A FRAMEWORK FOR ASSESSING ALTERNATE PROLIFERATION PATHWAYS IN THE AGE OF NON-STATE ACTORS

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Abstract

While the nonproliferation community has long acknowledged the possibility of nuclear terrorism, its prevention has become a central focus area in recent years. For decades it has been assumed that, with access to special nuclear material (SNM), the steps to indigenously develop an improvised nuclear device are within the reach of non-state actors. At the same time, indigenous development of the SNM itself has generally been dismissed as it is perceived as an infeasible option. Recognizing how recent trends of technology democratization, the open exchange of information, and globalization have eroded certain barriers to proliferation by non-state actors, this research explores whether indigenous development of SNM is feasible given the current capabilities of non-state actors. Additionally, methods were developed to screen which approaches should be further investigated to devise and enact general and non-state actor specific countermeasures.

1. Introduction

In his statement on the release of the 2010 Nuclear Posture Review, former President Obama stated that, “the greatest threat to US and global security is no longer a nuclear exchange between nations, but nuclear terrorism by violent extremists.” The Nuclear Posture Review went on to declare the prevention of nuclear terrorism as the number one US nuclear policy objective.[1] More recently, preventing nuclear terrorism was a central theme of the 2016 Nuclear Security Summit.[2] While there is broad agreement on the threat, there is disagreement within the nonproliferation community on the non-state actor’s optimal route to an improvised nuclear device (IND). The four paths generally put forth are: 1) state sponsorship, 2) theft of intact nuclear weapon or fissile material, 3) black market purchase of fissile material, or 4) indigenous development.[3]

There is historical evidence for attempts by non-state actors at paths one and two, but considering there have been no past successes, decreased nuclear weapon and fissile

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[1] US Department of Defense, *Nuclear Posture Review Report*, April 2010, <https://www.defense.gov/Portals/1/features/defenseReviews/NPR/2010_Nuclear_Posture_Review_Report.pdf>.

[2] Maya Rhodan, “Terrorism, Climate Take Center Stage at Nuclear Security Summit,” *Time Magazine*, March 31, 2016, <http://time.com/4278085/nuclear-summit-terrorism-climate-change-barack-obama/>.

[3] Evan B. Montgomery, *Nuclear Terrorism: Assessing the Threat, Developing a Response*, Center for Strategic and Budgetary Assessments (Washington DC, 2009); Matthew G. Bunn, Rolf Mowatt-Larssen, Simon Saradzhyan, William H. Tobey, Yuri Morozov, Viktor I. Yesin, and Pavel S. Zolotarev, “The US-Russia Joint threat assessment of nuclear terrorism,” June 6, 2011, <http://www.belfercenter.org/publication/us-russia-joint-threat-assessment-nuclear-terrorism>.

material vulnerabilities, and increased international transparency and cooperation, these options are becoming increasingly difficult.[4] Path three has often been cited as the most viable based on the 2,734 nuclear materials incidents reported to the International Atomic Energy Agency (IAEA) between 1993 and 2014. However, only nineteen involved highly enriched uranium (HEU) or plutonium. Specific incident data is not released to the public, but the IAEA states, "the majority involved gram quantities."[5] The known trafficking of special nuclear material (SNM) indicates a rate of less than one incident per year of amounts representing a small fraction of the quantity necessary to make an IND.[6]

Path four is typically subdivided into indigenous development of the IND given another SNM source and indigenous development of the SNM and IND. It has been widely assumed for decades that given the SNM, the steps to indigenously develop an IND are within the capabilities of non-state actors.[7] Conversely, indigenous development of SNM is often summarily dismissed as it is perceived as an infeasible option.[8] The research on proliferation that supports this premise almost exclusively employs several implicit assumptions derived from the historical record on attempted and successful nation-state proliferation, e.g., that non-state actors would not possess the "knowledge, infrastructure, and finances"[9] of a state. Many of those assumptions do not hold for proliferation by some non-state actors. By addressing these assumptions, a fresh look

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[4] Bunn et al., "The US-Russia Joint threat assessment."

[5] IAEA, "IAEA Incident and Tracking Database (ITDB): 2015 Fact Sheet," (2015), <http://large.stanford.edu/courses/2016/ph241/wolk1/docs/itdb-fact-sheet.pdf>.

[6] Graham T. Allison, "Nuclear Terrorism Fact Sheet," Policy Memo, Belfer Center for Science and International Affairs, Harvard Kennedy School (2010).

[7] Bunn et al., "The US-Russia Joint threat assessment"; W. J. Frank, "Nth-Country Experiment," UCRL-50249 (1967).

[8] Montgomery, *Nuclear Terrorism*.

[9] Montgomery, *Nuclear Terrorism*, pp. ix.

can be taken towards the viability of the SNM indigenous development path for non-state actors.

It is commonly assumed that a proliferator will seek to develop a stockpile of nuclear weapons. Indeed, the historical record and prevailing nuclear theories that require the establishment of "a significant military capability" offer little to contradict this assumption.[10] However, these theories and the historical record do not account for the limited goals espoused by any of the six non-state actors that have sought nuclear weapons.[11] Additionally, recent trends of technology democratization have eroded some of the barriers to proliferation by non-state actors. For example, additive manufacturing, high-performance computing, the open exchange of information, globalization, and diversification of technologies have eroded traditional proliferation choke points.[12] At the same time, the net worth and cash assets of the richest non-state actors have exploded,

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[10] Thomas C. Reed and Danny B. Stillman, *The nuclear express: a political history of the bomb and its proliferation*, (Minneapolis: Zenith Press, 2010); Fred Kaplan, *The Wizards of Armageddon*, (Stanford: Stanford University Press, 1983).

[11] Allison, "Nuclear Terrorism Fact Sheet"; Khidhir Hamza, and Jeff Stein, *Saddam's bombmaker: the daring escape of the man who built Iraq's secret weapon*, (New York: Simon and Schuster, 2001); John Cantlie, "The Perfect Storm," *Dabiq,* Issue 9, (May 2015), pp. 74–77.

[12] Bruce T. Goodwin, "Additive Manufacturing & High Performance Computing: Disruptive Latent Technologies Impacting Our National Security," (presentation, Center for International Security and Cooperation Seminar, Stanford, CA May 2, 2016); Bob Graham, James M. Talent, Graham Allison, Robin Cleveland, Steve Rademaker, Tim Roemer, Wendy Sherman, Henry Sokolski, and Rich Verma, "World at Risk: The Report of the Commission on the Prevention of Weapons of Mass Destruction Proliferation and Terrorism," (New York: Vintage, 2008); Stanley A. Erickson, "Economic and technological trends affecting nuclear nonproliferation," *The Nonproliferation Review* 8, No. 2 (2001), pp. 40–54.

reducing the financial prohibitions.[13] These trends, coupled with the removal of the requirement for a robust, reliable nuclear weapons production line, significantly lower the barrier to indigenous SNM development.

This research aims to develop methods by which indigenous SNM development pathways for a non-state actor can be evaluated at a concept-screening level of precision. The goal of this approach is two-fold. First, it aims to answer whether indigenous development of SNM is feasible given the current capabilities and resources of non-state actors. Second, it aims to develop methods to screen which approaches should be further investigated in order to devise and enact general and non-state-actor-specific countermeasures. In this context, approaches are developed to bound the requirements for a stripped-down, single-use fuel cycle that is initiated with the implicit goal of developing 50 kilograms (kg) of 90 percent HEU for a gun-type IND. Only the stages required to produce the HEU are considered in this paper (plutonium pathways, conversion and fabrication of the metal, and device weaponization are ignored in this paper) as many other studies have considered the viability of non-state actors turning a sufficient mass of HEU into an IND.[14] General evaluation metrics and a framework model are then developed to assess the efficacy of each technology and path. Finally, the metrics and models developed are adapted and applied using the Islamic State in Iraq and the Levant (ISIL) as a case study.

2. A Single-Use Fuel Cycle

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[13] Vasudevan Sridharan, “List of World’s Richest Terror Networks Revealed,” *IB Times*, November 12, 2014, < http://www.ibtimes.co.uk/list-worlds-richest-terror-networks-unveiled-1474351>.

[14] Bunn et al., “The US-Russia Joint threat assessment”; Frank, “Nth-Country Experiment.”

A traditional weapons fuel cycle for both uranium and plutonium pathways is shown in Figure 1. For this study, three major assumptions are made on the choice and objectives of a potential non-state proliferant fuel cycle. First, a development goal of one IND – consistent with the stated limited aims of non-state actors – was made. This allows the back-end steps of the fuel cycle to be eliminated. Second, the plutonium path was eliminated from consideration. From the proliferant's point of view, this simplifies the non-state actor's fuel cycle considerably by eliminating the need for fuel fabrication, a nuclear reactor, reprocessing, and potentially enrichment. While, the evidence for a proliferant preference amongst states is mixed, all proliferation attempts since the inception of the Nonproliferation Treaty using the plutonium pathway have either failed or had significant foreign assistance in the form of technology and equipment. [15] The elimination of the plutonium pathway simplifies the fuel cycle to four steps—uranium sourcing, milling, conversion, and enrichment—as shown in the non-shaded region in Figure 1. Finally, a development goal of 50 kg of HEU was chosen instead of the IAEA significant quantity to allow for development of any type of IND (i.e. implosion or gun-type) without concern for efficient design, and 90% enrichment was used as that is generally the minimum considered for weapons-grade (which would be necessary to not only lessen the amount of HEU necessary for criticality, but also would ensure the weapon would work as designed).

Simplifying the fuel cycle is not the sole benefit from a single-use fuel cycle. By prioritizing cost and speed with the goal of only developing one nuclear weapon, factors such as reliability, efficiency, maintainability, compliance, and safety can be sacrificed. The removal of each of these constraints comes with cost and schedule benefits to the potential proliferator. Quantifying these benefits is challenging due to the dearth of data; therefore, surrogate analogies are used to develop reasonable bounds for cost- and schedule-scaling factors.

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[15] Joel Ullom, "Enriched Uranium Versus Plutonium: Proliferant Preferences in the Choice of Fissile Material," *The Nonproliferation Review* 2, No. 1 (1994), pp. 1-15.

For example, one high-technology systems analog is the re-usable rocket concept. Studies have shown re-usable rockets have an initial development cost that is 10–100 percent higher than that of expendable rockets.[16] The simplifications in design result in material and research and development savings for the single-use system.

The field of reliability engineering provides more analogies into the cost savings associated with sacrificing reliability. The purchase cost typically increases as the reliability of the system increases, but the shape of this distribution is non-linear and highly system-dependent. For example, studies have found that a 40,000-mile tire only costs 15 percent more than a 20,000-mile tire, but a 75,000-mile tire could cost several times that of a 40,000-mile tire. Similarly, the percent reliability to percent cost ratio associated with increases in military systems reliability has varied from 1:1 to 35:1.[17]

Given the intense regulatory, safety, and commercial requirements governing nuclear facilities, all commercial examples fall into the high-reliability region of the trade-space where reductions in reliability, efficiency, maintainability, compliance, and safety result in large cost savings. For this research, the single-use fuel cycle reduced baseline costs by a cost-scaling factor of 0.5 that is applied as a multiplier to the system capacity-scaled costs. Although this is a conservative assumption and greater savings could be realized based on the analogies presented, the supposition of uniform savings across each technology could bias the results towards one path and/or technology in cases

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[16] Mohamed Ragab and F. McNeil Cheatwood, "Launch Vehicle Recovery and Reuse," (In AIAA SPACE 2015 Conference and Exposition, 2015*)*, pp. 4490; James R Wertz, "Economic model of reusable vs. expendable launch vehicles," (in IAF, International Astronautical Congress, 51 st, Rio de Janeiro, Brazil, 2000).

[17] Arthur J Alexander, *The cost and benefits of reliability in military equipment*, No. RAND/P-7515, (Santa Monica, CA: Rand Corp, 1988).

where there are large disparities between the cost-scaling factor and actual achievable savings among the available fuel cycle processes.[18]

There are two insightful analogs that can be used to assess the schedule impact of the single-use approach. First, an expert opinion assessment of the timeline for a "quick and secret" plutonium reprocessing plant found that a typical 60-month development time could be shortened to as few as 4–6 months, although some pegged the timeframe closer to 24–30 months.[19] Second, an analysis of the impact of wartime acceleration of the Manhattan project found that the 4-year timeline would correspond to an 18-year development under normal peacetime conditions.[20] From these estimates, a conservative schedule-scaling factor of 0.5 is used as a multiplier to adjust baseline schedules for each technology. Although these factors will vary from technology to technology and non-state actor to non-state actor, a non-state actor utilizing the single-use fuel cycle should be able to *at least* obtain these cost- and schedule-scaling factors.

Each fuel cycle step and associated technology are described briefly in the following sections to highlight key considerations for a non-state actor, but it is beyond the scope of this paper to describe each in full technical detail.

2.1 Uranium Sourcing

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[18] US Congress Office of Technology Assessment, "Technologies Underlying Weapons of Mass Destruction December 1993," OTA-BP-ISC-115, December 1993.

[19] General Accounting Office, "Quick and Secret Construction of Plutonium Reprocessing Plants: A Way to Nuclear Weapons Proliferation?" EMD-78-104 (1978), < http://archive.gao.gov/f0902c/107377.pdf>.

[20] Harry Thayer, "Management of the Hanford Engineer Works in World War II: How the Corps, DuPont, and the Metallurgical Laboratory Fast Tracked the Original Plutonium Works," (New York, NY: ASCE Publications, 1996).

Five potential sources of natural uranium were considered: uranium mining, phosphate rock (PR) extraction, seawater extraction, open market purchase, and theft/diversion. Other potential sources such as black shale deposits exist, but they were eliminated due to localization of those known deposits in stable regions.[21] Approximately 12.6 metric tons (MT) of uranium oxide (U_3O_8) is required to produce 50 kg of 90 percent uranium-235, assuming a tails concentration of 0.3 percent U-235. However, to account for process inefficiencies associated with a single-use fuel cycle and to limit scaling issues associated with going from large commercial facilities (> 450 MT) to a much smaller operation, commercial data associated with uranium sourcing are scaled to produce 40 MT U_3O_8 (88,000 pounds) in one year for use in metric quantification in this analysis.

Mining from uranium ores currently accounts for 100 percent of the world's commercial supply of natural uranium.[22] Typically, uranium mines are large open pit mines, but underground mines and in situ leaching can minimize the footprint and detection probability.[23] Approximately 80 percent of known reserves are available at less than $50 per pound (lb) of U_3O_8.[24] This cost is typically amortized over the life of the mine thereby hiding the significant upfront capital expenses that would be required to develop a new mine, which can cost upwards of $20 million and take approximately 2–4 years for traditional development, including the milling costs.[25]

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[21] IAEA, "Uranium 2014: Resources, Production and Demand," NEA No. 7209 (2014), <https://www.oecd-nea.org/ndd/pubs/2014/7209-uranium-2014.pdf>.

[22] ibid.

[23] World Nuclear Association, "Uranium Mining Overview," *World Nuclear Association*, February 2016, <http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/uranium-mining-overview.aspx>.

[24] IAEA, "Uranium 2014."

[25] IAEA, "Guidebook on the Development of Projects for Uranium Mining and Ore Processing," IAEA-TECDOC-595 (1991).

The known uranium reserves in PR approximately equal the reserves found in conventional ores.[26] There is no current commercial extraction of uranium from PR, but there is significant historical experience worldwide.[27] Mobile pilot extraction plants the size of two 8 feet (ft) by 40 ft shipping containers have been developed, transported around the world, and successfully attached to existing wet phosphoric acid (WPA) production plants.[28] Costs are projected as low as $20 per lb of U_3O_8, and development expenses costs, assuming an existing WPA plant, are $10 million–15 million.[29]

By far, the largest known reserves of uranium are in seawater, but its concentration is in the 3–4 parts per billion range, making the extraction cost-prohibitive to date.[30] Ongoing development has pegged operating costs at $600 per lb of U_3O_8. While located underwater, the virtual footprint, seen as ocean surface area, is approximately 7 kilometers (km) by 5 km, and it would require approximately ten ships and 200 people to

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[26] IAEA, "Uranium 2014."

[27] Nuclear Threat Initiative, "Nuclear 101," <http://tutorials.nti.org/nuclear-101/overview/>; Joe Guida, Doug Royster and Regis Stana, "Uranium Extraction from Wet Process Phosphoric Acid, The Third Time Around," (2008) <http://www.aiche-cf.org/Clearwater/2008/Paper1/8.1.1.pdf>; Marten Walters, Thomas Baroody, and Wes Berry, "Technologies for Uranium Recovery from Phosphoric Acid," (presented at AIChE Central Florida Section 2008 Clearwater Convention, June 7, 2008), <http://www.aiche-cf.org/Clearwater/2008/Paper1/8.1.4.pdf>.

[28] PhosEnergy, "The Phosenergy Process," (2013), <http://www.phosenergy.com/wp-content/uploads/2013/09/PhosEnergy_FS_aug2013.pdf>.

[29] Vaughn Astley and Regis Stana, "There and Back Again 2.5Again Who did What in Solvent Extraction? A Demonstrated & Proven Technology for Uranium Recovery from Phosphoric Acid," *Procedia Engineering* 83 (2014), pp. 270–278; Guida et al., "Uranium Extraction from Wet Process Phosphoric Acid."

[30] IAEA, "Uranium 2014."

moor and recover. Additionally, the support infrastructure and development is extensive, requiring multiple facilities, several dozen workers, and capital expenses in the range of \$100 million.[31]

Uranium could be purchased on the open market as was done in Iraq, although that would be more complicated for a non-state actor.[32] This would be the most economical and fastest route by far as the spot price is \$20 per lb of U_3O_8 (as of September 25, 2017), no facility development is necessary, and the milling stage could be skipped. However, any attempts to purchase the quantities needed would face export control limitations imposed by the Nuclear Suppliers Group and the IAEA.[33] The Additional Protocol implemented by the IAEA was partly in response to the Iraqi program, and provisions in the new restrictions potentially make open-market purchase less viable for non-state actors. It is impossible to assess the potential costs associated with a black market purchase as no known cases of this magnitude exist in the open literature.

Diversion or theft is most commonly cited as the most plausible source of uranium for non-state actors.[34] Due to the sheer bulk of yellowcake transported worldwide, this is

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[31] Erich Schneider and Darshan Sachde, “The cost of recovering uranium from seawater by a braided polymer adsorbent system,” *Science & Global Security* 21, No. 2 (2013), pp.134–163.

[32] IAEA, “Iraq Nuclear File: Key Findings,” <https://www.iaea.org/OurWork/SV/Invo/factsheet.html>.

[33] IAEA, “Communication Received from the Permanent Mission of the Czech Republic to the International Atomic Energy Agency regarding Certain Member States’ Guidelines for the Export of Nuclear Material, Equipment and Technology,” INFCIRC/254/Rev.12/Part 1a, November 13, 2013, <https://www.iaea.org/sites/default/files/publications/documents/infcircs/1978/infcirc254r12p1.pdf>.

[34] Bunn et al., “The US-Russia Joint threat assessment.”

not an unreasonable assumption. However, while the timelines from fissile material to nuclear device are potentially short enough to complete the process prior to detection, the timeline necessary to convert, enrich, and build the device from yellowcake greatly increases the probability of detection and interdiction of stolen or diverted material under IAEA safeguards in any abrupt diversion scenario. It is difficult to assess costs and schedule, but it is worth noting that large-scale heists can take years in detailed planning.[35]

2.2 Milling

If uranium is obtained as an ore, the uranium must be chemically extracted from the ore to produce yellowcake, a product with a minimum 65 percent uranium content.[36] Uranium ore milling options are largely dependent on the geographic location of the sourced uranium, as the process of milling is almost exclusively determined by, and dependent on, the composition of the uranium ore or source material used.[37] In general, the process can be broken into five stages, some of which can be eliminated for certain uranium sourcing approaches: crushing and grinding, leaching, solid-liquid separation and washing, solvent extraction or ion exchange, and yellowcake precipitation and drying.[38] The options that can be used for milling should be tailored to the specifications of a particular uranium sourcing option.

2.3 Conversion

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[35] J. Lafleur, L.K. Purvis, and A.W. Roesler, “The Perfect Heist,” *Sandia Report* (2015), pp. 9-15.

[36] D. C. Seidel, “Extracting uranium from its ores,” *IAEA Bulletin* 23, No. 2 (1981), pp. 24–28.

[37] D. Connelly, “Uranium Processing,” *International Mining* (January 2008), pp. 58–61; Seidel, “Extracting uranium from its ores,” pp. 24–28.

[38] Seidel, “Extracting uranium from its ores,” pp. 24–28.

Conversion removes impurities and converts the output of the milling step into a form that is usable for the enrichment process. For example, gaseous diffusion and centrifuges use uranium hexafluoride (UF_6) while electromagnetic isotope separation (EMIS) uses uranium tetrachloride (UCl_4). By and large, the chemistry processes necessary for conversion are determined based on the form of the material obtained from the sourcing and milling steps and the enrichment process chosen. Within a given starting material and enrichment choice, there can be several options; for example, the wet or dry process for conversion from U_3O_8 to UF_6. These potential conversion processes and techniques should be mapped based on starting material and enrichment process to account for the proliferation paths that a non-state actor could choose.

2.4 Enrichment

Seven enrichment techniques are considered: gaseous diffusion, gaseous centrifuge, laser, electromagnetic, chemical, aerodynamic, and plasma separation. For enrichment, commercial data associated uranium enrichment are scaled to build a 10,000 separative work unit (SWU) facility that can produce 50 kg of HEU in one year, assuming a tails assay of 0.3 percent U-235.

Gaseous diffusion was one of the first full-scale enrichment techniques developed. Conceptually, the process is not difficult, but construction of barriers and the sheer scale of the facilities required make diffusion a difficult process to implement.[39] This size, coupled with the energy consumption, thermal signatures, manpower, and feedstock required has led to the assessment that, “clandestine enrichment with them is well-nigh

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[39] US Congress Office of Technology Assessment, “Technologies Underlying Weapons of Mass Destruction December 1993.”

impossible."[40] Scaled costs are approximately $25 million, and the plant can take several years to construct.[41]

Since the introduction of gaseous centrifuges, they have been recognized as a proliferation risk due to their relative concealability.[42] Centrifuge technology has been assessed to be within reach of "nearly any country, including many developing countries," and was sold by the AQ Khan network.[43] Gaseous centrifuge enrichment also has the advantages of limited signatures that can be detected at distance, a limited footprint where 10,000 centrifuges would only require a 40,000 ft^2 facility, and electricity

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[40] John Kirge, "The Proliferation Risks of Gas Centrifuge Enrichment at the Dawn of the NPT: Shedding Light on the Negotiating History," *The Nonproliferation Review* 19, No. 2 (2012), pp. 219–227; R. Scott Kemp and Alexander Glaser, "The Gas Centrifuge and the Nonproliferation of Nuclear Weapons," in *Proceedings of the Ninth International Workshop on Separation Phenomena in Liquids and Gases (SPLG)*, (Beijing: 2007), pp. 18–21; Adam Bernstein, "Monitoring large enrichment plants using thermal imagery from commercial satellites: A case study," No. SAND2000-8671, Sandia National Labs, Albuquerque, NM (US); Sandia National Labs, Livermore, CA (US), 2000.

[41] G. Rothwell and C. Braun, "International Nuclear Fuel Cycle Cost Analysis," *Science and Global Security* (2008).

[42] Kirge, "The Proliferation Risks of Gas Centrifuge Enrichment," pp. 219–227.

[43] Quote from: R. Scott Kemp, "Centrifuges: A New Era for Nuclear Proliferation," in Henry Sokolski, ed., *Nuclear Nonproliferation: Moving Beyond Pretense*, (Nonproliferation Policy Education Center, 2012). Additional information from: C. Collins and D. Frantz, "Fallout from the AQ Khan Network and the Clash of National Interests," in "Symposium on International Safeguards," Vienna (2010), <https://www.iaea.org/safeguards/symposium/2010/Documents/PapersRepository/2012749789382198030766.pdf>.

consumption that is over an order magnitude lower than gaseous diffusion.[44] Additionally, a small facility, producing 50 kg of HEU per year, is estimated to cost between $15 million–$80 million, with others pegging the estimate closer to $27 million.[45] Production time could run as little as three to four years with only a couple dozen workers.[46] However, the Iranian clandestine program was revealed to the public during its construction, detected much earlier, and has been fifteen to twenty years in the making.[47]

While there are two primary types of laser enrichment, this paper focuses on Molecular Laser Isotope Separation (MLIS). MLIS has low power consumption requirements (roughly on par with gaseous centrifuges) but has a much higher separation factor. While the MLIS system is highly technical, it is slightly less complicated than other laser methods as it utilizes UF_6 instead of hot uranium vapor. No country has successfully utilized laser technology to enrich uranium on a commercial or military level, which means significant research and development, money, and time will need to be invested

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[44] Kirge, “The Proliferation Risks of Gas Centrifuge Enrichment,” pp. 219–227; Kemp and Glaser, “The Gas Centrifuge and the Nonproliferation of Nuclear Weapons,” pp. 18–21; US Congress Office of Technology Assessment, “Technologies Underlying Weapons of Mass Destruction December 1993.”

[45] Note: This assumes limited centrifuge research and development costs – i.e. the proliferator is working with a previous known design such as the IR-1; US Congress Office of Technology Assessment, “Technologies Underlying Weapons of Mass Destruction December 1993”; Geoffrey Rothwell, “Market Power in Uranium Enrichment,” *Science and Global* Security 17 (2009), pp. 132–154.

[46] Kemp, “Centrifuges: A New Era for Nuclear Proliferation.”

[47] Kemp and Glaser, “The Gas Centrifuge and the Nonproliferation of Nuclear Weapons,” pp. 18–21.

to make this process viable.[48] Because MLIS can be operated in stages, it is theoretically dispersible. The footprint and cost is estimated to be much smaller than that of diffusion or centrifuges.[49]

EMIS is a proven process used in the calutron design at Oak Ridge during the Manhattan Project. Because the science behind EMIS is relatively basic, many nuclear states and attempted proliferators, such as Iraq, have researched and/or utilized EMIS. However, there are high power demands, large costs, a large footprint, and strict export controls. Based on UN reports, it is estimated that the Iraqi program would have been capable of producing 14 kg of HEU per year, which leads to an estimate of around three years to produce enough fissile material for one IND. A facility with 1,000 calutrons in the first stage and 300 calutrons in the second enrichment stage could produce 50 kg of 90 percent HEU in one year.[50]

French and Japanese researchers have pioneered enrichment research based on chemical-exchange (CHEMEX) and ion exchange, respectively. While no large-scale chemical- or ion-exchange enrichment facilities for either civilian or military use have been built, the technology and knowledge involved in these processes are widespread. However, scaling up from laboratory to multiple-kilogram enrichment would prove money- and time-intensive, especially with the necessary exchanges in each cylinder

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[48] Allan S Krass, Peter Boskma, Boelie Elzen, and Wim A Smit, *Uranium Enrichment and Nuclear Weapon Proliferation. Stockholm International Peace Research Institute*, (London: Taylor & Francis Ltd, 1983).

[49] P Parvin, B Sajad, K Silakhori, M Hooshvar, and Z Zamanipour, “Molecular Laser Isotope Separation versus Atomic Vapor Laser Isotope Separation,” *Progress in Nuclear Energy* 44 (2004), pp. 331–45.

[50] Andre Gsponer and Jean-Pierre Hurni, “Iraq’s Calutrons: Electromagnetic Isotope Separation, Beam Technology, and Nuclear Weapon Proliferation,” ISRI-95-03, (October 1995), pp. 1–18.

occurring over long time periods (ion-exchange is an order of magnitude faster than CHEMEX). Both chemical methods demand smaller power draws than other enrichment methods and have fairly small footprints, but they are not dispersible. The cost would be substantial, especially for CHEMEX, as significant quantities of natural uranium and chemical agents are needed.[51]

Although there are multiple types of aerodynamic enrichment, this paper focuses on the Helikon vortex tube separation process used in South Africa for weapons and reactor fuel enrichment.[52] Aerodynamic processes are favorable as they have high separation factors and can have lower costs and power consumption than gaseous diffusion.[53] The vortex tubes are quite large (around 10 meters (m) in length and 6 m in diameter) and regulated by the IAEA, but only a couple modules are required, which could lead to a smaller footprint.[54] The modules, however, are not dispersible. Considering South Africa as a test case, around 93 kg of HEU could be produced per year once the process is up and running, which could take as long as a decade.[55]

The two primary methods used in plasma separation processes are plasma centrifuge and ion-cyclotron resonance (ICR). Both plasma processes are still in the experimental stages, which mean that it would take substantial amounts of time and money to

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[51] Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation*.

[52] R R Eaton, R L Fox, and K J Touryan, “Isotope Enrichment by Aerodynamic Means: A Review and Some Theoretical Considerations,” *Journal of Energy* 1 (1977), pp. 229–36; Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation*.

[53] Eaton et al., “Isotope Enrichment by Aerodynamic Means,” pp. 229–36.

[54] Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation*; IAEA, “Communication Received from the Permanent Mission of the Czech Republic to the International Atomic Energy Agency.”

[55] Thomas B Cochran, “Highly Enriched Uranium Production for South African Nuclear Weapons.” *Science & Global Security* 4 (1994), pp. 161–76.

develop them into suitable enrichment techniques. While ICR has high separation factors, it requires greater amounts of feed material than plasma separation, which increases costs and detection probability. Both would need to be arranged in cascades, which would require large power draws (mainly for the plasma centrifuges) and a large footprint, as they are not dispersible.[56]

3. Evaluation Metrics

Quantitative metrics were created to evaluate different combinations of options in the single-use fuel cycle. These metrics take what may otherwise be relatively opaque measures of performance, assign objective rankings based on available data and expert evaluation, and compare the relative attractiveness of each of the single-use fuel cycles using individual fuel cycle steps. The evaluation metrics developed by the Proliferation Resistance and Physical Protection Evaluation Methodology Working Group of the Generation IV International Forum to evaluate the response of a generation IV nuclear energy system to security challenges from the state owner or an outside attacker were used as a starting point.[57] This working group developed specific measures of advanced nuclear energy systems' response to proliferation and security threats/attacks in order to better design these systems. These evaluation measures were then inverted to define measures of fuel cycle components' adaptability and desirability for the purpose of proliferation rather than nonproliferation.

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[56] Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation*.

[57] The Proliferation Resistance and Physical Protection Evaluation Methodology Working Group of the Generation IV International Forum, "Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems," Generation IV International Forum, GIF/PRPPWG/2011/003 Revision 6, Sept. 15, 2011.

The three metrics developed from this process for evaluating a potential HEU single-use fuel cycle are detectability, cost, and technical feasibility. For each metric and their associated sub-metrics, a quantitative measure or data-driven qualitative assessment is made to provide a score between zero and ten for each of the pathways along each of these dimensions, with zero indicating low favorability and ten indicating high favorability. Normalizing each metric and sub-metric to a rating between zero and ten converts a variety of measurements into a unit-less scale, thereby allowing the metrics for each pathway to be combined into an overall “attractiveness” score as described in Section 4.

Uncertainty in the measures of each metric and sub-metric are reflected through the width of the bins used for that metric or sub-metric. A more thorough uncertainty analysis is performed in Section 5.5. Table 1 provides the breakdown of metrics and sub-metrics, the quantitative/qualitative measure used, the bins for each metric/sub-metric, and the resulting score for each bin. The metrics and sub-metrics are described in detail below, including potential data sources that will satisfy each metric and sub-metric.

3.1 Detectability

Detectability is a measure of the likelihood or probability that a pathway component will be detected by a watchdog group, such as the IAEA, an intelligence organization such as the US Office of Intelligence and Counterintelligence, or a non-governmental organization—such as the Institute for Science and International Security. The four quantifiable sub-metrics that can be used to evaluate the detectability of a fuel cycle stage are square footage (*SF*), power draw (*PD*), manpower (*M*), and timeline (*T*). Each of these indicators measures different potential exposure mechanisms of the clandestine program and can be used to assess the relative potential for detection.

Square footage (ft^2) is a traditional measurement of the physical footprint indicating the ease at which open-source imagery or geospatial intelligence could detect the facility.

The size of the facility, whether it is a single building or a multi-building compound, is compared to average building sizes in the area to provide a score for this sub-metric. Power draw (megawatt-hours (MWh) collected over a specified length of time, generally in months, to provide an idea of typical power usage) measures the power required for the operation of the facility, which can be detected using measurements and signals or open-source intelligence. The power draw can then be compared to historical power consumption of the region where the facility is located to provide a sub-metric score where each bin represents a standard deviation from the norm. It is important to note that if a fuel cycle activity is dispersible, the required facility square footage and power draw are more difficult to detect, and conservative estimates for these sub-metrics are assumed. The bins for each of these sub-metrics are relatively coarse to indicate relatively high uncertainty in the detection capability for these sub-metrics. Depending on the quality of the reference data sets, these bins could be refined.

Manpower measures the required personnel and is used as an indicator for detection via open-source analysis, signals, and human intelligence. Finally, shorter timelines will limit the program's exposure and the detection probability. Manpower and timeline are difficult sub-metrics to convert to a zero-to-ten score for this analysis. We use the John Jay and ARTIS Transnational Terrorism Database to provide a reasonable justification for the bin sizing of the manpower sub-metric based on the network size of successful large-scale terrorism attacks.[58] In general, data on typical timelines to plan, develop, and execute an attack of relevant nature do not exist. Furthermore, limited information is available on foiled or interdicted plots in general. The bins employed herein represent reasonable first approximations.

3.2 Cost

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[58] John Jay & ARTIS Transnational Terrorism Database (2016), <http://doitapps.jjay.cuny.edu/jjatt/index.php>.

The cost of a fuel cycle step (*C*) is a measure of both the feasibility and relative probability of success. As the cost decreases, more resources can be devoted to other areas of development and a particular pathway becomes more viable. However, cost estimation for a clandestine, small-scale facility is notoriously difficult due to the lack of data and uncertainties in the procurement route.[59] In lieu of exact data, cost estimates are made using parametric models, capacity factors, and expert judgment. This allows for concept screening with typical cost variations falling within a factor of two.[60] The cost-scaling factor is then applied as a multiplier to the capacity-scaled system costs. The fuel cycle element's cost is then compared to the proliferating organization's total budget, and scores are then made based on the percentage of total budget required. This metric's use of the organization's entire budget as a baseline is conservative, commensurate with many of the assumptions in this study. Choosing the entire budget also removes bias/preference decisions that come from using a specific part of an organization's budget, such as military spending, as the metric's baseline.

3.3 Technical Feasibility

The technical feasibility metric assesses the technical challenges of the process as well as the technical abilities of the potential proliferator. By necessity, this metric is more qualitative, although judgments are driven by historical data and expert evaluation of current technologies based on two sub-metrics: technical difficulty *(TD)* and technical expertise (*TE)*.

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[59] US Congress Office of Technology Assessment, "Technologies Underlying Weapons of Mass Destruction December 1993."

[60] Association for the Advancement of Cost Engineering International, "Cost Estimate Classification System As Applied in Engineering, Procurement, and Construction for the Process Industries," 18R-97, 2016.

Technical difficulty measures the maturity and complexity of a step and is informed by patent dates, development data, technical publications, technology readiness level (TRL), and previous development experience. Export controls and natural resources will help inform the technical difficulty sub-metric, but export controls may be circumvented to some degree by non-industrial components that are viable in a single-use fuel cycle. The bins used for this sub-metric are modified TRLs that we refer to as technology levels (TLs).[61] TL1 equates to existing publications detailing a theoretical basis, TL2 to proven experimental results, TL3 to successful lab-scale results, TL4 to a complete prototype, and TL5 to full-scale, industrial demonstration and application.

Previous development of a given technology in locations from which the non-state actor draws its membership provides data to assess the technical expertise sub-metric. The score for this sub-metric increases as basic knowledge and technology-specific experts are available within the organization's recruitment network. This sub-metric also incorporates resource availability such that the bin score is zero if the material or basic knowledge is not available in the non-state actor's region of operation. A bin score of two indicates that basic knowledge required for the technology is generally available through recruitment, universities, etc. in the region of operation; five indicates basic knowledge experts are known to have been recruited into the organization; eight indicates technology experts are known to exist in the region of operation due to previous research, programs, trafficking, etc.; and ten indicates technology experts are known to have been recruited into the organization.

4. Model

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[61] Assistant Secretary of Defense for Research and Engineering (ASD(R&E)), "Technology readiness assessment (TRA) guidance," Department of Defense, May 13, 2011, <http://www.acq.osd.mil/chieftechnologist/publications/docs/TRA2011.pdf>.

A framework was developed to incorporate the metrics discussed in Section 3 into an overall score at both the technology and pathway level. This score captures the attractiveness of a given technology or pathway to a given non-state actor. This valuation allows for group-by-group adjustment at the model level, in addition to the specific bins of the technology evaluation metrics, to ensure the framework is consistent with the diverse organizational resources, goals, and practices of various non-state actors.

4.1 Technology Model

At the technology level, a mathematical model is used to combine the detectability, cost, and technical feasibility metrics to assess the attractiveness of a particular technical solution, and condense the information into a single technical attractiveness score (TAS). The TAS is formulated as:

Equation 1 $$TAS = w_\delta \delta + w_\gamma \gamma + w_\zeta \zeta$$

Here, w_δ is the non-state-actor-specific detection weight, and δ is the detection metric defined as:

Equation 2 $$\delta(SF, PF, M, T) = Min(SF, PD, M, T)$$

The minimum detection sub-metric is used as the detection metric score to signify detection being dominated by the most visible aspect of the program. Additionally, w_γ is the non-state-actor-specific total cost weight, and γ is the total cost metric. Finally, w_ζ is the non-state-actor-specific technical feasibility weight, and ζ is the technical feasibility metric given by:

Equation 3 $$\zeta(TD, TE) = \begin{cases} \frac{TD+TE}{2}, & if\ TE > 0 \\ 0, & otherwise \end{cases}$$

The two technical feasibility sub-metrics are averaged to develop the technical feasibility metric score to signify that a successful program requires both technology availability and expertise. Additionally, this averaging avoids implicit weighting by keeping the technical feasibility metric on the same scale as the other metrics.

Each of the weights enables the TAS model to reflect specific non-state actor organizational priorities similar to what has been observed in nuclear weapon programs at the nation-state level. Of course, these may or may not be known given the dynamic nature and rapid rise of many non-state actors and can be set to one in order to consider each technical component of the pathway attractiveness score (PAS) equally, which is discussed in the next section.

The TAS model also has two points that result in a zero TAS for a particular technology to rapidly eliminate infeasible solutions for a given non-state actor. The first arises when the technology exceeds the budget for that non-state actor, resulting in a score of zero for the cost metric. The second arises when a requisite technology or material cannot be obtained by the non-state actor, yielding a zero score for the technical feasibility metric. For example, a landlocked non-state actor would not have readily-available access to the ocean, making seawater sourcing of uranium infeasible.

4.2 Pathway Model

The pathway model incorporates each stage of the single-use fuel cycle into a relative assessment of the attractiveness of a particular combination of technologies. In general, the PAS for a single-use fuel cycle from sourcing to HEU is defined as:

Equation 4 $$PAS = w_{\sigma}\sigma + w_{\mu}\mu + w_{\tau}\tau + w_{\varepsilon}\varepsilon$$

where w_σ is the weight for the sourcing stage, σ is the sourcing TAS, w_μ is the weight for the milling stage, μ is the milling TAS, w_τ is the weight for the conversion stage, τ is the conversion TAS, w_ε is the weight for the enrichment stage, and ε is the enrichment TAS. The use of weights allows the model to be adapted for the infrastructure, resources, and limitations of a given non-state actor.

Several approaches to the quantification of the weights are available for practical implementation of the model. Options such as the Delphi method[62], intelligence estimates, or analysis of historical factors and case studies provide a semi-quantitative method for assessing the perceived motivations and decision capacity of a given non-state actor.

Another approach would be to use an idealized optimum decision analysis based on an objective function (e.g. one of the metrics) and a set of constraints (e.g. the other remaining metrics) informed by the aforementioned methods. In other words, instead of quantifying weights, the analysts could quantify the limiting metric (i.e. cost) and the minimum workable threshold for the remaining metrics (i.e. technical feasibility and detectability) for a given non-state actor. The best pathway would then be the pathway that minimized the limiting metric (objective) and met minimum thresholds (constraints) on the remaining metrics. More advanced optimization approaches including graduated constraints and multi-objective optimization are also possible within the model framework. In the model demonstration presented in this work, all weights were set equal to one in calculation of the PAS as discussed in Sec. 5.

4.3 Model Uncertainty

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[62] Gregory J. Skulmoski, Francis T. Hartman, and Jennifer Krahn, “The Delphi Method for Graduate Research,” *Journal of Information Technology Education*, Vol. 1 (2007); Chitu Okoli and Suzanne D. Pawlowski, “The Delphi Method as a Research Tool: An Example, Design Considerations and Applications,” *Information and Management*, Vol. 42, No.1, (2004), pp. 15-29.

The publicly available information on non-state actors is often limited, and what is available is often rapidly dated due to dynamic shifts within the organization or international pressures or actions. Literature on proliferation evaluations of nuclear technologies for non-state actors and single- or limited-use fuel cycles is even sparser and largely nonexistent. As such, any assessment of the proliferation of a given technology by a non-state actor has uncertainty that must be addressed.

In this model, the uncertainty is captured in the technology assessments for each of the evaluation metrics described in Section 3. For each metric, a specific, assessed value is determined from the available literature as described in Section 3, 5.2, and 5.3. Additionally, a range of plausible values, if applicable, is determined based on the range in the literature or uncertainties in extrapolation of existing literature. Equations 1–4 are then evaluated for all possible permutations of the range of uncertainties for each assessment metric. From this, a distribution of possible TASs are developed to better quantify the range of attractiveness scores for a given technology. An example of this is shown in Section 5.5.

5. ISIL Model Demonstration Study

ISIL is treated as a case study to evaluate the model developed using a well-resourced non-state actor. ISIL makes a credible case because it has expressed interest in utilizing nuclear weapons and has pursued weapons of mass destruction.[63] While ISIL holds territory like a state, for purposes of this analysis, it is still classified under proliferation path 4 (indigenous development) versus path 1 (state sponsorship) as no state is harboring ISIL. Syria, Iraq, and their partner states are actively working to remove ISIL from its claimed territory while state-sponsored groups, like the Taliban, enjoy freedom of movement and territory within host state borders. While it may be easier for ISIL to pursue path 4 than other organizations that do not hold as much

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[63] Cantlie, “The Perfect Storm,” pp. 74–77.

contiguous territory, the analysis framework developed herein can apply to other non-state actors as long as appropriate re-definition of the bins and metrics are applied.

This analysis is intended to be a snapshot that captures their resources and capabilities (as of January 2015) as a baseline to assess the viability of particular technologies and pathways. However, it is neither intended to be predictive, an extrapolation into a potential future program, nor does it attempt to capture the degrading capabilities of ISIL due to international pressure since 2015. Instead, it explores the realm of the possible with regards to nuclear terrorism in the twenty-first century to allow for coherent discussion regarding nuclear terrorism and the role that current and future non-state actors may play.

5.1 ISIL-Specific Metrics

Adapting the metric structure developed in Section 3 to the ISIL case study is relatively straightforward, and is outlined in Table 2. For this analysis, the milling stage of the fuel cycle was collapsed into the sourcing stage. Generally, the way uranium is milled directly depends on the uranium's source, making the milling stage a false option in this analysis. This is also generally true for enrichment and conversion, where the conversion process is a false option given a fixed enrichment technology. To emphasize, while generally this simplification is true, a deeper analysis of the milling and conversion technologies that a potential proliferant may choose from may influence the proliferant's choice of overall fuel cycle options.

Three bin definitions require additional ISIL-specific information: power draw, cost, and technical expertise. Power draw is scaled to fit the power draw of ISIL’s region of operation. The data used here reflects a Gaussian distribution of power draw over October 2014 to January 2015 for the Salah al'Din province. The power draw information uses aggregate data on the last quarter of 2014, and the sigma for this period is 300 MWh.[64] The bins for the cost metric scale from ISIL's total budget published in January of 2015, which was $2 billion per year.[65] Finally, the technical expertise bin relies on knowledge and expert assessment of the resources available to ISIL, both material and human resources in the form of technical knowledge and/or capability.

The bin for square footage could be improved with ISIL-specific information; however, a first approximation using generic building sizes was utilized in this project. Specifications for average large industrial buildings, average medium industrial buildings, and average house sizes in the regions where ISIL operates could improve the effectiveness of this bin in comparing and contrasting single-use fuel cycle options. As discussed briefly in Section 3, the binning of each metric and sub-metric could also be refined through better quality data for which the user has high confidence.

To demonstrate the framework for the assessment process, example cases of sourcing and enrichment using PR and EMIS, respectively, are briefly described in the following sections in further detail (a full description of the literature and data supporting these two assessments is beyond the scope of this paper).

5.2 Sourcing Example: Phosphate Rock

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[64] Andrew Shaver and David Ensign, "Lights off in the Islamic State," Foreign Affairs, October 23, 2015, <https://www.foreignaffairs.com/articles/syria/2015-10-23/lights-islamic-state>.

[65] Damien Sharkov, "Isis 'Releases 2015 Budget Projections' of $2bn with $250m Surplus," Newsweek, January 1, 2015, <http://www.newsweek.com/isis-release-2015-budget-projections-2bn-250m-surplus-296577>; Stacey Vanek Smith, "Leaked Budget Document Provides Glimpse Into How ISIS Makes Money," NPR, December 10, 2015, <http://www.npr.org/2015/12/10/459249994/leaked-budget-document-provides-glimpse-into-how-isis-makes-money>.

There is no current commercial extraction of uranium from PR, but there is significant historical experience worldwide and ongoing interest for both commercial and health reasons.[66] Additionally, uranium extraction from PR was used in the Iraqi nuclear weapons program, and Syria has operated a plant with small production quantities for nearly two decades in Homs.[67] Given that Iraq and Syria have significant PR reserves and ongoing commercial production, some of which has been captured by ISIL, uranium extraction from PR is an attractive potential pathway for ISIL sourcing of natural uranium.[68] An overall score of twenty-four was calculated for PR in the model, with sensitivity analysis showing a potential range of twenty to twenty-five. Table 3 contains the assessed value and ranges for each assessment metric pertaining to potential ISIL pursuit of uranium sourcing through extraction from PR.

The PR process scored a five in the detectability metric, which is primarily driven by the timeline. Concerning square footage, current PR extraction technology has been demonstrated in mobile pilot plants the size of shipping containers.[69] However, past commercial ventures have resulted in much larger plants ranging up to 9,000 ft^2,

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[66] Nuclear Threat Initiative, “Nuclear 101”; Guida et al., “Uranium Extraction from Wet Process Phosphoric Acid”; Walters et al., “Technologies for Uranium Recovery from Phosphoric Acid.”

[67] The International Institute for Strategic Studies, “Nuclear Programs in the Middle East: In the Shadow of Iran,” *Chapter 4: Syria, Jordan, Lebanon, Iraq*, 2007; David Albright and Robert Avagyan, “Syria’s Past, Secret Nuclear Program Poses Proliferation Risks,” Institute for Science and International Security, September 2013.

[68] US Geological Survey, “Mineral Commodity Summaries,” 2015; Christine Duhaime, “Terrorist Financing and the Islamic State,” White Paper on Islamic State Funding, 2015.

[69] PhosEnergy, “The Phosenergy Process.”

resulting in a range of possible solutions available to ISIL.[70] Previous commercial ventures have used approximately 55 kilowatt-hours (kWh) per lb of U_3O_8 per day. Studies by the IAEA have pegged the required manpower in the range of a dozen personnel to build and three to four operators, but there is some variability in this number.[71] Finally, the same IAEA studies pegged the construction timeframe in the range of 2.5–5 years.[72] For the assessed value, a timeline of 3.5 years with a schedule-scaling factor of 0.5 was used, resulting in a 1.75 year construction time. Adding in the fixed one-year production timeline, it will take 2.75 years to produce enough U_3O_8 for one IND using this process.

Costs are projected as low as $20 per lb of U_3O_8, and development expense costs, assuming an existing WPA plant, are $10 million–$15 million to produce a plant capable of production of 88,000 lb of U_3O_8 per year.[73] Given that full-scale plants cost in the range of $125 million–$156 million, there is no associated uncertainty with the assessed bin value given the enormity of ISIL's financial resources as even the high estimate falls well within the lowest bin.

The PR extraction process has been well studied, documented, and applied commercially and within weapons programs. The prior history of PR extraction in general falls into the TL5 classification, but some of the newer processes have only been demonstrated at the pilot plant level resulting in a range of TL4 to TL5. While PR extraction has been used in both Iraq and Syria, it is difficult to find literature to support

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[70] International Atomic Energy Agency, "The Recovery of Uranium from Phosphoric Acid." IAEA-TECDOC-533, Vienna, 1989.

[71] ibid.

[72] ibid.

[73] Astley and Stana, "There and Back Again," pp. 270–278; Guida et al., "Uranium Extraction from Wet Process Phosphoric Acid."

recruitment of PR experts by ISIL.[74] As such, it was assessed that the technology experts are available, and it is possible that they are within the ISIL network already.

5.3 EMIS Example

The most relevant example for this case was Iraq's use of EMIS for the early-stage development of its nuclear weapons program. An overall score of nineteen was calculated for EMIS in the model, with sensitivity analysis showing a potential range of nineteen to twenty-three. Most of the assessment is composed of conservative estimates as the Iraqi program was never fully successful. Table 4 contains the assessed value and ranges for each assessment metric pertaining to potential ISIL pursuit of uranium enrichment through EMIS.

For detectability, EMIS scored a zero due to the long lead time and extensive manpower required. The site where Iraq housed its EMIS program was 800,000 m^2; however, its program was larger as it was not pursuing a single-use fuel cycle.[75] Therefore, it was assessed that enough machines for 50 kg of 90 percent enrichment could likely be housed in a large industrial building (a score of three) with potential for an even larger building (a sensitivity analysis score of zero). Based on the Al Tarmiya facility, the Iraqis planned for approximately 13 kg of HEU to be produced per year, which would mean, at best, four years of operation.[76] The facility took six years to construct; however, with the time scale factor, this would be reduced to three years.[77]

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[74] Albright and Avagyan, “Syria's Past, Secret Nuclear Program”; The International Institute for Strategic Studies, “Nuclear Programs in the Middle East.”

[75] David Albright, “Iraq's Programs to Make Highly Enriched Uranium and Plutonium for Nuclear Weapons Prior to the Gulf War,” October 2002, <http://www.isis-online.org/publications/iraq/iraqs_fm_history.html>.

[76] ibid.

[77] ibid.

Power draw is minimal as it is estimated that EMIS requires 3,000–4,000 kWh/SWU, which means 21–28 MWh/day would be needed.[78] There is no known estimate for how many people worked solely on EMIS for Iraq, but it is assumed that each machine would require a dedicated team (especially if it is to operate every day); therefore, tt is estimated that the number of employees required is well over 100.[79]

Al Tarmiya cost $110 million in construction, and when the cost-scaling factor is accounted for, the potential ISIL construction costs would be $55 million.[80] Operational costs for Iraq's programs were difficult to find, so potential ISIL operational costs were calculated using a US Department of Energy report on domestic capabilities, which estimated a yearly cost of $5.2 million.[81] All of this is well below the upper bound of $200 million for a score of ten.

EMIS is considered one of the least technically difficult of the enrichment technologies, and many countries have pursued EMIS in at least a minimal capacity for their weapons programs. Additionally, as Iraq had an extensive EMIS program and one of ISIL's main territories is in Iraq, technology experts are assumed to be available; however, there is no known evidence that ISIL has indoctrinated EMIS experts into the ISIL network.

5.4 Results

Technology assessments similar to those illustrated for PR and EMIS were carried out for the remaining fuel cycle technologies. This section presents the ISIL case study

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[78] Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation*.

[79] Robert E. Kelley, "The Iraqi and South African Nuclear Weapon Programs," *Security Dialogue* 27, No. 1 (1996), pp. 27–38.

[80] Albright, "Iraq's Programs to Make Highly Enriched Uranium and Plutonium."

[81] US Department of Energy Office of Inspector General, "Audit Report: Calutron Isotope Production Capabilities," DOE/IG-0574, November 2002.

results for each technology based on the TAS calculation from Equation 1 and each pathway based on the PAS calculation according to Equation 4. The weights in these equations were set to one for this case study so each technology and pathway could be compared directly to each other without assessing ISIL's decision process and priorities.

As formulated for the ISIL case study, these are *relative* TAS and PAS scores. This method does not purport to represent the likelihood of success for ISIL given a particular pathway, but instead indicates the relative attractiveness of each pathway given the combination a given technologies detectability, cost, and technical feasibility and ISIL's resources and capabilities. In other words, ISIL could fail with the most attractive path or succeed with the least, but it would be to their advantage to choose according to the TAS/PAS scores with all things being equal. Conversely, with limited nonproliferation resources, the results presented here represent an itemized prioritization of where to look for key indicators of proliferation activity. Finally, it is important to note that the results are ISIL-specific. The framework outlined in this paper is applicable to other non-state actors, but they would have a different ranking thus enabling an adaptive approach to nonproliferation.

Figure 2 shows the TAS and PAS scores for each possible pathway given the technologies considered for the ISIL case study. Due to the location of the territory they held in early 2015, uranium mining and seawater extraction were immediately eliminated due to non-availability of resources, thereby resulting in a TAS of zero. However, every other option was within the scope of ISIL's resources to varying degrees.

On the uranium sourcing side, there is little differentiation among the remaining options of PR, open market purchase, or theft/diversion. In large part, this is due to the inadequacy of the metrics to capture the impact of export controls and safeguards on the detection of outside materials acquisition. The absence of this aspect of detectability raises the relative scores of open market purchase and theft/diversion, but no suitable method to quantify this increased likelihood of detection was found based on openly available data or literature. Given the history of some success with open market purchases and the tendency for theft/diversion to be identified as the most likely route in studies of non-state actors obtaining a nuclear weapon, these sourcing methods were left in this study despite the limitations of the framework in these cases.[82] The other attractive option to ISIL, uranium extraction from PR, is somewhat unique to this particular non-state actor due to the large amount of PR resources, some of which were captured by ISIL, and the comparative lack of uranium ores.

On the enrichment side, some trends emerge. First, ISIL's tremendous financial resources at the start of 2015 resulted in every option being considered feasible from a financial and availability of technology perspective. Export controls and their standing on the international stage would make acquisition of key technology difficult, but not impossible as evidenced by the A.Q. Khan network, Iraq, and North Korea. Second, the immature technologies such as laser, chemical, and ICR enrichment were deemed quite unattractive, both in terms of detectability (due to the long development time required) and technical feasibility. However, as the technology is matured by nation-states, laser and chemical could become significantly more attractive in the future as they otherwise score very well in detectability. Conversely, mature technologies such as aerodynamic and gaseous diffusion were deemed unattractive due to their detectability limitations in size and construction time, and this is unlikely to change over time or with the non-state actor under consideration. EMIS, another mature option performs much better as it presents a low technological barrier and an ability to disperse. However, it is a

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[82] The National Counterterrorism Center, "2011 Report on Terrorism", <https://fas.org/irp/threat/nctc2011.pdf>; Los Alamos National Laboratory, "Nuclear Weapons Development: From Decision to Delivery," Report LA-UR-07-3211, <http://www.lanl.gov/orgs/nso/docs/fy07/LA-UR-07-3211_Nuclear_Weapons_Development_From Decision_to_ Delivery.pdf>; E. B. Montgomery, "Nuclear Terrorism: Assessing the Threat, Developing a Response," *Center for Strategic Budget. Assessments*, 2009.

manpower- and footprint-intensive option that has also struggled with long development times, even by nation-states.[83] Finally, centrifuge, which has been acknowledged as a highly likely proliferation route for nation-states, scores high here as well.[84] This is in part aided by the regional development of the Iranian and Iraqi programs and the spread of centrifuge technology through the Middle East and North Africa by the A.Q. Khan network.[85]

5.5 Uncertainty Quantification Results

Uncertainty quantification of the results presented in Figure 2 was carried out at the individual metric assessment level based on the spread or uncertainty in the available open-source literature. The ranges of scores were propagated through to the calculation of the TAS for sourcing (Figure 3), the TAS for enrichment (Figure 4), and the PAS (Figure 5). A couple of features of these plots are worth highlighting. First, the blue-shaded boxes represent the 25-75 percentile of the results with the solid vertical line in the box representing the median. The black whiskers on either end extend from +/- 1.5 times the interquartile range. In a normally distributed data set, the whiskers would cover the 0.35 to 99.65 percentiles. Any outliers are shown as red stars, and the assessed value from Figure 2 is shown as open circles.

Figure 3 shows the spread of possible TASs for uranium sourcing. Since there are no known significant deposits of uranium ore, uranium mining always scores a zero, and there is no spread in the possible TAS. Seawater also scores a zero in our assessed

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[83] Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation*; Kelley, “The Iraqi and South African Nuclear Weapon Programs.”

[84] Kemp and Glaser, “The Gas Centrifuge and the Nonproliferation of Nuclear Weapons.”

[85] C. Collins and D. Frantz, “Fallout from the AQ Khan Network and the Clash of National Interests,” in *Symposium on International Safeguards*, 2010.

value, but ISIL, as of early 2015, was not far away from access to the sea. There is a large spread in the possible TAS for seawater due to variation in the literature and the immaturity of the technology. However, even under the most optimistic scenarios, seawater still scores below PR extraction, open market purchase, and theft/diversion.

Figure 4 shows the spread of the possible TASs for the enrichment phase. The assessed TAS for EMIS is rather bearish based on the experience of the Iraqi program, from which it is likely ISIL would draw expertise, but there is upside based on other nation's experience and the open literature. Aerodynamic, laser, and chemical have large spreads due to the immaturity or localized nature of the technology, whereas gaseous diffusion and centrifuge are both well studied in the literature and have been implemented all over the world.

Figure 5 shows the uncertainty quantification for the overall PASs. The largest driver for a pathway decision is the uranium sourcing stage of the single-use fuel cycle. This is due to the limited options available to ISIL in the region. Consequently, the pairing of enrichment technologies with open market purchase, theft/diversion, or PR scores well. If the open market purchase and theft/diversion results are set aside (the red boxes in Figure 5), then the top pairings are PR with either centrifuge or EMIS. The enrichment options are both consistent with the literature of likely proliferation paths for nation-states and the experience of the nuclear programs in the Middle East. PR was also explored and pursued by several nations in the Middle East. While non-state actors' approaches to developing nuclear weapons may differ significantly from nation-states in goals and scope of any potential program, they are constrained by many of the same factors as nation-states in similar geographical regions in that they draw on the same human and natural resources.

Although the immature enrichment technologies currently score poorly, Figures 4 and 5 show there is tremendous upside to each. Over time, as research is carried out on these technologies by nation states, the attractiveness to potential non-state proliferation will increase. In other words, the results presented here are specific to both the time period and non-state actor; however, the overall framework presented can be adapted and used to assess any timeframe or non-state actor.

6. Conclusion and Future Work

This model was developed to evaluate the feasibility of indigenous SNM development per a variety of pathways given the means and resources of non-state actors. Defining the technological threshold as the development of one HEU IND, the model identifies which pathways should be investigated further in order to design and implement countermeasures for states and non-state actors alike. While the case study demonstration of this framework is limited by the scarcity of open-source data related to scenarios involving nuclear terror efforts by non-state actors, this model greatly adds to the literature by bringing this open-source data together into one research project and allowing for further improvements and applications. The model's three main metrics of detectability, cost, and technical feasibility have made it possible to provide an attractiveness score for each technology and pathway. The case study of ISIL demonstrates how the model may be used to pinpoint heightened security threats in cases of nuclear terror attempts, PR extraction in this example.

Including metric weights to scale detectability, cost, and technical feasibility to be commensurate with a non-state actor’s priorities will increase the model’s accuracy and applicability. Currently, all metric weights are equivalent to one, indicating that ISIL views the impact of potential failure in the areas of detectability, cost, and technical feasibility equally. In the future, this model can be improved by incorporating metric weights that account for a non-state actor’s mission priorities, adapting the model to be more accurate to the ideology of distinct non-state actors who may have widely differing goals.

Alternatively, the framework can be adapted to an optimization approach where one of the metrics serves as the objective function with the others serving as constraints. Under this approach, the best possible pathway is sought that maximizes one metric and meets a specified threshold for the other metrics. Variations of this scheme using graduated constraints and multi-objective optimization are possible within the model framework, and this would be an interesting avenue for future research.

The ability to tune the model to match a non-state actor’s ideology and mission may also make the model applicable to state actors wishing to develop an IND without the cost and commitment required to establish a robust nuclear weapons stockpile. Achieving a high degree of adaptability to non-state and state actors alike who are seeking to develop a singular IND without creating a full arsenal makes this model well-suited for use by the IAEA and other safeguards organizations for analyzing import/export vulnerabilities.

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Disclaimer

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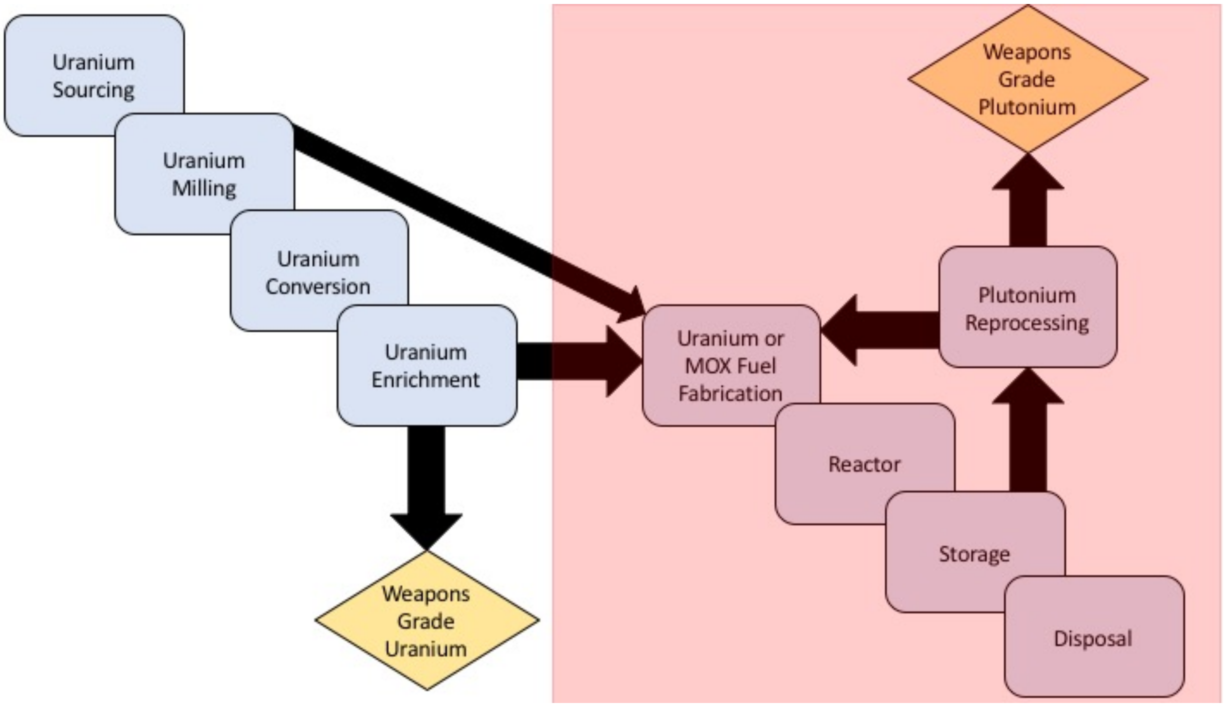
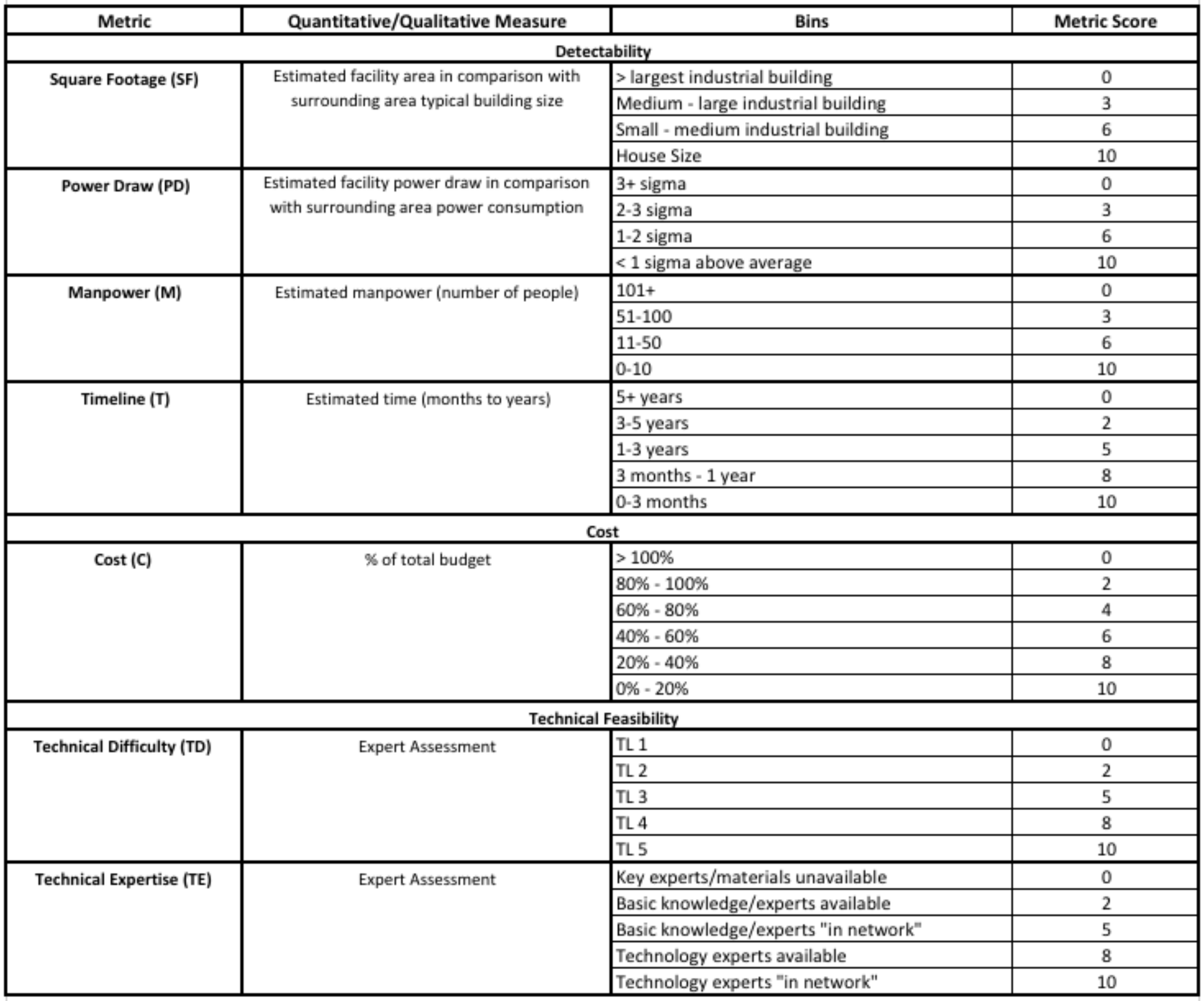
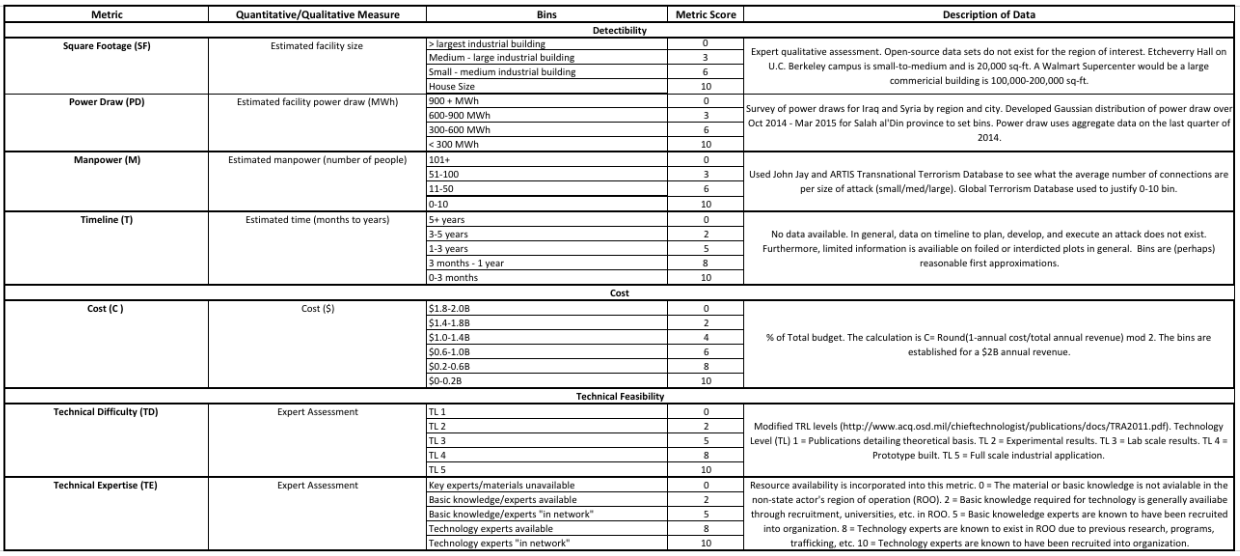


Figure 1: Representation of nuclear fuel cycle for an HEU weapon pathway. The red box indicates eliminated portions of the fuel cycle for this non-state actor scenario.



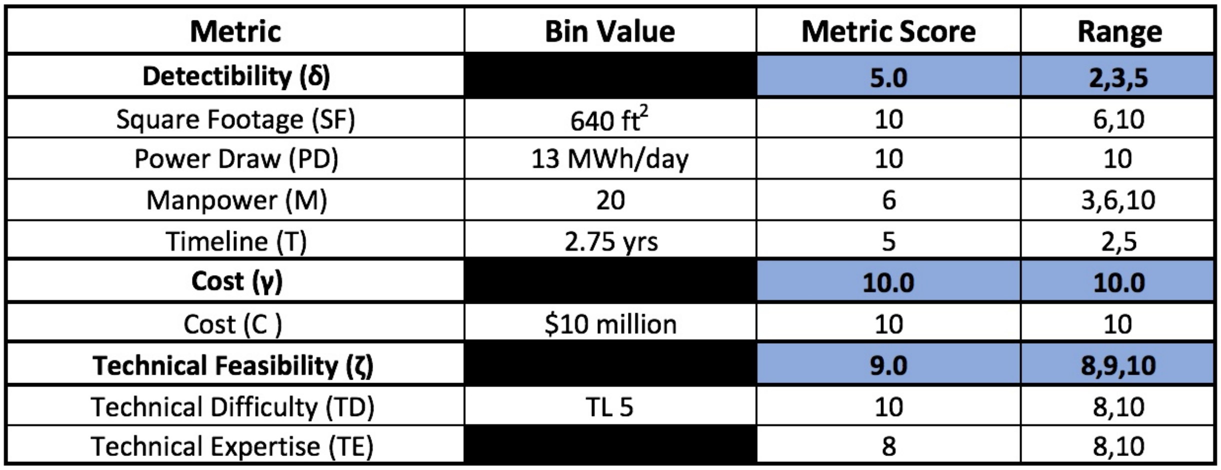
Metric	Quantitative/Qualitative Measure	Bins	Metric Score
Detectability			
Square Footage (SF)	Estimated facility area in comparison with surrounding area typical building size	> largest industrial building	0
		Medium - large industrial building	3
		Small - medium industrial building	6
		House Size	10
Power Draw (PD)	Estimated facility power draw in comparison with surrounding area power consumption	3+ sigma	0
		2-3 sigma	3
		1-2 sigma	6
		< 1 sigma above average	10
Manpower (M)	Estimated manpower (number of people)	101+	0
		51-100	3
		11-50	6
		0-10	10
Timeline (T)	Estimated time (months to years)	5+ years	0
		3-5 years	2
		1-3 years	5
		3 months - 1 year	8
		0-3 months	10
Cost			
Cost (C)	% of total budget	> 100%	0
		80% - 100%	2
		60% - 80%	4
		40% - 60%	6
		20% - 40%	8
		0% - 20%	10
Technical Feasibility			
Technical Difficulty (TD)	Expert Assessment	TL 1	0
		TL 2	2
		TL 3	5
		TL 4	8
		TL 5	10
Technical Expertise (TE)	Expert Assessment	Key experts/materials unavailable	0
		Basic knowledge/experts available	2
		Basic knowledge/experts "in network"	5
		Technology experts available	8
		Technology experts "in network"	10

Table 1: Detailed evaluation metrics breakdown.



Metric	Quantitative/Qualitative Measure	Bins	Metric Score	Description of Data
Detectibility				
Square Footage (SF)	Estimated facility size	> largest industrial building	0	Expert qualitative assessment. Open-source data sets do not exist for the region of interest. Etcheverry Hall on U.C. Berkeley campus is small-to-medium and is 20,000 sq-ft. A Walmart Supercenter would be a large commericial building is 100,000-200,000 sq-ft.
		Medium - large industrial building	3	
		Small - medium industrial building	6	
		House Size	10	
Power Draw (PD)	Estimated facility power draw (MWh)	900 + MWh	0	Survey of power draws for Iraq and Syria by region and city. Developed Gaussian distribution of power draw over Oct 2014 - Mar 2015 for Salah al'Din province to set bins. Power draw uses aggregate data on the last quarter of 2014.
		600-900 MWh	3	
		300-600 MWh	6	
		< 300 MWh	10	
Manpower (M)	Estimated manpower (number of people)	101+	0	Used John Jay and ARTIS Transnational Terrorism Database to see what the average number of connections are per size of attack (small/med/large). Global Terrorism Database used to justify 0-10 bin.
		51-100	3	
		11-50	6	
		0-10	10	
Timeline (T)	Estimated time (months to years)	5+ years	0	No data available. In general, data on timeline to plan, develop, and execute an attack does not exist. Furthermore, limited information is availiable on foiled or interdicted plots in general. Bins are (perhaps) reasonable first approximations.
		3-5 years	2	
		1-3 years	5	
		3 months - 1 year	8	
		0-3 months	10	
Cost				
Cost (C)	Cost ($)	$1.8-2.0B	0	% of Total budget. The calculation is C= Round(1-annual cost/total annual revenue) mod 2. The bins are established for a $2B annual revenue.
		$1.4-1.8B	2	
		$1.0-1.4B	4	
		$0.6-1.0B	6	
		$0.2-0.6B	8	
		$0-0.2B	10	
Technical Feasibility				
Technical Difficulty (TD)	Expert Assessment	TL 1	0	Modified TRL levels (http://www.acq.osd.mil/chieftechnologist/publications/docs/TRA2011.pdf). Technology Level (TL) 1 = Publications detailing theoretical basis. TL 2 = Experimental results. TL 3 = Lab scale results. TL 4 = Prototype built. TL 5 = Full scale industrial application.
		TL 2	2	
		TL 3	5	
		TL 4	8	
		TL 5	10	
Technical Expertise (TE)	Expert Assessment	Key experts/materials unavailable	0	Resource availability is incorporated into this metric. 0 = The material or basic knowledge is not avialable in the non-state actor's region of operation (ROO). 2 = Basic knowledge required for technology is generally availiabe through recruitment, universities, etc. in ROO. 5 = Basic knoweledge experts are known to have been recruited into organization. 8 = Technology experts are known to exist in ROO due to previous research, programs, trafficking, etc. 10 = Technology experts are known to have been recruited into organization.
		Basic knowledge/experts available	2	
		Basic knowledge/experts "in network"	5	
		Technology experts available	8	
		Technology experts "in network"	10	

Table 2: Detailed ISIL evaluation metrics breakdown.



Metric	Bin Value	Metric Score	Range
Detectibility (δ)		**5.0**	**2,3,5**
Square Footage (SF)	640 ft^2	10	6,10
Power Draw (PD)	13 MWh/day	10	10
Manpower (M)	20	6	3,6,10
Timeline (T)	2.75 yrs	5	2,5
Cost (γ)		**10.0**	**10.0**
Cost (C)	$10 million	10	10
Technical Feasibility (ζ)		**9.0**	**8,9,10**
Technical Difficulty (TD)	TL 5	10	8,10
Technical Expertise (TE)		8	8,10

Table 3: Technology assessment for ISIL sourcing of uranium through extraction from PR.

Metric	Bin Value	Metric Score	Range
Detectibility (δ)		**0.0**	**0,2,3**
Square Footage (SF)	Large Industrial	3	0,3
Power Draw (PD)	28 MWh/day	10	10
Manpower (M)	100+	0	0,3
Timeline (T)	7 yrs	0	0,2,5
Cost (γ)		**10.0**	**10.0**
Cost (C)	$76 million	10	10
Technical Feasibility (ζ)		**9.0**	**9,10**
Technical Difficulty (TD)	TL 5	10	10
Technical Expertise (TE)		8	8,10

Table 4: Technology assessment for ISIL enrichment of uranium through EMIS.

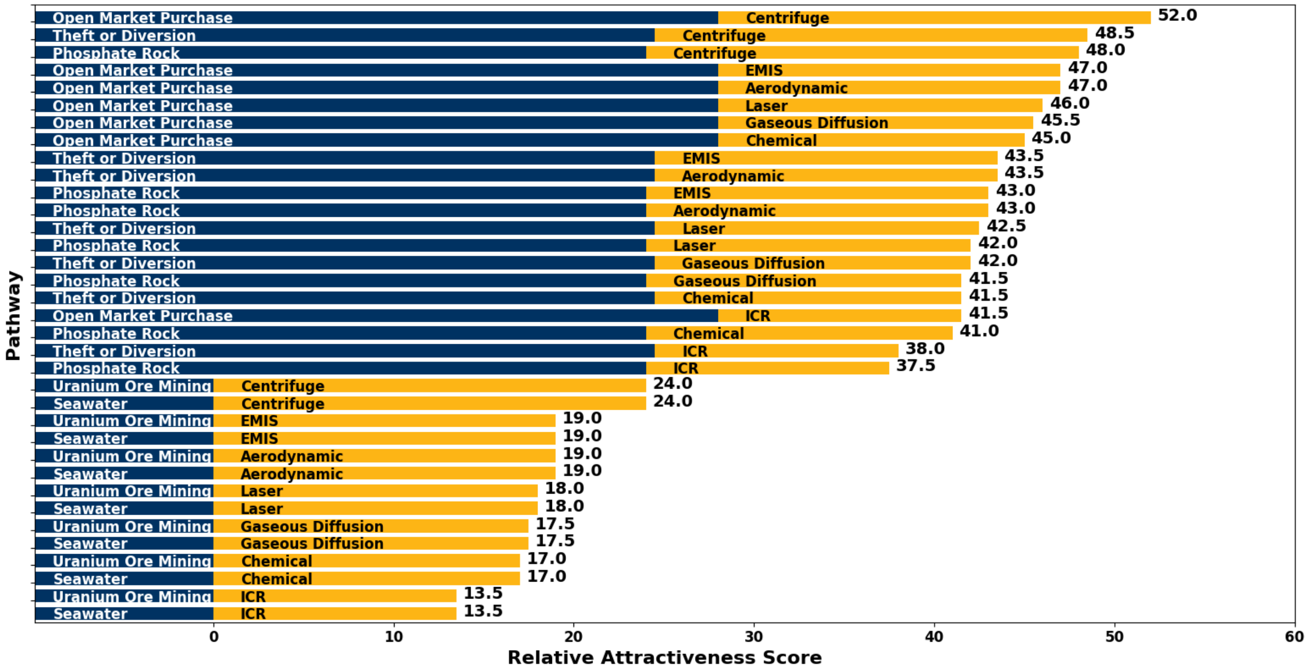


Figure 2: TAS and PAS scores for the technologies and components of the single-use fuel cycle assessed in this work. The numbers at the right of each bar represent the PAS for each pathway, and the TAS scores for each component are indicated by the labeled, shaded bars.

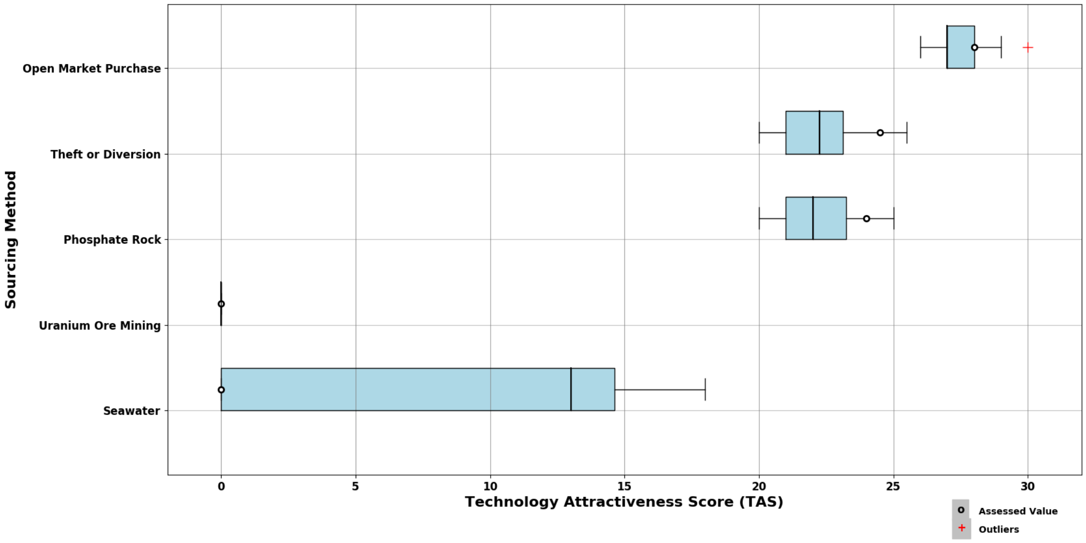


Figure 3: TASs for uranium sourcing. The shaded box represents the middle 50% of the distribution of scores for that particular technology pathway, and the whiskers represent the range from +/- 1.5 times the interquartile range. Outliers are indicated by red crosses, and the assessed values presented in Figure 2 are show as open circles.

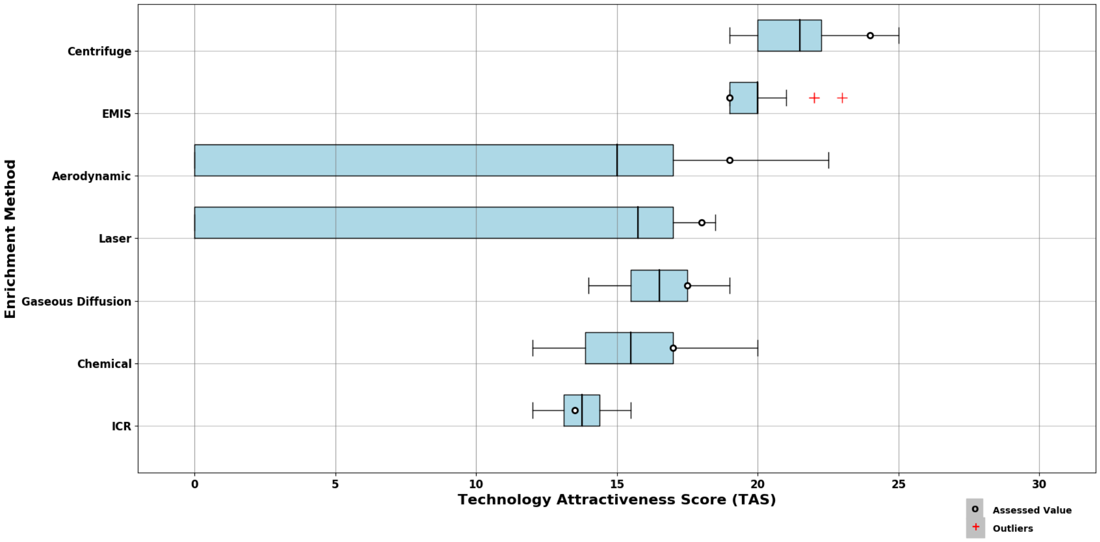


Figure 4: TASs for enrichment. The shaded box represents the middle 50% of the distribution of scores for that particular technology pathway, and the whiskers represent the range from +/- 1.5 times the interquartile range. Outliers are indicated by red crosses, and the assessed values presented in Figure 2 are show as open circles.

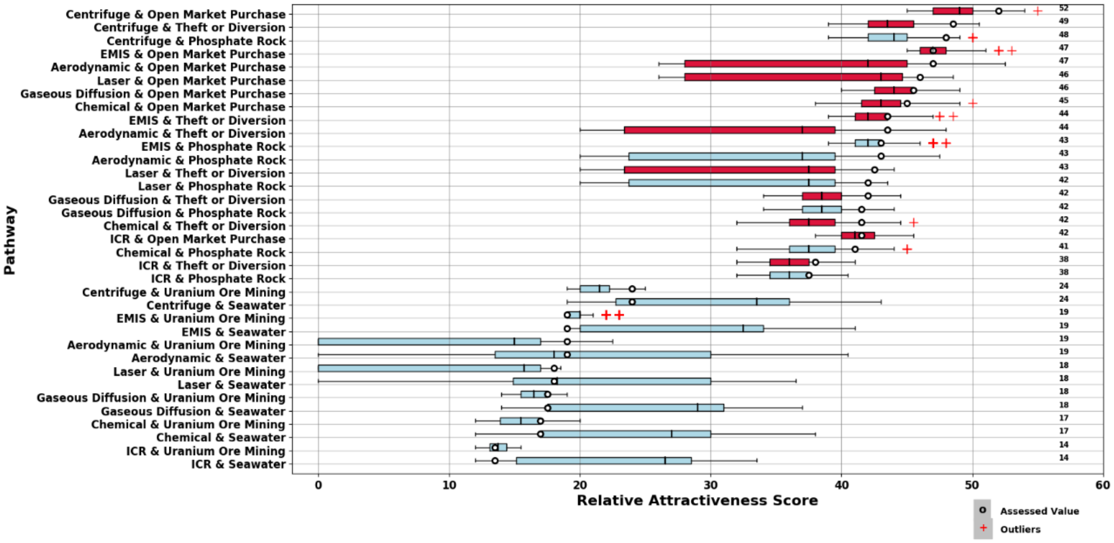


Figure 5: PASs. The shaded box represents the middle 50% of the distribution of scores for that particular technology pathway, and the whiskers represent the range from +/- 1.5 times the interquartile range. Outliers are indicated by red crosses, and the assessed values presented in Figure 2 are show as open circles. Red boxes indicate a pathway includes open market purchase or theft/diversion.