Alternate Nuclear Proliferation Pathways in the Age of Non-State Actors

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INTRODUCTION

President Obama has stated that "the greatest threat to U.S. and global security is no longer a nuclear exchange between nations, but nuclear terrorism by violent extremists [1]." In the 2010, the Nuclear Posture Review named the prevention of nuclear terrorism as the number one U.S. nuclear policy objective [2]. More recently, preventing nuclear terrorism was a central theme of the 2016 Nuclear Security Summit [3]. While there is broad agreement on the threat, the non-state actor has no clear route to an improvised nuclear device (IND). The four paths generally put forth are: 1) state sponsorship, 2) theft of a weapon or fissile material, 3) black market purchase of fissile material, or 4) indigenous development [4, 5].

There is historical evidence for attempts at paths one and two, but the trends of zero past successes, decreasing nuclear weapon and fissile material vulnerabilities, and increasing international transparency and cooperation make these options increasingly difficult and less achievable [5]. 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 1993-2014. However, only 19 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 [6]." 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 [7].

Path four is typically subdivided into indigenous development of the IND given another SNM source or 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 [5, 8]. Conversely, indigenous development is often summarily dismissed as a viable option [4]. The research on proliferation that supports this premise of a non-state actor being unable to develop SNM almost exclusively employs several implicit assumptions derived from the historical record on attempted and successful proliferation. Many of those assumptions do not hold for proliferation by a non-state actor. By addressing these assumptions, a fresh look can be taken towards the viability of the 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 [9, 10]. These theories and the record do not account for the limited goals espoused by any of the six non-state actors that have sought nuclear weapons [7, 11, 12]. Additionally, recent trends of technology democratization through additive manufacturing, high powered computing, the open exchange of information, globalization, and diversification of technologies enabling traditional proliferation choke points have eroded some of the barriers to proliferation by non-state actors [13, 14, 15]. At the same time, the net worth and cash assets of the richest non-state actors has exploded reducing the financial prohibitions [16]. These trends, coupled with the removal of the requirement for a robust, reliable nuclear weapons "production line," significantly lowers 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 of non-state actors. Second, it aims to develop methods to screen which approaches should be further investigated 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 kg of 90% HEU for a gun-type IND. Only the stages required to produce the HEU are considered in this paper as many other studies have considered the viability of non-state actors turning a sufficient mass of HEU into an IND [5, 8]. Evaluation metrics and models are developed to assess the efficacy of each technology and path. Finally, the metrics and models developed are applied using the Islamic State of Iraq and the Levant (ISIL) as a case study. A thorough implementation of the methods outlined herein is forthcoming in a full report.

ISIL Background

ISIL is considered as a case study to evaluate the approach developed against the resources and capabilities of a well resourced non-state actor that has expressed interest in employing nuclear weapons and has pursued weapons of mass destruction [12]. This analysis is intended to be a snapshot in time that captures their capabilities and resources as a baseline to assess the viability of particular technologies and pathways. It is not intended to be an ISIL-specific extrapolation into a potential future program given any current trends or capabilities. In general, the approach is kept as independent of ISIL as possible, but for readability and conciseness, organization specific details are added throughout to provide context from which to evaluate each metric and pathway. While ISIL has many unique advantages and the specific details used to evaluate the pathways will vary from other non-state actors, the methods developed and factors considered are applicable to any non-state actor and could be adapted accordingly.

EVALUATION METRICS

The three metrics developed for evaluating a potential HEU single-use fuel cycle, shown in Fig. 1, are detection probability, cost, and technical feasibility. For each metric and sub-metric, a quantitative measure or data-driven qualitative assessment is made to provide a score for each of the pathways along each of these dimensions. 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 normalizing constant is used to scale these metrics between 0 and 1, where 0 indicates poor performance and 1 indicates strong performance. This normalization converts a variety of measurements into a unit-less scale allowing the metrics for each pathway to be combined into an overall "fitness" score, where fitness is defined as the relative probability of success for a non-state actor attempting to develop SNM. For example, the fitness, F, for pathway i can be given by the product of its scores along the three metrics of detection probability (D), cost (C), and technical feasibility (T):

$$F_i = D_i * C_i * T_i \tag{1}$$

A product is used because it allows for a pathway to be considered unfeasible if it is deemed prohibitive in terms of one of the factors. Weights are not used in the specification of the fitness model because the three metrics D, C, and T are internally weighted through the normalizing constant. While this model specification makes some simple assumptions, such as independence of the three factors, it can provide a reasonable overall metric for a pathway's fitness, which can then be subjected to a sensitivity analysis.

Detection Probability

The three quantifiable sub-metrics that can be used to evaluate the detection probability of a fuel cycle stage are footprint, manpower, and timeline. Each of these indicators measures different potential exposure mechanisms of the clandestine program and can be used to assess the relative potential for detection. The footprint category is further subdivided by measurements of square footage, power draw, and dispersibility. Square footage is a traditional measurement of the physical footprint indicating the ease at which open source imagery or geospatial intelligence could detect the facility. Power draw measures the power required for the operation of the facility, which can be detected using measurement and signals or open source intelligence. If a fuel cycle activity is dispersible, the required facility square footage and power draw are more difficult to detect. Manpower measures of the required persons 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.

Cost

The cost of a fuel cycle step is a measure of the relative probability of success for a step. 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 [17]. 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 [18].

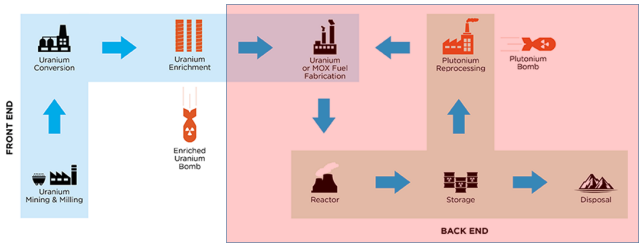

Fig. 1: Representation of nuclear fuel cycle for an HEU weapon pathway [19]. The red box indicates eliminated portions of the fuel cycle for this non-state actor scenario.

Technical Feasibility

This metric assesses the technical challenges of the process as compared to the technical abilities of the potential proliferator. By necessity, this metric is more qualitative, although judgments will be driven by historical data and expert evaluation of current technologies based on three sub-metrics: resource availability, technical difficulty, and technical expertise. Export controls and natural resources will help inform the resource availability sub-metric, but export controls may be circumvented to some degree by non-industrial components that are viable in a single-use fuel cycle. Technical difficulty measures the maturity and complexity of a step, and it is informed by patent dates, development data, technical publications, the technology readiness level, and previous development experience. Finally, 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.

A SINGLE-USE FUEL CYCLE

A traditional weapons fuel cycle for both U and Pu pathways is shown in Fig. 1. The assumption of a development goal of one HEU IND simplifies the non-state actor's fuel cycle considerably by eliminating the "back end" of the fuel cycle along with the fuel fabrication step shown in Fig. 1.

Simplifying the fuel cycle is not the only 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, so surrogate analogies are used to develop reasonable bounds for cost and schedule scaling factors (SFs). For example, perhaps the best high-technology systems analog is the re-usable rocket concept where studies have shown re-usable rockets have an initial development cost that is 10-100% higher than that of expendable rockets [20, 21].

The field of reliability engineering provides more analo-

gies 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% 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 cost associated with increases in military systems reliability has varied from a 1:1 to 35:1 percent reliability to percent cost ratio [22].

Given the intense regulatory, safety, and commercial requirements governing nuclear facilities, all commercial examples fall into the high reliability region of the tradespace where reductions in reliability, efficiency, maintainability, compliance, and safety result in large cost savings. For this research, baseline cost reductions of 20% and 50% are used to bound the range of cost SFs for a single-use fuel cycle. Although it is believed this is a conservative assumption [17], the supposition of uniform savings across each technology misses the nuances associated with each technology and could bias the results towards one path and/or technology.

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 [23]. 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. [24]. From these estimates, baseline schedule reductions of 50% and 75% are used to bound the range of reasonable expected schedules SFs.

Uranium Sourcing

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 [25]. Approximately 12.6 metric tons (MT) of U_3O_8 is required to produce 50 kg of 90% ^{235}U assuming a tails concentration of 0.3% ^{235}U. 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, all scaling is to produce 40 MT in one year.

Mining from uranium ores currently accounts for 100% of the world's commercial supply of natural uranium [25]. Typically, uranium mines are large open pit mines, but underground mines and in situ leaching can minimize the footprint and detection probability [26]. Approximately 80% of known reserves are available at <$50 per lb U_3O_8 [25]. 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 [27].

The known uranium reserves in PR approximately equal the reserves found in conventional ores [25]. There is no current extraction of uranium from PR, but there is significant historical experience worldwide [19, 28, 29]. Mobile pilot extraction plants the size of two 8' x 40' shipping containers have been developed, transported around the world, and successfully attached to existing wet phosphoric acid (WPA) production plants [30]. Costs are projected as low as $20 per lb U_3O_8, and development expenses costs, assuming an existing WPA plant, are ~ $10-15 Million [31, 28].

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 [25]. Ongoing development has pegged operating costs at ~ $600 per lb U_3O_8. While located underwater, the footprint is approximately 7 by 5 km, and it would require approximately 10 ships and 200 people to 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 [32].

Uranium could be purchased on the open market as Iraq did, although that would be complicated for a non-state actor [33]. This would be the most economical and fastest route by far as the spot price is $30 per lb U_3O_8 as of 30 March, 2016, 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 [34]. It is impossible to assess the potential costs associated with a black market purchase as no known cases exist in the open literature.

Diversion or theft is most commonly cited as the potential source of uranium for non-state actors [5]. Due to the sheer bulk of yellowcake transported world-wide, this is 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 the stolen material. It is difficult to assess costs and schedule, but it is worth noting that large-scale heists can take years in detailed planning.

Milling

After the uranium ore is mined the next step in the fuel cycle is to chemically extract the uranium from the ore to produce what is commonly termed yellow-cake, a product with a minimum 65% uranium content [35]. Uranium ore milling options are largely dependent on the geographic location of the uranium sourced, as the process of milling is almost exclusively determined by and dependent on the composition of the uranium ore or source material used [36, 35]. In general, the process can be summed up in 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 yellow-cake precipitation and drying [35]. The options that can be used for milling will be tailored to the specifications of a particular uranium sourcing option.

Conversion

Conversion removes impurities and converts the output of the milling step, typically yellowcake, into a form that is usable for the enrichment process. For example, gaseous diffusion and centrifuges use UF_6 while electromagnetic isotope separation (EMIS) uses 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, like the wet or dry process for conversion from U_3O_8 to UF_6. These potential conversion processes and techniques will be mapped based on starting material and enrichment process to account for the proliferation paths that a non-state actor could take.

Enrichment

For this stage of the fuel cycle, a total of seven techniques are explored as possible enrichment routes: gaseous diffusion, gaseous centrifuge, laser, electromagnetic, chemical, aerodynamic, and plasma separation. For enrichment, all scaling is 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% ^{235}U.

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 makes diffusion a difficult process to implement [17]. 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 impossible [37, 38, 39]." Costs are ~$7 Million and the plant can take several years to construct [40].

Since the introduction of gaseous centrifuges, they have been recognized as a proliferation risk due to their relative concealability [37]. Centrifuge technology has been assessed to be within reach of "nearly any country, including many developing countries [41]" and sold by the AQ Khan network [42]. There are limited signatures that can be detected at distance, 10,000 centrifuges would only require a 40,000 ft^2 footprint, and the electricity consumption is over an order magnitude lower than gaseous diffusion [37, 38, 17]. Additionally, a small facility, producing 50 kgs of HEU per year might cost only $5-13 Million, although others peg the estimate closer to $27 Million [17, 40]. Production time could run as little as 3-4 years with only a couple dozen workers [41]. However, the Iranian clandestine program was revealed to the public during its construction, detected much earlier, and has been 15-20 years in the making [38].

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 high 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 yet 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 to make this process viable [43]. 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 [44].

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, costs, a large footprint, and export controls based on Iraq's use of EMIS in their covert program. 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 3 years to produce enough fissile material. A facility with 1,000 calutrons in the first stage and 300 calutrons in the second enrichment stage could produce 50 kg of 90% HEU in 1 year [45].

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-scale enrichment would prove money- and time-intensive, especially with the necessary exchanges in each cylinder 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 [43].

There are seven different types of aerodynamic enrichment [46], but this paper focuses on the Helikon process implemented in South Africa for weapons and reactor fuel enrichment [43]. Aerodynamic processes are favorable as they have high separation factors and can have lower costs and power consumption than gaseous diffusion [46]. The vortex tubes are quite large (around 10 m in length and 6 m in diameter) and regulated by the IAEA, but only a couple modules are required, which leads to a smaller footprint [43, 34]. 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 [47].

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 means that it would take substantial amounts of time and money to 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 [43].

SUMMARY AND FUTURE WORK

This research area has become increasingly significant at a time when the democratization, globalization, and diversification of technology and the financial stability of non-state actors makes the successful pursuit of a nuclear device a reality to be avoided at all costs. Though indigenous development of fissile material has historically been viewed as unviable for non-state actors, the limited nuclear aims espoused, coupled with unprecedented resource and technology availability, might enable a non-state actor to pursue this path to obtain an IND. To obtain the necessary fissile material, a non-state actor can pursue a number of paths to develop their single-use indigenous fuel cycle. Each of these pathways will have an unique probability of success that can be assessed according the the metrics and models developed.

This summary has laid out the framework of a critical research effort, but there is work to be done to fill in the details. There are three key elements to the path forward. First, the normalization constants and bin structures for each of the metrics and sub-metrics need to be completed. For the purposes of this research, these will largely be based on ISIL capabilities. Second, each potential single-use fuel cycle technology needs to be assessed on the established metric scale using the cost and schedule SF developed for a single-use fuel cycle. Finally, the sub-metrics and metrics will be combined into a coherent model to yield a relative probability for success for each potential pathway. It is anticipated that this work will be completed and presented at the 2016 ANS ANTPC.

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