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A Game-Theoretic Analysis of the Nuclear Non-Proliferation Treaty

Peter Revesz
University of Nebraska-Lincoln, prevesz1@unl.edu

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Peter Z. Revesz
Department of Computer Science and Engineering
University of Nebraska-Lincoln
Lincoln, Nebraska 68588-0115
Email: revesz@cse.unl.edu
http://cse.unl.edu/revesz
Telephone: (1+) 402 472–3488

Abstract—**Although nuclear non-proliferation is an almost universal human desire, in practice, the negotiated treaties appear unable to prevent the steady growth of the number of states that have nuclear weapons. We propose a computational model for understanding the complex issues behind nuclear arms negotiations, the motivations of various states to enter a nuclear weapons program and the ways to diffuse crisis situations.**

I. Introduction

Numerous international treaties are made with the best of intentions. However, every treaty needs to be examined on its actual affects rather than on its intentions. The *Treaty on the Non-Proliferation of Nuclear Weapons*, commonly referred to as the *Non-Proliferation Treaty (NPT)* aimed to make the world more secure from nuclear weapons. The treaty divided all countries based on their nuclear status as of January 1, 1967, into nuclear weapon states (NWSs), which included China, France, the Soviet Union, the United Kingdom, and the United States, and non-nuclear weapon states (NNWSs), which included all the other states. All the NWSs signed the treaty as well as all the NNWSs except India, Israel and Pakistan. North Korea is the only country that withdrew from the treaty. Hence the NPT enjoyed a great popularity and is often considered a great success.

The essence of the NPT is a bargain between the NWSs and the NNWSs. The NWSs committed themselves to nuclear disarmament and to help the NNWSs to develop civilian use of nuclear technology. In return, the NNWSs committed themselves to foresake ever developing nuclear weapons. Unfortunately, this bargain did not work out as planned. After forty years, the NWSs increased the total number of their nuclear weapons, while many NNWSs engaged in clandestine nuclear weapon development programs. The world does not look safer than it was forty years ago. Nevertheless, NPT defenders claim that the NPT slowed down nuclear proliferation. In other words, without the NPT, nuclear proliferation would have been even worse than it is actually today. In this paper we examine this hypothetical claim using game theory. We start our analysis with some definitions.

Uranium enrichment is the process of dividing any uranium compound into two parts, one part with a higher and another part with a lower concentration of U 235 atoms. Uranium ore has a very low percent of U 235 atoms. Most nuclear reactors can work on *low enriched uranium (LEU)*, where the proportion of U 235 is less than 20 percent. Nuclear bombs require *highly enriched uranium (HEU)*, where the proportion of U 235 is greater than 80 percent. The uranium enrichment technology is the same for LEU and for HEU. To obtain HEU, the uranium enrichment process simply needs to be repeated several times until the desired level is reached.

Plutonium reposessing is the process of separating the plutonium, a byproduct of uranium fission, from the rest of the spent fuel in an uranium atomic reactor. The plutonium can be used either as fuel for plutonium atomic reactors or as material for plutonium atomic bombs.

Dual-use technology is any technology that can be used for both civilian or military purposes. For example, uranium enrichment and plutonium reposessing are both dual-use technologies.

The NPT allows any NNWS to aquire and develop any dual-use nuclear technology. Moreover, citing the NPT, many NNWSs expect the NWSs to provide assistance in aquiring dual-use technologies including uranium enrichment and plutonium reposessing. When a NNWS aquires these technologies, it essentially develops 80 percent of an atomic bomb because civilian and military nuclear technologies largely overlap. Such a NNWS could be tempted to invest the 20 percent extra effort required to develop an atomic bomb. Hence any of its adversaries may become concerned whether it will decide to develop a bomb. Moreover, these adversaries need to be prepared for all eventuality. That means that these adversaries also need to build up their NPT-allowed dual-use nuclear technologies and be ready to activate a nuclear weapons program of their own just in case any of their adversary NNWSs decides to build a nuclear weapon. This leads to a situation, which we define as follows.

Soft arms race occurs when states develop nuclear-related dual-use technologies with the intent to be strategically prepared to develop nuclear weapons.

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Several experts are concerned about a soft arms race in the Middle East and North Africa, where many energy rich states insist that they need to develop peaceful nuclear reactors. Developing nuclear technology is expensive, and most of these countries would not have been able to aquire any nuclear technology without direct or indirect assistance from NWSs. Hence the question can be raised whether the NPT contributed to a soft arms race regarding nuclear technology. Further, if there is a soft arms race, how likely it is to lead to an active nuclear weapons program? We try to answer these difficult questions using game theory, and thereby contributing to the theoretical study of nuclear proliferation [2], [4], [8].

This paper is organized as follows. Section II briefly reviews game theory and the history of its use for analyzing nuclear issues. Section III describes a game theoretic analysis of the NPT. Section IV gives a game theoretic analysis of what may happen in a world without the NPT. Finally, Section V gives some conclusions and offers some hope of improving the current nuclear non-proliferation situation.

II. A Review of Game Theory

During the Cold War, game theory was a reasonable approach to arms control negotiations because nuclear tests and total arsenal numbers were hard to verify. Virtually the only thing that could be detected was an already approaching*intercontinental ballistic missile (ICBM)*. There was not enough time and technological sophistication to shield against nuclear ICBM strikes. Therefore, in case of a nuclear attack, each side faced the choice between continued restraint or nuclear retaliation. Table I shows the nuclear options of Russia and the United States during the Cold War expressed in a hypothetical payoff matrix using game theory [9]. The table assumes that it would cost each side 20 points to be destroyed in a nuclear attack. However, if any side is destroyed, at least it can derive a satisfaction of five points by retaliating and destroying the other side too.

Russia ↓ US →	**no strike**	**first strike**	**retaliation**
no strike	*0, 0*	-20, 0*	NA
first strike	*0, -20	-20, -20	*-20, -15*
retaliation	NA	*-15, -20*	NA

TABLE I: A hypothetical payoff matrix during the Cold War.

Clearly, some entries in the table, shown as NA, are not available or logically impossible. For example, it is not possible to retaliate against something that did not happen. Even the case of both countries deciding on a first strike simultaneously would have an extremely small possibility. In this example, game theory gives three *Nash equilibrium points* [3], which are shown as the matrix entries with two stars, that is, one star on the left and another star on the right of the entry. In this case, the rational choice would be *0,0*, which is the best equilibrium point for both sides. This is the game theoretic explanation for how the *mutually assured destruction (MAD)* nuclear posture worked during the Cold War.

The idea behind MAD is that if one side attacks, then it will get destroyed. That is supposed to be the ultimate deterrence. However, for it to work the leaders with access to the nuclear triggers have to be non-delusional and non-suicidal (otherwise, the payoff matrix values could change.) Unfortunately, that cannot be guaranteed. Today there is an increasing danger that not only possible delusional dictators but also terrorist chiefs and suicide bombers may gain access to nuclear weapons.

The success of MAD also depended on maintaining a retaliatory capability because MAD would be impossible if either side could make a first strike that debilitates all the nuclear weapons of the other side. This aspect of MAD tends to lead to an arms race as both sides feel that they need some extra (numerous and/or advanced) weapons to successfully deter the other side.

Russia ↓ US →	**no strike**	**first strike**	**retaliation**
no strike	*0, 0*	-20, 0*	NA
first strike	*0, -20*	-20, -20*	NA
retaliation	NA	*-15, -20*	NA

TABLE II: Modified payoff matrix in case Russia would gain completely debilitating first-strike capability.

To illustrate this last point, Table II shows the changed cost matrix in case Russia could attain such a first strike capability. Here the -20,-15 outcome would no longer be available, and *0,-20* would be a new equilibrium point. Russia would prefer the two equilibria *0,0* and *0,-20* to the third equilibrium *-15,-20*. However, the first two equilibria would be extremely unnerving to the U.S. population. This situation is symmetric. Hence both sides need to maintain a retaliatory capability as a credible deterrent. To maintain a retaliatory capability, both sides kept secret the locations of their nuclear weapons and increased the number of their nuclear warheads to very high levels, leading to a nuclear arms race. Hence Table II is a game theoretic explanation of the nuclear arms race during the Cold War.

In summary, game theory provides insights for cases when there is little or no trust between the participants. Since neither side can trust the other side, they need to play safe first and foremost. Game theory fails to account for trust among the partners in negotiations. Normally, people participate in negotiations because they trust that their partners will keep the agreements, which can be enforced by verification procedures, courts, or the threat of breaking off a relationship. Game theory explains well the purely adversarial strategies but fails to provide a realistic model for negotiations [5], [6], [7].

III. A Game Theoreric Analysis of The NPT

In our analysis, we consider a set of variables shown in the first two columns of Table III. The exact values of these variables can be only estimated, which is something beyond the scope of this paper. However, it is only the relative strength of these variables that is important for our analysis. As shown in the third column, each variable can have either a single

	None	Reactor	Bomb
NWS ally	*0, 0	*0, 2*	*−1, 1
NWS adversary	*0, 0	−7, 3	−9, 4*

TABLE V: Payoff matrix.

number value, meaning that it is the same for all countries, or it can have two different values for allied and adversary countries, respectively. In the following, we index the variables by 1 for allies and 2 for adversaries if there are differences in values.

For each of the estimates, we provide some explanation in the fourth column of Table III. We assume extra trade benefit *etb* to the NWS states to be zero because the NWS countries were forbidden to sell weapons-related nuclear technology to other countries. This regulation restricted the market and the clandestine transactions that still occurred seem to have been done from political rather than from financial motivations [2].

Table IV shows a matrix where the last three columns describe the three choices of any NNWS: (1) build nothing, (2) build only peaceful nuclear reactors, and (3) build nuclear bombs too. The two rows of the matrix describe the two choices of any NWS. Each NWS could consider the NNWS as either an ally or an adversary. Alliances can shift over long periods of time due to strategic reasons.

Substituting the values in Table III for the variables in Table IV, we obtain Table V. Table V shows that there is a Nash equilibrium, again indicated by two stars, for any NWS and NNWS pair. The Nash equilibrium would mean that the two states would be allies and the NNWS would restrain itself to only a peaceful use of nuclear energy. In practice, this Nash equilibrium may not be reachable because states are locked into various alliances due to other considerations. Hence some countries are bound to remain NWS adversaries. Table V does not show any equilibrium for NWS adversaries. In fact, a NWS would rather have a NNWS adversary with no nuclear technology at all, while the NNWS would rather develop nuclear weapons. The NWS could be naturally suspicious about the peaceful intentions of any adversary NNWS. Hence the current NPT environment encourages peaceful development of nuclear energy among ally NNWSs. This leads to a soft arms race among the ally NNWSs and their adversaries.

IV. Analysis Without the NPT

Imagine a world without the NPT. How the absence of the NPT would effect the values of the variables listed in Table III? First, the development cost for civilian nuclear technology would increase in general. We estimate that for NWS adversaries the development cost may double to 6 as they would have to do essentially everything themselves or pay heavy prices for nuclear technology. NWS allies would also no longer get any free nuclear technology, although they may be able to buy some at a discount. Hence their development cost would increase to about 5.

	None	Reactor	Bomb
NWS ally	*0, 0*	*0, −1	*−1, −4
NWS adversary	*0, 0*	−7, −1	−9, −2

TABLE VII: The revised payoff matrix.

When the price of civilian nuclear technology increases, the demand decreases. The price increase and demand decrease tend to cancel each other out, hence the trade benefit would not change drastically. We continue to assume that trade benefit is 1. With the increase of civilian nuclear technology, the price of military nuclear technology would also increase. Hence the extra development cost may increase from 2 to 3.

The decreased demand for civilian nuclear technology may prevent the development of the soft arms race in dual-use nuclear technology among the NNWSs. Therefore, the security benefit of civilian nuclear reactors decreases to about 1 for allies and 2 for adversaries. The extra security benefit would decrease to 0 for allies and 2 for adversaries. At the same time, the security cost and the extra security cost to NWSs would remain the same because the NWSs would be still be constrained and lose control over NNWSs that aquire nuclear technology.

To summarize the above discussion, Table VI lists all the variables whose values would be likely different in a world without the NPT.

Repeating now the game theoretic analysis with the new values as shown in Table VII reveals that the no NPT environment has a Nash equilibrium for both NWS allies and NWS adversaries. In both cases the equilibrium implies the choice of developing no nuclear technology.

V. Conclusion

We provided a game theoretic analysis of the choices of NNWSs regarding the use of nuclear technology. According to our estimates of the costs and benefits of certain strategies, it appears that without the NPT, all NNWSs states would choose no nuclear energy. On the other hand, with NPT the NNWS allies of NWSs would choose to develop only civilian nuclear energy, and the NNWS adversaries of NWSs would choose to go all the way to developing nuclear weapons.

Hence according to our analysis, the NPT seems to have made the world less secure by encouraging among the NNWSs a soft arms race of dual-use nuclear technology. Although only a few NNWSs would cross the threshold and later enter an outright nuclear arms race, their entry seems more likely because of the already present soft arms race.

These conclusions depend on the exact values of the costs and the benefits. Each state can have a particular situation which would mean that these values need to be adjusted. In addition, our game theoretic analysis did not include many other cultural, historical and political considerations that influence policy makers' decisions regarding the development of civilian or military nuclear technology. Hence we cannot

Name	Symbol	Value	Explanation
Energy benefit	eb	3	Similar reactors always yield similar amount of energy.
Trade benefit (NWS)	tb	1	Companies equally eager to sell to all.
Extra trade benefit (NWS)	etb	0	Prohibited. Negligible commercial motivation for violations.
Development cost	dc	3	Cost overruns are common in every country.
Extra development cost	edc	2	Construction costs only. Sanctions belong to *esb*.
Security cost (NWS)	sc	1, 8	Both allies and adversaries limit NWS countries' freedom.
Extra security cost (NWS)	esc	1, 2	However, allies are less dangerous.
Security benefit	sb	2, 3	Allies already have security guarantees from NWS.
Extra security benefit	esb	1, 3	Hence allies get a diminished return.

TABLE III: Variables used in the game theoretic analysis.

	None	Reactor	Bomb
NWS ally	0, 0	$tb - sc_1,\ eb + sb_1 - dc$	$tb + etb - sc_1 - esc_1,\ eb + sb_1 - dc + esb_1 - edc$
NWS adversary	0, 0	$tb - sc_2,\ eb + sb_2 - dc$	$tb + etb - sc_2 - esc_2,\ eb + sb_2 - dc + esb_2 - edc$

TABLE IV: The choices of any pair of nuclear weapon state (NWS) and non-nuclear weapon state (NNWS).

Name	Symbol	Value	Explanation
Development cost	dc	5, 6	Cost overruns are common in every country.
Extra development cost	edc	3	Construction costs only. Sanctions belong to *esb*.
Security benefit	sb	1, 2	Allies already have security guarantees from NWS.
Extra security benefit	esb	0, 2	Hence allies get a diminished return.

TABLE VI: Variables with changed values.

draw from our game theoretic analysis any firm conclusion about any particular state. Nevertheless, our game theoretic model suggests that the NPT may have affected the cost and benefit structure of the nuclear technology market, both overt and covert, in a way that encourages instead of discourages non-proliferation. This should raise a concern for the non-proliferation community. The NPT, like any other international treaty, should be evaluated by its actual affects instead of its professed intent. Although the intent of the NPT was to prevent proliferation, its actual affects may have been the opposite.

Our pessimistic analysis of the effects of the NPT, need not be the end of the story. Although it is unlikely that the NPT can be abandoned completely, there are some promising current suggestions by some nuclear non-proliferation experts. One proposal is to offer to replace free the older reactors that produce significant amounts of plutonium with newer *Liquid Fluoride Thorium Reactors (LFTRs)*, which allows for fuel utilization exceeding 99 percent and produces very little weapons grade material. Such a replacement offer may cut down on the temptation to repossess plutonium and use it or sell it to other states. We hope that continued arms control negotiations will lead to a solution that is both well-intentioned and mathematically sound.

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