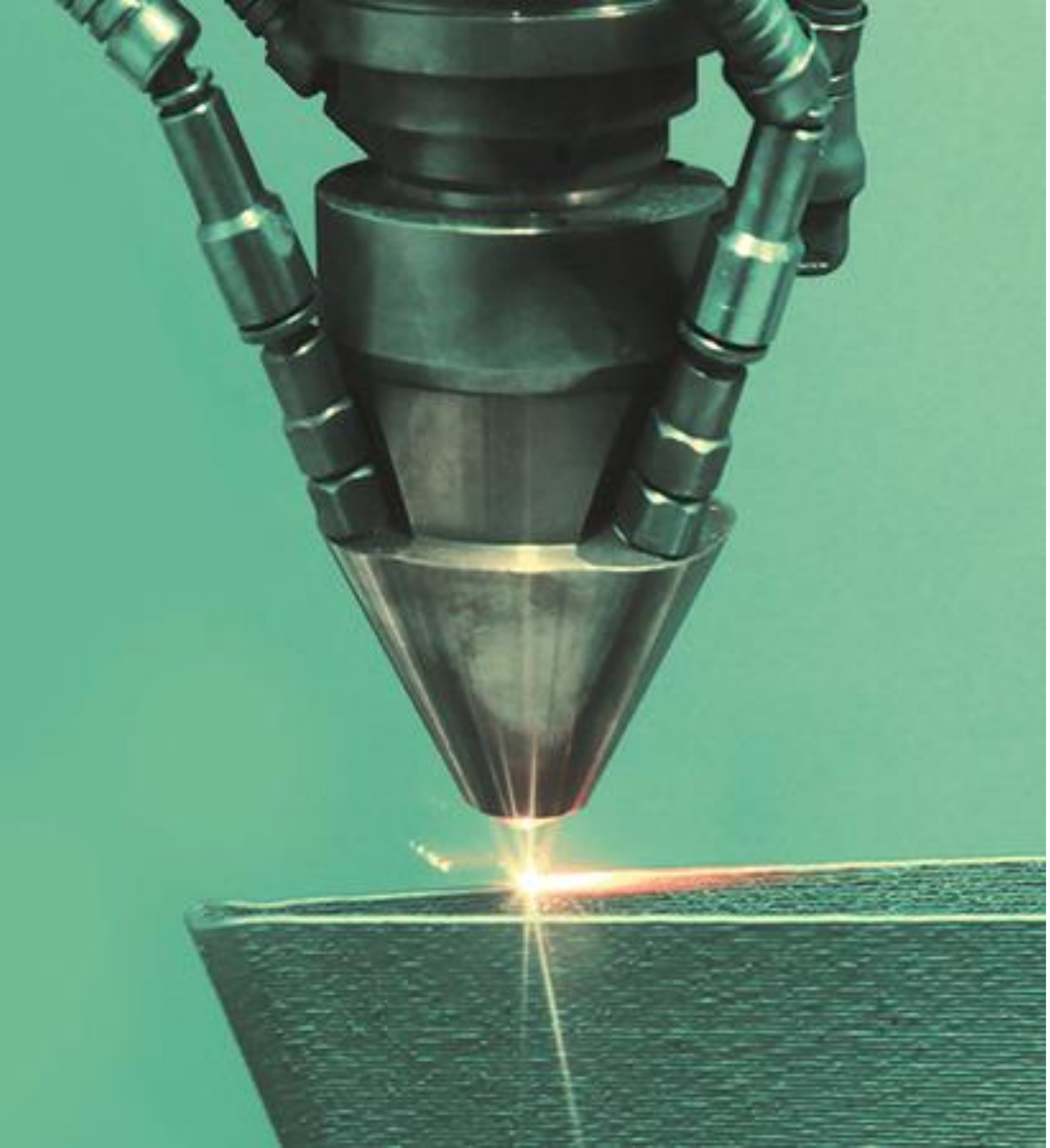

# Additive Manufacturing: A Challenge to Nuclear Nonproliferation

ETI ANNUAL WORKSHOP

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# Outline

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- Additive Manufacturing: Traditional vs. Modern
- Nuclear Nonproliferation Challenges due to AM
  - Nuclear Weapons
  - Nuclear Fuel Cycle
  - Existing Export Controls
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# Introduction

- The nuclear industry has already begun to shift towards producing complex parts using additive manufacturing techniques.
- AM techniques have been used to fabricate nuclear components for the Prototype Fast Breed Reactor at IGCAR.
- Though AM technologies have been around for several decades, developments over the past decade have allowed complicated 3-D objects to be manufacturing in a similar way to an inkjet printer.
- Thus, AM technologies have the capability of producing a growing number of items that are controlled under nuclear export controls.
- AM provides an alternative solution to export-controlled manufacturing technologies and allows for sensitive information in the form of CAD files to be shared via the internet.
- Though there are existing controls for AM, the lack consistency and are difficult to implement on a national or global scale.

# Additive Manufacturing: Traditional

- Additive Manufacturing has been a staple in industry for decades, however it has not been until the past decade that the idea of additive manufacturing as 3-D printing has become the mainstream.
- Requires a substrate or mandrel to provide the shape of the object being formed.
- Must be specifically designed to operate within pre-established technical parameters.
- Traditional Techniques: PVD, CVD, Sputtering, Filament Winding.
  - Implemented industries: semiconductors, aerospace, nanotechnology, and advanced composites.
- Legislation and export is easily by the Missile Technology Control Regime (MTCR) list.

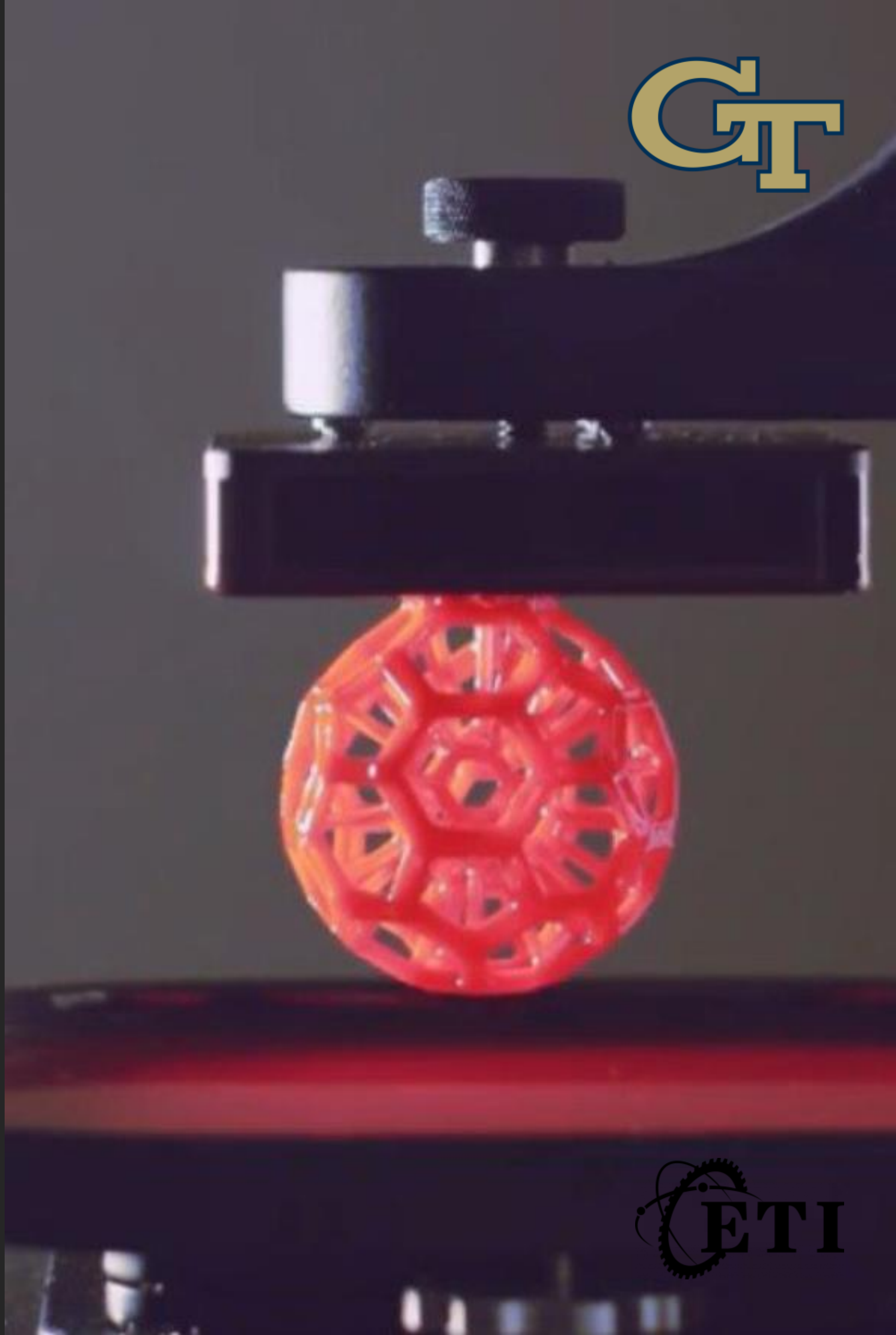
# Additive Manufacturing: Modern

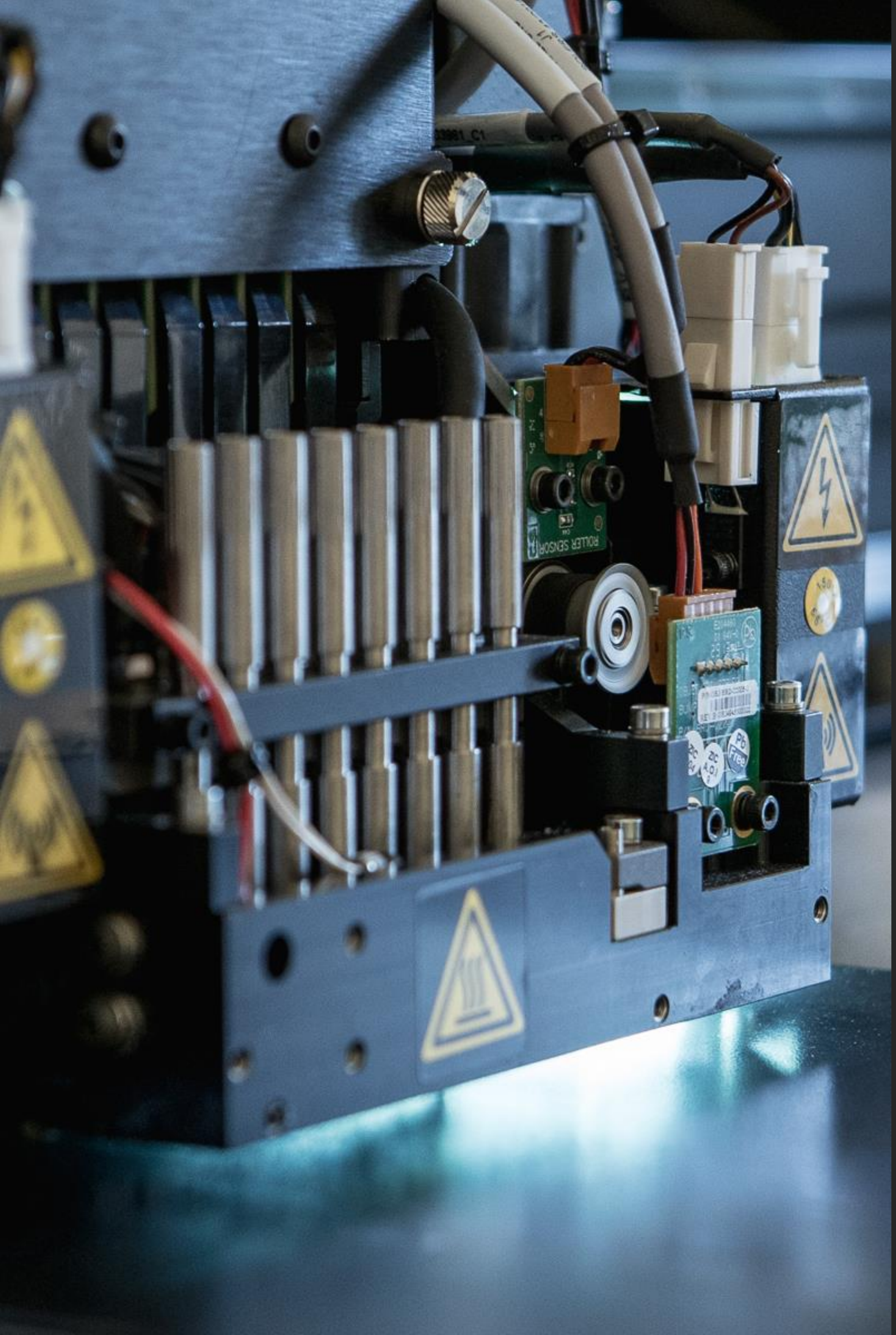
Modern Additive Manufacturing Techniques:

- Not limited to specific shapes as they do not require a substrate or mandrel.
- Can manufacture items of great complexity with a high degree of automation.
- The process of printing the object is very flexible, allowing for the program, material, or properties of the object to be changed with relative ease.
- The rapid advancement of AM techniques has allowed for a wide range of materials to be used a feedstock, from polymers to metals, alloys, carbon fibers, biological tissue, and superalloys.
- Now fall into the category of 'disruptive technologies' and pose a significant risk to nuclear nonproliferation.

# Vatphotopolymerization

- 3-D objects are manufactured by selectively curing liquid resin through targeted, light-activated polymerization.
- An efficient and accurate process that prints large models and prototypes.
- The material properties of photopolymers do not have strong structural characteristics.
  - Resulting parts are naturally prone to degradation and deformation over time.
- Encompasses stereolithography, digital light processing, continuous liquid interface production, and daylight polymer printing AM technologies.





# Material Jetting (MJ)

- The process involved with material jetting is similar in fashion to 2-D printers.
- A printhead dispenses photosensitive material that solidifies under ultraviolet (UV) light, which builds the item layer-by-layer.
- It's considered to be one of the fastest and most accurate AM techniques and is primarily used to produce realistic prototypes
- Material jetting (MJ), is a branch of AM technology that includes drop on demand, nanoparticle jetting, multi-jet, and poly-jet printing.

# Binder Jetting

- Includes metal, furan, silicate, phenolic, and aqueous-based jetting, requires two materials: a powder-based material and a binder.
- The binder, which is typically a liquid, acts as an adhesive between layers of the powder build material.
- The printhead moves horizontally along the x and y axes of the machine and deposits alternating layers of the build and binding material.
- Widely used for cast patterns and sand models as it is excellent for high-volume and low-cost components.
- However, this technique is not considered to be strong or very accurate

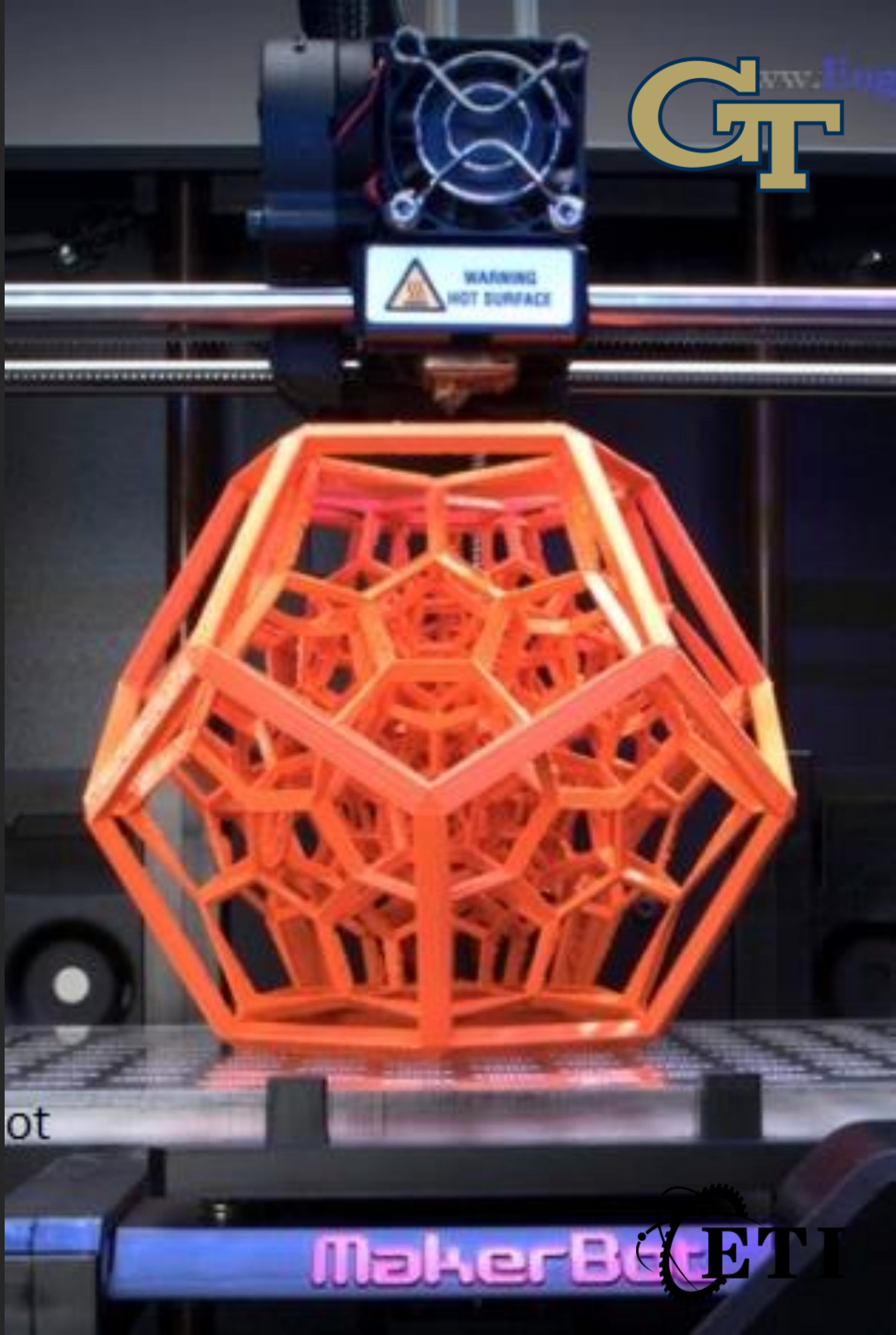
# Material Extrusion

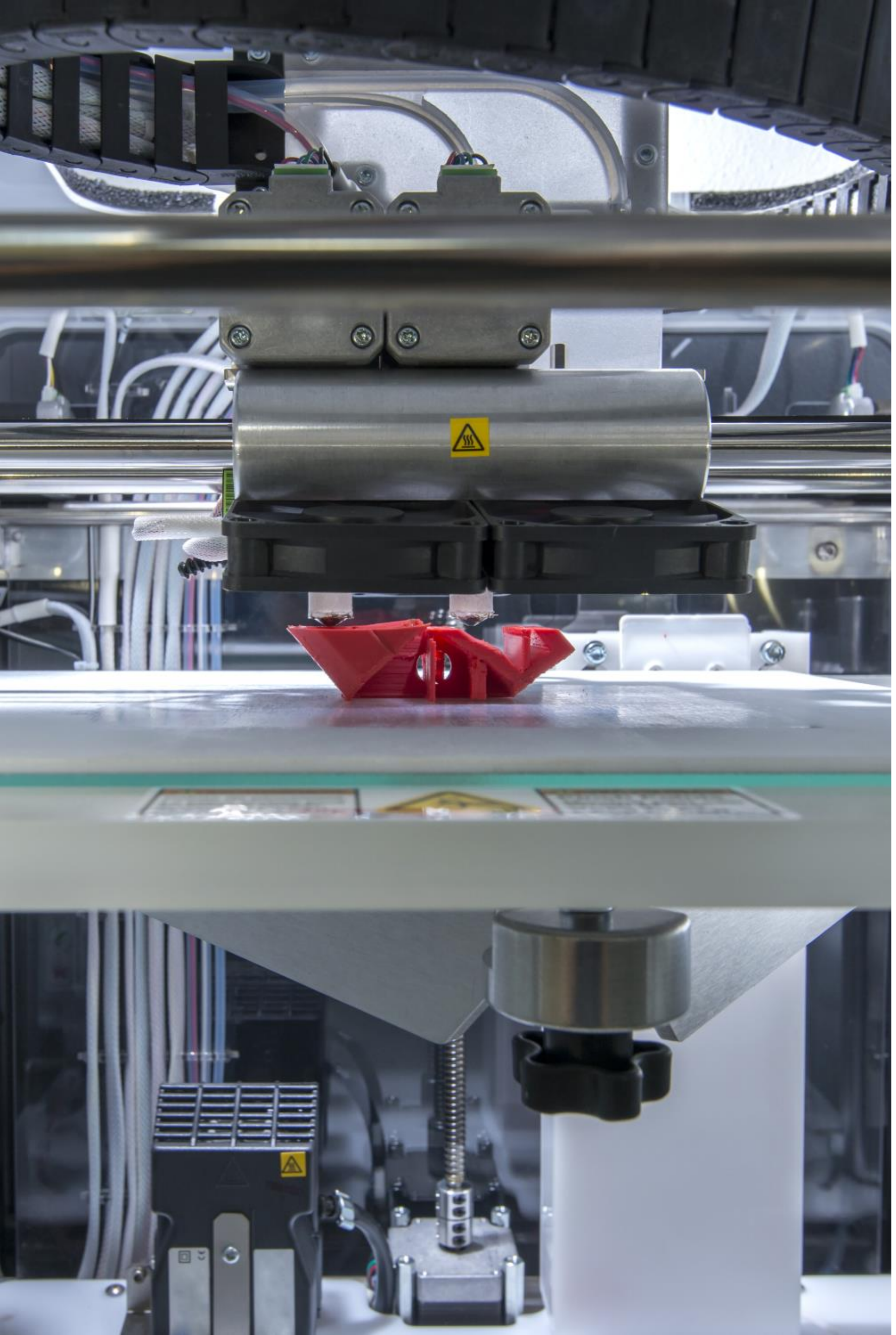
Material extrusion includes fused deposition modelling and composite filament fabrication (CFF).

Most hobbyist 3-D printers can be classified as material extrusion printers.

In this process, material (typically ABS plastic) is drawn through a nozzle, heated, and then deposited layer by layer onto a build platform.

The process is widespread and easily accessible to beginners, making it the most popular form of AM.





# Sheet Deposition

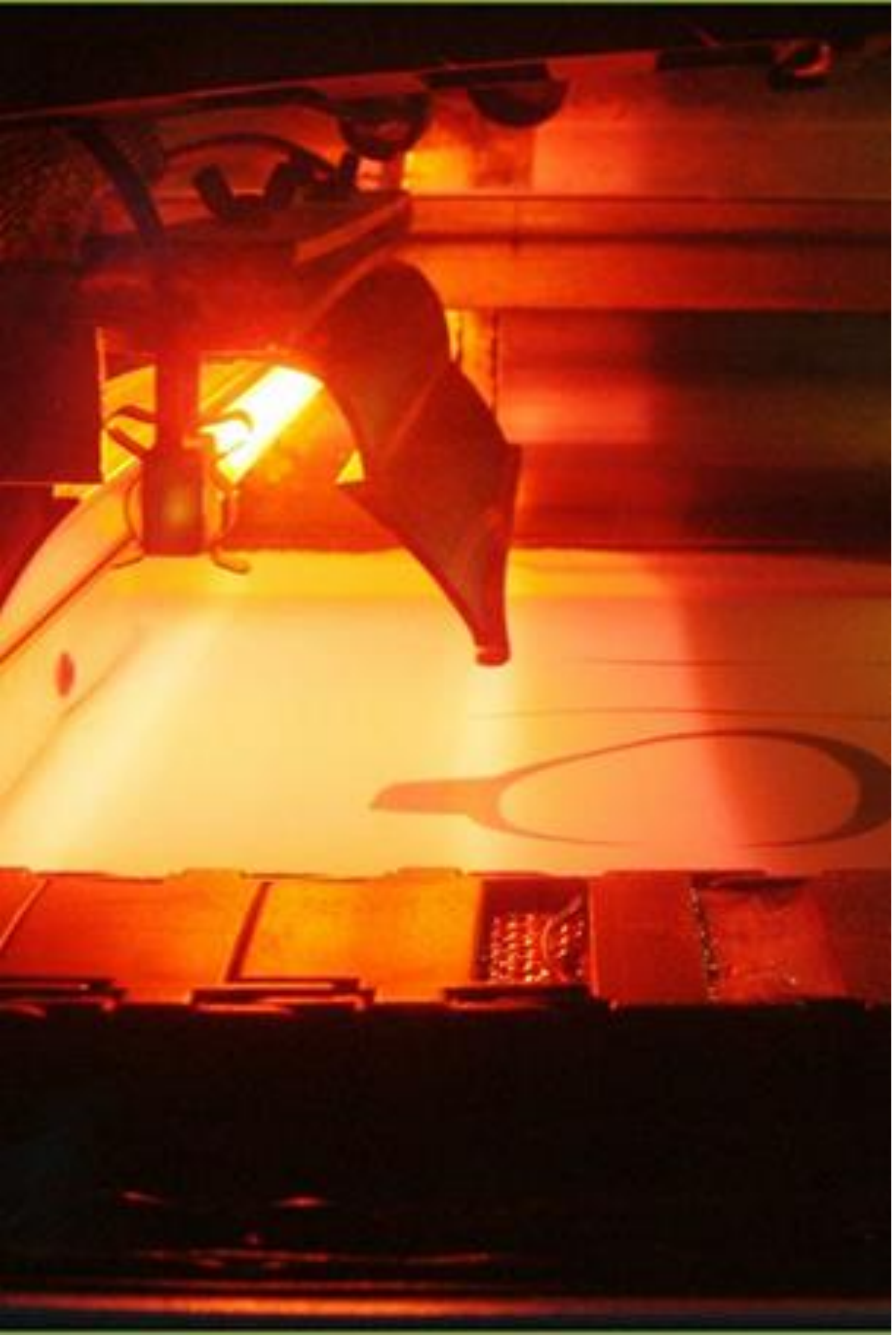
- Selective lamination composite object manufacturing (SLCOM) and composite based additive manufacturing (CBAM) are members of the sheet deposition category.
- Sheet deposition uses sheets of metal that are typically bound together using ultrasonic welding.
- The process often requires additional CNC machining to remove the excess unbound metal.
- This technique has typically been used to produce high quality composite ceramic and fiber parts.

# Directed Energy Deposition (DED)

Directed energy deposition (DED) is an AM technique that encompasses laser engineered net shaping, electron beam additive manufacturing, rapid plasma deposition, and wire arc additive manufacturing.

DED uses a focused energy source, such as a laser, plasma arc, or electron beam to melt material that is simultaneously deposited by a nozzle.

This technique has typically been used to add material to existing components, such as for repairs, or occasionally to manufacture new parts



# Powder Bed Fusion (PBF)

Powder bed fusion (PBF) refers to selective laser and direct laser sintering, selective laser melting, selective heat sintering, and electron beam melting.

This technique uses either an electron beam or laser to melt powdered material together.

Powder is typically spread over previous layers using a mechanism such as a roller or a blade.

# Nuclear Nonproliferation Challenges: Nuclear Fuel Cycle

The most common way to carry out the enrichment of U235 is with a gas centrifuge, which is a tube containing uranium hexafluoride (UF6) gas that spins several tens of thousands of revolutions per minute in an evacuated chamber.

AM could be a way of making thousands of small parts autonomously instead of using conventional methods.

There are several applications of AM for maraging steel and AM has shown to be able to mimic the casting process required for such a high-strength steel.

Literature has highlighted the risk of non-state agents using unmanaged AM technology to manufacture gas centrifuge components using maraging steel.

In recent years, huge strides have been made in using additive manufacturing for nuclear energy systems.

As additive manufacturing technologies continue to develop, its applicability to the nuclear industry will only grow.

# Existing AM Export Controls

Open sources on the internet provide a wealth of information about additive manufacturing and associated topics.

For printed products, additive manufacturing relies significantly on CAD files; nevertheless, controlling and monitoring the interchange of such files has proven to be extremely difficult.

Because technology transfers carry considerable proliferation concerns, there are numerous export regulations in place to prevent the dissemination of critical technologies to hostile countries.

Law enforcement agencies do not have sufficient response time to remove potentially harmful design files from the internet.

Currently, export rules for additive manufacturing are little more than controls for multi-axis subtractive manufacturing with minor differences.

# Methodology

This paper was written to showcase 33 different additive manufacturing techniques and the risks they pose to nuclear proliferation.

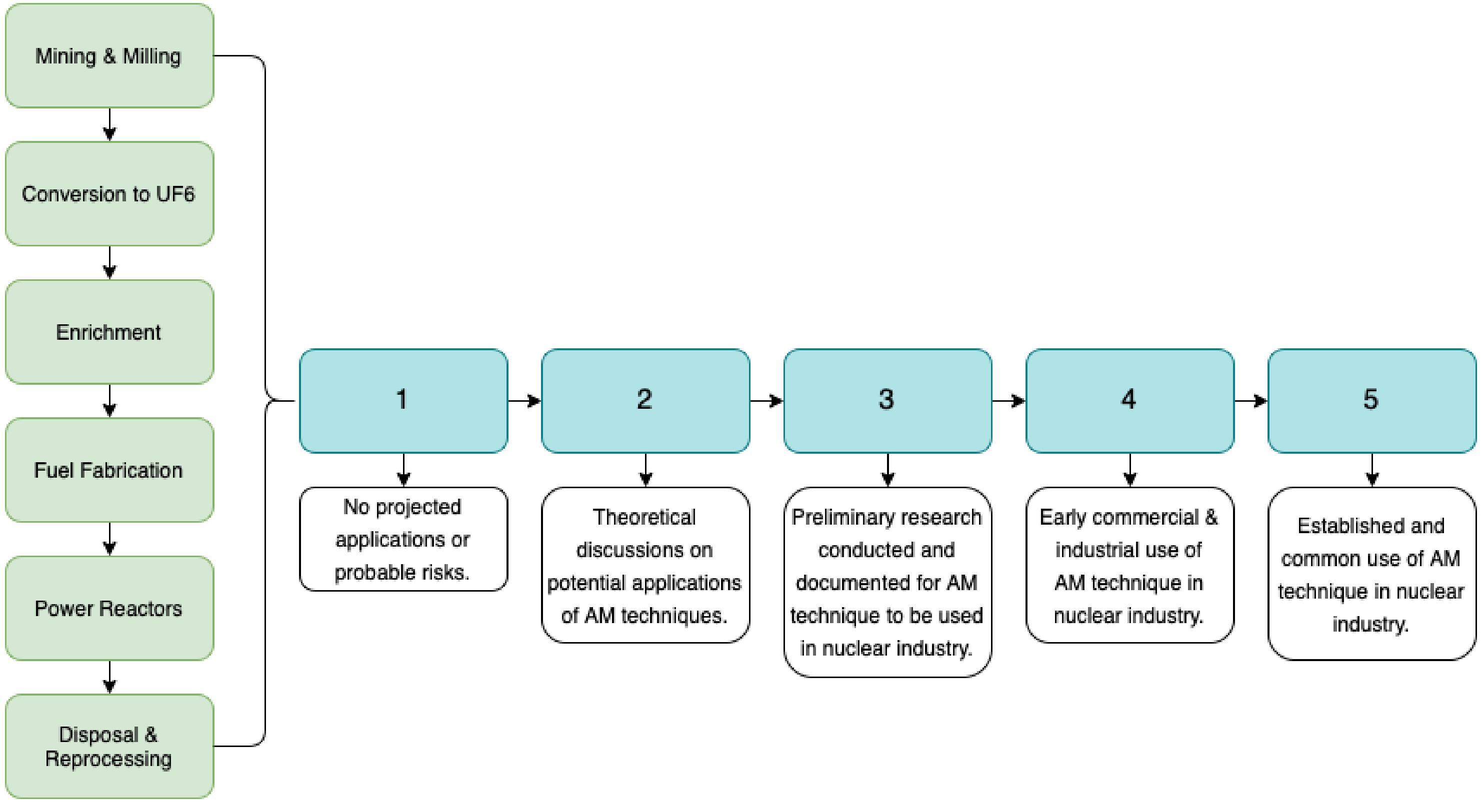
To standardize this process, each technique was rated on a numerical scale from 1 to 5, 1 meaning there is no perceived proliferation risk and 5 meaning there are current applications to the nuclear fuel cycle.

The technique's manufacturing process, design, finished product quality and complexity, and current/experimental applications are compared to the manufacturing processes and products of the nuclear fuel cycle.

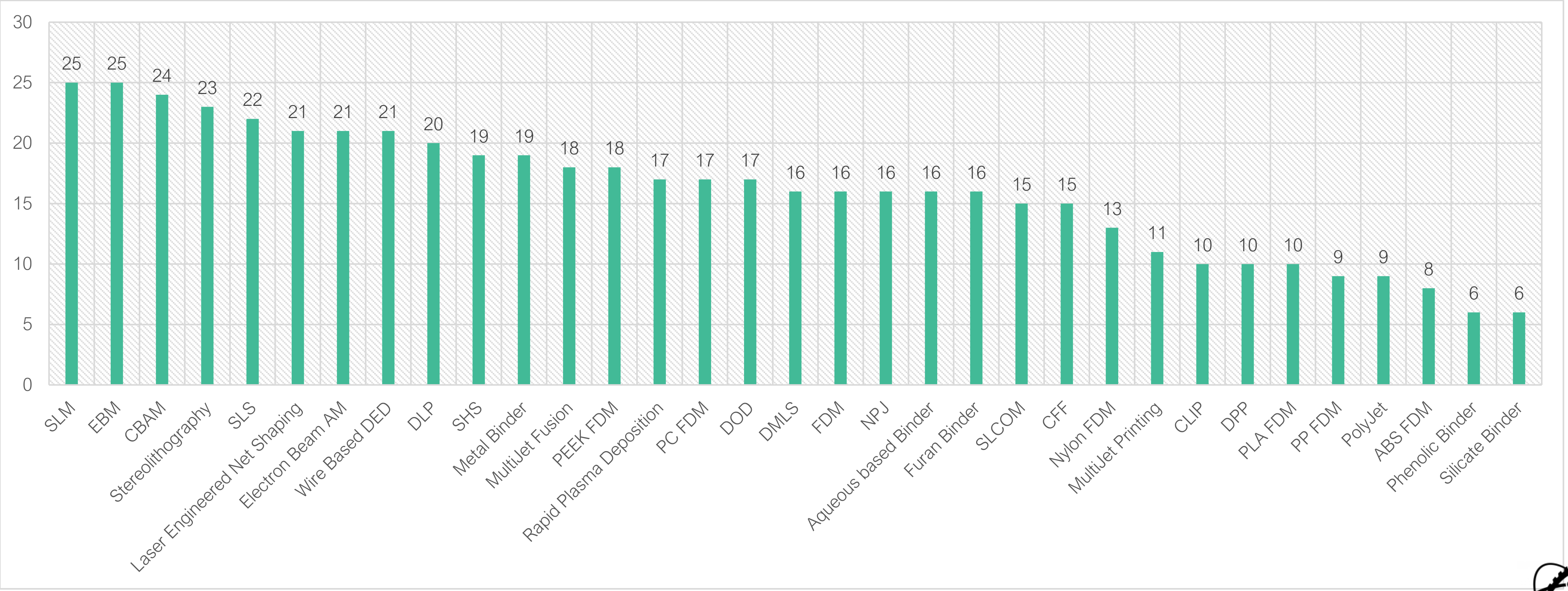
After each technique is scored using the rubric, the numerical results are compared within their categories and from highest risk to lowest risk.

Finally, recommendations will be made on possible AM export legislation to close these proliferation pathways.

# Methodology



# Results



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SLM
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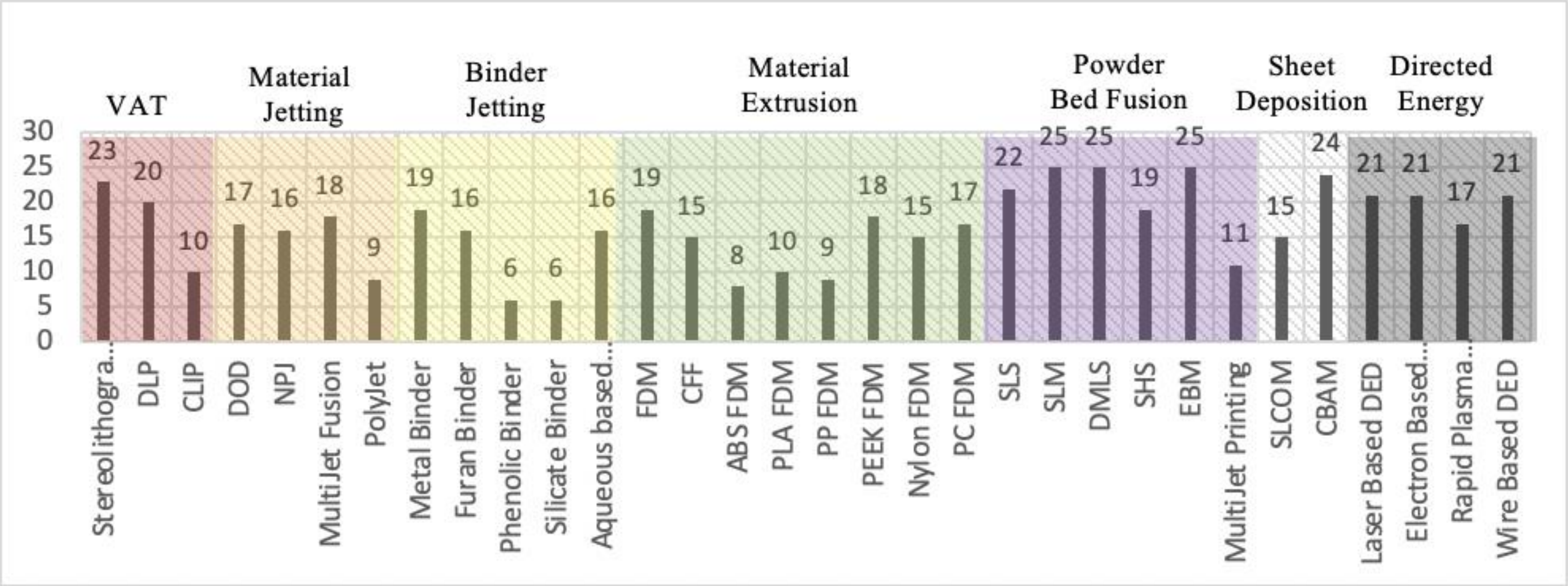
CBAM
Stereolithography
SLS
Laser Engineered Net Shaping
Electron Beam AM
Wire Based DED
DLP
SHS
Metal Binder
MultiJet Fusion
PEEK FDM
Rapid Plasma Deposition
PC FDM
DOD
DMLS
FDM
NPJ
Aqueous based Binder
Furan Binder
SLCOM
CFF
Nylon FDM
MultiJet Printing
CLIP
DPP
PLA FDM
PP FDM
PolyJet
ABS FDM
Phenolic Binder
Silicate Binder

# Results



VAT
Material Jetting
Binder Jetting
Material Extrusion
Powder Bed Fusion
Sheet Deposition
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Silicate Binder
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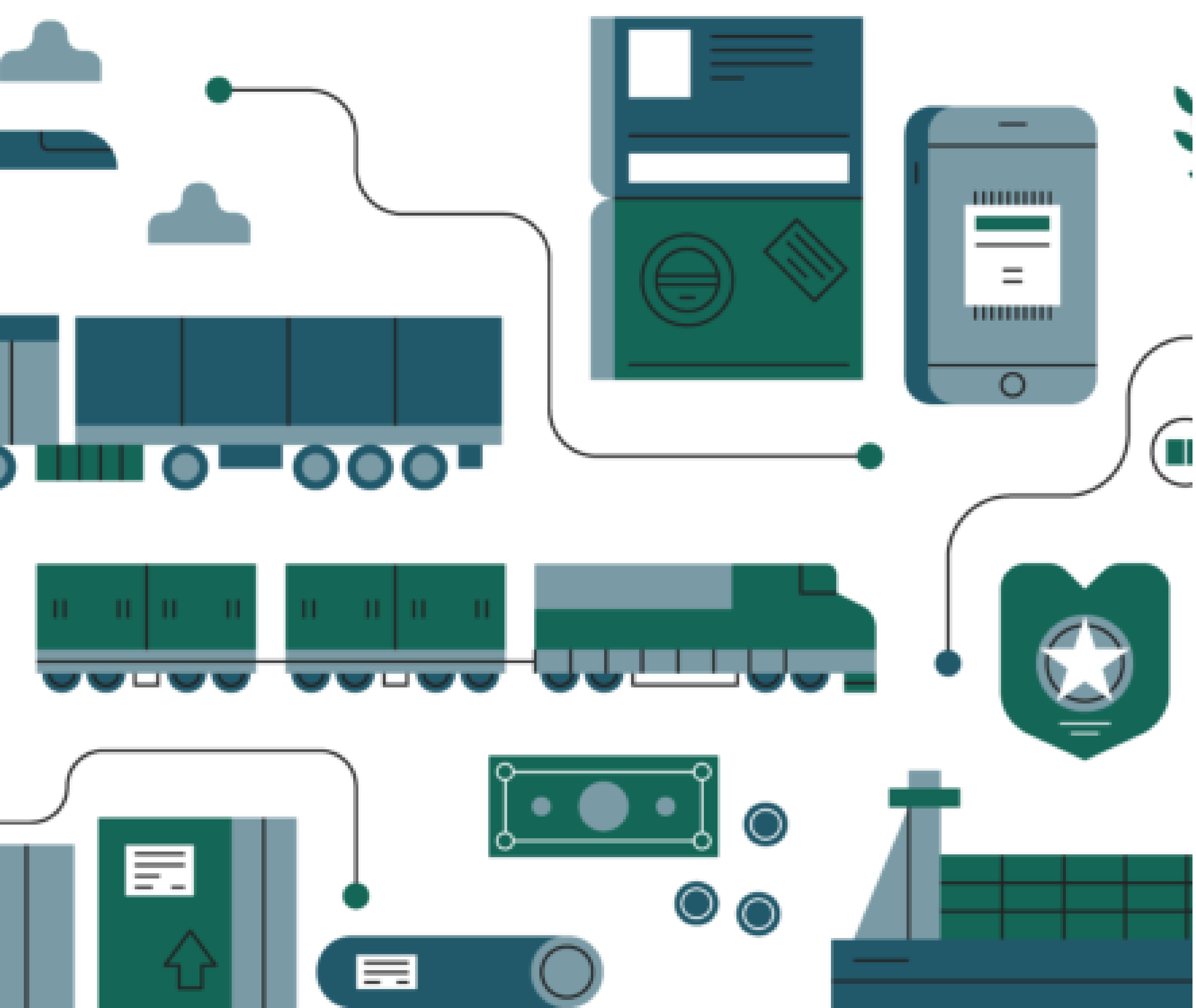
CFF
ABS FDM
PLA FDM
PP FDM
PEEK FDM
Nylon FDM
PC FDM
SLS
SLM
DMLS
SHS
EBM
MultiJet Printing
SLCOM
CBAM
Laser Based DED
Electron Based...
Rapid Plasma...
Wire Based DED

# Conclusions

Additive manufacturing is a constantly evolving field that requires export controls that can be easily adapted to fit precise and varying technical parameters.

While putting individual techniques into broader categories, such as what was done above, seems like an appropriate way to simplify and streamline AM control legislation, it is not.

This system will only work for categories that contain techniques that all have nuclear applications, such as DED and PBF.



# Recommendations

Creating blanket legislation for the 8 different categories will stunt the growth of technologies that are unnecessarily bogged down by export controls.

Additionally, export controls should be as unique as the technique it is attempting to control.

Applying a generic policy to a "high risk" technique will only allow for loopholes and oversights.

Legislation written should be a collaboration between AM manufacturers, legislatures, nuclear nonproliferation advocacy groups, and scientists.

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