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Keeping Nuclear Programs From Becoming Nuclear Weapons: A Game Theoretic and Econometric Analysis

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There are currently only nine countries which possess nuclear weapons, but twenty-four countries have pursued the requisite technology. The question remains as to why nations ceased their programs, and whether the policies of the international community had anything to do with that decision. This paper uses both a game theoretic and a probit model with limited assumptions to attempt to uncover: a) what are the determinants of a country shuttering their nuclear weapon program, b) when "sticks and carrots" can be credible (subgame perfect), and c) how large of a role they play in the potential nuclear country's decision-making. I find that sanctions can only be credible when the cost to future prestige of doing nothing is enough to outweigh the residual cost for the international community. In turn, there is little empirical evidence that international levers have much effect. I also find that delaying benefits could make the offer more credible, but could also create a perverse incentive whereby the weapon-pursuing nation continues their program solely to receive future benefits. There is evidence of this moral hazard as greater foreign aid makes a country less likely to cease their program, and greater GDP per capita makes them more likely. Finally, I find that there is great inertia within programs, making them harder to cease as time increases.

I. Introduction

We live in a world where a rogue nation acquiring nuclear weapons is a constant national security threat. While there has been debate over the actual negative externalities of additional countries acquiring nuclear capabilities (Intriligator & Brito, 1978, 1981, 1996; Mearsheimer, 1993), the conventional wisdom remains that international policy should be directed towards deterring additional nations from making the nuclear leap.

Of the twenty-four nations that have pursued nuclear weapons since the first detonation in 1945, only nine currently possess bombs. This relatively low completion rate raises important normative questions. First, what caused the other fourteen countries to give up their pursuit?[1] Second, and perhaps more importantly, is there room for international non-proliferation measures, such as trade sanctions, foreign aid, or conditional benefits, to help in getting nations to cede their programs? If I can capture the determinants of nuclear cessation, the international community may be able to better optimize their coercion strategy.

In this paper, I will be proposing a game theoretic model to be used towards exploring these determinants. By understanding how rational nations *should* behave, I can better test how they actually *do* behave, and reconsider our expectations of what drives countries pursuit of nuclear weapons. This model will be followed by such a test, seeking the determinants of program cessation. Additionally, I examine the potential for modification of these factors by the international community. I find that there is little room to act for the international community and that most factors are demand-side and require careful examination, as they may not adhere to the conventional wisdom. Additionally, any desired action must be taken quickly to avoid program inertia.

In section II, I will identify the literature that already exists on the topic, and detail how it can be synthesized and improved. In section III, I will lay out the payoffs and structure of a model of the behavior of potential nuclear countries, and of the international community towards them. In section IV, I will use the model to explore a few realistic scenarios involving various potential international sanction and benefit packages. Sections V and VI will summarize the data, methodology, and model that will be used in examining these questions. Section VII will examine the results and section VIII will briefly discuss the limitations of the model. Finally, in section IX, I will conclude and explain where research still needs to be done on this topic.

II. Previous Literature

There have been surprisingly few attempts at formal modeling of the behavior of countries during the period between beginning nuclear weapons research and either actual acquisition or cessation. This void is additionally jarring due to the way that more general deterrence theory has seemed to fail to explain "rogue" nations such as North Korea and Iran continuing their program in the

[1] Iran is one of the fifteen countries that have pursued nuclear weapons but failed to acquire them at the time of this writing. However, since they are still believed to be in active pursuit, I consider there to be fourteen countries which have ceded their programs to international will.

face of international sanctions, as well as countries such as South Africa and the former Republics of the Soviet Union, who gave up weapons that they already possessed (Morgan, 2006). This previous work tends to be short-sighted and oversimplified, as the authors tend to over-apply traditional concepts such as the Prisoner's Dilemma.

The one key exception is Arce and Sandler's recent work on the application of deterrence to terrorism, nuclear proliferation, and rogue nations (Arce and Sandler, 2009). They sought to explain why Cold War-era deterrence research was not well-suited for the dangers of the twenty-first centuries: rogue actors are playing a different game with different payoff sets than the international community. They attempt to show that for any coercive action to be credible it must be disproportionate to what the rogue nation is attempting to accomplish. This is due to the fact that rogue actors are playing "chicken" while the superpowers find themselves within a pseudo-Prisoner's Dilemma. Upon Arce and Sandler's introductory examination, there is a great amount of room to further refine these asymmetries. It is particularly necessary to do so in order to better reflect the particulars of international relations between the greater international community and the nations seeking nuclear weapons, which may have a negative externality to the community as a whole. Additionally, a model needs to take into account that the payoff sets of the two players are based upon mostly independent factors.

While there has not been previous work done upon the empirical determinants of program cessation, there has been some study of the determinants of beginning and completing programs. Singh and Way sought to determine what makes a country begin exploring nuclear weapons and, conditional upon that exploration, what makes the country become a nuclear weapons state (Singh and Way, 2004). They found that the largest determinants of exploration were the presence of a military rival and the industrial capacity requisite to such a program. While these are demand-side factors that are unlikely to be open to modification by the world at large, they did find that the largest deterrents to beginning pursuit were the presence of a "great power" ally and openness to trade. An additional deterrent in preventing actual acquisition is satisfaction with the current balance of power. They admitted that this was based upon case-study level data. This, however, makes it susceptible to selection bias whereby false explanations can be found through the choices of countries.

Jo and Gartzke attempted to improve upon the methodology of this paper in 2007 by expanding the data available and increasing the amount of variation within the variables examined (Jo and Gartzke, 2007). They similarly found that the largest determinant of nuclear exploration was the presence of a conventional threat and a nuclear capacity capable of such a feat. However, they found a surprising result in that the only statistically significant deterrent of nuclear exploration was the presence of a nuclear threat. Based upon previous case study-based international relations work, it was assumed that a nuclear threat would bring about increased desire for nuclear weapons for deterrent purposes. A potential explanation of this counterintuitive result is that international norms, which would discourage use of nuclear weapons against a non-nuclear state, might change the perception of security for a potential nuclear aspirant, as they may now find that acquiring nuclear weapons would put them at greater risk since it would make them a legitimate target for their rival. In terms of the actual acquisition of weapons conditional upon pursuit, they find that technology diffusion and the presence of a

conventional threat are the chief incentives, while the presence of a nuclear threat and an ally with a nuclear weapon are the largest deterring factors.

Both the Singh and Way (2004) and Jo and Gartzke (2007) studies noted that these coefficients could not be simply inverted to help determine how to coerce a nation into giving up their nuclear program. Thus, there is a great gap in the literature in so far as the question of why fourteen countries have ended nuclear weapon programs short of actual weapons. Creating a more detailed theoretical and empirical framework will allow all of these results to be synthesized and should affect current policy towards nuclear aspirants.

III. Theoretical Model

In the case of nuclear research and deterrence, the game is played between two rational and strategic actors: the country with a nuclear program and the "international community". I assume (**A1**) that the international community (IC) acts in concert as a single entity with a single pay-off structure.[2] The IC has four possible actions: they may threaten sanctions conditional on the country continuing their nuclear program, offer benefits conditional on the country ceasing their nuclear program, do both, or do neither. I will take a further assumption (**A2**) that the IC will only take an action upon which they can credibly be expected to follow through, thus simplifying the need to distinguish threats from actions. The country faces a discrete choice between continuing their program or ceasing it.

The game is modeled as an infinitely-repeated game of incomplete information. Every iteration of the game has three stages:

1. The IC chooses an action.
2. The country responds to the action.
3. Any benefits/sanctions the IC laid upon the table are applied and payoffs are awarded.

The payoff structure in any given round for the country if it continues is:

$$\pi(\text{country}|\text{continue}) = M \cdot q_C^P - C - S_C(\alpha) \quad (1)$$

where the individual variables represent:

- M = military benefit to the nation from possessing nuclear weapons
- q_C = Discount rate
- P = Round in which nuclear capacity will be achieved[3]

[2] While there are obvious problems with this assumption concerning the reality that different nations have different stakes in the non-proliferation regime and free-riding becomes possible (see Kroenig 2009), these controversies are outside of the realm of this model. Additionally, the model still works if we slightly modify it as a bi-lateral game, with a superpower such as the United States acting in place of the IC.

[3] The reason for the algebraic set-up of $M \cdot q^p$ being used, as opposed to a more traditional alternative such as multiplying M by the probability that nuclear capacity will be achieved in that round is that, when combined over multiple rounds, this method allows for a more realistic payoff by assuming that nuclear programs bring no military value until they actually exist. Thus, it begins taking value at round P, at the discounted rate for that period.

- C = Budgetary cost of nuclear program
- $S_C(\alpha)$ = Cost of sanctions (if IC strategy α contains sanctions)

The payoff structure in any given round for the country if it ceases is:

$$\pi(\text{country}|\text{cease}) = B_C(\alpha) \quad (2)$$

where $B_C(\alpha)$ represents the benefits offered by the IC if IC strategy α contains benefits.

The payoff structure in any given round for the IC if the country continues is:

$$\pi(\text{IC}|\text{continue}) = -S_{IC}(\alpha) - R \cdot q_{IC}^{P} - I(\alpha) \quad (3)$$

where the individual variables represent:

- $S_{IC}(\alpha)$ = Cost of sanctions to the IC (if IC strategy α contains sanctions)
- R = Military risk of country possessing nuclear weapons
- q_{IC} = Discount rate[4]
- I(α) = Weakening of the international non-proliferation regime from country continuing its nuclear weapons program. This weakening is some function based upon the IC's strategy.

The payoff structure in any given round for the IC if the country ceases is:

$$\pi(\text{IC}|\text{cease}) = N(\alpha) - B_{IC}(\alpha) \quad (4)$$

where N(α) represents the strengthening of the non-proliferation regime from the country ceasing, as a function of the IC's strategy and $B_{IC}(\alpha)$ is the cost of offering benefits, conditional on benefits being offered.

While all actions are observed and the general payoff structures are known, the specific values of the variables are never known by the respective players. Thus, beliefs play an important role in the determination of rational strategies. The notion of subgame perfect equilibrium will be used, in concert with these beliefs, to determine which long-term strategies will ever be rational or credible in the iterated game. Since, as with any infinitely repeated game, any strategy for one player can be maintained with the right strategy for the other player (see Rubinstein, 1979), I will limit ourselves to looking at realistic and normatively interesting scenarios which can be examined in an econometric setting. In particular, I will focus on credible decision making for the IC, since our goal is to discover what, if any, credible actions can be taken by countries attempted to coerce a country into giving up their nuclear weapons program.

[4] Same logic as footnote 3 applies here.

IV - Potential Scenarios

Scenario 1 - Sanction Forever

Due to **A2**, it is important that I consider the credibility of a threat from the IC before attempting to solve for the equilibrium in this scenario. Under SPE, I can define "credibility" as any situation where it would be rational for the IC to actually follow through with their action after the country has moved. For example, they need to be willing to sanction *even if* the country continues its program, and they need to be willing to provide the promised benefits *even if* the country ceases its program. In this case, it can be shown, using equations (3) and (4), that it can only be credible if:

$$I(\text{Do nothing}) - I(\text{Sanctions}) \geq S_{IC} \quad (5)$$

This seems intuitive. If you are threatening continuous sanctions, the country will have no reason to wait to cease its programs; it would receive the greatest payoff from ceasing immediately. Thus, if they continue once, the IC knows that the country will continue forever. In order for them to follow through with their sanctions, they need the extra psychic cost to the international regime of doing nothing to outweigh the tangible cost of putting up sanctions.

If condition (5) holds, than I must look at how the country should respond. I can show, using equations (1) and (2), that the nation will cease if:

$$C + S_C \geq M \cdot q_c^P \quad (6)$$

Scenario 2 - One-shot Sanction

The case of a strategy of one-shot sanction, followed by do nothing, reveals an interesting finding in the condition necessary for the strategy to be credible:

$$q \cdot I(\text{Do Nothing}) - I(\text{Sanction}) \geq S_{IC} \quad (7)$$

Comparing condition (7) to condition (5), I can see that it is likely more difficult to sanction just once than it is to sanction forever. The intuition behind this result is that sanctioning once you know that the country is going to continue requires the "cost" of doing nothing to be significantly amount higher than the "cost" of sanctioning. However, when you are sanctioning only once, you are already committing to doing nothing for the remainder of the game after that first round. Thus, the international community is signaling to the potential nuclear nation that they do not view their acquisition of nuclear weapons as much of a threat.

Under this scenario, if condition (7) holds, I can show that the nation will cease if:

$$C + (1-q) \cdot S_C \geq M \cdot q_c^P \quad (8)$$

Condition (8) is tougher to meet than condition (6). This, when combined with the higher credibility threshold of condition (7), shows that scenario 2 is not likely to ever occur, something that is revealed as true through historic experience.

Scenario 3 - Adding Conditional Benefits

Adding benefits to the mix provides an additional wrinkle. With benefits involved, I must consider whether it would make sense *ex ante* for benefits to be offered. For an offer of benefits to be rational and credible for the IC when added to Scenario 1, it must fulfill the following requirement:

$$\text{N(Sanction \& Benefit)} - B_{IC} + \geq (\text{I(Sanction)} + S_{IC} + R_{IC}{}^{P})\cdot(1-q_{IC})^{-1}$$

$$\lambda\cdot(\text{N(Sanction)} + (\text{I(Sanction)} + S_{IC} + R_{IC}{}^{P})\cdot(1-q_{IC})^{-1}) \quad (9)$$

where:

$$\lambda = \text{The IC's belief probability that } \frac{C+S}{M} \geq q_C{}^{P} \quad (10)$$

Condition (9) bases the ability of the IC to offer benefits positively on the perceived risk of the country acquiring nuclear weapons, both tangible and intangible, and negatively upon the belief that the country may give up its program with just sticks. Additionally, since I can assume **(A3)** that N(Sanction) will be higher than N(Sanction & Benefit), the larger the size of that difference, the harder it will be to offer benefits.[5]

Since offering benefits along with sanctions requires both conditions (5) and (9) to be met, offering benefits makes offering sanctions harder. However, it changes condition (6) to:

$$C + S_C + (1-q)\cdot B_C \geq M\cdot q_c{}^{p} \quad (6^*)$$

Condition (6*) is easier to reach than condition (6), and thus, if condition (9) can be met, it makes sense for the IC to offer carrots along with sticks.

Scenario 4 - Delayed Benefits

One thing that may be noticed from Scenario 4 is that the reason offering benefits is so difficult is due to the belief that the same result may be possible with just sanctions. This problem could be potentially avoided by delaying benefits. By delaying benefits, λ effectively becomes 0 if the country continues and 1 if they cease. This makes offering benefits in future rounds more likely to be rational by modifying condition (9) to:

$$(\text{I(Sanction)} + S_{IC} + R_{IC}{}^{P})^*(1-q_{IC})^{-1} \quad (9^*)$$

However, there is a problem with waiting on benefits: it could create an incentive for a country that would otherwise end its program immediately, even if condition (6) holds, to continue its program

[5] This assumption is based upon the fact that, if the IC gives benefits to a country to give up its nuclear program, it could provide an incentive for other countries considering nuclear programs to enter into them solely for the purpose of receiving expected benefits when they give them up. This, to some extent, offsets the benefit to the international non-proliferation regime of the country giving up its program, and so N(Sanction) > N(Sanction & Benefit).

until benefits are on the table.[6] Even with condition (6) holding, there is an additional condition needed to get the country to give up its program in an early round rather than wait for benefits:

$$C + S_C + \sum_{i=1}^{x} C^i + \sum_{i=1}^{x} S_C{}^i \geq B_C \cdot q^x \quad (11)$$

where x = the belief of the country as to which round benefits will be made available.

Thus, delaying benefits, while making it easier to credibly and rationally offer benefits for the IC, could lead to a delay in cessation of the country's program since both conditions (6) and (11) need to hold to make the country give up its program in the first round. If they do not both hold, but condition (6*) does, they will only give up the program when the benefits become available.

In sum, these theoretical explorations show that:

- Time-limited coercion packages are never credible.
- The extra risk to international norms from doing nothing must be sufficiently high enough to get the international community to act, regardless of the tangible military risk of the country's nuclear program.
- Benefit packages may significantly increase the chance of cessation and efficiency of such negotiations, but they also generate moral hazard by incentivizing nations to hold out their programs for the best possible package.

These results seem to show the significant constraints that the international community faces in attempting to put together any coercive package that possesses the ability of actually changing the nation's perceived cost-benefit determination. This is especially true since the latter two become increasingly severe as the size of the stick and carrot package grows, emphasizing the difficulty of making something persuasive enough to influence decision-making.

V. Methodology & Econometric Model

To find the determinants of nuclear cessation, I will use a maximum-likelihood probit model, defined as:

$$\Pr(Y = 1|X) = \Phi(\beta_0 + \beta_1 M + \beta_2 C + \beta_3 S + \beta_4 R + \varepsilon) \quad (12)$$

In this model, the dependent variable is equal to one when a nation no longer has a nuclear program, conditional upon them having such a program at some point in the past. This modeling decision recognizes the fact that a country, once it gives up a program, continues to make the decision every period to not restart its program. Since this is modeling a different situation than previous empirical work on proliferation, I am assuming that this decision is more similar to the decision to give up the program rather than the decision to start a program for the first time, as studied elsewhere (**A4**). This is realistic as a nation always possesses "quick-start" capabilities once the state has seized the low-hanging technological fruit that comes along with first beginning a program (Einhorn, 2004).

[6] This has been seen in North Korea, among other places.

The decision depends upon four vectors of factors: the military value to the state of acquiring nuclear weapons (M), the cost to the state of the program (C), the international levers that can act as room for sanction and benefit packages (S), and the perceived risk to the international community of the state acquiring nuclear weapons (R).

VI. Data

I use the Jo and Gartzke (2007) measure for whether or not a state has a nuclear program from the years 1949 until 1991 as the dependent variable, providing 533 observations. For the purpose that I am interested in here, I have inverted the variable so that 1 means that the country no longer has a program. As mentioned above, a country enters the sample the year that it begins its program, but will then remain for the rest of the study.

Military Value Variables -

The perceived value of nuclear weapons would be based upon both the availability of a conventional alternative and the demand for military advantage in absolute terms. I can proxy for the pre-existing conventional military strength of a nation by including *military expenditures*. I use the a logged version of the Correlates of War data to represent this variable. One would expect that as conventional weapon expenditures grow, the willingness to bear the cost of an unconventional program would decrease. Thus, I expect this to be negatively related with program cessation.

The presence of a *nuclear ally*, as seen in the previous literature, is a potentially important variable. I would assume that a state that is under the nuclear shield of another would be less likely to complete their nuclear project. I will use the nuclear ally variable as coded by Jo and Gartzke (2007).

The presence of a *rival* has similarly been seen in previous work as a serious determinant of whether a nation begins to pursue nuclear weapons. I can similarly expect that having a rival would make a country less likely to give up their program once they possess it. However, there is some question as to whether that opponent being a *nuclear rival* would have a positive or negative impact upon his decision to continue or cease his program, as discussed earlier. This data also comes from the Jo and Gartzke (2007) data set.

Finally, I need to note the actual military situation that the nation finds itself in. As such, I will look at whether the state has been in a *war within the last 5 years*, including the year in question. One would expect that a nation that has recently been involved in a war would feel more at threat and would thus be less likely to sacrifice their security blanket nuclear program. This data comes from the Correlates of War dataset as well.

Cost Variables -

The cost side of the cost-benefit ledger is also made up of a variety of factors. I need to look at both the underlying *economic and nuclear capacities* of the nation in question. I use the Jo and Gartzke-developed variables in these areas. Economic capacity is represented by:

$$\text{Economic capacity} = (\frac{\text{Energy}}{\sum \text{Energy}} + \frac{\text{Iron and Steel}}{\sum \text{Iron and Steel}})/2 \quad (13)$$

where energy and iron and steel are the availability of those types of resources within the state. The summation operator is the total of each within all nation worldwide. Nuclear capacity is represented on a scale of 1 to 7 as a function of uranium deposits, metallurgists, chemical engineers, nuclear engineers/physicists/chemists, electronic/explosive specialists, nitric acid production capacity, and electricity production capacity. Based upon previous work, I should expect that as these factors increase they reduce the cost of a nuclear program and make it easier for a country to continue. I will also look at logged *real gdp per capita* as recorded by Maddison in his Historical Measures of the World Economy. By controlling for this in addition to the underlying economic capacity, it can measure whether the economy is over or underperforming. The assumption is that overproduction would further lower cost and decrease the chance that the program will be stopped.

Additionally, I can look at whether the nation is receiving *nuclear assistance* in developing weapons. Nuclear assistance would lower the cost of the program as it saves the state from having to develop its own technological innovations. One would expect that this would decrease the chance of a state losing its weapons program. It is measured upon the Kroenig (2009) data set on sensitive assistance.

International Lever Variables -

This vector proxies for a more precise measure of economic sanctions and benefits, but has the added advantage of picking up the soft power effects of the threat of sanctions and cut-off aid. I use logged versions of *import and export* data taken from the Mesquita, Siverson, Morrow, and Smith (2003) data set on political survival and the Roodman (2008) data set on net aid transfers to represent foreign aid flows. I would expect that the more trade in which a country is involved and the more aid it received, the more susceptible they will be to outside pressure, and thus the more likely it is that they will give up their nuclear programs.

One quick note on a limitation within the aid data: it is not available prior to 1960, and I thus see a drop in the number of observations from 533 to 459. I will thus run the regression with and without the NAT variable to see any potential effects of this drop in the number of observations. I do not expect this to be significant, however, because there are no nations which gave up their program prior to 1960 when the NAT variable becomes available.

Risk Variables -

The threat that the international community faces from a potential nuclear nation depends in large part upon the perceived *antagonism* of that state. However, that is not something that can be perfectly quantified. As a proxy, I will use a probit regression developed by the Correlates of War data team that looks at the probability that a nation will be involved in a war within the next five years. This regression is specified as:

$$\Pr(Y = 1|X) = \Phi(\beta_0 + \beta_1 \text{milex} + \beta_2 \text{previous wars} + \beta_3 \text{rival} + + \varepsilon) \quad (13)$$

In this specification, previous wars looks at the length of time since each war, the severity of the wars, and whether the nation was the provocateur. I then take the predicted values and insert them into my main regression equation (12). I expect that a state that is viewed as more antagonistic will actually be more likely to give up their nuclear program as they will be viewed as a greater threat by the international community, and thus worthy of greater commitment. I expect that this effect may be different depending upon whether the state has been involved in a recent war, and so I will also interact it with the *war last 5 years* variable.

Additionally, I look at the *program age* of the nuclear program. I expect that program inertia and sanction fatigue will set in, as seen in the theoretical model, and that as time passes, it will become more difficult to get a nation to give up its program. Observationally, many such programs end relatively early, with one ending after two years and the average cessation age being twelve.

Domestic unrest could also be an important determinant of international commitment. One of the biggest fears concerning nuclear proliferation is that a nation will acquire a bomb that lacks proper custodial controls, and that the technology will leak to a non-state actor that cannot be deterred. As such, I expect that a state with more domestic instability, measured by a logged function of riots, protests, and violent crime provided through the political stability dataset, will be more likely to give up its program. This effect is because the international community will be more committed. Also, I would guess that a *non-democratic change in the head of state within the previous five years* would increase the commitment of the international community to achieve cessation, since they may see a new leader as less predictable and more unstable. Alternatively, a new leader may be more persuadable regarding the benefits of a program started under their predecessor. I will also interact the two variables in order to find a better understanding of the underlying causes of any discovered relationships.

It is important to note that these vector assignments are, to some extent, arbitrary. There are certainly effects among some of these variables that may be theoretically understood under a different header. For example, many of the international risk variables may have demand-side implications, such as program age and a change in head of state, while some factors such as conventional military strength may make the acquisition of a nuclear bomb riskier for the international community to stomach. It will be important to keep this in mind when interpreting the results.

On a final note concerning the data, I use five year smoothed averages for non-binary variables unless I specify otherwise, such a war-related variables and program age. Since many of these variable changes may take time to take effect, this is a more accurate way to examine the results. This does open the results to attenuation bias, however, since for each coefficient determination, the cease program states and non-cease program states have some overlap. This should mean, however, that my results are lower-bounds of the effects of the variables. Being able to bound the bias will make this convenience more workable.

Table A: Probit Results

Dependent Variable: Cease Program

	(1)			(2)		
	β	p-value		β	p-value	
Military Value						
-ln(Military Expenditures)	0.332	0.245		0.351	0.220	
-Nuclear Ally	-2.596	0.000	***	-2.415	0.000	***
-Rival	-2.546	0.000	***	-2.495	0.000	***
-Nuclear Rival	1.732	0.009	***	1.613	0.017	**
-War Last 5	1.094	0.455		1.039	0.478	
Cost						
-Economic Capacity	-116.856	0.004	***	-123.981	0.014	**
-Nuclear Capacity	1.046	0.009	***	0.951	0.007	***
-ln(GDP Per Capita (1999$))	0.902	0.058	*	0.792	0.168	
-Nuclear assistance	-0.038	0.932		0.096	0.833	
International Levers						
-ln(Imports)	0.241	0.640		0.318	0.536	
-ln(Exports)	0.355	0.475		0.314	0.530	
-Net Aid Transfers				-0.0002	0.430	
International Commitment						
-Predicted war: Next 5 years	1.567	0.476		1.200	0.595	
-Predicted War * War Last 5	-3.565	0.129		-3.349	0.157	
-Program Age	-0.175	0.000	***	-0.169	0.000	***
-Domestic Unrest	0.225	0.371		0.398	0.266	
-Change in Head of State	-8.225	0.007	***	-9.383	0.005	***
-Domestic Unrest*Change in HoS	3.101	0.080	*	3.303	0.092	*
N	533			459		
Pseudo-R^2	0.626			0.623		
% Correctly Predicted	0.938			0.926		

Notes: Also controlled for year; ***, **, * are significant at 1%, 5%, and 10% respectively; with exception of Nuclear Ally, Rival, Nuclear Rival, War variables, and Program Age, variables are smoothed five year averages.

VII. Results

Table A shows the initial probit results. For the most part, the results are relatively the same regardless of the inclusion of the aid variable, which limits the number of observations. There does appear to be a change in the effect of GDP per capita, which is biased up without the NAT variable. This makes sense as a state with larger GDP is less likely to get aid, and aid receipt is negatively related to program cessation. The nuclear rival dummy loses some significance as well, though this seems to be due to an increase in the standard error from lost observations.

All of the vectors, besides the international levers, are statistically significant at the one-percent level. International levers has a p-value of .3228, leaving it far from being significant at any traditional level. This seems to indicate that the credibility and size constraints placed upon sanction and benefit packages, as discussed in the theoretical model, do actually limit the options of the international community.

The pseudo-R^2, while an imperfect measure of model robustness, shows that I am picking up most of the variation within program cessation decision-making. It is low enough, however, to accurately state that it is clearly missing some other factors that play a role in the process. While it is certainly possible that there are more quantifiable variables that could be added to the model, it includes every variable that has been used in traditional proliferation studies, and have even included others, such as domestic unrest and regime change, that are usually limited to only qualitative studies. This may indicate that irrationality, as has been noted in case studies of North Korea and Iraq, is more substantial than commonly thought (Litwak, 2007). It is important to note that the model does correctly predict 92-94% of decisions correctly. Studying the inaccuracies will help to understand the models limits and will be discussed in section VII.

The model is also robust to the exclusion of the United States and the Soviet Union, which would be expected to make decisions in a very different way due to the unique, post-WWII circumstances under which they pursued their program. In this scenario, none of the variables change significance, nor do they substantially change coefficient. This provides both validation to the model and evidence that the United States and USSR were acting within the same rational framework as other nations when choosing how to handle the new nuclear age.[7] Additionally, no other interaction not listed in this model had any statistical significance, nor significantly changed other coefficients or significance.

Of course, since probit results are not interesting in and of themselves, it is crucial to find a solid mode of analysis. Here, I will use the method of recycled predictions to determine the amount of variation in the probability of cessation that can be attributed to a particular variable. I first examine the probability of cessation when all continuous variables are set to their median and all dummies are set to zero. Then, each variable is individually shifted from the median to determine how the risk of the program ending changes. Risk in these cases is measured by looking at the percentage of the distance between the current probability and guaranteed cessation that is closed by shifting the variable. I only report the results from model 2 (including the NAT variable).

Military Value Variables -

It is not surprising to find that a nation possessing a rival is almost certain to keep their nuclear program. Such a nation, as found in previous case studies and empirical surveys, is likely to see the benefit to their security as so high that no trade threats or aid offers will entice them. Additionally, I find compelling evidence reaffirming the surprising outcome found in Jo and Gartzke (2007) that having a rival possess a nuclear weapon will decrease the aforementioned perceived security advantage from possessing a weapon. I can now provide additional logic to this result. Since the model is looking at whether a country fully gives up the *program* and not whether the country simply *fails to acquire weapons*, I discover that states must perceive a security disadvantage in even having a nuclear program

[7] In fact, there is great evidence that the United States and Soviet Union both legitimately considered destroying their incipient nuclear stockpiles during the early phases of the Cold War in order to end the nuclear age before it began, though this had little to do with international pressure, as nuclear weapons were not fully understood at this time, and more to do with views of security, providing further affirmation for the model's results (Intriligator & Brito, 1978).

Table B: Risk Increases (via Method of Recycled Predictions)

	(2)				
	Median	Maximum	Change in Prob.	Relative Risk	
Military Value					
-ln(Military Expenditures) (Excluding "great powers")	15.315	17.419	0.142	62.00%	
-Nuclear Ally	0	1	-0.716	-92.87%	***
-Rival	0	1	-0.708	-91.83%	***
-Nuclear Rival	0	1	0.214	93.45%	**
-War Last 5	0	1	0.151	65.94%	
Cost					
-Economic Capacity (Excluding "great powers")	0.012	0.084	-0.771	-100.00%	**
-Nuclear Capacity	6.4	7	0.12	52.40%	***
-ln(GDP Per Capita (1999$)) (Excluding "great powers")	8.670	9.778	0.167	72.93%	
-Nuclear assistance	0	1	0.026	11.35%	
International Levers					
-ln(Imports) (Excluding "great powers")	9.265	11.186	0.139	60.70%	
-ln(Exports) (Excluding "great powers")	9.250	11.111	0.131	57.21%	
-Net Aid Transfers	0	4328.212	-0.353	-45.78%	
International Commitment					
-Predicted war: Next 5 years	0.111	0.949	0.11	48.03%	
-Predicted War * War Last 5	0.000	0.948	-0.927	-92.70%	
-Program Age (see below)					***
-Years 0 to 10	n/a	n/a	-0.083	-10.77%	
-Years 10 to 20	n/a	n/a	-0.502	-65.11%	
-Domestic Unrest	0.896	3.820	0.198	86.46%	
-Change in Head of State	0	1	-0.771	-77.10%	***
-Domestic Unrest*Head of State	0	3.82	0.802	350.22%	*
P(Cease Program)	0.771				

Notes: Also controlled for year; ***, **, * are significant at 1%, 5%, and 10% respectively; with the exceptions of Nuclear Ally, Rival, Nuclear Rival, War variables, and Program Age. Variables are smoothed five year averages.

if a nuclear rival is present. This may indicate a feeling that international norms would allow their rival to strike against them to preserve nuclear asymmetry, as seen with the Israeli strikes upon Iraq's program at Osirak in 1981 and Syria's potential program at Dia El-Zor in 2007. Thus, giving up a program now has the advantage of taking this option off of the table. Preserving this norm allowing militaristic defense of nuclear asymmetry will help coerce countries into giving up their programs.

A significantly more surprising result was the very large, negative risk associated with having a nuclear ally. Based upon the conventional wisdom holding that nuclear allies reduce security needs and previous empirical research showing that nuclear alliances make a country less likely to pursue nuclear weapons, one would predict the opposite relationship. In fact, this has been a major basis of modern coercion theory, as states have used the offer of nuclear protection as a replacement for comprehensive packages of sticks and carrots. This result seems to indicate counter productivity in such a method.

Jo and Gartzke (2007), however, showed that having a nuclear ally makes a country less interested in the initial pursuit of nuclear weapons, and potentially delays their physical acquisition. This may indicate the presence of a moral hazard component within the result in my model. If this is an accurate interpretation, alliances with nuclear weapon states disincentives actual acquisition through security guarantees, but also signals to states that they will not feel an outside threat to their program. With a great power protector, they will be able to extract maximum benefits from the international community for agreeing to eventual cessation; meanwhile, they can also feel secure that they are immune from military strikes until such a maximum is reached.

Unsurprisingly, I find, as expected, that increased conventional military strength makes a country more amenable to giving up their nuclear weapon program. I exclude the United States and the Soviet Union when computing the maximum for this variable due to the unique size of their militaries during the Cold War. This effect is not statistically significant, however, and does not have as much potential, relative to other variables, for changing the probability of cessation. Thus, a conventionally strong military is not a pure substitute for nuclear weapons.

Cost variables -

As expected, the largest effective (non-interaction) coefficient was the underlying economic capacity of a state. Interestingly, however, adjusting gdp per capita while holding economic capacity constant can negate much of that effect.[8] While gdp per capita is not statistically significant at conventional levels, it was nearly significant at the five percent level without the inclusion of the aid variable and the limitation in years, and the two are jointly significant at the one-percent level with a p-value of 0.0013. An explanation for this effect is that when a state over performs economically, it has less need for aid, and thus less need for a nuclear program that it intends to use as a bargaining chip. This would indicate that much, though not all, of the appeal of a program is the chance to extract benefits from the international community, which is more evidence for moral hazard.

[8] It is important to also note that I excluded the U.S., U.S.S.R., U.K., and France when calculating the maximum, due to their relatively oversized economies.

Another surprising outcome is that having greater nuclear capacity makes a nation more likely to give up their program. Based upon the same logic as the economic capacity variable, I would expect that this would have an inertia effect whereby greater nuclear capacity reduces cost and thus makes pursuit easier and less of a burden. In fact, this is the result found for the initial program start in the existing literature. While the risk effect is relatively small, that is mostly due to the fact that the average country that has a program has nearly full nuclear capacity, leaving little room for movement to the maximum. Thus, with a statistical significance at the one-percent level, this is a result that cannot be ignored. Since energy generation is included within the nuclear capacity function, the effect I am picking up here could that of energy needs. In other words, a country that needs more energy will be more likely to pursue a nuclear program as a means for getting access to dual-use energy and/or receiving "atoms for peace" style energy help from the international community. If a country does not need energy, that incentive for continuing a program is removed. Extended work on this topic should include a separate variable for energy production and remove it from the nuclear capacity function in order to examine if this bias is occurring.

International Lever variables -

As mentioned above, the international lever variables have no statistical significance, even when trying different permutations of joint significance. Additionally, the actual effects are relatively small. This does not bode well for the ability of the international community to directly influence the program cessation decision of a state.

While the openness variables run in the proper directions, increasing the likelihood that they will give up their program, the foreign aid variable shows a distressing result above and beyond its lack of significance: increased aid decreases the probability of program cessation. Thus, while I cannot reject the hypothesis that foreign aid transfers have no effect, it appears that any effect that does exist runs counter to the common intuition and actually prolongs program life. This may provide further evidence of moral hazard, as aid has been the primary mechanism, along with nuclear protection, that has been used to incentivize states to reenter the international community and give up their programs.

Risk variables -

Holding the presence of a past war constant, the predicted antagonism of a state does, as expected, increase the probability that they will give up their nuclear program. This lends credibility to the international community's threats, and thus aids in their ability to coerce. However, when I look at whether a state is expected to take part in a future war interacted with their previous military excursions, I find that the effects mostly wash out. Additionally, no permutation of joint significance has a p-value below 0.5, further indicating the limited strength of interpreting these measures.

The program age variable, as expected, shows significant inertia effects within nuclear programs. What is interesting about these results is that the effect really takes hold between years ten and twenty. It is clear that program age has a constant build-up effect whereby the older a program is, the harder it is to stop it. This effect ramps up during the second decade. This provides clear evidence that any action taken against a nuclear program needs to be immediate. This also provides signs of

reputation constraints, both on the state, which is unlikely to give up an old, treasured program, and the international community, which would have already buttressed itself against the institutional costs discussed in the theoretical model from allowing the nation to continue its program. As such, they would be less willing to face the cost of putting together a coercive package.

Turning to the domestic situation in the country in question, I find important evidence for the surprising result that a peaceful change in the head of state significantly lowers the possibility of program cessation. This may be evidence that a new leader who inherits a nuclear program is unlikely to give up the prestige that goes along with such a program early in his term. This calls into question the idea that promoting regime change in and of itself is the proper way to go about getting a nation to give up their program.

There is the finding, however, that regime change coming amidst domestic unrest, is the strongest promoter of cessation. In fact, the probability change is so large that it is actually over three times the difference between 100% cessation and the probability at the medians. There are two ways to interpret this result. Hawks would show this, along with the failure of traditional sanction and benefit levers, as evidence that forced regime change and subsidized revolution are the greatest way to bring about an end to a nuclear program. However, this seems weak on a normative level, since military regime change requires such a great cost. Promoting instability, meanwhile, possibly increases the chance for the program to end, but will also increase the chance of a loss in custodial control for nuclear technology, which is the biggest fear concerning nuclear proliferation (Intrilligator and Brito, 1981).

Additionally, it is likely, as explained above, that increased instability only increases the chance of cessation because it adds credibility to the international community's threats due to their added concern with loss in custodial control. If this is, in fact, the driver of this result, then incentivizing instability will do nothing to aid the nonproliferation regime. The normative implications of such an explanation is that the strongest way to get a nation to give up its nuclear program would be to provide regime assurance in which one promises to not subsidize revolutionaries in return for an end to the nuclear work. This has been shown in case studies to have succeeded in Libya in 2003 and Syria in 2008, and may have wider applicability than currently acknowledged (Litwak, 2007).

Table C: Largest Risk Increases

	Relative Risk
Economic Capacity	-100%
Nuclear Rival	93.45%
Nuclear Ally	-92.87%
Rival	-91.83%
Domestic Unrest	86.46%
Change in Head of State	-77.10%
ln(GDP Per Capita (1999$))	72.93%

Table 3 sums up the top (non-interacted) risk producers that are statistically significant at the ten-percent level. In summary, it is clear that demand-side variables that are mostly outside of the international control are the biggest determinants of cessation. The only one that is directly responsible to international influence is the presence of a nuclear ally, which now provides more controversial utility, as it appears that a nuclear defense actually incentivizes program continuity.

VIII. Limitations

It is important to note, as in the methodology section, that it is difficult to determine through what mechanisms the multiple variables affect the changes in probability. For example, there is difficulty in determining whether domestic unrest should be filed within the international risk vector, due to its effects upon the fear of a loss in custodial control, or under the cost vector, due to the added price to the program from needing to spend resources upon protecting the program that could be spent on enhancing the social contract that is often used to keep unrest in line.

What about the missed guesses? There are four countries that find that the model fails to place them on the right side of the 50% chance of the cessation divide. I should examine each of the four failures:

Sweden (1970-1971)

In 1970, Sweden gave up their nuclear weapon program. The model, however, predicts that it should have continued for two more years. It seems, therefore, the Swedes simply understood the trends that were coming in the near future and gave up their program a little earlier than otherwise predicted. This does not seem to raise questions about the efficacy of the model.

Yugoslavia (1982-1987)

In 1983, Yugoslavia restarted its nuclear program, which had been defunct since 1964. This is despite the fact the model predicts probability of cessation between 83 and 98 percent. Based upon previous case studies, the primary driver of this resumption was based upon the death of Tito in 1980 and the rise to power of Defense Minister Admiral Branko Mamula. This actually meshes with the model's result that peaceful regime change decreases the probability that a pre-existing program can be, or remain, scuttled (Potter, Milijanic, and Slaus, 2000).

The reason for the false predictions, then, seems to be decreasing economic capacity combined with increasing GDP per capita. From 1982 to 1987, underlying economic capacity, as quantified in the model, fell from an already low .005 to .004, while GDP per capita increased from $6,139 to $6,418. This further enhances the interpretation that the effects seen in the underlying model related to economic capacity and GDP were based upon moral hazard and the decreased need for aid that comes from increasing productivity. In Yugoslavia's case, however, it appears that temporary resumption of the program, which again ceased in 1988, came from reputation and security concerns, and that the desire for international bribes to scuttle the program did not play as large a role here as elsewhere.

Brazil and Argentina (1991)

In 1991, Brazil and Argentina both gave up long-standing nuclear programs in return for international aid. This is the model's biggest failure, as the probability listed for such a cessation were two and seven percent, respectively. This raises the question of whether there are new variables affecting these decision-making processes that did not play a role during the Cold War. For example, both states faced large amounts of debt to the foreign community (Goldman, 1991). It is possible, in the post-Cold War world where full-scale nuclear war is much less of an option, that this debt could be the strongest lever for the international community to use against states. Unfortunately, measuring such data is very difficult, especially for rogue states such as Iran, North Korea, and Libya. A future resumption of this research should expand beyond 1991 and include a debt variable in order to attempt to determine what has changed since the fall of communism.

IX. Conclusion

In summary, I can see it is not easy to make any "stick and carrot" package credible. Commitment is key to the credibility of sanction threats, while the perceived risk of not offering some sort of incentive for opting out is critical for benefits to work. Attempts to take time to determine the actual risk can actually have perverse incentives that make things worse for the international community. In reality, patience may not always be a virtue.

The empirical evidence further enhances the pessimism about the ability of the international community to take any actions to quicken the cessation of a nuclear program. In addition to the lack of statistical or economic significance of trade openness and foreign aid upon cessation, there appears to be many counterintuitive results for most of the current chief aspects of foreign policy towards potential proliferators. For example, providing a nuclear shield may actually further enhance the security of a nuclear program and cause programs to last longer than they would have otherwise, and a peaceful change in head of state may actually make a nation value their nuclear program more. All of this is further evidence of moral hazard within these coercive packages.

This model has potentially wide applicability across other areas of asymmetric international relationships. It is not difficult to re-imagine this game for other issues. Further work should look into how these variables affect other unconventional weapons programs, such as biological, nuclear, and cruise missile technology, as well as the effects upon so-called "revisionist states" that seek to sponsor revolutions in other nations, such as Iran.

Also, it would be useful to design a future model that can take into account the reality that the game really amounts to n-players, with the international community often being at odds with each other. This collective action problem could certainly affect the outcomes and messages to be taken away from this study.

Additional work can also find ways to explain some of the problematic results within this model. For example, post-1991 data should be added in order to pick up any differences in results since the end of the Cold War. This would help explain the surprising end of Brazil and Argentina's programs. Also,

data that deals specifically with debt held by the international community should be added. This data does not currently exist prior to the 1970's, but if it could be expanded back to World War II, it would potentially explain these failed predictions. Additionally, one could find a way to separate energy production from the nuclear capacity variable and create that as a variable in and of itself. This would help to interpret the surprising positive result of that coefficient within this model and see if my prediction that it is due to dual-use energy needs is true.

There are some problems I faced in designing this model when it came to finding proxies for some variables, particularly moral hazard. While the results show quite a bit of evidence of moral hazard, it would be useful to design a stronger empirical model for moral hazard that could be applied to models such as this in the future. Additionally, a sanction/benefit package level exploration would be useful, though such a study would require parsing out whether a coercive package was meant to end a nuclear program, change some other element of state behavior, or some combination. This determination is critical before such a study can be undertaken.

Once I understand both how rogue actors should and have behaved in the past, I can stop treating them as random exogenous factors and start actually understanding the states' actions, and planning our own responses in kind. These models take a first in-depth look at the causes of nuclear cessation and finds results that could have a strong influence upon policy. The clear overarching message, though, is that nations must be careful when trying to influence the payoff structures of their allies and adversaries: few mechanisms are useful, and many can actually create a moral hazard problem costlier to the international community than the initial program.

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