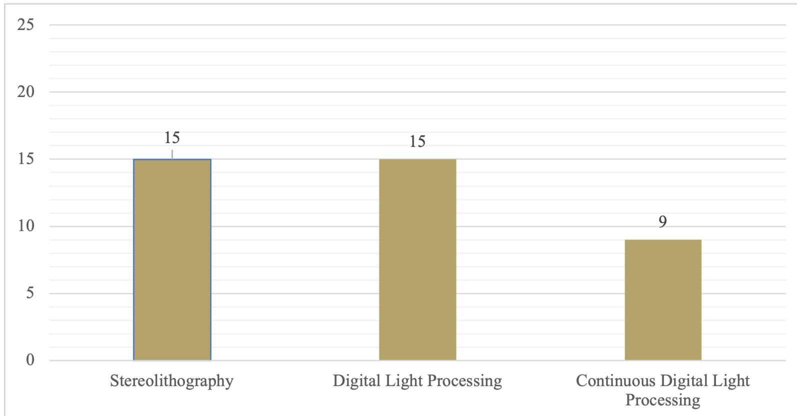

Figure 6.7: Total Values of Sheet Deposition

6.7.1 Stereolithography

Table 6.29: Results of Stereolithography

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
SLA	1	2	2	3	3	2	2	15

Stereolithography is an additive manufacturing process that uses a laser to cure layers of liquid photopolymer resin into a solid part. It is classified as a moderate-risk technology with a score of 15. Stereolithography has found a range of applications in the nuclear industry, such as the production of molds for casting nuclear fuel elements, the manufacturing of radioactive waste encapsulation containers, and the creation of radiation shields. The high resolution and accuracy of SLA printing make it possible to produce intricate and detailed parts with tight tolerances. For example, SLA has been used to create fuel assembly tooling for nuclear reactors, which are used to handle fuel rods safely and accurately during assembly and disassembly. Additionally, SLA has been employed to produce nuclear instrument housings, which require a high degree of precision and durability. Another application of SLA in the nuclear industry is the fabrication of prototype designs for nuclear systems and components, allowing for rapid design iteration and optimization before committing to expensive production runs. [98]

6.7.2 Digital Light Processing

Table 6.30: Results of Digital Light Processing

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Digital Light Processing	1	1	3	4	3	2	1	15

Digital Light Processing uses a digital micromirror device to selectively cure a liquid resin into a solid part. It is considered a moderate-risk technique with a calculated risk value of 15 . One such application is the production of molds and dies that are used in the casting of complex shapes for nuclear reactor components. [99]

Another area of application for DLP in the nuclear industry is the production of specialized radiation shielding components. DLP has also been used in the production of small, complex nuclear components such as fuel rods and control rods. Additionally, DLP has been applied in the development of models and prototypes of nuclear components, which are critical for testing and validation before their actual production. [99]

6.7.3 Continuous Digital Light Processing

Table 6.31: Results of Continuous Digital Light Processing

Technique	Mining	Milling	Enrichment	Fuel Fab.	Power Reactors	Reprocessing	Disposal	Total
Continuous Digital Light Processing	1	1	1	2	1	1	2	9

Continuous Digital Light Processing uses a moving window to selectively cure the liquid resin in a continuous motion, allowing for a more efficient and faster printing process. It is a low-risk technology with a total of 9. CDLP could be used to manufacture sensor casings and out-of-vessel low-strength components. It can also be utilized to produce prototypes and functional parts for testing and validation in nuclear research and development. Continuous Digital Light Processing is not the best fit for nuclear applications due to the relatively low precision and resolution of the parts it produces. CDLP utilizes a continuous projection of light to cure a liquid resin into a solid part, which can result in a lower level of detail and accuracy compared to other additive manufacturing techniques. [90]

CHAPTER 7
DISCUSSION

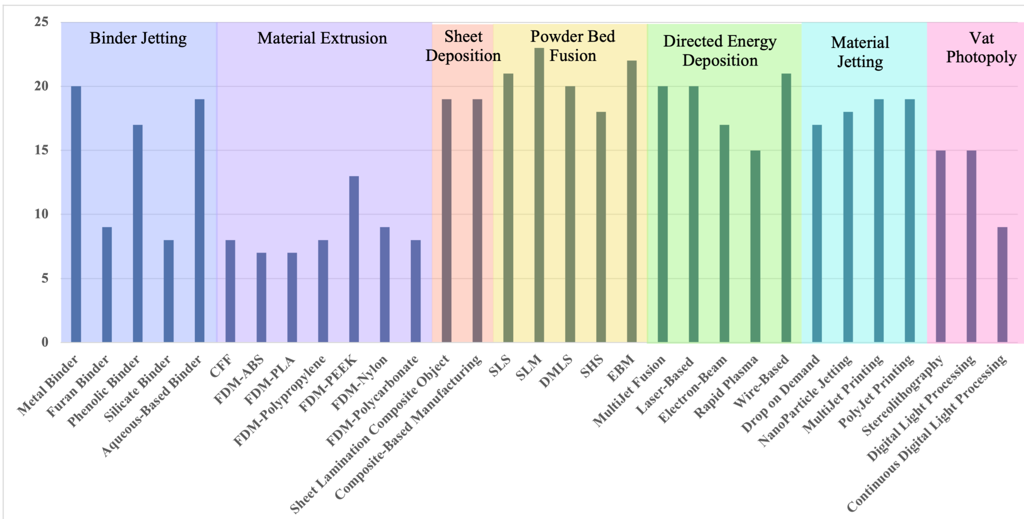

Figure 7.1: Graphed Totals by Technique

As outlined in the results section, there are various additive manufacturing techniques available, each with different levels of risk associated with them based on the materials and processes used. Binder jetting technology is a promising technology for manufacturing complex and high-precision parts required for uranium enrichment and power reactors, but the degree of risk associated with the technology depends on the specific materials used in the process. Material extrusion techniques, such as FDM and CFF, are generally considered low risk due to the materials used and the limited size and complexity of the components produced. Sheet deposition techniques, such as SLCOM and CBAM, are generally considered high-risk due to their potential to create complex parts and structures that could be used in nuclear applications. Powder bed fusion techniques, such as SLS, SLM, DMLS, and EBM, are widely regarded as high to moderate-high risk due to their ability to produce intricate and precise nuclear components with enhanced material properties. Directed energy deposition techniques are typically moderate to high risk due to the materials used and the precision and accuracy of the technology. DoD technology and NPJ, MJP, and PolyJet Printing technologies are all rated as high risk due to their high-resolution capabilities. Vat photopolymerization, particularly the CDLP technique, is considered a low to moderate-risk technology.

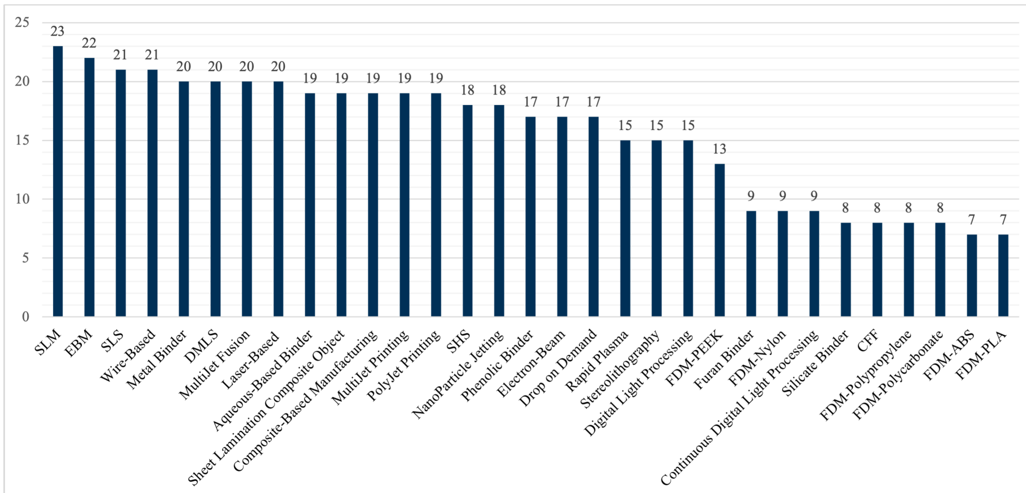

Figure 7.2: Values Ranked High to Low

7.1 Binder Jetting

Binder jetting technology has the potential to revolutionize the nuclear industry by enabling the manufacture of complex and high-precision parts required for uranium enrichment and power reactors. However, the use of binder jetting technology in the nuclear industry must be carefully considered to ensure that it does not contribute to nuclear proliferation. [18]

The degree of risk associated with binder jetting technology in the nuclear industry depends on the specific materials used in the process. Metal binder jetting, for example, is considered high-risk due to its theoretical capacity to create parts used in milling uranium or related ore. On the other hand, furan binder jetting is considered relatively low risk, with limited applications in the nuclear industry. Phenolic binder jetting is a promising technology that holds significant potential, while silicate binder jetting is classified as a low-risk technology with limited research in the nuclear industry. Aqueous-based binder jetting is a technology that shows potential due to its ability to fabricate high-density, high-strength, and thermally resistant parts required for uranium enrichment and power reactors. [64]

In the context of nuclear nonproliferation, the binder jetting technique presents an intriguing scenario as it spans the entire spectrum of risk. As mentioned earlier, the extent of risk related to binder jetting and its corresponding technologies is contingent upon the specific materials utilized in the process. Hence, to reduce the potential risk of nuclear proliferation, meticulous regulation and oversight of the materials employed in the process must be designed to ensure the safe application of the technology.[65]

7.2 Material Extrusion

Material extrusion techniques, including Fused Deposition Modeling and Continuous Fiber Fabrication, are generally considered low risk for nuclear nonproliferation for several reasons. [70]

First, the materials used in these techniques are typically thermoplastics, which are not suitable for high-stress or high-temperature applications required in nuclear facilities. These materials also lack the necessary strength and properties to be used in critical nuclear applications such as enrichment, fuel fabrication, and power reactors. [71]

Second, the components produced by material extrusion are typically limited in size and complexity, making it difficult to produce large or intricate nuclear components that could be used for nefarious purposes.

Third, the use of material extrusion techniques is primarily limited to hobbyists and low-stakes applications, reducing the likelihood that the technology could be exploited for malicious purposes. [73] Overall, while there may be theoretical applications for certain materials produced by material extrusion in the nuclear industry, further research is necessary to determine their feasibility and suitability for use in critical applications. Nonetheless, the relatively low risk associated with material extrusion techniques makes them un-likely candidates for nuclear nonproliferation concerns.

7.3 Sheet Deposition

Sheet deposition techniques like SLCOM and CBAM are generally considered high-risk due to their potential to create complex parts and structures that could be used in nuclear applications, such as fuel elements, reflectors, and moderator components. The use of these techniques in the nuclear industry could lead to significant advancements in nuclear energy technology, but it also raises concerns about the potential for nuclear proliferation.

The high-quality, lightweight, and strong parts produced by SLCOM and CBAM make them promising techniques for various industries, but the same properties also make them attractive to those seeking to develop nuclear weapons covertly. Furthermore, the use of SLCOM and CBAM in the nuclear industry highlights the need for continued research and development to determine their feasibility and suitability for use in critical applications such as enrichment, power reactors, and disposal. This research must consider not only the potential benefits of these techniques but also the associated risks and the necessary safeguards to mitigate those risks. [76]

Although SLCOM and CBAM possess the potential to be a valuable addition to nuclear component manufacturing, their usage, and export require meticulous evaluation, accompanied by the implementation of rigorous measures to deter the misuse of nuclear materials and technology.

7.4 Powder Bed Fusion

Powder bed fusion techniques, namely SLS, SLM, DMLS, and EBM, are widely regarded as high to moderate-high risk to nuclear nonproliferation owing to their remarkable capacity to produce intricate and precise nuclear components with enhanced material properties.

The ability to produce molds for casting nuclear components can reduce the time and cost of traditional manufacturing methods. SLM has the potential to create fully dense metal parts with high strength and heat resistance, making it suitable for manufacturing nuclear reactor components. DMLS has been extensively employed in fabricating nuclear fuel assemblies, including their bottom nozzles, and has the potential to create high-density radiation shielding materials, which protect equipment and workers against the harmful effects of ionizing radiation.[85]

The moderate-high-risk technology SHS can be utilized in the nuclear industry for the fabrication of fuel pellets made from enriched uranium or plutonium, cladding materials for fuel rods, and radiation shielding materials for use in nuclear facilities with complex geometries that optimize radiation shielding while minimizing the weight and volume of the material [87]

Powder bed fusion is a prominent additive manufacturing technique being explored for nuclear applications. It's crucial to ensure that legislative processes do not hinder the progress of these technologies. However, it's equally important to identify the potential proliferation pathways for powder bed fusion by assessing the global accessibility of these technologies.

7.5 Directed Energy Deposition

Material extrusion technologies, such as directed energy deposition, are typically at moderate to high risk for nuclear nonproliferation due to the materials used and the physics behind the technologies. DED techniques use high-power laser beams, electron beams, plasma torches, or wires to melt and deposit material layer-by-layer onto a substrate. [94]

One reason why DED technologies are considered high risk for nuclear nonproliferation is the materials used. DED technologies often involve the use of materials that have nuclear applications, such as uranium and plutonium. These materials are highly regulated and monitored to prevent their use in unauthorized nuclear applications. However, the use of unregulated materials in DED technologies increases the risk of nuclear proliferation. [95]

Another reason why DED technologies are considered high risk is the technologies precision and accuracy. DED technologies are highly precise and accurate, making them suitable for the manufacture of nuclear components, such as fuel cladding and storage containers. However, their precision and accuracy also make them attractive to produce small, high-quality nuclear components that could be used in nuclear weapons.

Additionally, DED technologies are increasingly accessible and widely used in various industries, including the nuclear industry. This accessibility makes it easier for countries or organizations to acquire and use these technologies for unauthorized nuclear applications. These technologies are based on the principles of physics, such as the transfer of energy from high-power laser beams, electron beams, plasma torches, or wires to the material being deposited.

While these technologies have potential benefits, such as the manufacture of fuel cladding and storage containers, it is crucial to closely monitor their international accessibility to prevent their use in unauthorized nuclear applications.

7.6 Material Jetting

DoD technology is a moderately-high risk because of its ability to create intricate and precise fuel pellet shapes, miniature sensors, and customized nuclear-grade materials. While this precision and versatility make it a promising option for creating complex nuclear components with tight tolerances and high-performance requirements, DoD technology is currently unregulated and thus is a proliferation pathway.

NPJ, MJP, and PolyJet Printing technologies are all rated as high risk due to their high-resolution capabilities, which make them powerful tools for creating intricate and complex components with specific shapes and configurations. These technologies can be used to create compact heat exchangers, radiation shielding components, customized molds and fixtures, and advanced sensors for nuclear applications. However, the use of these technologies to create components with optimized designs raises concerns. [90]

To mitigate the risks associated with material jetting additive manufacturing processes, it is essential to implement robust controls and safeguards that address how these technologies manufacture components. These measures should include strict regulations and monitoring of the use and transfer of nuclear materials and technology, comprehensive end-use monitoring, and verification mechanisms to ensure that these technologies are used exclusively for peaceful purposes.

7.7 Vat Photopolymerization

Vat photopolymerization, particularly the Continuous Digital Light Processing technique, is considered a low-risk technology concerning nuclear nonproliferation due to the relatively low resolution and accuracy of the parts it produces. The continuous projection of light utilized in CDLP can result in a lower level of detail and accuracy compared to other additive manufacturing techniques, making it unsuitable to produce intricate and complex parts that are critical to nuclear nonproliferation. Therefore, the application of CDLP in the nuclear industry is limited to manufacturing sensor casings and out-of-vessel low-strength components, as well as producing prototypes and functional parts for testing and validation in nuclear research and development.

On the other hand, Stereolithography and Digital Light Processing are classified as moderate-risk technologies due to their higher resolution and accuracy compared to CDLP. However, the precision of SLA and DLP parts is still limited and may not meet the stringent requirements for nuclear nonproliferation, particularly to produce high-stress components such as fuel assemblies and control rods. As such, while SLA and DLP can be used to manufacture molds, radiation shields, and some small nuclear components, they are not considered high-risk technologies that pose significant risks to nuclear nonproliferation. [98]

7.8 Limitations

There are several limitations to the study, including potential confounding variables or biases. One limitation is that the result does not fully consider the broader context of the nuclear industry, including regulations, security protocols, and international agreements aimed at preventing nuclear proliferation. Future studies could address this limitation by embedding the regulatory and security framework into the results.

Another limitation is that the study does not discuss the potential for dual-use technology, where a technology intended for peaceful purposes can also be used for military purposes. Future studies could address this limitation by analyzing the dual-use potential of each 3D printing technology and identifying how this could affect export controls & regulations.

Furthermore, the study does not provide empirical data or case studies to support its claims. This could be addressed by conducting empirical research on the use of 3D printing technologies in the nuclear industry and analyzing the potential risks and benefits in real-world scenarios.

CHAPTER 8
CONCLUSION

Additive Manufacturing has fundamentally transformed the manufacturing industry in recent years by enabling the creation of complex objects through layer-by-layer addition of material. This technology's benefits, such as greater design flexibility, enhanced customization, and reduced waste, have made it well-suited for various industries, including aerospace, healthcare, and the nuclear sector. Nonetheless, the lack of consistency in export controls for AM poses significant challenges in regulating its proliferation, particularly given its intricate nature. Despite these hurdles, the rapid evolution of AM has made it a disruptive technology that has revolutionized the traditional manufacturing industry. Its history dates to the 1980s, and it has evolved to become increasingly applicable in the production of functional products. Furthermore, AM's modernization has freed the manufacturing process from the constraints of geometry, making it feasible to automate the production of intricate objects while also mitigating the need for specialized training. In conclusion, the impact of AM on the manufacturing industry is unmistakable, and it will continue to shape the future of production.

In brief, the nuclear fuel cycle encompasses a series of interrelated processes, including uranium extraction, conversion, enrichment, fabrication, and consumption. The cycle commences with the mining of uranium ore, which is subsequently subjected to milling and chemical treatment to extract the valuable uranium. The enrichment stage is a crucial step that involves boosting the concentration of U-235 in the uranium. Following enrichment, the enriched uranium is converted into pellets and assembled into fuel rods for deployment in nuclear reactors. During reactor operation, nuclear fission transpires, resulting in the production of heat, which is then harnessed to generate electricity. The radioactive spent fuel that remains after a period of reactor use necessitates specialized handling and storage measures to ensure environmental and human safety. Ultimately, spent fuel is either reprocessed or stored in specialized facilities until a viable disposal solution is implemented.

US domestic policies regulating additive manufacturing technologies aim to balance the growth of the US additive manufacturing industry with national security standards. However, achieving this balance is complex, and policymakers should consider various factors such as the growing availability of hobbyist printers and the need to embed cybersecurity capabilities in the technology's design files and materials. While some advocate for strict export controls to protect national security, others argue that this may stifle the growth of domestic companies. Industry leaders are urging the government to engage in a nuanced assessment of the trade-offs involved and create clearly defined objectives and limitations through a consensus-building process.

International discussions on regulating the spread of additive manufacturing technology have been taking place since 2014 within the Missile Technology Control Regime, the Wassenaar Arrangement, and the Nuclear Suppliers Group. However, progress has been slow, with proposals for specific controls being rejected. The current multilateral export control only covers a specific set of applications and a specific AM technique. High-risk AM machines that are mounted with high-powered lasers lack controls, and the existing control lists do not align with the requisite properties for AM utilization. The transfer of build files poses significant challenges to export controls, and there are varying interpretations and national practices as to what information qualifies as required. National licensing authorities are required to collaborate with industry and companies must ensure the security of their build files. Concerning nuclear technology, export controls on nuclear technology, reactor components, and radioactive materials are exercised exclusively at the national level. While there is little indication that this arrangement will be altered in the foreseeable future, both suppliers and export control authorities have a role to play in facilitating legitimate trade in nuclear materials, components, technology, and safety-related information exchange. Strategic export controls are considered an indispensable component of governments' armory in preventing the acquisition of weapons of mass destruction by unauthorized entities.

The United States maintains strict export control regulations on various materials and technologies that could pose a threat to national security or be used for military purposes. These materials include certain high-strength materials such as maraging steel, aluminum alloys, boron or boron alloys, guanidine nitrate, nitroguanidine, ceramic powder of titanium diboride, and fibrous or filament materials. Additionally, the Wassenaar Arrangement's List of Dual-Use Goods and Technologies and the Nuclear Suppliers Group control the export of other materials and related equipment with dual-use characteristics, including aramid fibers, boron fibers, carbon fibers, beryllium, depleted uranium, and certain types of ceramics. [49]High-pressure synthesis equipment and specific types of furnaces are also included in these controls. It's important to note that specific characteristics of these materials, including heat treatment, can affect regulations. Overall, these export control regulations aim to prevent the proliferation of sensitive materials and technologies that could be used for military purposes. [100]

the results section has shown that there are various additive manufacturing techniques available, each with different levels of risk associated with them based on the materials and processes used. While some techniques, such as binder jetting and material extrusion, are generally considered low risk, others like sheet deposition, powder bed fusion, directed energy deposition, and high-resolution technologies such as DoD, NPJ, MJP, and PolyJet Printing are generally considered high to moderate-high risk. However, the degree of risk associated with each technology ultimately depends on the specific materials used and the precision and accuracy of the technology. Vat photopolymerization, particularly the CDLP technique, is considered a relatively low to moderate-risk technology.

Several US domestic policy recommendations could help ensure the growth of the additive manufacturing industry while meeting national security standards. Firstly, policymakers should develop clear export control regulations for additive manufacturing technologies, which would involve a nuanced assessment of the trade-offs involved and create clearly defined objectives and limitations through a consensus-building process. Additionally, cybersecurity capabilities must be embedded in the design files and materials of additive manufacturing technologies. Strengthening international discussions and collaborations within the Missile Technology Control Regime, the Wassenaar Arrangement, and the Nuclear Suppliers Group would help regulate the spread of additive manufacturing technology. National licensing authorities must collaborate with the industry to ensure that the security of build files is maintained. Maintaining strict export control regulations on materials and technologies that could endanger national security or be used for military purposes is critical. To ensure environmental and human safety, a comprehensive national strategy for the nuclear fuel cycle, including uranium extraction, conversion, enrichment, fabrication, consumption, and spent fuel management, needs to be developed. Finally, investing in RD to advance additive manufacturing technologies would help revolutionize the traditional manufacturing industry while also creating new job opportunities.

Internationally, policymakers should engage in a consensus-building process to balance the growth of the additive manufacturing industry with national security standards. This process should include industry leaders and consider the growing availability of hobbyist printers and the need for embedded cybersecurity capabilities in the technology's design files and materials.

There should be international discussions to regulate the spread of additive manufacturing technology. Proposals for specific controls should be considered within multilateral export control regimes such as the Missile Technology Control Regime, the Wassenaar Arrangement, and the Nuclear Suppliers Group. National licensing authorities should collaborate with the industry to ensure the security of build files, and companies must ensure the security of their build files. National export control authorities should facilitate legitimate trade in nuclear materials, components, technology, and safety-related information exchange.

Governments across the world should maintain strict export control regulations on various materials and technologies that could pose a threat to national security or be used for military purposes. The regulations should cover specific materials and related equipment with dual-use characteristics, including high-strength materials, aramid fibers, boron fibers, carbon fibers, beryllium, depleted uranium, and certain types of ceramics. International policymakers should assess the risks associated with different additive manufacturing techniques and materials and ensure that export controls are consistent with the requisite properties for AM utilization. High-risk AM machines that are mounted with high-powered lasers should be subject to controls, and there should be guidelines on what information qualifies as required for export controls.

The management of radioactive spent fuel should include specialized handling and storage measures to ensure environmental and human safety. The spent fuel should be either reprocessed or stored in specialized facilities until a viable disposal solution is implemented. Policymakers should develop national security standards for AM technologies and their associated build files and materials. These standards should be designed to prevent unauthorized acquisition of weapons of mass destruction.

Overall, international policy recommendations should focus on balancing the growth of the additive manufacturing industry with national security standards while considering the risks associated with different AM techniques and materials. Additionally, multilateral export controls should be developed to regulate the spread of AM technology, and national collaboration should be encouraged to ensure the security of build files and legitimate trade in nuclear materials, components, technology, and safety-related information exchange.

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