# Predicting the Responses of States to the Nuclear Proliferation Issue Using Game-Theory

Peter Z. Revesz

***Abstract*—This paper argues that the willingness of countries or states to sign onto international treaties regarding nuclear non-proliferation and honor their former commitments is largely determined by their economic and security conditions that can be expressed by a few key parameters and whose interactions can be analyzed using game theory.**

***Index Terms*—arms race, dual-use technology, game theory, non-proliferation, nuclear deterrence.**

## 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 forsake 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 reprocessing** 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 reprocessing are both dual-use technologies.

The NPT allows any NNWS to acquire and develop any dual-use nuclear technology. Moreover, citing the NPT, many NNWSs expect the NWSs to provide assistance in acquiring dual-use technologies including uranium enrichment and plutonium reprocessing. When a NNWS acquires 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 possibilities. 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.

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 acquire 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

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theoretical study of nuclear proliferation [1], [2], [10].

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 considers the effect of 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 [11]. 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.

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.

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 [4], [5], [6].

## III. A Game Theory Model of Nuclear Proliferation

### A. Variables considered

In our analysis, we consider the following set of variables:

- eb — measures the *energy benefit* to a state that develops nuclear reactors. Similar reactors always yield similar amount of energy, but local energy prices are different in different states.
- tb — measures the *trade benefit* to a state for selling peaceful nuclear technology. This measure is equivalent to the *profit* that the state's companies make by selling abroad peaceful nuclear technology. Companies are usually eager to sell their products to any country if such a trade is allowed.
- etb — measures the *extra trade benefit* to a NWS that sells nuclear weapons technology. Since the selling of nuclear weapons technology is widely prohibited and violators can be heavily fined, there is usually only a negligible commercial motivation to sell such technology. Nevertheless, with local political approval companies may engage selling nuclear weapons technology.
- dc — measures the *development cost* of building peaceful nuclear reactors. This cost is frequently underestimated. Hence cost overruns are common.
- edc — measures the *extra development cost* of going beyond peaceful to weapons development. The edc measures only the extra construction costs, not sanctions and other political costs. The construction costs can be high due to the extra need for secrecy, i.e., building facilities deep underground and in remote areas raises the cost.

| 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.

| 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.

$sc_1$ measures the security cost to a NWS for providing peaceful nuclear technology to allies.

$sc_2$ measures the security cost to a NWS for providing peaceful nuclear technology to adversaries.

$esc_1$ measures the *extra security cost* to a NWS for providing nuclear weapons technology to allies. Both allies and adversaries limit NWS countries' freedom but to a different degree because allies are less dangerous.

$esc_2$ measures the *extra security cost* to a NWS for providing nuclear weapons technology to adversaries.

$sb_1$ measures the *security benefit* to a NNWS ally for building peaceful nuclear reactors.

$sb_2$ measures the *security benefit* to a NNWS adversary for building peaceful nuclear reactors.

$esb_1$ measures the *extra security benefit* to a NNWS ally for building nuclear weapons.

$esb_2$ measures the *extra security benefit* to a NNWS adversary for building nuclear weapons.

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.

*B. The options*

Regarding nuclear technology, each NNWS has three options:

**none** means it does not seek any kind of nuclear technology.

**reactor** means it is only trying to build nuclear reactors for energy generation.

**bomb** means it is trying to develop nuclear weapons.

At the same time, each NWS has the same three options for selling to the NNSW:

**none** means it does not sell any nuclear technology.

**reactor** means it is only willing to sell nuclear reactors for energy generation.

**bomb** means it is willing to sell also nuclear weapons technology.

*C. Counting total benefits*

The estimated costs and benefits to a NWS when it deals with a NNWS are greatly influenced by the NWS considering the NNWS to be an ally or an adversary. In the following we first consider the possible choices between a NWS and an ally NNWS.

**ally NNWS chooses none:** This would be zero total benefit for the NNWS.

**ally NNWS chooses reactor:** The NNWS ally would enjoy an energy benefit $eb$, a security benefit $sb_1$ that would be generated by its nuclear knowledge and growing capability to build a nuclear weapon if desired. These benefits would be offset by the development cost $dc$ of building the nuclear reactor. Therefore, the total benefit to the NNWS ally would be:

$$eb + sb_1 - dc$$

**ally NNWS chooses bomb:** For an ally NNWS, the decision to expand from peaceful reactor technology to nuclear weapons technology would entail extra security benefit $esb_1$ by increased independence even from an ally NWSs and extra development costs $edc$. Hence the total benefit to the ally NNWS would be:

$$eb + sb_1 - dc + esb_1 - edc$$

**NWS chooses none for ally NNWS:** In today's nuclear market we can assume that states that are bent on either nuclear reactor or nuclear weapons technology, they will obtain them eventually. Therefore, the NWS would have zero benefit if the ally NNWS chooses none, $-sc_1$ benefit if the ally NNWS chooses rector, and $-sc_1 - esc_1$ if the NNWS chooses bomb. The NWS would have some security costs because the ally NNWS would get the nuclear technology that it desires.

**NWS chooses reactor for ally NNWS:** If the ally NNWS buys reactor technology from the NWS, then the NWS would have a trade benefit $tb$ but lose some security benefit $sc_1$ because there is a small chance that the ally would later turn against it or sell the nuclear technology to another state, which is not considered an ally by the NWS. Therefore, the total benefit to the NWS would be:

$$tb - sc_1$$

**NWS chooses bomb for ally NNWS:** When an ally seeks nuclear weapons, the NWS that is willing to sell nuclear weapons technology may gain extra trade benefits $etb$ but has to risk extra security costs $esc_1$ in case the ally turns against it or passes the technology to third states. Hence the total benefit to the NWS would be:

$$tb - sc_1 + etb - esc_1$$

**Adversary NNWS:** In the interaction between a NWS and an adversary NNWS only the option of “none” or “reactor” are politically acceptable for the NWS. For the “none” and the “reactor” choices, the same total benefits can be assumed except the values $sc_1, esc_1, sb_1, esb_1$ should be replaced by $sc_2, esc_2, sb_2, esb_2$, respectively. We can make the following assumptions:

1) All variable values are greater than zero.

2) $sc_2 > sc_1$ because the security cost to a NWS is much greater when it sells to an adversary than when it sells to an ally.

3) $sb_2 > sb_1$ because the security benefit is greater to an adversary NNWS, which may not have any strong NWS allies, than to an ally NNWS.

4) The extra security cost $esc_2$ would be normally prohibitively high. That is, $tb - sc_2 + etb - esc_2 < 0$.

5) The extra security benefit $esb_2$ is generally overestimated beyond its real value. NNWS adversaries that have few friends tend to behave in a paranoid manner, which leads to an overestimation of $esb_2$. That is, $esb_2 - edc > 0$ and $eb + sb_2 - dc + esb_2 - edc > 0$.

6) The extra development cost $edc$ is equal for both an ally and an adversary. Some adversaries may be attacked and sabotaged by the NWS, which may suggest that the adversaries could have a higher extra development cost. However, any ally of one NWS could be an adversary of another NWS and could be similarly attacked and sabotaged. In practice, both allies and adversaries would try to hide their nuclear weapons programs from the public, which drives up the cost for both allies and adversaries that may embark on nuclear weapons development.

7) The extra trade benefit *etb* to the NWS states is small because the NWS countries are prohibited to sell weapons-related nuclear technology to other states. This regulation restricts the market and the clandestine transactions that still occur seem to have be done from political rather than from financial motivations [1].

### D. A game-theoretic analysis

Tables III and IV show the game-theory payoff matrices when a NWS deals with an ally NNWS or an adversary NNWS, respectively. As before, each entry of the payoff matrix shows two values. The first value is the total benefit to the NWS and the second value is the total benefit to the NNWS.

*Theorem 1:* In Table III the following conditions hold:

1) If $eb + sb_1 - dc > 0$ or $eb + sb_1 - dc + esb_1 - edc > 0$ then the NWS and the ally NNWS both choosing ”None” is not a Nash equilibrium.

2) If $esb_1 - edc > 0$ then the NWS and the ally NNWS both choosing ”Reactor” is not a Nash equilibrium.

3) The NWS and the ally NNWS both choosing ”Bomb” is always a Nash equilibrium.

**Proof:** In Table III, we can mark in each column by a star on the left the values that are the maximum for the NWS. Nash equilibrium would mean that is we mark in each row by a star on the right the values that are the maximum for the ally NNWS, then we have a doubly starred case. To prove the theorem, we argue for each case as follows:

1) If $eb + sb_1 - dc > 0$ then the ally NNWS would rather choose ”Reactor” over ”None.” Similarly, if $eb + sb_1 - dc + esb_1 - edc > 0$ then the ally NNWS would rather choose ”Bomb” over ”None.” Hence in neither case would the NNWS choose the ”None” option, which means that both the NWS and the ally NNWS choosing ”None” cannot be a Nash equilibrium.

2) If $esb_1 - edc > 0$ then the ally NNWS would rather choose ”Bomb” over ”Reactor.” Hence the NWS and the ally NNWS both choosing ”Reactor” cannot be a Nash equilibrium.

3) In the third row, the only choice for the ally NNWS is ”Bomb.” In the last column, the maximum choice for the NWS is also ”Bomb.” Hence the NWS and the ally NNWS both choosing ”Bomb” is always a Nash equilibrium.

*Theorem 2:* In Table IV the Nash equilibrium is the case when the NWS chooses ”Reactor” and the adversary NNWS chooses ”Bomb.”

**Proof:** We can mark in each column by a star on the left the values that are the maximum for the NWS. In Table IV, we can mark also in each row by a star on the right the value that

| **NWS sells** | **ally NNWS buys** | | |
|---|---|---|---|
| | None | Reactor | Bomb |
| None | *0, 0 | $-sc_1,\, eb + sb_1 - dc$ | $-sc_1 - esc_1,\, eb + sb_1 - dc + esb_1 - edc$ |
| Reactor | NA | $*tb - sc_1,\, eb + sb_1 - dc$ | $tb - sc_1 - esc_1,\, eb + sb_1 - dc + esb_1 - edc$ |
| Bomb | NA | NA | $*tb - sc_1 + etb - esc_1,\, eb + sb_1 - dc + esb_1 - edc$ |

TABLE III: The choices of any pair of NWS and ally NNWS.

| **NWS sells** | **adversary NNWS buys** | | |
|---|---|---|---|
| | None | Reactor | Bomb |
| None | *0, 0 | $-sc_2,\, eb + sb_2 - dc$ | $-sc_2 - esc_2,\, eb + sb_2 - dc + esb_2 - edc*$ |
| Reactor | NA | $*tb - sc_2,\, eb + sb_2 - dc$ | $*tb - sc_2 - esc_2,\, eb + sb_2 - dc + esb_2 - edc*$ |

TABLE IV: The choices of any pair of NWS and adversary NNWS.

is the maximum for the adversary NNWS. By Assumption (5) above, this will be the last entry of both rows of Table IV.

Theorems 1 and 2 are pessimistic results because they both imply that there is a danger that both NNWS allies and adversaries could well choose to develop nuclear weapons. Theorem 2 implies that the existence of such a Nash equilibrium tends to make NWSs to try to pacify the adversary NNWSs by offering them peaceful nuclear technology in return for them promising never to develop nuclear weapons. However, adversaries have economic and security interests to break their promises. That is, exactly the essence and the history of the NPT. Only in the case when all NWSs are in complete agreement not to sell weapons-grade technology, can the efforts of NNWSs be rolled back. Fortunately, there are a few cases of that happening. Hence perhaps the optimistic conclusion could be that the above analysis reveals the need for all the NWSs to make a unified effort never to sell nuclear weapons technology to NNWSs.

## IV. The Effect of the NPT

In this section, let us consider the effect of the NPT. One can argue that without the NPT, the values of some of the variables considered in Section III-A would change. In particular, we can expect the following:

- dc $\uparrow$ Without the NWSs' commitment to help NNWSs in the development of civilian nuclear technology, NNWS adversaries would have to do everything themselves or pay a heavy price for any nuclear technology. NNWS allies would also no longer get any free nuclear technology, although they may be able to buy some at a discount. Hence the development cost $dc$ would increase for all NNWSs.
- edc $\uparrow$ With the increase of civilian nuclear technology, there would be a slower development of the nuclear industry and fewer nuclear experts and likely the price of military nuclear technology would increase too.
- sb$_1$ $\downarrow$ 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 for NNWS allies.
- sb$_2$ $\downarrow$ Similarly, to the previous item, 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 for NNWS adversaries too .
- esb$_1$ $\downarrow$ The extra security benefit would decrease too for the NNWS ally.
- esb$_2$ $\downarrow$ The extra security benefit would decrease too for the NNWS adversary too.

Many of the other variables would not change. For example, the $eb$ would not change because the NPT does not affect the amount of energy that can be obtained from nuclear reactors. The security cost $sc$ and the extra security cost $esc$ to NWSs would remain the same because the NWSs would be still fearful for losing control over the NNWSs that acquire civilian or military nuclear technology. When the price of civilian nuclear technology increases, the demand decreases. The price increase and the demand decrease tend to cancel each other out. Hence the trade benefit $tb$ would not change drastically.

*Theorem 3:* If the direction of change of the variables are as shown above, then without the NPT, there would be more NNWSs choosing "None" or "Reactor."

**Proof:** By Theorem 1, if $eb+sb_1-dc>0$ or $eb+sb_1-dc+esb_1-edc>0$, then the Nash equilibrium where NWS and ally NNWS both choose "None" cannot develop. Note that

$$eb + sb_1 - dc > eb + sb_1 \downarrow -dc \uparrow$$

and

$$eb+sb_1-dc+esb_1-edc > eb+sb_1 \downarrow -dc \uparrow +esb_1 \downarrow -edc \uparrow$$

Hence wihout the NPT the left hand side of both conditions of Theorem 1 could be easier less than 0, increasing the chance of a Nash equilibrium.

Further, Theorem 1 also shows that if $esb_1 - edc > 0$ then the NWS and the ally NNWS both choosing "Reactor" is not a Nash equilibrium. Note that

$$esb_1 - edc > esb_1 \downarrow - edc \uparrow$$

Hence without the NPT the left hand side of the condition of Theorem 1 could be easier less than 0, increasing the chance of a Nash equilibrium.

Finally, with more with chance of Nash equilibriums developing that involve for NNWSs the choice of ”None” or ”Reactor,” more NNWSs would make one of those choices.

## 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 means 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 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. More generally, we hope that mathematical models will increasingly inform the debate on other pressing subjects, such as climate change [7] and health insurance in the face of predictability of diseases [8].

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