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AI and Atoms: How AI is Revolutionizing Nuclear Material Production

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Policy Memo

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1. Executive Summary

The associability of artificial intelligence (AI) as a dual-use technology for nuclear material production (NMP) within the academic and practitioner communities remains widely neglected, and thus, a widening opportunity for AI to aid in illicit and covert non-peaceful applications exists. To address this emerging gap, this paper investigated the evolving and applicable uses of AI and found broad evidence of its use to optimize performance, innovate and reduce costs associated with the development and production of nuclear material; thereby, facilitating broader accessibility of peaceful uses of nuclear science and technology, while at the same time eliciting concerns that said improvements can also facilitate the illicit development of nuclear weapons. As such, this paper advocates for the following three-dimensional solution to manage the evolving dual-use concern of AI: (a) advance states-centric monitoring and regulation; (b) promote intellectual exchange between the non-proliferation sector and the AI industry; and (c) encourage AI industrial contributions.

2. Introduction

The recent decade has witnessed the accelerated integration of Artificial Intelligence (AI)[2]. into both the civilian and military fields; resultantly, rising attention to the challenges of AI governance has manifested in three ways. The first challenge lies in the dual-use nature of AI in the civilian and military domains, which renders it both difficult to monitor and oversee the militarization of AI. The second derives from the policy influencing power of the private sector, who have traditionally been limited to utilizing lobbying instruments. The third results from the changing nature of government-industry relations, where industries are leading the development and application of AI and governments are falling behind industry in understanding its technological potential and regulating military applications.

A review of existing literature demonstrates that AI is well discussed within the military and broader strategic stability domain[3], including discussions surrounding AI use within the nuclear sphere to hack cyber systems, poison AI training data, and manipulate its inputs (Avin and Amadae 2019). The

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[1] This memo was written as a requirement of the 2022 - 2023 Arms Control Negotiation Academy program. Views expressed in the memo are the opinions of the authors and do not reflect the views of their employers.

[2] Artificial Intelligence (AI) refers to a collection of computer systems capable of empowering machines to generate human-like knowledge through data-driven training. The concept of AI emerged in the 1950s and was realized with the introduction of Machine Learning in the 1990s and Deep Learning in the 2000s.

[3] AI is analyzed as part of the decision-support system (without direct participation in nuclear launch) (Geist and Lohn 2018); intelligence, surveillance, and reconnaissance (ISR) (especially helpful in antisubmarine warfare and tracking mobile ICBM) (Geist and Lohn 2018); automated target recognition and terminal guidance (Rickli 2019); autonomous nuclear-weapon system (Geist and Lohn 2018); and delivery and defense systems used against nuclear attacks (including warning system) (Vincent 2019). There are three main views on AI and strategic stability. One viewpoint argues that creating AI-based technologies capable of undermining nuclear deterrence is challenging. In contrast, the second asserts that AI-based technologies will be capable of such tasks in the future (Rickli 2019; Avin and Amadae 2019), thus causing an arms race and strategic instability. The third point of view stands between the previous arguments claiming that AI has destabilizing and stabilizing effects (Horowitz 2019; Geist and Lohn 2018; Kaspersen and King 2019).

expert community further addresses AI and its applicability to nuclear safeguards.[4] However, the current state of available research largely ignores nuclear material production (NMP), which is an essential phase in the development of nuclear weapons.

This article bridges the gap through assessing the potential role of AI in NMP whilst considering industrial practices.[5] In employing an industrial approach to technology scouting, the present contribution argues that AI has significant potential to improve the NMP by improving system inefficiencies and deficiencies with the aim of optimizing output, reducing costs, and enhancing safety in production associated with the development and production of nuclear weapons. A comprehensive list of the existing AI applications to NMP critical equipment and to related non-nuclear industry applications integrable to the NMP is presented in Appendix 1.

While improvements in NMP are essential to facilitating broader accessibility of peaceful uses of nuclear science and technology, concerns arise that said improvements can also facilitate the illicit development of nuclear weapons. To properly manage the dual-use concern of AI, this article advocates a three-dimensional solution: (a) advance states-centric monitoring and regulation; (b) promote intellectual exchange between the non-proliferation sector and the AI industry; and (c) encourage AI industrial contributions. Specific action plans for various actors are suggested to demonstrate the feasibility of the proposed solution. Although NMP is the focus of this article, the findings, concerns, and solutions being addressed are also applicable to the broader debate on the production of material used to build weapons of mass destruction, including radiological, biological, and chemical weapons.

3. Proliferation-Sensitive Stages in NMP

The NMP consists of several steps, including mining and milling, conversion, enrichment, fuel fabrication, electricity generation, spent fuel storage, and reprocessing.[6] While each step in the NMP is important, the enrichment and reprocessing phases are its most proliferation sensitive phases on the basis that enriched uranium and/or the separation of uranium and plutonium isotopes during reprocessing are integral pillars[7] to the development of a nuclear weapon. Thus, presenting both horizontal and vertical proliferation risks[8] within the NMP process (Gartzke and

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[4] For instance, research by the Vienna Center for Disarmament and Non-Proliferation recognizes that AI could increase efficiency in the analysis of large amounts of information, as demonstrated by the International Atomic Energy Agency's current use of AI techniques to categorize data, detect changes, and process natural language through its collaborative analysis platform (Rockwood et al. 2021).

[5] Today, technical giants are principal players in the development and delivery of AI. Yet, these key stakeholders have, to date, had limited influence in government-initiated policy discussions around the risk of the proliferation of AI to furthering weapons mass destruction capabilities. The inclusion of the private sector in these discussions, while simultaneously balancing the necessity to innovate for peaceful purposes is an important mechanism for constructing an effective non-proliferation regime, of informal or formal means.

[6] Today's NMP most commonly uses uranium, a naturally occurring element. Natural uranium (U) is predominantly composed of two isotopes, U-238 (99.3%) and U-235 (0.7%); however, in order to sustain a nuclear reactor, uranium fuel must contain about four times as much U-235 as is found in natural uranium. As such, enrichment of U-235 to 3-5% is necessary and most pursued using gas centrifuge technology. Following enrichment, the fuel is fabricated into a structure, such as a fuel assembly, that enables it to be burned inside a nuclear reactor. The reactor, however, only uses a very small amount of the total nuclear material before the fuel is discharged, and therefore, much of the nuclear material, predominantly uranium and plutonium isotopes, in the discharged fuel, or more commonly known as spent fuel, can be reused. In order to facilitate its reuse, the uranium, plutonium, and waste products found in spent fuel are chemically separated and the plutonium (Pu) and uranium are re-introduced into the NMP process enabling it to begin again.

[7] Fissile isotopes of uranium and plutonium are foundational to the development of a nuclear weapon or other explosive device, and thus, require the enrichment of U-235 using centrifugal technology, the production of plutonium-239 through the irradiation of uranium, and/or the production of U-233 through the irradiation of thorium-232 (Council on Foreign Relations n.d.). Fissile isotopes, Pu-239 and U-233, must then undergo chemical separation through an operation called reprocessing, as fissile nuclear material, whether plutonium or uranium based. This nuclear material is then integrated into a weapons system, which generally includes a casing, reflector, communication system, and trigger components. Following which, the configuration is tested to determine its effectiveness (Cochran et al. 2022).

[8] "Horizontal proliferation is the spread of nuclear weapons to new countries through banning the trade of nuclear arms and …stop[ping] any capability …. for producing nuclear weapons", whereas "vertical proliferation refers to the advancement and stockpiling of nuclear weapons (The

Kroenig 2014).

At the same time, enrichment and reprocessing are also critical stages to furthering the application of nuclear science and technology for good, and thus, improving system efficiencies in the deployment and modernization of enrichment and reprocessing capacities is a central priority for nuclear weapon state and non-nuclear weapon state users alike. However, given the largely neglected associability of AI as a dual-use technology for NMP within the academic and practitioner communities, a widening opportunity for AI to aid in illicit and covert non-peaceful applications exists. As such, this article will investigate the evolving and applicable uses of AI to improve reprocessing and enrichment technologies in the context of both nuclear and non-nuclear applications.

4. AI’s Potential Applications in the NMP

Industrial applications of AI can be broadly divided into three categories: anomaly detection, automated optimization, and automated discovery. The present section examines how each of these techniques functions, have been applied in civilian industries, and can affect the proliferation-sensitive stages of NMP. A summary of the key potential application of AI in the NMP is illustrated in Table 1 with potential use cases specified in the text below and Appendix 1.

Table 1: Key potential applications of AI in the NMP

	Anomaly Detection	**Automated Optimization**	**Automated Discovery**
Critical Equipment (see Appendix 1)	Alert and prevent equipment failure and production accidents	Improve equipment configuration and design	Advance computational and data processing power through hardware innovation
Computer Systems	Alert and prevent system failure	Promote production line efficiency	Accelerate computer system development and upgradation
Revolutionary Knowledge	Facilitate human-centric knowledge production to revolutionize NMP	Facilitate human-centric knowledge production to revolutionize NMP	Realize machine-centric knowledge production to revolutionize the NMP at an exponential rate

Sources: authors’ compilation

4.1. Anomaly Detection

An AI anomaly detection algorithm is trained to recognize machine or system data featuring “normal behaviors”. When real-time data deviates from the normality pattern, the AI algorithm will identify the anomaly. Early-stage defection alarms make inspection and fixation possible before

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Nuclear Times 2016).

mechanical or system breakdown.

The use cases of AI anomaly detection fall into two categories. First, AI is used by industries to monitor, detect, and diagnose faults in machines. An example is the anomaly detection of centrifugal pumps (Al Tobi et al. 2022; Nabli and Hassani 2009). Second, AI is also widely applied in cyber defense products to detect anomalies led by cyberattacks or infections, which is a growing threat to sophisticated nuclear programs (Al Tobi et al. 2022; Nabli and Hassani 2009). An example is General Electric's AI cyber defense solution, Digital Ghost, which serves the U.S. Department of Energy, an agency responsible for managing the nation's enriched uranium supply, in protecting critical infrastructure (General Electric n.d.a).

The aforementioned applications can be readily integrated into the NMP process provided that the training, testing, and verification data of the critical machines and computer systems involved in the producing process are accessible. Specific applications include adopting AI anomaly detection solutions to prevent failure of critical NMP equipment (e.g., centrifuges) and computer systems (e.g., management or cyber defense systems). Similar AI solutions can also advance the efficiency and safety in human-centric knowledge production processes that facilitate NMP (e.g., advanced fissile isotope separation methods[9]).

4.2. Automated Optimization

Automated optimization solutions train the AI algorithms to analyze data of predefined parameters in an industrial process. Based on this analysis, the algorithms can predict product quality and correct the problematic parameters to improve it. When applied to complex systems, AI algorithms can set up many factors at different levels, simulate their performance, and identify the best combination for achieving optimized solutions.

The use cases of AI automated optimization in civilian industries are three-fold. The first is industrial production. For instance, artificial neural networks, a type of deep learning algorithm, are used to monitor and adjust the performance of centrifuges in the separation processes (Funes et al. 2009; Jiménez et al. 2008; Menesklou et al. 2021). The second is industrial design. Examples include determining the optimum configuration for race cars used in different races (Monolith AI n.d.), the optimum design of computer chips (Mirhoseini et al. 2021), and the optimum shape for the crown of a piston in a diesel engine (Bogaisky 2019). The third is logistic planning. Examples are the reduction of the airplane turnaround time and the optimization of delivery fleet routing (General Electric n.d.b; Google n.d.).

These AI optimization solutions can also be integrated into the NMP with the availability of machine or system data. This has already been applied to optimize the dimensions of a rotating baffle in gas centrifuges for uranium enrichment (Migliavacca et al. 2002). Further potential NMP use cases include the improvement of the machine (e.g., nuclear centrifuges) configuration; the design of machine (e.g., centrifuge) parts; and the efficiency of the NMP lines (e.g., the arrangement of centrifuge cascades and the broader management of the NMP process). Further human-centric nuclear research can also benefit from automated optimization solutions, which may in turn revolutionize the NMP.

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[9] For relevant research, see Kerman 2022a.

4.3. Automated Discovery

AI algorithms are trained to understand the rules of a game by identifying key parameters at an initial stage, after which AI will develop its own algorithms to determine the best solution for the game. For example, from playing games (e.g., AlphaGo, AlphaZero) (Silver et al. 2017; Silver et al. 2018), to protein structure prediction (e.g., AlphaFold) (Jumper et al. 2021), code generation (e.g., AlphaCode) (Li et al. 2022), and faster matrix multiplication discovery (e.g., AlphaTensor) (Fawzi et al. 2022), AI has demonstrated its capability to revolutionize the scientific world at an exponential rate. Nevertheless, the application of automated discovery remains in an early development stage in the nuclear sciences. Consequently, few existing industrial applications are ready to be integrated into the NMP or even feasibility research.[10]

Automated discovery techniques can not only advance computational and data processing power through hardware (e.g., AI chips and computers) innovation, but also accelerate the development and upgradation of computer systems through automatic code generation (e.g., cyber defense or industrial management systems). More significantly, the technique foresees the realization of machine-centric NMP knowledge production like in the case of protein structure prediction[11], which accelerates the speed and accuracy of human-based research (e.g., on new fissile isotope separation methods[12] and more efficient materials[13]). Resultantly, automated discovery is the most advanced AI application, among the three mentioned, with the potential to fundamentally impact the entirety of the NMP lifecycle process.

5. The Way Forward

As demonstrated, AI has already impacted several stages of NMP, and thus, its premise as a dual-use technology must be properly managed. While this endeavor requires an all-out effort from all involved parties, the scope of this discussion may focus on a three-dimensional solution.

5.1. Recommendation 1: State actors should be responsible for designing and executing effective NMP-related data and infrastructure governance.

To account for the emergence of new dual-use technologies, such as AI, the existing legal and non-legal frameworks need to evolve.[14] However, the current political environment has further compounded global consensus building even in such cases where reaching consensus benefits all parties.[15] Nonetheless, states remain decisive actors in monitoring and regulating dual-use applications of AI as it relates to NMP.

In monitoring and regulating dual-use applications of AI, the scope should exclude AI algorithms as they are open-sourced and globally accessible, and therefore, impossible to monitor and regulate.

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[10] Examples of existing research are limited but include the use of automated discovery to accelerate decision making as it relates to the selection of optimal alloy concentration for use in nuclear fuel cladding (University of California - Berkeley Nuclear Engineering, n.d.).

[11] Protein structure prediction is important to the development of vaccines, but at the same time, this technology, without proper regulatory controls, could also enhance the production, delivery, and accessibility of bioweapons.

[12] For relevant research, see Kerman 2022a.

[13] For relevant research, see University of California - Berkeley Nuclear Engineering, n.d.

[14] An example of a legal framework is the Additional Protocol (International Atomic Energy Agency, 1997) and an example of a non-legal framework is the Nuclear Suppliers Group guidelines (Nuclear Suppliers Group n.d.b).

[15] For example, in 2021, many States, including the United States and Russia, worked together in the framework of an Open-Ended Working Group on developments in the field of information and telecommunications to create a code of responsible behavior in cyberspace in the context of international security. Despite having built consensus around a viable solution, States ultimately submitted two competing resolutions to the UN General Assembly as a result of diverging opinions on the war in Ukraine (Chernenko 2022).

Instead, the scope should focus on two AI-supporting elements. The first focus should be on the data. Since the precision of an AI solution depends on the quality and quantity of the training and testing data, the transfer of sensitive data around NMP, including the peaceful production of nuclear material, should be safeguarded through enacting proper regulatory measures on technologies, data transfer, and security standards (e.g., cybersecurity).[16] The second focus should be on information infrastructure. As the function of AI-powered systems depend on advanced information infrastructures, including fast-speed broadband, cloud storage, AI chips, and supercomputers, among other things, the acquisition and transfer of these critical AI infrastructures should also be monitored. Therefore, export control of AI systems should focus on the transfer of training data and testing data as well as supporting infrastructure.

Data and infrastructure governance can be achieved via unilateral, bilateral, or multilateral solutions as well as informal and formal means. A ready-to-implement platform is national export control regimes. Hitherto, the United States, European Union, Russia, China, and other political entities with nuclear capabilities have increasingly fortified national legislation around functional export control mechanisms for technologies and data critical to their national security interests (Pacific Northwest National Laboratory, n.d.; PRC 2017; PRC 2020; PRC 2021; European Union 2021; Federal Service for Technical and Export Control of Russia n.d.; Vladimirova et al. 2014). In addition to unilateral efforts, states should also pursue related multilateral discussions based on a shared interest in improving AI specific export control regime mechanisms, rather than enabling diverging political positions to hinder such discussions (Fisher 1991). An existing conduit for facilitating discussions and future negotiations in this regard is the Nuclear Suppliers Group (NSG), where member state participants agreed to voluntarily implement "guidelines for nuclear exports and nuclear-related exports" (Nuclear Suppliers Group n.d.a).[17]

5.2. Recommendation 2: The non-proliferation sector should develop an AI proficient workforce supported by external AI industry partnerships.

Given that State actors, nongovernmental organizations (NGOs), and intergovernmental organizations (IGOs) within the nuclear domain and AI experts have had limited interactions with one another, this has produced a knowledge gap that can be reduced through collective discussions.[18] As such, building awareness and sustainable partnerships, both formal and informal, is vital.

To mobilize industry engagement in the non-proliferation sphere, a two-step approach must be taken by states, NGOs, and IGOs. First, researchers and scientists must develop and maintain a comprehensive understanding regarding the state-of-the-art AI research as well as most advanced industrial use cases associated with the NMP. A visualized example is illustrated in Appendix 1. This can be self-initiated or under institutional cooperation[19]. Ideally, a fully developed table, as illustrated in Appendix 1, summarizing AI's applicability to NMP would be shared within the nuclear

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[16] While the existing international framework and many State specific legal frameworks safeguard the transfer of sensitive nuclear technology, such as sensitive datasets, increasingly sophisticated cyber security threats and the industry's inability to sufficiently safeguard against such threats is well recognized (Nuclear Threat Initiative, n.d.).

[17] Maria Roskoshnaya, Head of Export Control Department at Rosatom, affirmed in personal communication with the authors that AI is currently not being discussed within the context of improving NSG issued export control guidelines (Roskoshnaya 2023). There are no publicly available documents with reference to AI on the NSG website.

[18] Maria Roskoshnaya indicates that ongoing informal discussions with industry and academia is not always fruitful given that the regulator does not always have the full amount of information nor understanding of advanced technologies related to AI (Roskoshnaya 2023).

[19] The United States Nuclear Regulatory Commission (NRC) has initiated a plan to develop an AI proficient workforce under their AI Strategic Plan beginning in 2023 (Dennis et al. 2022).

policy making community to develop a shared understanding on the subject, which in turn could serve as the foundation for future policy discussions.

Second, platforms and initiatives must be created and expanded to integrate the AI-related industry into the nuclear policy debate. For example, several United Nations (UN) based organizations initiated an "AI for Good" program to identify and promote AI applications that accelerate the furtherment of the United Nations Sustainable Development Goals (UN SDGs). A recent sub-initiative, entitled "AI for Atom," addresses AI applications, methodologies, and tools that can advance nuclear science and technology (Peeva 2021). However, the impact of AI on NMP and modernization, as well as its potential risks have yet to be addressed. As such, the broader "AI for Good" program could be expanded to include AI industrial partners to facilitate knowledge exchange around dual-use applications of AI and their potential implications in maintaining the non-proliferation regime.

Third, industrial advisory boards must be established within the relevant policy-making bodies. These advisory boards would serve two purposes: the minimization of the AI knowledge gap and the creation of effective export control guidelines. This could rely on IGOs, including the International Atomic Energy Agency and United Nations Office for Disarmament Affairs, and by extension, the Wassenaar Arrangement and World Customs Organization to promote discussions around emerging technologies and their potential implications for the maintenance of the non-proliferation regime. Meanwhile, the NSG, as a binding mechanism, presents another means for member states to create effective export control guidelines through the inclusion of an industrial advisory board.[20]

5.3. Recommendation 3: Civil society and international community should promote ethical AI as a means to incentivize government- and self-compliance in the AI industry.

Industries do not always comply with states' policy goals or collective interests. Therefore, measures should be taken to stimulate industry compliance and engagement in non-proliferation efforts. This may include reputational costs, moral considerations of employees, the existence of an outreach program, and the actions of governments in building a narrative that encourages compliance (Stewart et al. 2016). For example, when considering reputational costs and moral considerations, demonstrable industry-based association with the UN SDGs have become increasingly important as companies manage employee and customer expectations surrounding sustainability, integrity, and values in an increasingly global and competitive market (United Nations Global Compact n.d.). Some of the leading suppliers of AI technology, including Amazon (Amazon n.d.), IBM (IBM 2018), and C3.ai (C3.ai n.d.), have expanded their business model to this end. Thus, the UN SDGs are promising instruments for governments, NGOs, and IGOs to leverage when negotiating for transparency and accountability within the AI industry.

NGOs and civil society must be fully aware of their responsibility as gatekeepers of the non-proliferation regime, and thus, utilize their influence to counteract governmental policy preferences and industrial incentives that have the potential to negatively impact the regime's effectiveness. The first step to achieving this goal is to increase civil society's exposure of AI industrial activities to the potential proliferation of nuclear material. The second step is to translate

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[20] The NSG currently encourages national authorities to work closely with industry to ensure effective export control regimes (Nuclear Suppliers Group n.d.a) but does not offer a mechanism for internalizing this suggestion.

the policy preferences of civil society into customer-based reputational costs to the AI industry. For example, a grassroots initiative centered around building peaceful uses of dual-use AI technologies into their development and distribution under the auspices of UN SDG 16[21] could be introduced to minimize reputational costs. Under this initiative, companies would thereby agree to report end-users when transferring data, AI-powered systems, and supporting infrastructures with a potential to facilitate high-enriched uranium and plutonium production to another party, thus stimulating market self-regulation through the indoctrination of AI for good.

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[21] UN SDG 16 corresponds to the furthering of international peace and security through "the promot[ion] of peaceful and inclusive societies for sustainable development, [that] provide[s] access to justice for all and build effective, accountable and inclusive institutions at all levels" (United Nations n.d.).

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Appendix 1: Existing AI Applications to NMP Critical Equipment and to Non-Nuclear Industry Integrable to the NFC

Application	**Critical Equipment**	**Industrial Applications of AI**	
		Internal (Nuclear)	**External (Non-Nuclear)**
NMP Critical Stage: Enrichment			
Gas Centrifuge Rotating Components	Rotor tube and assemblies	N/A	- AD: diagnose rotor fault in accordance with different phases (Nath et al. 2021) - AD & AO: improve machine security and inform Operator of rotor service needs through automatic centrifuge rotor state recognition (Chen 2013)
	Gas centrifuge	- AD: construct a digital representation or simulation of the chemical separations component to determine anomalies, failures, and trends (Kerman 2022a)	- AO: monitor and adjust the performance of centrifuges in the olive oil production processes (Funes et al. 2009; Jiménez et al. 2008; Menesklou et al. 2021)
	Rings or bellows	N/A	N/A
	Baffles	- AO: study the influence of four construction variables, including the dimension of the rotating baffle, to optimize centrifuge performance (Migliavacca et al. 2002) - AO: study the optimal arrangement of scoops and rotating baffles, to optimize centrifuge performance (Migliavacca et al. 1999)	N/A
	Top and bottom caps	N/A	N/A
Gas Centrifuge Static Components	Magnetic suspension bearings	N/A	N/A

	Dampers & bearings	N/A	- AD: monitor and diagnose faults of bearings, sensors, lubrication, seals and remanufacturing (SKF 2020)
	Molecular pumps	N/A	- AO: monitor and adjust the performance of vacuum pumps (Pal 2016)
	Motor stators	N/A	- AD: monitor and fault identification scheme for motor (Vinoth Kumar et al. 2018)
	Centrifuge housings/ recipients	N/A	N/A
	Scoops	- AO: study the optimal arrangement of scoops and rotating baffles, to optimize centrifuge performance (Migliavacca et al. 1999)	N/A
Gas Centrifuge Plant auxiliary systems, equipment and components	Feed, product and tail withdrawal systems	N/A	N/A
	Machine header piping systems	N/A	- AO: improve design, using predictive models, of early-stage piping systems (Telci 2021)
	UF6 mass spectrometers /ion sources	N/A	N/A
	Frequency changers	N/A	N/A
	Gaseous diffusion barriers	N/A	N/A

	Diffuser housing	N/A	N/A
	Compressors and gas blowers	N/A	- AO: model "blade profiles with specified performance metrics and operating and manufacturing constraints" (University of London City n.d.) - AO: model 2D and 3D profiles of compressor blades (Xu et al. 2023)
	Rotary shaft seals	N/A	N/A
	Heat exchangers (for cooling UF6)	N/A	- AO: model and estimate the outlet temperatures of working fluid through heat exchangers (Mohan 2020)
Gaseous Diffusion Enrichment auxiliary systems, equipment and components	Feed, product and tail withdrawal systems	N/A	N/A
	Header piping systems	N/A	- AO: improve design, using predictive models, of early-stage piping systems (Telci 2021)
	Vacuum systems	N/A	N/A
	Shut-off and control valves	N/A	- AD: monitor and diagnose valve fault (Shelly n.d.) - AO: model and estimate valve performance based on flow performance parameters (Jadhav 2018)
	Separation nozzles	N/A	N/A
Aerodynamic Enrichment Plant auxiliary systems, equipment and components	Vortex tubes	N/A	- AO: monitor and adjust the performance of vortex tubes (Pouraria 2016) - AO: optimize performance of vortex tubes (Agarwal et al. 2020)

	Compressors and gas blowers	N/A	- AO: model “blade profiles with specified performance metrics and operating and manufacturing constraints” (University of London City n.d.) - AO: model 2D and 3D profiles of compressor blades (Xu et al. 2023)
	Rotary shaft seals	N/A	N/A
	Heat exchangers (for gas cooling)	N/A	- AO: model and estimate the outlet temperatures of working fluid through heat exchangers (Mohan 2020)
	Separation element housings	N/A	N/A
	Feed systems / product and tail withdrawal systems	N/A	N/A
	Header piping systems	N/A	- AO: improve design, using predictive models, of early-stage piping systems (Telci 2021)
	Vacuum systems and pumps	N/A	- AO: monitor and adjust the performance of vacuum pumps (Pal 2016)
	Shut-off and control valves	N/A	- AD: monitor and diagnose valve fault (Shelly n.d.) - AO: model and estimate valve performance based on flow performance parameters (Jadhav 2018)
	UF6 mass spectrometers / ion sources	N/A	N/A

	UF6 gas separation systems	N/A	N/A
Exchange Enrichment Plant auxiliary systems, equipment and components	Liquid-liquid exchange columns (chemical exchange)	N/A	N/A
	Liquid-liquid centrifugal contactors (chemical exchange)	N/A	N/A
	Feed preparation systems (Chemical exchange)	N/A	N/A
	Uranium oxidation systems (chemical exchange)	N/A	N/A
	Fast-reacting ion exchange resins/ absorbents (ion exchange)	- AO: map existing relations between nucleus radius and resin's exchange time efficiency to find most ideal pelicula dimension (Cabral et al. 2005)	N/A
	Ion exchange columns (ion exchange)	N/A	N/A

	Ion exchange reflux systems (ion exchange)	N/A	N/A
Laser-based Enrichment Plant systems, equipment and components	Uranium vaporization system (Atomic vapor laser isotope separation [AVLIS])	N/A	N/A
	Liquid uranium metal handling system (AVLIS)	N/A	N/A
	Uranium metal 'product’ and 'tails' collector assemblies (AVLIS)	N/A	N/A
	Separator module housings (AVLIS)	N/A	N/A
	Supersonic expansion nozzles (Molecular laser isotope separation [MLIS])	N/A	N/A
	Uranium pentafluoride product collectors (MLIS)	N/A	N/A

	UF6/carrier gas compressors (MLIS)	N/A	- AO: model “blade profiles with specified performance metrics and operating and manufacturing constraints” (University of London City n.d.) - AO: model 2D and 3D profiles of compressor blades (Xu et al. 2023)
	Rotary shaft seals (MLIS)	N/A	N/A
	Fluorination systems (MLIS)	N/A	N/A
	UF6 mass spectrometers / ion sources (MLIS)	N/A	N/A
	Feed withdrawal systems (MLIS)	N/A	N/A
	Laser systems (ALVIS, MLIS, Chemical reaction by isotope selective laser activation [CRISLA])	N/A	N/A

Plasma Separation Enrichment Plants systems, equipment and components	Microwave power sources and antenna	N/A	N/A
	Ion excitation coils	N/A	- AD: condition monitoring and fault detection of superconducting apparatuses in large-scale power applications (Yazdani-Asrami et al. 2022) - AO: improve design, using predictive models, of superconducting apparatuses (Yazdani-Asrami et al. 2022)
	Uranium plasma generation systems	N/A	N/A
	Liquid uranium metal handling system	N/A	N/A
	Uranium metal “product” and “tails” collector assemblies	N/A	N/A
	Separator module housings	N/A	N/A

NMP Critical Stage: Reprocessing			
Reprocessing Components	NM flow verification	- AO: develop real-time tracking of spent fuel material flow within a given facility (General Electric n.d.c.)	N/A
	Plasma separation applied to reprocessing	N/A	- AD: condition monitoring and fault detection of superconducting apparatuses in large-scale power applications (Yazdani-Asrami et al. 2022) - AO: improve design, using predictive models, of superconducting apparatuses (Yazdani-Asrami et al. 2022)
	Dissolvers	N/A	N/A
	Metal cutting shears	N/A	N/A
	Solvent extractors	- AO: characterize stages within solvent extraction process to increase target metals recovery, indicate process faults, account for special nuclear material, and inform near real time decision making (Kerman 2022b) - AO: process improvement through identification of better design alternatives for determining pH level and chemical structures of dissolved nuclear fuel (Papich 2021)	- AO: improve design with aim of lowering activation barrier of the rearrangement reaction (Gastegger 2021)
	Chemical holding or storage vessels	N/A	N/A
	Plutonium nitrate to oxide conversion systems	N/A	N/A
	Plutonium oxide to	N/A	N/A

	metal production system		
	Hydrogen fluoride	N/A	N/A
	Ceramic crucibles	N/A	- AO: confirm accuracy of AI based modeling of Al2O3 nanoparticles reinforced with A356 matrix composites (Shabani et al. 2012)

Sources: Authors' compilation based on selective open-source analysis (AD-Anomaly Detection; AO-Anomaly Optimization; Automated Discovery remains in the early research stage hitherto without a publicly known application to equipment in nuclear or non-nuclear industry, and therefore is excluded from the table.) Note: Appendix 1 is a template that is offered to better understand the application of AI to the NMP, and it does not provide a complete review of the NMP process. However, it is envisioned that researchers could use this template as a means to further this research.