State-Level Decision-Making In Cyclus to Assess Multilateral Enrichment

Meghan B. McGarry[1], *Chris Hoffman*[1], *Baptiste Mouginot*[1], *Drew Buys*[1], *Paul P.H. Wilson*[1]

[1]**Department of Nuclear Engineering and Engineering Physics, University of Wisconsin-Madison**

Abstract

Proposed treaties and agreements that aim to reduce the spread of nuclear weapons are often stalled by skepticism regarding their efficacy. For example, the concept of multilateral enrichment, in which multiple states co-own and operate an enrichment facility, has the potential to reduce the spread of enrichment technology. However, detractors point to the improved international networking opportunities inherent in multinational organizations as a risk factor for increased proliferation. A framework to compare the relative risk between a multilateral enrichment paradigm and the status quo, on a regional scale, can help inform the discussion and potentially identify ways to reduce global risk of nuclear proliferation. As part of the Consortium for Verification Technology, the Cyclus fuel cycle simulator is being used as a test-bed for the development of such new technologies and approaches to treaty verification. Cyclus is a systems-level nuclear fuel cycle simulator that models the interactions between actors in the nuclear arena. While designed to track the flow of nuclear material between facilities, Cyclus also incorporates an innovative Facility-Institution-Region hierarchy that can capture the dynamics of state-level interactions. Drawing on social science literature to identify factors that motivate states to pursue weapons programs, we have developed a regional proliferation model that captures causes and effects of state-level nuclear weapons proliferation. The model identifies eight key factors that influence a states decision to pursue nuclear weapons. These factors include motivations internal to the state, such as military spending and governing structure, as well as interactive factors such as conflict between states. Historical data is used to identify the relative importance of these factors and translate them into a likelihood of pursuing a weapon. The model also provides a feedback mechanism such that acquisition of a nuclear weapon by one state influences the decision-making of the other states. This model will be used to assess the effectiveness of policy approaches, such as multilateralization of the fuel cycle, that seek to reduce the regional risk of proliferation over time.

1 Introduction

Progress in preventing the spread of nuclear weapons is contigent both upon preventing access to the required technology as well as disincentivizing weapons programs. An effective global nonproliferation regime must synthesize knowledge from the realms of political science, international relations, nuclear physics and engineering, and even behavioral psychology. An understanding of when and why states proliferate can inform future treaties and agreements on the policy side to minimize this risk. For example, the concept of multilateral enrichment, in which multiple states co-own and operate an enrichment facility, has the potential to reduce the spread of enrichment technology. However, detractors point to the improved international networking opportunities inherent in multinational organizations as a risk factor for increased proliferation. A regional or global framework to compare the relative risk between proposed treaty paradigms and the status quo can help inform the discussion and potentially identify ways to reduce global risk of nuclear proliferation.

As part of the Consortium for Verification Technology, the Cyclus fuel cycle simulator is being used as a test-bed for the development of such new technologies and approaches to treaty development. Cyclus is a systems-level nuclear fuel cycle simulator that models the interactions between actors in the nuclear arena. While designed to track the flow of nuclear material between facilities, Cyclus also incorporates an innovative Facility-Institution-Region hierarchy that can capture the dynamics of regional-level state interactions. We have developed a forward model in which a set of hypothetical states can be given individual political and technical attributes. This model then tracks whether each state develops nuclear weapons over time based on how these attributes evolve in time, including feedback on conflict levels between states.

2 Factors That Correlate to Pursuit of Nuclear Weapons

Social science literature has suggested that a variety of political and technical factors that may motivate a state to pursue nuclear weapons[1, 2, 3, 4]. Political factors include: degree to which governing structure is authoritarian versus democratic, level of military spending, degree to which state is isolated militarily, and level of conflict with other states. Technical factors include: degree to which the state's scientific expertise is integrated into the international community[5], nuclear reactor experience, indigenous reserves of natural uraniaum, and the ability to enrich uranium.

We have compiled a database of information that quantifies each of these eight factors for states at important historical points, publically available on github[1], along with documentation on source data and assumptions[2]. The set includes 42 unique states that have historically had either nuclear energy or weapons technology. The 24 states that have never pursued weapons have data compiled for 2015. The 19 states that have pursued weapons at some point in the past have data for the year in which they pursued as well as the year in which they acquired a weapon, if applicable. Pursuit and acquisition dates are coded from *Singh and Way*. The pursuit date as defined as the first year in which a significant decision to pursue nuclear weapons was made such as a political decision by cabinet-level officials, movement toward weaponization, or development of single-use, dedicated technology. Acquire date indicates the year in which either the first explosion of a nuclear device occurred or the complete assembly of a weapon since not all countries tested their nuclear weapons.

2.1 Pursuit Score

The source used to define each factor has been taken from social science literature and is listed in Table 1 The raw data for each attribute has been normalized on a 1-10 scale so that all factors can be compared directly, as described in Table 2. Conflict is shown separately in Table 3. Conflict has been defined for a given state by identifying three significant state-pair relationships. Each of these relationships is coded as enemy, neutral, or ally. Each of the two states in the pair is also identified as being a non-weapons state, known to be pursuing weapons, or a weapons-state. The combination of weapons status and relationship status is combined to provide a conflict score for each pair. The net conflict factor is the average of the state's three conflict scores. We consider that the pursuit phase is the most destabilizing, and have

[1] https://github.com/CNERG/historical_prolif/blob/master/clean_raw_data.csv
[2] https://github.com/CNERG/historical_prolif/blob/master/README.rst

Factor	Source Database
Authoritarian	Center for Systemic Peace Polity IV Annual Time-Series, 1800-2015[6]
Conflict	Uppsala Conflict Data Program Armed Conflict Dataset[7]
Enrichment/Reprocessing	Nuclear Latency Dataset [8]
Military Isolation	Rice University The Alliance Treaty Obligations and Provision Project[9]
Military Spending	Stockholm International Peace Research Institute Military Expenditure Database 1949-2015[10]
Nuclear Reactors	IAEA Power Reactor Database [11] IAEA Research Reactor Database [12]
Scientific Network	Authors' Expert Opinion[3]
Uranium Reserves	OECD Uranium: Resources, Production and Demand [13]

Tab. 1: Source data for each factor contributing to pursuit of nuclear weapons addressed in this paper.**TODO: SYSTEMIC PEACE HAS COPYRIGHT RESTRICTIONS**

incorporated considerations such as nuclear umbrellas **TODO: cite**, preventative war, increased low-level conflict between weapons states [14, 15, 16].

Once every state had been assigned a 0-10 score for each factor, a correlation analysis was applied to the derived factor scores to quantify the degree to which each individual factor is correlated to the decision whether or not to pursue weapons. The resulting weight for each factor is derived from the Pearson correlation coefficient. The bivariate correlation between the factor and the score and can be determined using the equation 1:

$$w_f = \frac{\sum_{i=0}^{N}(f_i - \bar{f})(s_i - \bar{s})}{\sqrt{\sum_{i=0}^{N}\left(f_i - \bar{f}\right)}\sqrt{\sum_{i=0}^{N}\left(s_i - \bar{s}\right)}}, \tag{1}$$

N corresponds to the number of states, f_i and s_i to the factor and the score of a given state i, respectively, and $\bar{f}$ and $\bar{s}$ to the mean factor and the mean score over all the states. The correlation coefficients are then normalized so that the final pursuit score for a state can be defined a weighted linear combination of its different factors. The normalized weights of the 8 factors are shown in Table 4.

Pursuit scores can range between 0 and 10. Confidence in the weights was gained by applying the weighted equation to the historical data and examining degree to which scores accurately matched historical pursuit decisions. Historically based scores are shown in Table 5 for the year in which each state explored or pursued a weapon, or 2015 for states that never developed weapons programs. The historical scores are ranked such that states that actually pursued weapons have the highest scores (red).

Two major insights arise from this analysis. Firstly, a state's reactor technology is anti-correlated to pursuing a nuclear weapon. Denoted in Table 4 with a minus sign for illustrative purposes, in practice the factor scale was inverted such that maximum reactors led to a minimum reactor score, and then the absolute value of the weight (18%) was used. Secondly, indigenous uranium reserves were uncorrelated to weapons programs. These two results were not predicted by the social science literature.

Factor Score (FS)	**Auth**	**Enrich/ Repro.**	**Military Iso.** $10-(A_{NNWS}+A_{NWS})$		**Mil. Spend (%GDP)**	**Reactors** (Power+Research) $10-R_{all}$	**Sci. Net.**	**Uran. Res**
			NNWS	NWS				
0	0	0	–	–	–	0	–	0
1	1	–	1-2	–	<1	1-3 planned	–	–
2	2	–	3-4	–	[1, 2)	4+ planned	–	–
3	3	–	5+	–	–	–	–	–
4	4	–	–	–	[2, 3)	1-3 built	1	–
5	5	–	–	1	–	–	–	–
6	6	–	–	2	–	–	–	–
7	7	–	–	3+	[3, 5)	4-7 built	2	–
8	8	–	–	–	–	–	–	–
9	9	–	–	–	–	–	–	–
10	10	1	–	–	5.0+	8+ built	3	10

Tab. 2: Conversion table from raw data to final factor score (FS). Square brackets are inclusive, parentheses are exclusive, such that [1,2) indicates $1 <= x < 2$. Reactors and military alliances (used to define military isolation) are both anti-correlated to pursuit so the final factor score for these factors is 10 minus the value shown in the table. Conflict factor is defined separately in table 3.

Nuc. Weapon Status	**Allies**	**Neutral**	**Enemies**
NNWS - NNWS	2	2	6
NNWS - Pursue	3	4	8
NNWS - NWS	1	4	7
Pursue - Pursue	4	5	9
Pursue - NWS	3	6	10
NWS - NWS	1	3	5

Tab. 3: Conflict score assignments are based on weapons status and relationship of pair states. Weapon status may be Non-nuclear Weapons State (NNWS), pursuing weapons, or Nuclear Weapons State (NWS). Relationship status is assumed to be symmetric and may be positive Allies, neutral, or enemies.

Factor	**Weight**
Authoritarian	0.12
Conflict	0.26
Enrichment & Reprocessing	0.10
Military Isolation	0.075
Military Spending	0.21
Reactors	-0.18
Scientific Network	0.05
Uranium Reserves	0.0

Tab. 4: Relative weighting of each factor toward pursuit decision as determined by correlation analysis of historical data. Note reactor technology is anti-correlated.

State	Year	Pursuit Score
USSR	1945	8.9
Iran	1985	8.3
Iraq	1983	8.2
N. Korea	1980	7.7
Libya	1970	7.4
Egypt	1965	7.3
Syria	2000	6.9
France	1954	6.8
Algeria	1983	6.6
Saudi Arabia	2015	6.5
US	1942	6.5
India	1964	6.4
China	1955	6.3
UAE	2015	6.3
Israel	1960	6.2
Argentina	1978	6.1
S. Africa	1974	5.9
UK	1947	5.8
Pakistan	1972	5.3
Armenia	2015	5.0
Algeria	2015	4.9
Sweden	1946	4.8
Romania	1985	4.5
Indonesia	1965	4.4
Switzerland	1946	4.4
Belarus	2015	4.4
S. Korea	1970	4.4
Brazil	1978	4.3
Australia	1961	3.9
Ukraine	2015	3.2
Kazakhstan	2015	3.1
Lithuania	2015	3.1
Japan	2015	3.0
Netherlands	2015	2.7
Finland	2015	2.5
Germany	2015	2.5
Bulgaria	2015	2.4
Mexico	2015	2.0
Slovakia	2015	1.8
Hungary	2015	1.6
Spain	2015	1.6
Czech Republic	2015	1.3
Canada	2015	1.2
Belgium	2015	1.0

Tab. 5: Historical scores assigned to states based on their factor values at the designated year. Weighting accurately gives high scores to states that acquired (red), pursued or explored (orange), and low scores to those that never investigated a nuclear weapons program (black).

3 A Cyclus Model of Nuclear Weapon Pursuit

We have applied the factors correlated to pursuit of nuclear weapons in a regional model of state interactions using CYCLUS [17, 18, 19]. The Computational Nuclear Engineering Research Group (CNERG)[4] group at the University of Wisconsin has developed the CYCLUS[5] nuclear fuel cycle simulator to model all aspects of the nuclear fuel cycle in a flexible way [20]. CYCLUS has three key features: it is *agent-based*, it tracks *discrete materials*, and it incorporates *social and behavioral interaction models*[21, 22]. This design allows customized facilities and institutions to engage in dynamic decision-making based on their preferences, needs, or political constraints across a wide range of scenarios. A specific agent might have preferences based on material composition, physical proximity between facilities, or preferred trading partners, which are implemented in a region-institution-facility hierarchy that enables economic modeling [23].

3.1 The Forward Model

The region-institution-facility design has been used to develop the Nuclear Weapons Pursuit Model (NWPM). This forward model features two custom archetypes, an interaction region (InteractRegion) and a state institution (StateInst)[6]. The state institution represents the a nation-state. It includes time-dynamic information about each of the pursuit factors. The interaction region is an omniscient presence in the simulation that tracks weapon status as well as interactive pursuit factors such as conflict(as described in section **??**), and communicates that factor to each individual state.

Each of the motivating factors is defined for every state in a time dynamic way. Individual factors must have values between 0-10. There are several tim dynamics currently available in the model: constant, linear growth or decline, step-function (at either a specified or a randomly chosen time), or power-law. These functions enable modeling of characteristics such as growth in military spending, development of new technologies such as enrichment, and sudden changes such as to governing structure or inter-state conflict. At each timestep, the state combines all of these factor values into a pursuit score using the weighted linear equation defined in section **??**.

3.2 Likelihood

The score is then converted into a likelihood that the state will pursue a weapon. The relationship between pursuit score and likelihood of pursuing a weapon has been characterized using historical data of the 42 states that have developed nuclear technology since 1942. 1 shows the fraction of states with a given pursuit score that pursued a weapon during that time. A power-law (red) or a weighted linear fit (black) are are equivalentl with the 42 state dataset. However, a global dataset of nation-states would have disproportionately lower scores, so we consider the power-law paramaterization to be more representative.

The data shown in 1 represents the total likelihood integrated over the course of 75 years (T). Equation 2 is used to convert to the likelihood of pursuit L in any given year, given a pursuit score s.

$$L = 1 - (1 - s)^{1.0/T} \tag{2}$$

In the NWPM forward model, each state's score is converted to a likelihood of pursuit at that timestep using Equation 2. The actual conversion is bounded using two heavy-side functions such that scores below a

[4] http://cnerg.github.io/
[5] http://fuelcycle.org/
[6] https://github.com/CNERG/mbmore

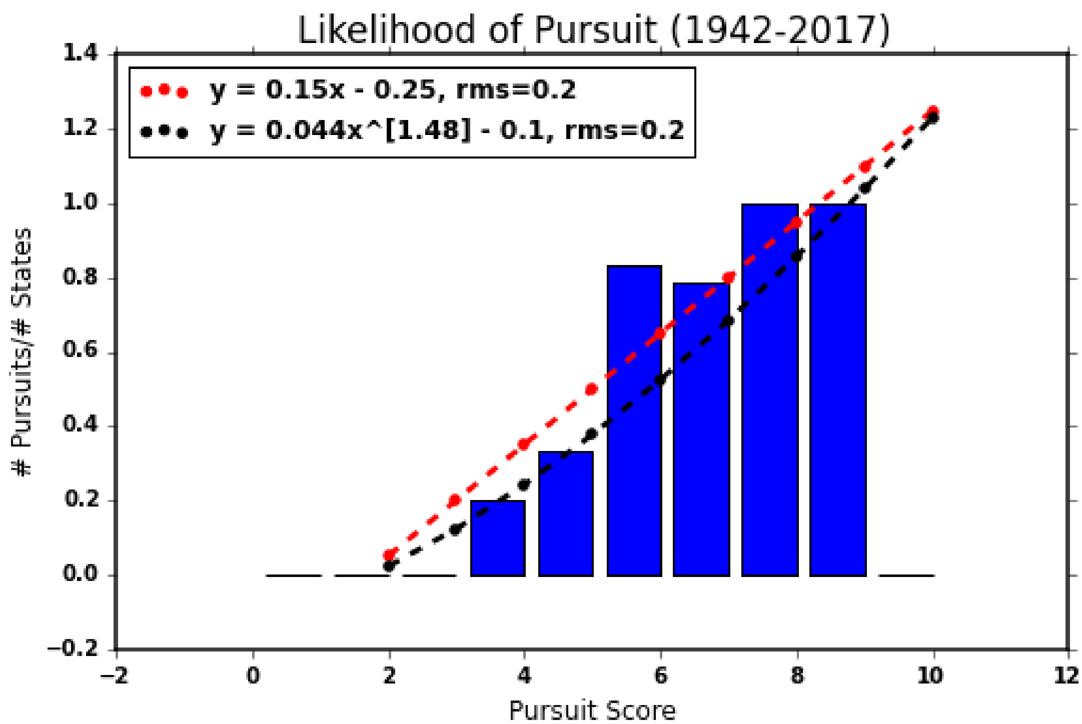

Fig. 1: Fraction of states with any nuclear technology (dataset from 2) that pursued weapons at some point in the last 75 years, given their pursuit scores. Although a power-law curve (black) and a weighted linear fit (red) are equivalent with the existing data, a complete set of nation-states would increase the relative weight of lower scores, making the exponential curve a better fit.

lower threshold (e.g. 4) are forced to a likelihood of zero, while scores above an upper threshold (e.g. 9) are forced to the value of the score at the threshold. A random number generator is used given the likelihood to determine whether or not the pursuit event occurs. If the determination is for pursuit to occur, the state deploys a secret enrichment facility. If a state is already pursuing a weapon, then the model determines whether it succeeds in acquiring a weapon at that timestep using a median time to acquire of 7.5 years, based on historical data for states that have acquired weapons. On the timestep in which a state succeeds in acquiring a weapon, highly enriched uranium is shipped out of the secret enrichment facility.

3.3 Limitations of the Historical Data

The use of historical data to develop a forward model has several limitations. One set of limitations could be improved with a larger historical dataset. Historical scores for non-nuclear states have not been calculated. Due to the influence of nuclear technology, a non-nuclear state could theoretically have a maximum pursuit score of 7. Considering that the majority of states that have high potential military spending and major historical conflicts have already been incorporated, this further reduces the potential maximum score to below 5, even if all other factors were maximized. A large fraction of states in the world are have scores on the order of 1-3. This large set of missing historical data, heavily weighted to the low score side, would reduce the likelihood of higher-score states from pursuing. The database could also be improved by collecting historical data for many years around dates of pursuit and acquisition rather than just for a single year. This analysis has identified factors that are correlated to weapons programs but there is insufficient data to confirm causal relationships.

This model is intrinsically limited by the small sample size and the degree to which the global landscape changes over time. With only 10 states that have acquired nuclear weapons throughout history, there is large uncertainty in any quantatitative analysis. Additionally, while conflict has been captured in a crude way, it is difficult to develop a parameterization with enough nuance to capture the varying impact of conflict under paradigms such as World War II, the Cold War, or post-9/11.

4 Discussion and Future Work

We have developed a forward model that characterizes the likelihood that a state will pursue a nuclear weapons progam based on a set of eight socio-political and technical factors: governing structure, military spending, military isolation, scientific network, inter-state conflict, reactor technology, enrichment technology, and indigenous uranium reserves. To develop this model, we first assembled a historical database of quantitative data to characterize the factors, and then used the database to quantify the degree to which each factor is actually correlated to a pursuit decision. Historical data was also used to inform the conversion between the pursuit score and a likelihood of actually developing a weapons program.

Two of the eight factors suggested by political science literature as motivations for pursuing weapons yielded unexpected results. The presence of uranium reserves was uncorrelated to a pursuit decision, suggesting that access to natural uranium is not a bottleneck. Perhaps more surprising, access to reactor technology was anti-correlated with a pursuit decision, meaning the more reactors a state had, the less likely they were to puruse. It is possible that this effect is a consequence of the existing nonproliferation regime - states that make the strongest nonproliferation commitments are rewarded with assistance in developing nuclear energy programs. It would be instructive to investigate both of these factors further, for example, to see whether there is a distinction in the correlation of research versus commercial reactors to a pursuit decision.

It is important to note that this model is meant to be indicative rather than predictive. Human behavior is fundamentally difficult to explain, let alone model. The actions of individuals can have outsized effects, for example A.Q. Khan's role in Packistan's weapons program. Humans do not always act rationally, and groups can make very different decisions from individuals. Expertise from psychology, game theory, sociology and international relations could certainly improve our model but there will always be some level of unpredictability in human behavior that prevents models such as this from being predictive.

Nonetheless, we believe this model can be used to offer valuable insights into the relative risks of proposed future paradigms. While we cannot predict whether or not State A will pursue a weapon in the next 10 years, we can investigate ways to reduce the risk of that pursuit occurring based on our understanding of these factors. For example, we plan to apply the model to scenarios investigating how regional multilateral enrichment facilities would affect proliferation risk on a regional or global scale. **TODO: ANY OTHER IDEAS FOR FUTURE WORK? PERHAPS HEDGING STRATEGIES?**

This work was funded by the Consortium for Verification Technology under Department of Energy National Nuclear Security Administration award number DE-NA0002534

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