Hacettepe University

Graduate School of Social Sciences

Department of International Relations

INTERNATIONAL NUCLEAR NONPROLIFERATION EFFORTS: THORIUM AS A VIABLE ALTERNATIVE TO PREVENT DIVERSION

Ahmet BİÇER

Master’s Thesis

Ankara, 2021

INTERNATIONAL NUCLEAR NONPROLIFERATION EFFORTS: THORIUM AS A VIABLE ALTERNATIVE TO PREVENT DIVERSION

Ahmet BİÇER

Hacettepe University Graduate School of Social Sciences

Department of International Relations

Master’s Thesis

Ankara, 2021

ACCEPTANCE AND APPROVAL

The jury finds that Ahmet BİÇER has on the date of 08.09.2021 successfully passed the defense examination and approves his Master's Thesis titled "International Nuclear Nonproliferation Efforts: Thorium as a Viable Alternative to Prevent Diversion".

Prof. Dr. Okan ÖZER (Jury President)

Assoc. Prof. Dr. Şebnem UDUM (Main Adviser)

Asst. Prof. Dr. Kadri Kaan RENDA (Member)

I agree that the signatures above belong to the faculty members listed.

Prof. Dr. Uğur ÖMÜRGÖNÜLŞEN

Graduate School Director

YAYIMLAMA VE FİKRİ MÜLKİYET HAKLARI BEYANI

Enstitü tarafından onaylanan lisansüstü tezimin/raporumun tamamını veya herhangi bir kısmını, basılı (kâğıt) ve elektronik formatta arşivleme ve aşağıda verilen koşullarla kullanıma açma iznini Hacettepe Üniversitesine verdiğimi bildiririm. Bu izinle Üniversiteye verilen kullanım hakları dışındaki tüm fikri mülkiyet haklarım bende kalacak, tezimin tamamının ya da bir bölümünün gelecekteki çalışmalarda (makale, kitap, lisans ve patent vb.) kullanım hakları bana ait olacaktır.

Tezin kendi orijinal çalışmam olduğunu, başkalarının haklarını ihlal etmediğimi ve tezimin tek yetkili sahibi olduğumu beyan ve taahhüt ederim. Tezimde yer alan telif hakkı bulunan ve sahiplerinden yazılı izin alınarak kullanılması zorunlu metinlerin yazılı izin alınarak kullandığımı ve istenildiğinde suretlerini Üniversiteye teslim etmeyi taahhüt ederim.

Yükseköğretim Kurulu tarafından yayınlanan ***"Lisansüstü Tezlerin Elektronik Ortamda Toplanması, Düzenlenmesi ve Erişime Açılmasına İlişkin Yönerge"*** kapsamında tezim aşağıda belirtilen koşullar haricince YÖK Ulusal Tez Merkezi / H.Ü. Kütüphaneleri Açık Erişim Sisteminde erişime açılır.

- o Enstitü / Fakülte yönetim kurulu kararı ile tezimin erişime açılması mezuniyet tarihimden itibaren 2 yıl ertelenmiştir. (1)
- o Enstitü / Fakülte yönetim kurulunun gerekçeli kararı ile tezimin erişime açılması mezuniyet tarihimden itibaren ... ay ertelenmiştir. (2)
- o Tezimle ilgili gizlilik kararı verilmiştir. (3)

21/09/2021

Ahmet BİÇER

[1] *"Lisansüstü Tezlerin Elektronik Ortamda Toplanması, Düzenlenmesi ve Erişime Açılmasına İlişkin Yönerge"*

(1) *Madde 6. 1. Lisansüstü tezle ilgili patent başvurusu yapılması veya patent alma sürecinin devam etmesi durumunda, tez **danışmanının** önerisi ve **enstitü anabilim dalının** uygun görüşü üzerine **enstitü** veya **fakülte yönetim kurulu** iki yıl süre ile tezin erişime açılmasının ertelenmesine karar verebilir.*

(2) *Madde 6. 2. Yeni teknik, materyal ve metotların kullanıldığı, henüz makaleye dönüşmemiş veya patent gibi yöntemlerle korunmamış ve internetten paylaşılması durumunda 3. şahıslara veya kurumlara haksız kazanç imkanı oluşturabilecek bilgi ve bulguları içeren tezler hakkında tez **danışmanının** önerisi ve **enstitü anabilim dalının** uygun görüşü üzerine **enstitü** veya **fakülte yönetim kurulunun** gerekçeli kararı ile altı ayı aşmamak üzere tezin erişime açılması engellenebilir.*

(3) *Madde 7. 1. Ulusal çıkarları veya güvenliği ilgilendiren, emniyet, istihbarat, savunma ve güvenlik, sağlık vb. konulara ilişkin lisansüstü tezlerle ilgili gizlilik kararı, **tezin yapıldığı kurum** tarafından verilir *. Kurum ve kuruluşlarla yapılan işbirliği protokolü çerçevesinde hazırlanan lisansüstü tezlere ilişkin gizlilik kararı ise, **ilgili kurum ve kuruluşun önerisi** ile **enstitü** veya **fakültenin** uygun görüşü üzerine **üniversite yönetim kurulu** tarafından verilir. Gizlilik kararı verilen tezler Yükseköğretim Kuruluna bildirilir.*
Madde 7.2. Gizlilik kararı verilen tezler gizlilik süresince enstitü veya fakülte tarafından gizlilik kuralları çerçevesinde muhafaza edilir, gizlilik kararının kaldırılması halinde Tez Otomasyon Sistemine yüklenir
** Tez **danışmanının** önerisi ve **enstitü anabilim dalının** uygun görüşü üzerine **enstitü** veya **fakülte yönetim kurulu tarafından karar verilir.***

ETİK BEYAN

Bu çalışmadaki bütün bilgi ve belgeleri akademik kurallar çerçevesinde elde ettiğimi, görsel, işitsel ve yazılı tüm bilgi ve sonuçları bilimsel ahlak kurallarına uygun olarak sunduğumu, kullandığım verilerde herhangi bir tahrifat yapmadığımı, yararlandığım kaynaklara bilimsel normlara uygun olarak atıfta bulunduğumu, tezimin kaynak gösterilen durumlar dışında özgün olduğunu, **Doç. Dr. Şebnem UDUM** danışmanlığında tarafımdan üretildiğini ve Hacettepe Üniversitesi Sosyal Bilimler Enstitüsü Tez Yazım Yönergesine göre yazıldığını beyan ederim.

Ahmet BİÇER

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to my supervisor Assoc. Prof. Dr. Şebnem UDUM. Without her encouragement and guidance, this interdisciplinary thesis would not have been completed. Her experiences and knowledge about the nuclear energy issues within the International Relations have provided me with a new sound perspective.

I am also grateful to Prof. Dr. Okan ÖZER and Asst. Prof. Dr. Kadri Kaan RENDA for their advices and constructive comments on my thesis.

ÖZET

BİÇER, Ahmet. *Uluslararası Nükleer Silahların Yayılmasının Önlenmesi Çabaları: Silahlanmayı Önlemede Bir Alternatif Olarak Toryum*, Yüksek Lisans Tezi, Ankara, 2021.

Uluslararası nükleer silahların yayılmasının önlenmesi çabaları İkinci Dünya Savaşı sonrası dönemde uluslararası ilişkilerin en önemli gündemlerinden biridir. Nükleer enerjinin ilk hedefinin askeri amaçlı olması ve nükleer silahların elde edildikten sonra yıkıcılığının savaş meydanında görülmesi sonucunda büyük güçlerin nükleer silahları elde etmek için bir yarışa girmeleri kaçınılmaz olmuştur. Ancak, nükleer enerji askeri kullanımın yanı sıra barışçıl amaçlarla da kullanılabilecek bir enerji türüdür. Bu bağlamda, nükleer silahların yayılmasının önlenmesi amacıyla nükleer enerjinin tıp, tarım ve elektrik üretimi gibi barışçıl amaçlarla da kullanımının yayılması çalışmaları başlamıştır. Nükleer enerjinin çift yönlü kullanım özelliği sebebiyle barışçıl amaçlar için sunulan imkânların askeri amaçlara dönüştürülmemesi için nükleer güvenlik, emniyet ve güvence konularında belirli önlemler geliştirilmiştir. Fakat bu önlemler nükleer yakıt çevrimi ile yakından ilgili olan nükleer güç reaktörleri konusunda teknik bağlamda daha da güçlendirilmeye ihtiyaç duymaktadır. Zira uranyumun yakıt olarak kullanılması nükleer yakıt çevriminde belirli aşamaların barışçıl kullanımdan silahlanmaya yönelimini kolaylaştırabilmektedir. Bu yüzden, bu tez toryumun yakıt olarak kullanılmasının ve bu amaçla geliştirilecek nükleer yakıt çevriminin nükleer silahların yayılmasının önlenmesi rejimine ve silahlanma endişelerinin azaltılmasına katkılarını ele almaktadır.

Anahtar Sözcükler

Nükleer Enerji, Nükleer Silahların Yayılmasının Önlenmesi Rejimi, Nükleer Yakıt Çevrimi, Silahlanmaya Dirençli Nükleer Yakıt, Toryum, Nükleer Reaktörler, Nükleer Silahlar

ABSTRACT

BİÇER, Ahmet. *International Nuclear Nonproliferation Efforts: Thorium as a Viable Alternative to Prevent Diversion*, Master's Thesis, Ankara, 2021.

International nuclear nonproliferation efforts have been one of the most important agendas of international relations after the World War II. Since the first aim of nuclear energy was for the military purposes and destructive power of nuclear weapons were experienced in a wartime, it has been inevitable for great powers to go into an arms race to obtain nuclear weapons. However, nuclear energy is a kind of energy which can be utilized for peaceful purposes as well as military purposes. In this context, initiatives have been started to promote the use of nuclear energy for peaceful purposes such as medicine, agriculture and electricity generation in order to prevent the proliferation of nuclear weapons. Due to the dual use aspect of nuclear energy, certain measures have been developed in safety, security, and safeguards so that the opportunities offered for peaceful purposes are not diverted into military purposes. However, these measures are needed to be further strengthened in technical terms with regard to the nuclear power reactors, which are closely related to the nuclear fuel cycle. Because, using uranium as a nuclear fuel can facilitate diversion of peaceful use in certain stages of nuclear fuel cycle. Therefore, this thesis deals with the contribution of thorium as a nuclear fuel and its fuel cycle to the international nuclear nonproliferation regime and the mitigation of proliferation concerns.

Keywords

Nuclear Energy, Nuclear Nonproliferation Regime, Nuclear Fuel Cycle, Proliferation Resistant Nuclear Fuel, Thorium, Nuclear Reactors, Nuclear Weapons

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

AHWR	Advanced Heavy Water Reactor
CANDU	Canada Deuterium Uranium
FBR	Fast Breeder Reactor
HEU	Highly Enriched Uranium
HTGR	High Temperature Gas Cooled Reactor
HWR	Heavy Water Reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
LEU	Low Enriched Uranium
LFTR	Lithium Fluoride Thorium Reactor
LWR	Light Water Reactor
MSBR	Molten Salt Breeder Reactor
NEA	Nuclear Energy Agency
NEI	Nuclear Energy Institute
NNWS	Non-Nuclear Weapon State
NPT	Nuclear Nonproliferation Treaty
NRC	Nuclear Regulatory Commission
NWS	Nuclear Weapon State
SQ	Significant Quantity
U.S.	United States of America

UK	the United Kingdom
UN	United Nations
USSR	Union of Soviet Socialist Republics
WMD	Weapons of Mass Destruction
WWII	World War II

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Nuclear energy is a unique form of energy since it has dual use aspects. Its applications range from military to peaceful purposes. Apart from peaceful applications, military applications, in particular, can play an important role for a state in terms of military power. With nuclear energy, much more devastating weapons, namely nuclear weapons, can be obtained as experienced in the case of World War II (WWII). In an anarchic international system, as realists assume, being a militarily powerful state is necessary to ensure survival. In this respect, having nuclear weapons in their military arsenals can be regarded as alluring for states to achieve their political and military goals. However, this kind of attitude, which is to pursue nuclear weapons, can cause an arms race since it potentially creates the security dilemma among states.[1] For example, after the WWII, Union of Soviet Socialist Republics (USSR), the United Kingdom (UK), France, and China obtained nuclear weapons capability by following the path of the United States.[2] This proliferation trend among states was an imminent threat for the international peace and security. Therefore, international nuclear nonproliferation efforts have begun to prevent further proliferation of nuclear weapons.

As a result of nuclear nonproliferation efforts, international institutions and regimes have been established to prevent the spread of the nuclear weapons.[3] According to liberal paradigm, these institutions and regimes can alleviate the impact of anarchy and create an environment in which cooperation can be achievable. In such an environment, states are able to know the intentions of each other. In this sense, by creating certain forms of behaviors and rules, nuclear nonproliferation regime not only aims at stopping the proliferation of nuclear weapons, but also helps states to benefit from the nuclear energy for peaceful purposes.[4] Additionally, within the nuclear nonproliferation regime, it can

---

[1] Randall L. Schweller, "Neorealism's Status-Quo Bias: What Security Dilemma?," *Security Studies* 5, no. 3 (1996/03/01 1996).

[2] T. C. Robinson, "What Do We Mean by Nuclear Proliferation?," *Nonproliferation Review* 22, no. 1 (2015).

[3] Şebnem Udum, "Peaceful Use of Nuclear Energy and the International Nuclear Nonproliferation Regime," *Energy and Diplomacy Journal* vol.1, no. 4 (2015).

[4] Joseph S. Nye, "Maintaining a Nonproliferation Regime," *International Organization* 35, no. 1 (1981).

be possible that a cheating state can be punished while a complying state can gain a positive reputation.

Given these points, nuclear nonproliferation efforts were initiated by the establishment of United Nations Atomic Energy Commission (UNAEC) in 1946. However, the rivalry between the US and USSR ended up with the acquisition of nuclear weapons capability by USSR in 1949.[5] Following USSR, the UK obtained nuclear weapons capability in 1952. Then, Eisenhower's "Atoms for Peace"[6] speech in 1953, which highlighted the peaceful applications of nuclear energy, created an opportunity for the establishment of International Atomic Energy Agency (IAEA) in 1957. Since then, the safeguarding of nuclear energy in international system have started with the establishment of IAEA.[7] Through IAEA safeguards, any diversion or misuse of technology and nuclear material for military purposes can be detected and compliance of states to peaceful applications can be verified. Following the establishment of the IAEA, the threat of a nuclear war during the Cuban missile crisis between the US and USSR in 1962 made it necessary to draft an international Treaty on the Nonproliferation of Nuclear Weapons (NPT), which was opened to signature in 1968 and entered into force in 1970. Regarded as the cornerstone of nuclear nonproliferation regime, NPT adopted the IAEA safeguards (Article III) within its principle of the peaceful use of nuclear energy.[8] Under NPT, parties of the Treaty are categorized as nuclear-weapons states (NWS) (detonated a nuclear weapon before January 1, 1967; China, France, USSR, UK, and the U.S.) and non-nuclear-weapons states (NNWS). In sum, the NPT contributes to international nuclear nonproliferation regime with its pillars; nuclear nonproliferation (Article I and II), nuclear disarmament (Article VI), and peaceful use of nuclear energy (Article IV) by complying with IAEA safeguards (Article III).[9]

---

[5] Edward A. Shils, "The Failure of the Unaec: An Interpretation," *Bulletin of the Atomic Scientists* 4, no. 7 (1948/07/01 1948).
[6] Dwight D. Eisenhower, "Atoms for Peace Speech," IAEA, accessed 24.04.2021. https://www.iaea.org/about/history/atoms-for-peace-speech.
[7] S. Eklund, "Iaea Safeguards in Perspective," *JNMM, Journal of the Institute of Nuclear Materials Management* 15, no. 4 (1987).
[8] G. H. Quester, "The Nuclear Nonproliferation Treaty and the International Atomic Energy Agency," *International Organization* 24, no. 2 (1970).
[9] Udum.

The compliance and declarations of the NNWS is verified by the IAEA safeguards system to prevent any diversion or misuse of nuclear material and related facilities.[10] However, the clandestine nuclear weapon program of Iraq using its undeclared materials and activities created an incentive to expand the boundaries of the IAEA safeguards system including undeclared materials and activities.[11] For this reason, Additional Protocol was introduced in 1997 to control undeclared facilities and activities.

Since nuclear energy has dual use aspects, the boundaries of its peaceful and military applications should be determined cautiously in the nuclear nonproliferation regime. In this respect, internal and external barriers to prevent proliferation have been embedded within the nuclear fuel cycle. However, uranium based nuclear fuel cycle has certain stages in which misuse and diversion of technology and nuclear material can take place by a potential proliferator when the lack of verification and compliance occurs.[12] According to the IAEA, moving from peaceful activities to obtain nuclear weapons is called as diversion.[13] In other words, it can be regarded as the acquisition of military use by misusing or diverting peaceful use of nuclear energy. And, this diversion process can happen in two ways; abrupt (capturing large amount of nuclear material) and protracted (accumulating nuclear material over a period of time).

Therefore, in this thesis, conventional or uranium based nuclear fuel cycle will be assessed in terms of the nonproliferation of nuclear weapons. During the nuclear age, nuclear power reactors utilizing uranium as a fuel have always not only dominated the nuclear power sector but also caused proliferation concerns. Those proliferation concerns stemming from uranium based nuclear fuel cycle and related nuclear reactor technologies have seemingly been an important issue for the spread of the peaceful use of nuclear energy.[14] Even though many kind of barriers have been created to mitigate the concerns for the nuclear weapons proliferation, uranium based nuclear fuel cycle is inevitably

---

[10] J. M. Acton, "Strengthening Safeguards and Nuclear Disarmament," *Nonproliferation Review* 14, no. 3 (2007).
[11] L. Rockwood, "Safeguards and Nonproliferation: The First Half-Century from a Legal Perspective," *Journal of Nuclear Materials Management* 35, no. 4 (2007).
[12] M. Asada, "The Treaty on the Non-Proliferation of Nuclear Weapons and the Universalization of the Additional Protocol," *Journal of Conflict and Security Law* 16, no. 1 (2011).
[13] IAEA, *Inpro Collaborative Project: Proliferation Resistance: Acquisition/Diversion Pathway Analysis (Prada)* (Vienna: International Atomic Energy Agency, 2012).
[14] Robinson.

facing many problems regarding enrichment of uranium and reprocessing of spent fuel, chiefly by diversion. However, there is another nuclear fuel option, thorium, which can also be utilized in nuclear reactors. Unlike uranium, thorium can provide with more proliferation resistant features that can improve the efficacy and soundness of the international nuclear nonproliferation efforts.[15]

Given these points, the main research question of the thesis is “Can Thorium Become an Alternative Nuclear Fuel to Prevent Diversion?” While scrutinizing benefits and challenges of thorium, following sub-questions will also be answered;

- Can nuclear energy grow peacefully via thorium fuel cycle?
- How can thorium be utilized in nuclear power reactors?

The scope of this thesis is mainly the peaceful use of nuclear energy within the international nuclear nonproliferation regime. It is a fact that the threat posed by the nuclear weapons has always been an important issue in the international politics since 1945.[16] Especially, after the WWII, great powers of the time searched for gaining the capability to build nuclear weapons to ensure their survival. This arms race to obtain nuclear weapons capability continued till the midst of 1960s. As a result of Cuban missile crisis, the US, UK, and USSR came together and initiated the efforts to draft an international nuclear nonproliferation treaty to stop further spread of nuclear weapons to other states in the system. At the end of these efforts, the Treaty on the Nonproliferation of Nuclear Weapons (NPT) was opened to signature in 1968 and entered into force in 1970.[17] During its existence up until now, NPT has played magnificent role in the prevention of the spread of nuclear weapons.[18] Although a few additional states obtained nuclear weapons capability after NPT, it is difficult to label NPT as a failure. Conversely,

[15] IAEA, *Thorium Fuel Cycle - Potential Benefits and Challenges* (Vienna: International Atomic Energy Agency, 2005).
[16] Simpson John, "Nuclear Non-Proliferation in the Post-Cold War Era," *International Affairs (Royal Institute of International Affairs 1944-)* 70, no. 1 (1994).
[17] UNODA, "Treaty on the Non-Proliferation of Nuclear Weapons (Npt)," UNODA, accessed 22.04.2021. https://www.un.org/disarmament/wmd/nuclear/npt/.
[18] B. A. Thayer, "The Causes of Nuclear Proliferation and the Utility of the Nuclear Nonproliferation Regime," *Security Studies* 4, no. 3 (1995).

the number of states having nuclear weapons capability have not increased up to 20 or 30 by the Millennia as expected in the beginning of 1960s.[19]

Although NPT makes a distinction between the status of states as NWS and NNWS, one of the pillars of the NPT is designed for maintaining the peaceful use of nuclear energy on the condition of complying with the IAEA safeguards as reflected in its Article IV.[20] To achieve this goal, in the course of peaceful applications, mainly for the electricity generation, numerous barriers have been developed depending on the types of the power reactors.[21] However, uranium based nuclear fuel cycle has become a matter of concern in terms of enrichment and reprocessing since these two stages overlap up to a level both for the peaceful and military use of nuclear energy. Therefore, some technical issues regarding these stages can potentially create problems for nuclear nonproliferation regime. Considering these points, this thesis proposes a nuclear fuel cycle, which is thorium fuel cycle, as an option in which more proliferation resistant technologies can be introduced into nuclear power generation. While doing this, current and proposed nuclear fuel cycle options for the peaceful use of nuclear energy will be explored. In the history of nuclear power reactors, uranium has been used mainly as a nuclear fuel. However, in the early years of reactor proposals, thorium fueled reactors were also considered since the abundant source of thorium exists in nature.[22] But, in the early commercialization years of the nuclear power reactors during 1960s, uranium turned out to be a challenge for thorium in that uranium resources were not scarce as it was expected.[23] As a result, nuclear power generation has been dependent mainly on the uranium fueled nuclear reactors.

As an objective, this thesis looks for the opportunities to benefit from the peaceful use of nuclear energy in more proliferation resistant terms. In particular, introduction of thorium fuel cycle into the nuclear power generation can potentially have an impact on degradation of the capabilities of the states about the production of nuclear weapons. In

---

[19] Robinson.
[20] H. Shenasaei and F. Shirvani, "Article Iv of the Npt Treaty and Legitimacy of Sensitive Nuclear Activities," *Asian Social Science* 10, no. 3 (2014).
[21] IAEA, *Technical Features to Enhance Proliferation Resistance of Nuclear Energy Systems* (Vienna: International Atomic Energy Agency, 2010).
[22] A. Nagaratnam, "Nuclear Fuels," *Energy Management (New Delhi)* 4, no. 2 (1980).
[23] IAEA, *Thorium Fuel Cycle - Potential Benefits and Challenges*.

other words, a state having intentions to misuse or divert from peaceful use cannot reach its goal since the aspects of thorium fuel cycle can already limit its capability.[24] In this respect, serving as a proliferation resistant fuel, thorium not only alleviates the concerns of the NWS by preventing proliferation of nuclear weapons, but also help spread the peaceful use of nuclear energy.

Given these points, this thesis benefits from International Relations theories, Realism and Liberalism, to explain the efforts of nuclear nonproliferation regime. Since the nuclear weapons changed the nature of war, Clausewitzian approach will also be adapted for both the nuclear weapons and international nuclear nonproliferation efforts. From the strands of these theories, the possible impact of a technical modulation in the nuclear power generation on the policies of the states will be scrutinized.

This thesis claims that international nuclear nonproliferation regime can be further strengthened by the introduction of thorium as a nuclear fuel into the nuclear power reactors. Uranium based nuclear power reactors have operated for many years with some 18900 years of operating experience till now.[25] At first glance, this much years of experience may seem to be enough for the maturity of nuclear power generation. Especially, during the course of the power generation, nuclear power reactors have been upgraded by considerable enhancements, good practices and lessons learned from the accidents. Along with these, numerous internal and external barriers have been created regarding safety, security, and safeguards aspects of nuclear energy.[26] Nevertheless, uranium based nuclear fuel option have included pitfalls in the enrichment of uranium and the reprocessing of spent fuel. In these two stages, military and peaceful use of nuclear energy overlaps up to some degree, which in fact is the main source of the concerns about diversion.

To eliminate these concerns, there have been lots of proposals regarding proliferation resistant nuclear reactor technologies. Especially, by the beginning of 2000s, these efforts

[24] IAEA, *Thorium Fuel Utilization: Options and Trends* (Vienna: International Atomic Energy Agency, 2002).
[25] IAEA, "Reactor-Years of Operation," last modified 13.05.2021, accessed 21.04.2021. https://pris.iaea.org/PRIS/home.aspx.
[26] D. Schriefer, "Safeguards, Security, Safety and the Nuclear Fuel Cycle," in *Nuclear Fuel Cycle Science and Engineering* (Elsevier Inc., 2012).

were labeled as “nuclear renaissance”.[27] New types of reactors have been proposed within the context of nuclear renaissance and these proposals have included uranium fueled and thorium fueled nuclear reactors.[28] In contrast to the uranium fuel cycle, reactors using thorium fuel cycle can intrinsically harden the ways of diversion, which makes it more proliferation resistant than uranium. In this respect, the interest in thorium fueled reactors can be regarded as an important step to support international nuclear nonproliferation efforts.

In this context, this thesis has two assumptions that will possibly increase the pressure on the nuclear nonproliferation regime. First, there will be considerable number of nuclear power reactors aging in incoming decades that their commissioning licenses will expire. Second, if building new nuclear power reactors and substituting aging ones with nuclear power reactors fueled with uranium fuel, the risk of proliferation and concerns for diversion will continue to constitute problems for international nuclear nonproliferation regime. To cope with these challenges, this thesis argues that thorium fuel cycle can help mitigate the risk of diversion, while promoting the peaceful use of nuclear energy.

This thesis consists of five chapters. The first chapter labels an introduction by giving scope, objective and argument of the thesis.

Second chapter provides a technical and theoretical background for the thesis. While doing this, it makes use of mainstream IR theories such as Realism and Liberalism to explain the threat of nuclear weapons and importance of safeguards within the nuclear nonproliferation regime. For the technical background, it explains the IAEA safeguards system, which offers some technical measures to prevent diversion.

Third chapter examines the risks of uranium as a fuel within the nuclear technology and nonproliferation. First part starts with the explanation of nuclear technology and nuclear weapons. Second one examines the possible proliferation routes within uranium based nuclear fuel cycle. Third one analyzes the conventional barriers including internal and external barriers, which have been established to prevent diversion.

---

[27] J. S. Lantis, "Economic Competition and Nuclear Cooperation: The "Nuclear Renaissance" Revisited," *Nonproliferation Review* 21, no. 1 (2014).
[28] R. Wigeland et al., *Nuclear Fuel Cycle Evaluation and Screening - Final Report* (Idaho National Laboratory, 2014).

Fourth chapter tackles with thorium as an alternative to prevent diversion and explains how it can mitigate proliferation concerns. After explaining thorium as a nuclear fuel in the first part, benefits and challenges of using thorium as a nuclear fuel is examined in the second part. Third part answers the questions regarding the deployment of thorium with its alternative approaches and proposed utilizations. Finally, the fourth part evaluates the chapter within the light of previously mentioned points.

Final chapter concludes the thesis by summarizing the points given in the previous chapters and argues how international nuclear nonproliferation efforts can be further strengthened by the utilization of thorium as a nuclear fuel.

CHAPTER I: THEORETICAL AND TECHNICAL BACKGROUND

Due to domain and context of nuclear nonproliferation, in this chapter, this thesis will primarily benefit from the International Relations theories; Realism and Liberalism. Additionally, Carl von Clausewitz's widely known book on the theory of war, On War, will play an auxiliary role in bridging between those two theories and help reader understand the transition between theories while examining the international nuclear nonproliferation efforts.

Being the most important product of nuclear technology, nuclear weapons have magnificent impact on the behaviors of the states.[29] Given that the implementation of two nuclear weapons and their success in the battlefield were unearthed in WWII, nuclear weapons have been regarded as the most powerful component of the military arsenal of the states.[30] However, use of nuclear technology has two faces; peaceful use and military use. So, it requires meticulous efforts to separate peaceful use from military use to prevent misuse or diversion. This situation constitutes the main problem on the share of the nuclear technology among states in the international system. On the one hand, as adopted in Article I of the NPT, nuclear-weapon states (NWS) do not want any additional state to obtain nuclear weapons capability by any means.[31] On the other hand, regarded as one of the main pillars of the nuclear nonproliferation regime, peaceful use of nuclear energy by implementation of IAEA safeguards for their facilities, as defined in the Article IV of the NPT, non-nuclear-weapon states (NNWS) are provided with "the inalienable right … to develop research, production and use of nuclear energy for peaceful purposes."[32] However, NWS and NNWS have not completely reached an agreement about to what extent nuclear energy can be peaceful.[33] Therefore, nuclear nonproliferation preferences and definitions of both have been unable to meet their expectations from each other and created prolonging conflicts.[34] As a result, finding solutions to these conflicting situations

---

[29] Kenneth N. Waltz, *Theory of International Politics* (Waveland Press, 2010), 180.
[30] Kenneth N. Waltz, "The Emerging Structure of International Politics," *International Security* 18, no. 2 (1993).
[31] "Treaty on the Non-Proliferation of Nuclear Weapons (Npt)," UNODA, accessed 10.04.2018, 2018. https://www.un.org/disarmament/wmd/nuclear/npt/text.
[32] Ibid.
[33] Hedley Bull, "Rethinking Non-Proliferation," *International Affairs* 51, no. 2 (1975).
[34] Scott D. Sagan, "Why Do States Build Nuclear Weapons?: Three Models in Search of a Bomb," *International Security* 21, no. 3 (1996).

requires meticulous international nuclear nonproliferation efforts through the ways of both intrinsic and extrinsic measures.

In this respect, Thorium, as an alternative to Uranium, is another nuclear fuel option that has the potential to prevent diversion of peaceful use and harden the ways of obtaining nuclear weapons.[35] It may serve as a sound intrinsic -or technical- measure on the peaceful use of nuclear energy. In this context, following sections of this chapter will deliver a theoretical and technical background to offer insights whether an alternative like Thorium can create a ground for harmonious synergy of both intrinsic and extrinsic measures through which the expectations of NWS and NNWS would converge.

1.1. REALISM

As being one of the mainstream theories of International Relations, Realism mainly concerns with power and security issues in the international politics.[36] Realists assume that these issues have widespread impact on the interactions of the states during their struggle for survival in an anarchic international system.[37] As a result of this approach, it is inevitable that the realists feel to handle important issues of international relations in terms of power and security. As an explanatory theory, Realism traces these issues through significant assumptions to come up with sound, if not perfect, explanations. On the assessments of the events stemming from the behavior of the states, it is difficult to say that there is only one camp of Realism.[38] Classical realism, neoclassical realism, and neorealism or structural realism can be regarded as the main camps of realist paradigm.[39] In the context of the thesis, strands of structural realism will be visited to explain the nuclear nonproliferation efforts.

According to Realism, "power is the currency of great-power politics, and states compete for it among themselves."[40] By extension, states use their power to perform their

[35] Mujid S. Kazimi, "Thorium Fuel for Nuclear Energy: An Unconventional Tactic Might One Day Ease Concerns That Spent Fuel Could Be Used to Make a Bomb," *American Scientist* 91, no. 5 (2003).
[36] John J. Mearsheimer, *The Tragedy of Great Power Politics* (New York: Norton, 2002), 17-22.
[37] T. Dunne, M. Kurki, and S. Smith, *International Relations Theories* (OUP Oxford, 2013), 62.
[38] Liu Feng and Zhang Ruizhuang, "The Typologies of Realism," *The Chinese Journal of International Politics* 1, no. 1 (2006).
[39] Stephen G. Brooks, "Dueling Realisms," *International Organization* 51, no. 3 (1997).
[40] Mearsheimer, 12.

interactions with each other. Because of this characterization, the importance of the power makes states seek for the opportunities to upgrade their share of the world power.[41] At this very point, classical realism deviates from the structural realism in terms of the driver for gaining power and handling the power whether it is as an end or as a means.[42] While looking at the source of the behavior of the states as the power seekers, the former takes the human nature into account, whereas the latter puts emphasis on the structure of the international system.[43] Hans Morgenthau, theoretical founder of human nature or classical realism, makes it clear that states seek power precisely the reason that drives them intrinsically.[44] To put it succinctly, Morgenthau takes into account the human nature that everyone is born with a “type-A” personality, which means that all human beings do the same thing when they want to achieve some advantages over others.[45] Their main goal is always pursuing to obtain power.[46] Consequently, for classical realism, states pursue power as an end itself and pursuing power inherently results in a competition and conflict among states as a result of human nature.[47] Unlike classical and structural realists, neoclassical strand of Realism does not treat the states as the billiard balls. In contrast, neoclassical realists assume that domestic politics and the individual composition of the states, such as regime types, strategic culture, society relations, and the perception of their leaders, impacts the behavior of the states.[48] In this respect, neoclassical realism is criticized for being as a tool for foreign policy analysis.[49]

On the other hand, structural realism emphasizes that “it is the structure or architecture of the international system that forces states to pursue power.”[50] Since the system is anarchic, which means that there is no higher authority that arbitrates among the states, each state has to take care of itself.[51] Furthermore, the structural constraints compel states to seek for power to ensure their prospects for survival.[52] In contrast to classical realists,

---

[41] Dunne, Kurki, and Smith, 80.
[42] A. Heywood, *Global Politics* (Palgrave Macmillan, 2011), 55.
[43] Dunne, Kurki, and Smith, 78.
[44] Heywood, 58.
[45] Mearsheimer, 19.
[46] Heywood, 55.
[47] Dunne, Kurki, and Smith, 78.
[48] Gideon Rose, "Neoclassical Realism and Theories of Foreign Policy," *World Politics* 51, no. 1 (1998).
[49] Feng and Ruizhuang.
[50] Dunne, Kurki, and Smith, 78.
[51] Ibid., 79.
[52] Waltz, "The Emerging Structure of International Politics."

structural realists claim that "power is a means to an end and the ultimate end is survival."[53] When it comes to the topic of the amount of the power that a state should possess, structural realism is divided into two camps; Defensive Realism and Offensive Realism.[54] Defensive realists underline that power maximization is an irrational move since the power maximizer would end up with the punishment by the system.[55] Therefore, states should consider structural constraints and hesitate from undermining the balance of power.[56] This approach, in fact, reflects the status quo bias of the defensive realism.[57] On the other hand, offensive realists endorse that "it makes good strategic sense for states to gain as much power as possible and, if the circumstances are right, to pursue hegemony."[58] In other words, the best way to survive in an anarchic system is to be overwhelmingly powerful.

1.1.1. Structural Realism

To better understand the Structural Realism, as a beginning, it is important to label its core assumptions. Indeed, theoretically, it has five assumptions that reflects the political posture of the actors and the environment that they take place in, mainly on certain issues, such as power and security, in the international system.[59] As a result of the combination of these five assumptions, structural realism concludes that the states are urged to exhibit certain forms of behavior in the international political arena.[60]

First assumption; existing in an anarchic system, states are the main actors of the international relations. Being opposite of the hierarchy, anarchy means that there is no higher authority that arbitrates among states.[61] To put it bluntly, there is nobody that defends the indefensible in the international system when one or more of them gets into trouble. Second assumption; each state has a capability to do harm to one another

---

[53] Dunne, Kurki, and Smith, 78.
[54] Mearsheimer, 20-21.
[55] Waltz, *Theory of International Politics*, 109.
[56] Mearsheimer.
[57] Schweller.
[58] Dunne, Kurki, and Smith, 78.
[59] Mearsheimer, 30.
[60] Ibid., 32.
[61] Waltz, *Theory of International Politics*, 114-16.

depending on their power levels, chiefly in military power.[62] Capability of a state can be measured in terms of material factors and be estimated at high-precision by the other states in the system.[63] Any alteration made by a state to increase its capability can be perceived as offensive by other states in the system, which eventually creates security dilemma.[64] Third assumption; intentions of the actors or governors of the states, cannot be known precisely. No state can be sure about the intentions of the other states. This uncertainty leaves very little room for states to trust each other. Unlike capabilities, intentions of the states are very hard to measure in amount and even impossible to predict for the future.[65] Fourth assumption; survival is the principal goal of the states. It is not the only goal, but the main goal of a state to perform its other goals. If a state does not survive, inherently it cannot pursue any other goals.[66] Fifth assumption; states are the rational actors who have to make serious calculations along with anarchy, capability, intentions and survival if they want to ensure the prospects for their survival.[67]

After labelling and explaining the core assumptions respectively, structural realism asserts that there are three forms of behavior that the states exhibit when those five assumptions are merged together.[68] First form of the behavior is "fear."[69] Two important points make states inevitably fear each other in the international system.[70] First point; one state may be neighbor with a powerful state and that neighboring state may have malign intentions against it.[71] Second point; if one state gets into trouble in international politics, there is no higher authority to respond its request since the system is anarchic.[72] Considering these circumstances, in such an anarchic system where there is no higher authority, states as the rational actors quickly become aware of that they are on their own and that they have to be as powerful as they can to prevent any harm possibly coming from others.[73] This situation breeds the second form of the behavior, which is called as

---

[62] Mearsheimer, 30.
[63] Waltz, *Theory of International Politics*, 144.
[64] Schweller.
[65] Mearsheimer, 31.
[66] Ibid.
[67] Ibid.
[68] Ibid., 32.
[69] Ibid.
[70] Ibid.
[71] Dunne, Kurki, and Smith, 80.
[72] Ibid.
[73] Waltz, *Theory of International Politics*, 105.

self-help.[74] In a self-help system, states have to take care of themselves and find ways to ensure and enhance the prospects for their survival.[75] However, self-help endeavors of a state can be perceived as offensive by other states, and then, other states also start to follow the trend as a response it.[76] These endeavors breed the security dilemma among states and possibly stimulate the arms race.[77]

Finally, third form of the behavior, which is pursuing hegemony, is that the best way for a state to ensure its survival is the maximization of its power at the expense of other states.[78] It is not to say that this is an offensive behavior.[79] In fact, it is the best way to survive in an anarchic system. To put it succinctly, being the most powerful state helps a state establish its hegemony.[80] Here, Structural Realism puts emphasis on two important points about hegemony; being a regional hegemon and preventing any other state from becoming a peer competitor.[81] First one, it is more applicable to establish a regional hegemony rather than building a global hegemony since the globe is too big to take it under control. Furthermore, being a regional hegemon means for a state that it has no threat in its backyard.[82] Second one, a regional hegemon should also prevent any other state from becoming a regional hegemon. Since regional hegemony provides a state with a secure backyard, it can freely turn its attention to the other regions of the world.[83] If there exists an additional regional hegemon somewhere in other regions of the world, it can be, for a regional hegemon, both difficult to feel secure in its backyard and dangerous to wander around the globe freely.[84] In this context, the United States constitutes a prominent example as being a regional hegemon in western hemisphere since the early 20th century.[85]

Given these points, it can be concluded that nuclear weapons with their destructive power can constitute wide spread impact on the international system since the balance of power

---

74 Dunne, Kurki, and Smith.
75 Waltz, *Theory of International Politics*, 111.
76 Ibid., 186-87.
77 Heywood.
78 Mearsheimer, 35.
79 Dunne, Kurki, and Smith, 81.
80 Ibid.
81 Mearsheimer, 41.
82 Ibid.
83 Ibid.
84 Ibid., 42.
85 Ibid., 41.

can significantly change. In order to analyze the role of nuclear weapons, following section will scrutinize the nuclear energy in the scope of On War.

1.2. NUCLEAR TECHNOLOGY IN THE SCOPE OF ON WAR

In this part, theoretical background of this thesis will mainly borrow central aspects of the theory of war to handle the international nuclear nonproliferation efforts. Being a widely accepted book of the theorization of war, “On War” will help the reader understand the relationship between the nuclear weapons and international politics. In this context, important characterizations that “On War” offers will be used to establish a communication between aspiration for the nuclear power and nuclear nonproliferation.

1.2.1. Clausewitzian Understanding of Nuclear Technology

Carl von Clausewitz (1780-1831), who was a Prussian General, had some opportunities to observe important wars in modern European history.[86] Starting from his early teens, he attended Napoleonic Wars and witnessed the war ambience by himself.[87] During his campaigns, he always wrote down his experiences in the battlefield. Besides his successful career on and off the battlefield, he was able to reach full resources of the Prussian State. Additionally and more importantly, he worked with his master Scharnhost in Prussian military academy.[88] Scharnhost was not a theoretical warfare lecturer, however, Clausewitz had learned some of the important aspects of warfare from Scharnhost to initiate his theorization efforts.[89] Later, in the light of his notes and ambitions, consisting of his experiences obtained mainly from the battlefield, he decided to write a theoretical book that reflects the warfare and its conduct so that his theorization of warfare could serve for many years.[90] He had known well that the theory of war would have progressed in line with the advancement of the way that the war is being conducted.

---

[86] Heywood, 245.
[87] Carl von Clausewitz, *On War*, ed. Beatrice Heuser, trans. Michael Howard and Peter Paret (Oxford University Press, 2007), xx.
[88] Ibid.
[89] Ibid., xv.
[90] Ibid., viii.

Thus, his purpose was to write his book during his lifetime.[91] Unfortunately, his death in 1831 did not let him finish his work. Although he had not managed to finish his book, his wife had been able to edit and compile his manuscripts to bring out On War.[92]

In his book, Clausewitz clearly defines the connection between war and policy. As his famous expression asserts that "war is nothing but the continuation of policy by other means."[93] Therefore, it is "an act of force to compel our enemy to do our will."[94] In this sense, "force is thus means of war; to impose our will on the enemy is its object."[95] Effective imposition of the will requires making the enemy "politically helpless and militarily impotent."[96] Theoretically, this is "the true aim of warfare."[97]

The emphasis put on the force brings out the required amount of military power to reach the political object securely, quickly and decisively. At this point, for a rational state, upgrade of its military power with destructive weapons takes the prime importance to perform its political will without any concern.[98] Therefore, emergence motivation of the nuclear technology, in terms of nuclear weapons, was a result of states' lust for enormous military power.[99] Since survival is the principle goal of all states in the world of Realism, power is the main means of the survival to secure other goals.[100]

1.2.2. Clausewitzian Approach to International Nuclear Nonproliferation Efforts

Unlike conventional weapons, nuclear weapons can totally destroy an enemy target in a matter of minutes whether it is a group of people or a city or a whole country. However, the utility of the nuclear weapons cannot be considerable if only one side has nuclear weapons in a conflict.[101] Since the monopoly of the nuclear weapons does not exist in the

---

[91] Ibid., 7-10.
[92] Ibid., xxv.
[93] Ibid., 7.
[94] Ibid., 13.
[95] Ibid.
[96] Ibid., 7.
[97] Ibid., 13.
[98] Ibid., 242-44.
[99] Robert Jervis, "The Political Effects of Nuclear Weapons: A Comment," *International Security* 13, no. 2 (1988).
[100] Waltz, *Theory of International Politics*, 126.
[101] Ibid., 185.

international system, nuclear weapon states cannot easily fight each other using their nuclear weapons due to their second strike capabilities.[102] It means that they can retaliate any nuclear attack by a counter nuclear attack, and this makes the first strike useless.[103] Additionally, even though any outbreak of the conventional war between nuclear weapon states may be possible, they most probably hesitate from the conventional war because of the fear that it may escalate to the nuclear war.[104] As a result, these characteristics make the nuclear weapons meaningful for only deterrent purposes.

The deterrence caused by the nuclear weapons for the outbreak of the conventional war or any nuclear war between nuclear weapon states brings back the importance of the connection and interchange between war and policy. Clausewitz emphasizes that “the political object is the goal, war is the means of reaching it, and means can never be considered in isolation from their purpose.”[105] Furthermore, he insists that “trend and designs of policy shall not be inconsistent with these means.”[106] When the political objective is not consistent with the military objective, as in the probabilistic case of the nuclear war between nuclear weapon states, he also suggests that “another military objective must be adopted that will serve the political purpose and symbolize it in the peace negotiations.”[107] In this sense, nuclear weapons urge their owners, nuclear weapon states, to take precautions that motivate the production of behaviors in terms of defensive and deterrent manners to each other.[108] To put it another way, war is transferred back into the realm of policy in which it is originally designed, shaped and decided.

Given these points, international nuclear nonproliferation efforts takes the upper hand to continue mostly in the international political arena since nuclear weapons are seen as useful for only deterrent purposes.[109] Given that any increase in the number of nuclear weapon states ultimately produces imminent threat for international peace and security by changing the balance of power and adding security risks into the international

---

[102] Ibid., 202.
[103] Dunne, Kurki, and Smith, 82.
[104] Stephen van Evera, "Offense, Defense, and the Causes of War," *International Security* 22, no. 4 (1998).
[105] Clausewitz, 29.
[106] Ibid.
[107] Ibid., 21.
[108] Jervis.
[109] Robert Jervis, "Cooperation under the Security Dilemma," *World Politics* 30, no. 2 (1978).

system[110], nuclear weapon states behave very cautiously on the share of nuclear technology with non-nuclear weapon states. To put it bluntly, nuclear weapon states hesitate from the spread of the nuclear technology mainly because of the double-use aspect of the nuclear technology.[111] Namely, it is such a technology that it can be used for both military purposes and peaceful purposes. Although a state's intention on the use of the nuclear technology is a concern of the political realm, the capability that can modify that intention is a matter of technical realm of nuclear technology. From a Clausewitzian point of view, efforts of a proliferator state depends on "the total means at its disposal and the strength of its will" and this can "only gauged approximately by the strength of the motive animating it."[112] In this sense, in order to prevent any diversion from peaceful use of nuclear energy, it is required to establish a regime, which is nuclear nonproliferation regime, in which internal (technical) and external (political) limits of nuclear technology can be well defined. After implementing well-established limits, internal and external measures of international nuclear nonproliferation efforts can cooperate in synergy to prevent the spread of nuclear weapons.

In the following section, it will be made use of another International Relations theory; Liberalism. In particular, Neoliberal Institutionalism and Regime Theory within liberal paradigm will be given to explain international nuclear nonproliferation efforts.

1.3. LIBERALISM

Unlike Realism, Liberalism has optimistic views of achieving safer and more peaceful international relations.[113] Indeed, its theoretical background takes its spirit from Kant's "universal and perpetual peace" thoughts and mainly regarded as "Idealism."[114] Beginning from the Enlightenment, Liberalism has been an important constituent of Western political thought.[115] Principally, its theoretical entrance into practice was in the aftermath of World War I through the establishment of League of Nations. However,

---

110 Waltz, *Theory of International Politics*, 118.
111 George Perkovich, "Nuclear Proliferation," *Foreign Policy*, no. 112 (1998).
112 Clausewitz, 16.
113 Heywood, 56.
114 Ibid., 61.
115 Mearsheimer, 15.

results of Versailles Settlement was regarded as the failure of Liberalism. Additionally, outbreak of the WWII and the rise of Realism during war time made Liberalism marginalized in International Relations discipline. Nevertheless, Liberal paradigm has achieved reasserting its impact on international relations by 1970s through producing new Liberal theories for international politics by refining its previous idealist trappings. Furthermore, Liberalism has obtained triumph by the end of Cold War and increasing effect of globalization and democratization processes in the 1990s.[116]

In the world of Liberalism, "harmony or balance amongst competing interests" can be achievable.[117] To put it succinctly, this implies that "individual, groups and, for that matter, states may pursue self-interest but a natural equilibrium will tend to assert itself."[118] In other words, competing interests can converge at some points where conflicts can be resolved. Following the balance of interests, possibility of peace and cooperation increases among the states in the international community.

There are three influential theories of Liberalism; Interdependence Liberalism, Republican Liberalism, and Neoliberal Institutionalism. In the context of this thesis, Regime theory, in addition to neoliberal institutionalism, will also be given to analyze international nuclear nonproliferation regime. Since international nuclear nonproliferation efforts consist of international monitoring and cooperation, these two sub-theories of Liberalism will be complement to the remaining part of the theoretical background for this thesis in addition to structural realism and the theory of war.

1.3.1. Neoliberal Institutionalism

Under the umbrella of Liberal paradigm, morality, peace and cooperation constitutes the main themes. However, anarchy, which is the absence of a higher authority as realists claim, is an important obstacle for morality, peace and cooperation to prevail.[119] From a structural realist point of view, it is almost impossible to know or gauge the intentions of states in the international system. Given that intentions of states cannot be known precisely, states mainly hesitate from cooperation because of the fear of being exploited

---

[116] Heywood, 62.
[117] Ibid., 61.
[118] Ibid., 61-62.
[119] Robert Jervis, "Realism in the Study of World Politics," *International Organization* 52, no. 4 (1998).

or defected.[120] Therefore, under the conditions of such a "state of nature", impact of egoism starts to crystallize and results in increasing possibility of conflict among states.[121]

To cope with anarchy, Neoliberal Institutionalism comes up with international institutions to "constrain the ambitions of sovereign states."[122] This approach, indeed, takes its roots from the social contract theory, which claims that "only the construction of a sovereign power can safeguard citizens from the chaos and barbarity of the 'state of nature.'"[123] In the same manner, institutionalists claim that creation of international institutions "enhance the prospects for cooperation among states and thus significantly reduce the likelihood of war."[124] In other words, in this way, "rule of law" can be achieved up to a point, where "jungle" of international politics turn out to be a "zoo."[125]

Although realists make harsh critics of international institutions, there are several points, with which international institutions can contribute international peace and cooperation. First of all, they can create an environment where states come together and make negotiations and bargaining on the important issues of international politics. In this way, states can determine "mutually accepted boundaries for behavior and for the achievement of collective goals."[126] To put it bluntly, institutions "prescribe acceptable forms of state behavior and proscribe unacceptable kinds of behavior."[127] Second, by providing monitoring for compliance and enforcement, international institutions play an important role in the prevention of defection. Through these mechanisms such as gathering and circulating information about member behaviors, a member state can be aware of other states' behaviors within the institution. Therefore, to a considerable extent, states can be sure about the intentions of each other, "combined with greater knowledge about the consequences of cheating and being cheated, which reduces the temptation to cheat generally."[128] Additionally, issue-linkage is important to deter states from defection by

---

[120] John J. Mearsheimer, "The False Promise of International Institutions," *International Security* 19, no. 3 (1994).
[121] Heywood, 55.
[122] Ibid., 64.
[123] Ibid., 65.
[124] Mearsheimer, *The Tragedy of Great Power Politics*, 17.
[125] Heywood, 65.
[126] Dunne, Kurki, and Smith, 121.
[127] Mearsheimer, *The Tragedy of Great Power Politics*, 17.
[128] Dunne, Kurki, and Smith, 123.

providing more than one binding element under the same institution.[129] Through the issue-linkage, a state thinking of defection on one issue cannot defect other states since other binding elements urge that state to give up its decision.[130] Finally, sometimes, international institutions cannot perform their missions effectively due to their "independent causal impact."[131] In fact, this dysfunction may not stem from state intentions or interests, but occur as a result of bureaucratic pathologies within international institutions.[132]

1.3.2. Regime Theory

Regime theory is a sub-theory of Liberalism which concerns with the impact of regimes on the behavior of states. Due to its approach to problems of international relations, regime theory is sometimes used interchangeably with Neoliberal Institutionalism. This mainly stems from their approach to cooperation among states and constraining their behaviors under anarchy.[133] The definition for an international regime suggested by Krasner is that it is a set of "principles, norms, rules and decision-making procedures around which actors' expectations converge in a given area of international relations."[134] In this respect, regimes can be bilateral, regional, and international with regard to the determined area of international relations. Here, it is important to note that regimes differ from institutions in terms of the specified area. Namely, while a regime can focus on a given area of international relations, an institution can deal with multiple areas of international relations.[135]

As its definition reflects, a regime includes principles, norms, rules and decision making procedures. Within a regime, states create rules and abide by them. In the light of a

[129] Robert Jervis, "Realism, Neoliberalism, and Cooperation: Understanding the Debate," *International Security* 24, no. 1 (1999).
[130] Jervis, "Cooperation under the Security Dilemma."
[131] Dunne, Kurki, and Smith, 125.
[132] Ibid.
[133] Robert Axelrod, "The Emergence of Cooperation among Egoists," *The American Political Science Review* 75, no. 2 (1981).
[134] Stephen D. Krasner, "Structural Causes and Regime Consequences: Regimes as Intervening Variables," *International Organization* 36, no. 2 (1982).
[135] Heywood, 67.

regime, states are informed about the acceptable or unacceptable forms of behavior.[136] In this way, any information about defection can be circulated among states and this mechanism would end up with the punishment of cheating state. So, regimes with such a punishment mechanism help states reduce their fear about being exploited. Additionally, abiding by the requirements of a regime can provide a state with positive reputation which can be useful for it in other areas of international relations. Similar to the international institutions, regimes help states reach a commonality as a result of cooperation.[137] This commonality also creates an expectation about the continuity of the cooperation. Through the regimes, replication of transactions can be prevented. Therefore, this reduces efforts and costs to reach an agreement in the future. By getting involved in a regime, a state can learn to assess the perception of other states while learning how other states perceive of it.[138] Consequently, regimes constraint the behavior of states, which reduces the impact of anarchy, so that expectations of the members can converge in a given area of international relations.

In the context of this thesis, international nuclear nonproliferation efforts require international cooperation to stop the proliferation of nuclear weapons. In this sense, nuclear nonproliferation regime plays a key role in the nonproliferation of nuclear weapons, nuclear disarmament, and peaceful use of nuclear energy. So, following section will analyze the nuclear energy within the nuclear nonproliferation regime.

1.4. NUCLEAR NONPROLIFERATION REGIME

Since end of the WWII, nuclear proliferation has been an important agenda for the international relations. It is important to emphasize that the dual use –civilian and military– aspect of nuclear technology makes the use of nuclear energy more complex than other sources of energy. In particular, the enormous amount of military power that states can obtain via nuclear technology constitutes significant problems for maintaining

---

[136] Robert O. Keohane, *After Hegemony: Cooperation and Discord in the World Political Economy* (Princeton University Press, 1984), 59.
[137] Heywood, 67.
[138] Jervis, "Realism, Neoliberalism, and Cooperation: Understanding the Debate."

peace and security in the international system.[139] In an anarchic world, obtaining nuclear weapons to increase military capability can be seen as the insurance of the survival of a state.[140] However, spread of nuclear weapons can cause and create much more problems for the survival of the international system since proliferation of nuclear weapons can cause to the total destruction of the world. Therefore, in order to eliminate these problems, nuclear nonproliferation regime can play an arbitrator role in determination and separation of the boundaries of peaceful and military applications of nuclear energy.[141] To further understand the importance of the nuclear nonproliferation regime for nuclear energy, following subsections will analyze how it emerged, what its pillars are, and what kind of challenges are awaiting for it while its implementation is being conducted.

1.4.1. Origin and Establishment of the International Nuclear Nonproliferation Regime

In its very beginning years, nuclear technology was a military-purposed technology. The importance of nuclear energy and its applicability for the purpose of building a nuclear weapon had been known before the WWII.[142] For the first time, building and implementation of nuclear weapon was achieved by the US during the WWII and used against Japan.[143] This became the demonstration of destructive power of nuclear weapons. Since then, the military use of the nuclear power has been alluring for states. Because, it is regarded as a sign of power and prestige.[144]

In the history of nuclear nonproliferation efforts, foundation and development of a nuclear nonproliferation regime started right after the WWII by the establishment of United Nations Atomic Energy Commission (UNAEC) in 1946. However, sound results could

---

[139] Jack S Levy, "The Causes of War and the Conditions of Peace," *Annual Review of Political Science* 1, no. 1 (1998).
[140] D. Sobek, D. M. Foster, and S. B. Robison, "Conventional Wisdom? The Effect of Nuclear Proliferation on Armed Conflict, 1945-2001," *International Studies Quarterly* 56, no. 1 (2012).
[141] Michael Brzoska, "Is the Nuclear Non-Proliferation System a Regime? A Comment on Trevor Mcmorris Tate," *Journal of Peace Research* 29, no. 2 (1992).
[142] H. A. Feiveson et al., *Unmaking the Bomb: A Fissile Material Approach to Nuclear Disarmament and Nonproliferation* (The MIT Press, 2014), 5.
[143] F. G. Gosling, *The Manhattan Project: Making the Atomic Bomb*, *National Security History Series* (United States Department of Energy, 2010).
[144] William Epstein, "Why States Go -- and Don't Go -- Nuclear," *Annals of the American Academy of Political and Social Science* 430 (1977).

not be achieved by the UNAEC due to the arms race started between the U.S. and USSR in terms of nuclear weapons.[145] In the following years, USSR in 1949 and UK in 1952 became nuclear weapon states. Upon these proliferation trend, U.S. President Eisenhower made a comprehensive call to the international community to stop further proliferation of nuclear weapons and to promote the peaceful applications of nuclear energy in his “Atoms for Peace” speech in 1953.[146] After this call, the International Atomic Energy Agency (IAEA) was established in 1957.[147] The critical role of the IAEA has been the safeguarding of nuclear material and related technologies along with the promotion of peaceful use of nuclear energy. By IAEA safeguards, commitments of states not to divert from peaceful use to military use can be independently verified through a set of technical measures.[148] To perform safeguards, IAEA signs agreements with states such as Comprehensive Safeguards Agreements (CAS), item-specific safeguards agreements and voluntary offer agreements. Therefore, the IAEA, as an international institution, creates an environment in which promotion of peaceful use and prevention of the spread of nuclear weapons can be achieved.[149]

However, after the establishment of the IAEA, spread of nuclear weapons continued by the proliferation of two additional states with nuclear weapons capability; France in 1960 and China in 1964. Furthermore, the Cuban missile crisis between the U.S. and USSR in 1962 reflected the danger of a nuclear disaster posed by the nuclear weapons. Therefore, the U.S., UK, and USSR started to draft an international treaty to stop the trend of proliferation and to eliminate the threat of nuclear weapons.[150] As a result of their efforts, the Treaty on the Nonproliferation of Nuclear Weapons (NPT) was opened to signature in 1968 and entered into force in 1970.[151] By the NPT, international nuclear nonproliferation efforts have gained an internationally binding legal instrument that based upon three main pillars; nonproliferation of nuclear weapons, nuclear disarmament, and

---

145 Edward A. Shils, "The Failure of the Unaec: An Interpretation," *Bulletin of the Atomic Scientists* 4, no. 7 (1948/07/01 1948), https://doi.org/10.1080/00963402.1948.11460220.
146 Eisenhower,
147 IAEA, "History."
148 Acton.
149 IAEA, *Iaea Safeguards 2016: Serving Nuclear Non-Proliferation* (Vienna: International Atomic Energy Agency, 2016).
150 L. J. Carter, "Nuclear Weapons: Nonproliferation and Test-Ban Talks to Be Resumed," *Science* 151, no. 3706 (1966).
151 "Treaty on the Non-Proliferation of Nuclear Weapons (Npt)."

peaceful use of nuclear energy. With its contribution to these pillars, the NPT has become the corner stone of the nuclear nonproliferation regime.

There are other components of the nuclear nonproliferation regime such as import and export control of nuclear material and related technologies (The Zangger Committee and Nuclear Suppliers Group), controlled production of nuclear materials (Fissile Material Cut-off Treaty), disarmament of nuclear weapons (Conference on Disarmament), and creating nuclear weapon free zones (Nuclear-Weapon-Free Zones).[152] All of these components contribute to the international nuclear nonproliferation efforts to mitigate the risk of diversion.

In the context of this thesis, pillar of the peaceful use of nuclear energy and the IAEA safeguards system provide NWS and NNWS with important opportunities, which potentially converge their expectations, that is, nonproliferation of nuclear weapons and peaceful use of nuclear energy. Following subsections will deal with the bargain for the use of nuclear energy between NWS and NNWS and how technical measures against diversion can be further enhanced by the introduction of thorium.

1.4.2. Rules of the Nuclear Nonproliferation Regime

According to the NPT, the parties of the Treaty are separated into two groups as nuclear-weapon states (NWS) and non-nuclear-weapon state (NNWS). Here, this difference in status of the states is very important to analyze the pillars of the NPT within the nuclear nonproliferation regime. First pillar, nonproliferation of nuclear weapons, is that NWS and NNWS pledge each other not to transfer or receive nuclear weapons and related nuclear material (Article I and II). Second pillar, nuclear disarmament, reflects the importance of ending nuclear arms race and dismantling nuclear weapons eventually (Article VI). Third pillar, peaceful use of nuclear energy, gives right to NNWS to use nuclear energy for peaceful purposes (Article IV) by complying with the Article III of the

---

[152] J. Carlson and R. Leslie, "Nuclear Nonproliferation: The Role of Complementary Regimes," *Journal of Nuclear Materials Management* 30, no. 4 (2002).

Treaty. According to Article III, any NNWS party to the Treaty accepts to negotiate and conclude a safeguards agreement with IAEA for their nuclear facilities and activities.[153]

Given these points, IAEA safeguards system is a key technical component for the NPT and the nuclear nonproliferation regime. Through safeguards system, nuclear material and activities can be monitored along with the verification of commitments and declarations of NNWS.[154] Especially, introduction of Additional Protocol expanded the authority of the IAEA to perform safeguards inspections for declared or undeclared facilities. In this way, nuclear facilities and activities can be inspected and monitored comprehensively whether they are used for peaceful or military purposes.[155]

However, being a party to the NPT alone is not enough to prevent the spread of nuclear weapons. For example, Iraqi clandestine nuclear weapon program was an important case that showed how a state could divert from peaceful use to military use even when it was party to the NPT and subject to the IAEA safeguards.[156] Keeping this case in mind, the commitments of the states can be further strengthened as they are included into all components of the nuclear nonproliferation regime. Therefore, in order to increase the efficacy and efficiency of the rules, principles, and procedures, both NWS and NNWS end up with putting emphasis on the importance of international institutions and nonproliferation regime for the maintenance of peace and security in the international system.

1.4.3. Challenges and Opportunities for the International Nuclear Nonproliferation Regime

The main challenge for the nuclear nonproliferation regime is the risk of diversion or misuse of peaceful use of nuclear energy. Actually, this situation stems from the duel use aspect of nuclear energy and the difficulty of determining the precise boundaries of civilian and military applications. In this context, the use of uranium in power generation creates possible routes for military purposes. Especially, existing nuclear power reactor

---

[153] "Treaty on the Non-Proliferation of Nuclear Weapons (Npt)."
[154] Udum.
[155] Asada.
[156] Udum.

systems have a great deal of potential diversion risks both in the front end and in the back end of nuclear fuel cycle. In order to eliminate these risks, sound measures are required while promoting peaceful expansion of the nuclear energy in the international system.[157]

Growing energy needs around the world increase the interest in nuclear power since it is a carbon free source of energy. As a result of this interest, there will be new nuclear power plants connected to the grid.[158] However, if these new nuclear power plants utilize uranium based nuclear fuel, the risk of diversion will potentially increase and the nuclear nonproliferation regime will be challenged immensely. Therefore, more proliferation resistant nuclear fuels can be introduced into the nuclear fuel cycle to prevent proliferation of nuclear weapons. In this respect, these risks can be reduced by the utilization of thorium in the nuclear reactors to be built in the future. Unlike uranium, thorium has unique features that can intrinsically disable the routes of proliferation of nuclear weapons.[159] In this way, expectations of NWS and NNWS can converge since the concerns for proliferation can be reduced and peaceful use of nuclear energy can be promoted.

[157] M. Lehtveer and F. Hedenus, "Nuclear Power as a Climate Mitigation Strategy - Technology and Proliferation Risk," *Journal of Risk Research* 18, no. 3 (2014).
[158] R. Prăvălie and G. Bandoc, "Nuclear Energy: Between Global Electricity Demand, Worldwide Decarbonisation Imperativeness, and Planetary Environmental Implications," *Journal of Environmental Management* 209 (2018).
[159] IAEA, *Thorium Fuel Cycle - Potential Benefits and Challenges*.

CHAPTER II: NUCLEAR TECHNOLOGY AND NONPROLIFERATION: RISKS OF URANIUM AS A FUEL

Diversion of the peaceful use of nuclear energy has always been an important issue for the nuclear nonproliferation regime. The risk of the diversion mainly stems from the dual use aspects of nuclear technology. Namely, nuclear energy can be used for both civilian and military purposes. In an anarchic world, states pursue for the military power to ensure their survival. This power can be obtained from the nuclear weapons with an enormous amount. So, states can turn their attention to military aspect of nuclear technology if required measures do not exist.[160] Therefore, international nuclear nonproliferation efforts have been initiated to prevent spread of nuclear weapons while promoting peaceful use of nuclear energy. These efforts are all placed under the nuclear nonproliferation regime.[161] Within this regime, behavior of the states can be contained since the impact of anarchy is reduced.

However, nuclear nonproliferation regime keeps facing challenges because of the current nuclear fuel cycle, which is based on uranium. Although internal and external measures have been developed, some of the states still managed to disable the measures to divert from peaceful use to military use.[162] Considered as the corner stone of the nuclear nonproliferation regime, the NPT with the IAEA safeguards system has been dealing with these challenges about diversion. In this journey, technical measures are implemented through IAEA safeguards system.

Within the context of the thesis, this chapter explains the nuclear technology and nuclear weapons, analyzes the possible diversion routes which exist in the uranium based nuclear fuel cycle, and scrutinizes the internal and external barriers to prevent proliferation of nuclear weapons.

---

[160] Perkovich.

[161] V. Gilinsky and H. Sokolski, "Serious Rules for Nuclear Power without Proliferation," *Nonproliferation Review* 21, no. 1 (2014).

[162] S. Y. Ahn and J. S. Wit, "North Korea's Nuclear-Weapon Program: Implications for the Nonproliferation Regime," in *Routledge Handbook of Nuclear Proliferation and Policy* (Taylor and Francis, 2015), 70-85.

2.1. NUCLEAR TECHNOLOGY AND NUCLEAR WEAPONS EXPLAINED

Nuclear energy is an important form of energy, which can be achieved through either fission or fusion reactions. Fission reaction takes place when a fissionable isotope of a radioactive element is bombarded with energetic neutrons and ends up with the released energy (~200 MeV per fission) by the split of that atom.[163] For example, isotopes of uranium and plutonium such as U235, U238, Pu239, and Pu240 are fissionable isotopes, which means that they can make fission under energetic neutron bombardment. Here, these energetic neutrons can be labeled as thermal, epithermal, and fast neutrons according to their energy levels and the modulation of these energy levels can be carried out by moderators such as light water, heavy water, and graphite.[164] Additionally, it is important to note that every fissionable isotope cannot sustain chain reactions. In nuclear science, odd numbered isotopes are called fissile isotopes, such as U233, U235, and Pu239, and they are able to sustain chain reactions.[165] Moreover, even numbered isotopes are called fertile isotopes, such as Th232, U238 and Pu240, and they have a potential to capture neutrons and give birth to artificial fissile isotopes, such as U233, Pu239, and Pu241.[166]

Fundamentally, a chain reaction starts with the bombardment of a fissile nucleus with an energetic neutron. When a fissile nucleus is hit and split by that energetic neutron, 2 or 3 neutrons come out in addition to release of energy around 200 MeV per fission.[167] If enough amount of fissile material is present, those neutrons split other fissile nuclei in the medium and chain reaction can be sustained in this way till the aimed result is achieved. Technically, sustainability of a chain reaction depends on the neutrons released after each split of fissile isotopes. In nuclear engineering terms, the ratio of newborn neutrons to the

---

163 B. Barré, "Fundamentals of Nuclear Fission," in *Energy from the Nucleus: The Science and Engineering of Fission and Fusion* (World Scientific Publishing Co. Pte. Ltd., 2016).

164 Weston M. Stacey, *Nuclear Reactor Physics*, Second Edition, Completely Revised and Enlarged ed. (Weinheim: WILEY-VCH Verlag GmbH & Co. KGaA, 2007), 30.

165 UNODA, "Fissile Material," last modified -not available-, accessed 03.03.2021. https://www.un.org/disarmament/fissile-material/#:~:text=Fissile%20materials%20are%20materials%20that,%2D239%20isotope%20of%20plutonium.

166 U.S.NRC, "Fertile Material," last modified December 2, 2020, accessed 03.03.2021. https://www.nrc.gov/reading-rm/basic-ref/glossary/fertile-material.html.

167 NTI, "Fission," last modified -not available-, accessed 01.02.2021. https://tutorials.nti.org/glossary/?term=Fission.

sum of captured and leaked neutrons is labeled as criticality of the system.[168] If this ratio is equal to 1, the system is critical or stable; if this ratio is smaller than 1, the system is subcritical; if this ratio is bigger than 1, the system is supercritical. The criticality, in other words, determines the aspects of a nuclear system whether it is for peaceful or military purposes. For example, in a nuclear power reactor, this ratio is kept around 1, while a nuclear weapon's core is designed to be supercritical.[169] Moreover, criticality calculations shed light on the evaluation of critical masses for fissile materials. Generally, critical mass is calculated for a bare sphere volume and it defines the minimum amount of fissile material alone within that bare sphere volume.[170] Indeed, such a critical mass for a fissile material also determines the minimum amount of the fissile material to make a crude nuclear weapon. In contrast to fission, fusion reaction occurs when two small atom numbered elements, under certain conditions, come together and fuse to create a bigger atom numbered element.[171] In other words, fusion reaction needs external heat at very high temperatures such as millions of Celsius degrees to fuse two small nuclei together. For example, deuterium and tritium can fuse to form helium.[172] If the required external heat is provided with the fission reaction, thermonuclear or hydrogen bombs can be designed through successive reactions of fission and fusion.[173] In brief, enormous amount of energy comes out as a result of these two reaction types. At this point, it should be considered that the intentions guiding these reactions play the primary role in whether the harnessed energy is for the peaceful purposes or for the military purposes.

In the early days, the motivations on the use of nuclear energy were mainly determined by its intense release of energy and its possible applicability for military purposes. Through nuclear energy, it was anticipated that millions order of the magnitude of the traditional explosives could be achievable.[174] Admittedly, this fact had become very alluring for states after the discovery of radioactivity in the late 1800s. According to Frederick Soddy, utilizing this much energy could change the destiny of the world.[175]

---

[168] Stacey, 37.
[169] *Nuclear Nonproliferation: The Spent Fuel Problem*, ed. Frederick C. Williams and David A. Deese, *Pergamon Policy Studies on Energy and Environment* (New York: Pergamon Press, 1979), 2-3.
[170] IAEA, *Technical Features to Enhance Proliferation Resistance of Nuclear Energy Systems*.
[171] *Fusion Physics* (Vienna: International Atomic Energy Agency, 2012), 14.
[172] Ibid., 22.
[173] Feiveson et al., 40-41.
[174] *Nuclear Nonproliferation: The Spent Fuel Problem*, 2.
[175] Feiveson et al., 21.

Keeping this in mind, in the 1930s, invention of the fission chain reaction also accelerated the studies for the realization of nuclear weapons. However, performing a fission chain reaction for a nuclear weapon was very difficult since enough amount of fissile material was very hard to accumulate in that time of the invention. In nature, only uranium has a fissile isotope U235 by 0.72% and the rest is the fertile isotope U238 by 99.28%. For a nuclear weapon, it was supposed to gather critical mass of U235 so that a supercritical chain reaction could be sustained.[176]

During World War II (WWII), the U.S. started to search for nuclear weapons through the Manhattan Project. This top secret project consisted of three phases: research and development; uranium enrichment and plutonium separation; design and production of deployable nuclear weapons.[177] In the beginning, these phases were very demanding. On the one hand, natural uranium was needed to separate its fissile isotope U235 and increase its percentage. However, this isotope separation process, which is called enrichment, was very difficult since U235 and U238 are chemically identical isotopes.[178] Therefore, this made enrichment possible by the physical isotope separation due to their around one and half percent of weight difference. This was carried out at the electromagnetic uranium enrichment facility, Y12, in Oak Ridge. On the other hand, the invention of the plutonium during research and development phase played an accelerative role in the project to produce another fissile material, Pu239, artificially. For the plutonium production, two natural uranium fueled reactors, X10 (1 MWth) air cooled graphite moderated reactor and B reactor (250 MWth) water cooled graphite moderated reactor, were built in Oak Ridge and Hanford, in 1943 and 1944, respectively. In those critical reactors, the fertile isotope (U238) of uranium was bombarded with energetic neutrons, then, some of U238s absorbed neutrons to give birth to plutonium, Pu239.[179] Here, it is important to emphasize that the rate of plutonium production is directly proportional to the power of reactors. So, plutonium production from the X10 reactor was in small amounts and primarily used for research and experiments in New Mexico. Enriched uranium from Oak Ridge and

---

[176] *Nuclear Nonproliferation: The Spent Fuel Problem*, 2-3.
[177] Gosling.
[178] NTI, "Uranium Enrichment," last modified -not available-, accessed 01.02.2021. https://tutorials.nti.org/glossary/?term=Enriched%20uranium.
[179] *Nuclear Safeguards, Security, and Nonproliferation: Achieving Security with Technology and Policy*, ed. James E. Doyle (Burlington, USA: Elsevier Inc., 2008), 81-82.

produced plutonium from Hanford were sent to the Los Alamos National Laboratory to design and produce the nuclear weapons. Finally, efforts gave birth to the atomic age on 16th July of 1945 in Trinity with a successful test of an atomic bomb.[180]

Historically, the Manhattan Project was the first effort that successfully produced fissile materials such as U235 and Pu239.[181] It was experienced that the design of a nuclear weapon depends on the neutronic properties of those fissile materials. "Little Boy" and "Fat Man" were the nuclear weapons fueled with U235 and Pu239 respectively. Little Boy was a nuclear weapon of gun-type, which works through merging two separate subcritical mass of fissile material, U235.[182] Fat Man was a nuclear weapon of implosion type, which works through the implosion of conventional explosives to squeeze the subcritical Pu239 core to make it supercritical.[183] After these fission based nuclear weapons were advanced, fusion based thermonuclear weapons were produced to boost the impact of the nuclear weapons through the successive reactions of fission and fusion.[184]

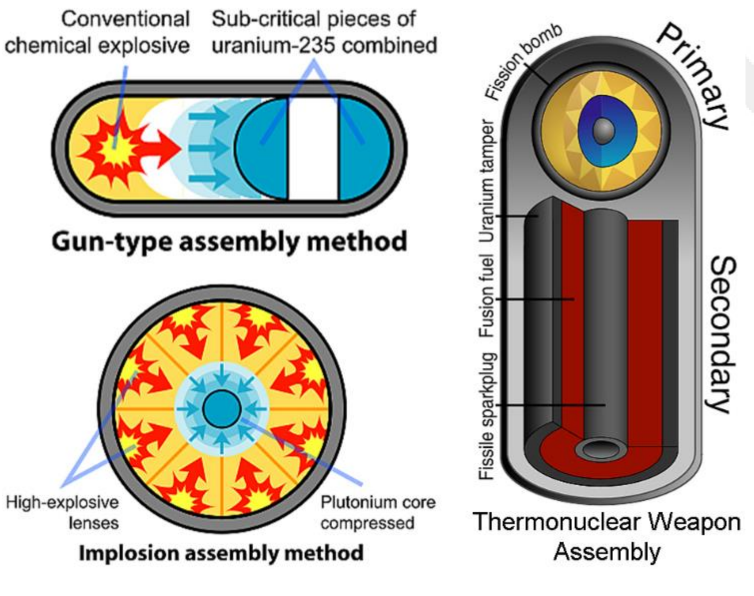

Figure 1: Types of Nuclear Weapons, **Source**: https://www.ctbto.org/nuclear-testing/types-of-nuclear-weapons/

---

180 Gosling.
181 Ibid.
182 *Nuclear Safeguards, Security, and Nonproliferation: Achieving Security with Technology and Policy*, 19.
183 Ibid., 406.
184 NTI, "Thermonuclear Weapon," last modified -not available-, accessed 01.02.2021. https://tutorials.nti.org/glossary/?term=Thermonuclear%20weapon.

Given these points, after producing enough amount of fissile material, nuclear weapons can be built with respect to required amount of the fissile materials. According to the IAEA, the required amount of fissile materials for nuclear weapons can be defined in terms of significant quantity or critical mass.[185] Here, it is important to explain why these two definitions should not be confused with each other. In technical terms, critical mass is calculated with respect to the neutronic properties of a fissile material, which is allocated in a bare sphere geometry.[186] Indeed, this equals to the minimum amount of fissile material alone. However, this amount can be decreased by using some sophisticated techniques such as neutron reflection. Since this technique prevents the neutron leakage to sustain supercriticality, same impact of a nuclear weapon could be achievable using less amount of fissile material.[187] As a result of these techniques, critical mass and significant quantity for a fissile material turn out to be different. In nonproliferation terms, significant quantities are considered as the important thresholds for safeguarding by the IAEA. For a simple comparison, significant quantities and critical masses for some fissile materials are given in Table 1.[188]

Table 1: Critical Mass and Significant Quantity Values for Some of the Fissile Isotopes

Isotope	Critical Mass (kg)	Significant Quantity (kg)
U233	16.4	8
U235 > 20%	47.9	25[a]
Pu239	10.2	8[b]

[a]: Including low enriched, natural and depleted uranium. [b]: For Pu containing less than 80% Pu238

Proliferation of nuclear weapons can happen in two major dimensions of the phenomenon; horizontal and vertical.[189] Horizontal proliferation means the increment in the number of states that previously did not have nuclear weapons. At this type of proliferation, the spread of nuclear weapons may happen in various ways such as acquisition, theft or purchase, and even latency. All of the behaviors regarding these ways

---

185 IAEA, *Safeguards Glossary 2001 Edition* (Vienna: International Atomic Energy Agency, 2002), https://www.iaea.org/sites/default/files/iaea_safeguards_glossary.pdf.
186 Stacey, 57.
187 Feiveson et al., 25.
188 IAEA, *Technical Features to Enhance Proliferation Resistance of Nuclear Energy Systems*; IAEA, *Safeguards Glossary 2001 Edition*.
189 E. Gartzke and M. Kroenig, "A Strategic Approach to Nuclear Proliferation," *Journal of Conflict Resolution* 53, no. 2 (2009).

constitute the main indicators of a state's intentions whether it is going for peaceful or military use of nuclear energy. In this respect, a proliferating state may consider one or more of them to obtain nuclear weapons. Vertical proliferation, on the other hand, means the increment in the quantity and quality of nuclear weapons by a nuclear weapon state that already has the capability to build nuclear weapons.

In terms of diversion, latency plays a key role in nuclear weapons proliferation since it is closely related with the intentions of a state that exploits the peaceful use of nuclear energy.[190] In this respect, latency can also mean the change in the intentions of a state after it gains capability to manage nuclear energy, which mostly happens during the peaceful applications of nuclear energy, to produce nuclear weapons.[191] Therefore, intrinsic and extrinsic measures have been developed and implemented to prevent diversion of peaceful use. However, these measures sometimes cannot work as intended and reduce the concerns of proliferation due to the possible diversion routes, which exist in the uranium based nuclear fuel cycle. So, following two sections firstly examine the possible proliferation routes and diversion steps, which exist in the uranium based nuclear fuel cycle, and then, the conventional barriers to prevent proliferation.

2.2. POSSIBLE PROLIFERATION ROUTES AND DIVERSION STEPS

In the nuclear fuel cycle for uranium, there are several stages at which the misuse of nuclear material may happen. To examine these stages, it would be appropriate to make a distinction between front end and back end of uranium based nuclear fuel cycle.[192] Both ends, by exceeding certain thresholds at some stages, may give a chance to a proliferating state to divert from peaceful use to military use of nuclear energy.[193] To be more precise, mainly enrichment of uranium and reprocessing of spent fuel can play the major role in

[190] Robinson.
[191] A. H. Montgomery and S. D. Sagan, "The Perils of Predicting Proliferation," *Journal of Conflict Resolution* 53, no. 2 (2009).
[192] D. L. York, G. Rochau, and C. Mendez, *Enhancing Nonproliferation through Nuclear Fuel Cycle Transparency*, vol. 95, *2006 Winter Meeting of the American Nuclear Society* (Albuquerque, NM: 2006).
[193] S. Squassoni, "Nuclear Energy and Nonproliferation: Todays Challenges," in *Business and Nonproliferation* (Brookings Institution Press, 2011).

the possibility of proliferation.[194] So, deep examination of the capabilities regarding these stages along with the intentions of a state reflects the possible indicators of diversion.[195] Following subsections will explain these steps and how they relate to the peaceful and military use of nuclear energy.

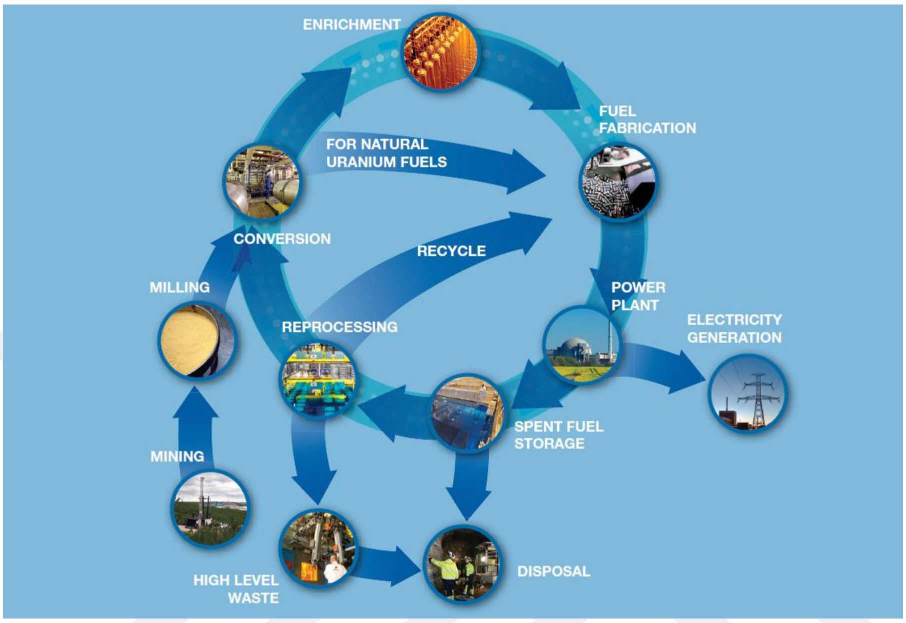

Figure 2: Nuclear Fuel Cycle, **Source**: https://www.iaea.org/sites/default/files/19/02/the-nuclear-fuel-cycle.pdf

2.2.1. Front End

In the nuclear fuel cycle, front end consists of several stages such as mining, milling, conversion, and fuel fabrication, respectively.[196] More generally, for the peaceful use of nuclear energy, it can be considered as the processes between uranium ore and irradiation of the fuel in the nuclear reactors.[197] Firstly, mining is the digging of the uranium ore to collect natural uranium from earth's crust. Then, milling is the process of distilling of natural uranium from other compounds or elements gathered from the ore. At the end of

---

[194] Y. Yudin, "Nuclear Energy and Non-Proliferation," in *The Handbook of Global Energy Policy* (Wiley Blackwell, 2013).
[195] IAEA, *Inpro Collaborative Project: Proliferation Resistance: Acquisition/Diversion Pathway Analysis (Prada)*.
[196] IAEA, *Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (Uram-2009)* (Vienna: International Atomic Energy Agency, 2014).
[197] L. N. Larson, "The Front End of the Nuclear Fuel Cycle: Current Issues," in *Key Congressional Reports for July 2019: Part Iv* (Nova Science Publishers, Inc., 2019).

milling, uranium is distilled into the chemical form of U3O8, which is sometimes called as "yellow cake" with the attribution to its color. Next step, conversion, is a chemical process, in which oxide form of uranium, U3O8, is converted into fluoride form of uranium, UF6. UF6 normally exists in the solid form, however, it can easily sublime at atmospheric pressure when it reach its melting point of 56.5 Celsius degrees.[198] Since uranium hexafluoride can be gaseous after certain temperature, natural uranium can be easily enriched up to the desired enrichment levels in an enrichment plant.[199] Final step before the irradiation of nuclear fuel is fuel fabrication. Through fuel fabrication, uranium, whether it is natural or enriched, is prepared to be in pellet forms, which are the compact form of fuel to be placed into the fuel rods (Figure 3). After following each stage successively, the front end is assumed to be finalized.[200]

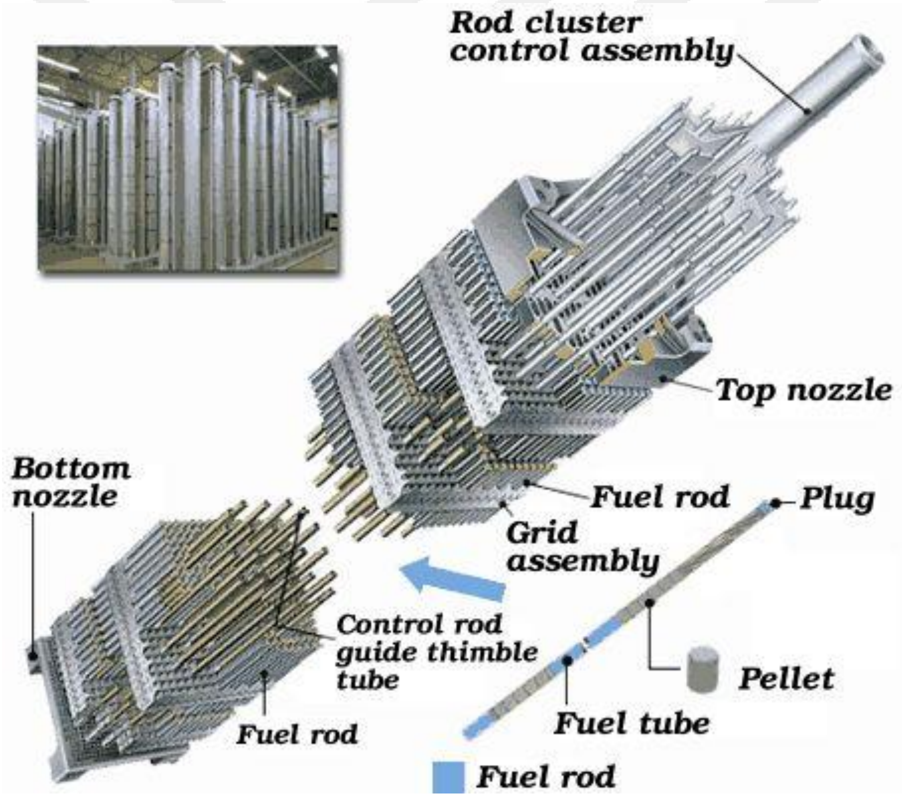

Figure 3: A PWR Fuel Assembly, **Source**: https://world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/fuel-fabrication.aspx

198 U.S. Department of Energy, *Safety Data Sheet Uranium Hexafluoride (Uf6)* (Oak Ridge, TN: NBL Program Office, 2020).
199 U.S.NRC, "Uranium Enrichment," last modified December 2, 2020, accessed 20.02.2021. https://www.nrc.gov/materials/fuel-cycle-fac/ur-enrichment.html.
200 IAEA, *Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (Uram-2009).*

In the front end, natural uranium production and uranium enrichment can be examined in terms of nuclear weapons proliferation. Here, enrichment process can be regarded as the most sensitive stage to diversion among those stages.[201] Specifically, it can be used as a direct route to obtain nuclear weapons after going beyond some thresholds of enrichment.[202] In other words, enrichment levels of uranium primarily reflect the position of a system whether it is peaceful or military purposes. As an indirect route, natural uranium can also be a proliferation concern when it is used within a heavy water or graphite moderated system.[203] Because, heavy water and graphite can effectively moderate fast neutrons to slow them in thermal energies so that fission chain reaction can be sustained without the requirement for the enrichment of natural uranium. In this respect, existence of natural uranium coupled with the heavy water or graphite moderation can constitute a potential for production of plutonium.[204] Therefore, reprocessing of plutonium discharged from the heavy water or graphite moderated system can be regarded as a secondary route for proliferation and this will be examined in detail in the back end of nuclear fuel cycle.

2.2.1.1. Enrichment of Uranium

As well-known from the Manhattan Project, the first and foremost aim of the uranium based nuclear fuel cycle was to obtain enough amount of fissile material, which was primarily U235, to build a nuclear weapon.[205] To achieve this, uranium was a convenient option since it contains both fissile (U235) and fertile (U238) isotopes naturally. However, natural uranium alone could not be utilized for a nuclear weapon to sustain a chain reaction with its isotopic ingredients. So, it was aimed at the increment of the fissile content of U235, which is around 0.7% of natural uranium. Through the enrichment

---

[201] U.S.NRC, "Uranium Enrichment."
[202] NTI, "Highly Enriched Uranium," last modified -not available-, accessed 01.02.2021. https://tutorials.nti.org/glossary/?term=Highly%20enriched%20uranium%20(HEU).
[203] *Nuclear Safeguards, Security, and Nonproliferation: Achieving Security with Technology and Policy*, 64-65.
[204] Feiveson et al., 107-11.
[205] Gosling.

process, in other words, fissile isotopic content of natural uranium was intended to increase beyond 90% to be weapon grade.[206]

Since the beginning of the nuclear age, several enrichment techniques have been used to enrich natural uranium. For example, two enrichment techniques were used in the Manhattan Project.[207] First technique was Calutrons, which was the separation of charged uranium ions through a strong magnetic field. The other technique was gaseous diffusion. In this simple technique, UF6 is pumped through a porous filter, which lets only U235 to pass from the filter. However, these techniques needed much energy. So, their energy efficiencies were very low.[208] Then, gas centrifugation was invented and has been widely used since 1970s. In this technique, UF6 is sent into the cascades of centrifuges, and each centrifuge performs an isotope separation in small fractions. So, there have to be thousands of centrifuges to reach a considerable grade of enrichment in a gas centrifugation plant. In contrast to the calutrons and gaseous diffusion, gas centrifugation is very efficient since they use very low energy.[209] There are other techniques such as aerodynamics separation, laser excitation, chemical exchange and ion exchange.[210] However, these techniques were abandoned and never became available on a commercial scale.

At this point, it is important to note that uranium has several grades regarding its enrichment levels. In addition to the natural uranium, these enrichment levels of uranium are mainly classified as low enriched uranium, LEU, (below 20% with U235) and highly enriched uranium, HEU, (over 20% with U235). 20% enrichment is an important threshold in the enrichment process. Up to this threshold of 20%, almost 75% of the separative work is done and around 25% additional separative work can enrich uranium beyond 90%. Additionally, remaining isotope U238 after the enrichment of natural uranium, which has less than 0.71% U235, is called depleted uranium.[211]

---

[206] NTI, "Weapons Grade Material," last modified -not available-, accessed 01.02.2021. https://tutorials.nti.org/glossary/?term=Weapons-grade%20material.
[207] *Nuclear Safeguards, Security, and Nonproliferation: Achieving Security with Technology and Policy*, 81.
[208] Gosling.
[209] U.S.NRC, "Uranium Enrichment."
[210] Manson Benedict, Thomas H. Pigford, and Hans Wolfgang Levi, *Nuclear Chemical Engineering*, Second ed. (New York: McGraw-Hill Education, 1981), 22-23.
[211] IAEA, *Safeguards Glossary 2001 Edition*.

For the civilian use of nuclear energy, especially in nuclear power reactors, slight enrichment of uranium (up to 5% enrichment) becomes a requirement for certain types of nuclear reactors. These reactors are thermal or moderated reactors and generally named with their moderator types such as light water reactors (LWRs), heavy water reactors (HWRs), molten salt reactors (MSRs), and graphite moderated high temperature gas cooled reactors (HTGRs).[212] Through these moderators, neutrons having much more energies are slowed down to thermal energies so that the nuclear chain reaction can be sustained. At this point, it is important to note that all of the thermal reactors do not necessarily require enrichment of uranium. For instance, reactors using moderators like heavy water in HWRs or graphite in HTGRs can be given as an example.[213] Lastly, for fast or unmoderated reactors, such as fast breeder reactors (FBRs), enrichment levels has to be high because of the neutronic requirements, like more than 5%, since it is designed to work within the fast neutron spectrum. Additionally, fast reactors are such reactors through which more fissile material can be produced than consumed.[214]

Given these points, enrichment of uranium is a primary indicator of proliferation in order to make a distinction between peaceful and military use of nuclear energy. As being performed in the front end, enrichment of the uranium has a potential to constitute a direct way to go for the military purposes.[215] Especially, significant progress that have been achieved in the enrichment techniques makes the diversion of peaceful use more possible. Therefore, uranium enrichment and its related technologies should be kept under control and certain thresholds.[216]

---

[212] Stacey, 41.
[213] Ibid., 219.
[214] S. Permana et al., *Analysis on Reactor Criticality Condition and Fuel Conversion Capability Based on Different Loaded Plutonium Composition in Fbr Core*, 1 ed., vol. 799, *5th International Conference on Advances in Nuclear Science and Engineering, ICANSE 2015* (Institute of Physics Publishing, 2017).
[215] WNA, "Uranium Enrichment," World Nuclear Association, last modified September 2020, accessed 20.04.2021. http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx.
[216] Squassoni, in *Business and Nonproliferation*.

2.2.1.2. Neutron Moderation by Heavy Water and Graphite

In the early years of the nuclear energy, it was important to follow the route of uranium enrichment to obtain weapon grade uranium. In addition to this route, another route came into the scene, which was the invention and production of plutonium in 1942.[217] As being produced by the irradiation of uranium (natural or enriched) in a reactor, plutonium can be retrieved from the irradiated fuel discharged from the reactor and be used directly in a nuclear weapon after acquiring significant quantity or critical mass of plutonium.[218] Since natural uranium contains U235 by 0.7%, a reactor fueled with natural uranium requires an economic neutron moderation to sustain fission chain reaction. In other words, neutron moderation should be performed in a way that the moderation of neutrons is conducted with lesser neutron losses. In this respect, graphite and heavy water are suitable elements to become moderators in a reactor fueled with natural uranium. The reason behind their usage as a moderator is that both heavy water and graphite have considerable moderation ratios in contrast to the light water. In technical terms, these moderators not only slow down the neutrons, but also they do not absorb neutrons as much as the light water. So, this makes the fission chain reaction continue with the enough amount of neutron flux in the reactor core without the need for the enrichment of uranium.[219]

In nonproliferation terms, these two moderators can constitute a route for the military use of nuclear energy. Considering the case for the Manhattan Project, graphite moderated reactors utilizing natural uranium were designed, built and operated in Oak Ridge and Hanford to produce weapon grade plutonium.[220] As being an example for the pressurized heavy water moderated reactors, CANDU (CANada Deuterium-Uranium reactor) also do not require the enrichment of uranium. In the context of the latency effect in the nuclear weapons proliferation, it is believed that India has exploited CANDU reactors to produce its nuclear weapons.[221] Since their possible contribution to divert peaceful use of nuclear energy is experienced by the examples of the nuclear weapons proliferation, these

---

[217] Gosling.
[218] M. Waldrop, "The Technology Behind Nuclear Proliferation," *Chemical and Engineering News* 55, no. 30 (1977).
[219] Stacey, 30.
[220] Manson Benedict, Thomas H. Pigford, and Levi, 458.
[221] J. S. Walker, "Nuclear Power and Nonproliferation: The Controversy over Nuclear Exports, 1974-1980," *Diplomatic History* 25, no. 2 (2001).

moderators should also be controlled or abandoned so that the diversion of peaceful use could be prevented.

2.2.2. Back End

Back end of nuclear fuel cycle mainly deals with the nuclear fuels discharged from the nuclear reactors.[222] In practice, fresh fuel installed in the reactor cores stays in there for some time to produce energy. During its operational time, fresh fuel consisting of fractional fissile content, undergoes fission reactions. As a result of fission reactions, initial fissile content of the fuel is spent while producing minor actinides such as plutonium (Pu), americium (Am), and curium (Cm).[223] Unlike fresh fuel, the spent fuel is highly radioactive due to the decay heat produced by those minor actinides. Therefore, spent fuel is kept in the cooling pools for some time ranging from a few years to a decade. In technical terms, spent fuel management can be conducted in two ways.[224] In literature, these are labeled as open or once-through fuel cycle and closed fuel cycle. In the case of open fuel cycle, discharged fuel or spent fuel, after cooling in the pools, is sent to the storage facilities without reprocessing. Conversely, in the case of the closed fuel cycle, spent fuel, after cooling in the pools, undergoes reprocessing so that the remaining reusable content of the discharged fuel can be retrieved. However, reprocessing also makes the retrieval of fissile content from the spent fuel possible, such as Pu239, which can be also used as a weapon material. So, following subsection will examine reprocessing in detail for both military and peaceful applications of nuclear energy.

---

[222] NTI, "Reprocessing," last modified -not available-, accessed 01.02.2021. https://tutorials.nti.org/glossary/?term=Reprocessing.
[223] A. Paulenova, "2 - Physical and Chemical Properties of Actinides in Nuclear Fuel Reprocessing," in *Advanced Separation Techniques for Nuclear Fuel Reprocessing and Radioactive Waste Treatment*, ed. Kenneth L. Nash and Gregg J. Lumetta (Woodhead Publishing, 2011).
[224] Ch Poinssot et al., "Assessment of the Environmental Footprint of Nuclear Energy Systems. Comparison between Closed and Open Fuel Cycles," *Energy* 69 (2014).

2.2.2.1. Reprocessing of Spent Fuel

While enrichment of uranium is a physical separation process, reprocessing of the irradiated fuel is a set of chemical processes.[225] In other words, reprocessing involves extraction methods under certain conditions such as heat, pressure, acidic solvents, and flow rate.[226] Indeed, it is essential that spent fuel can be ready for the reprocessing after spending several years in the cooling pools to decrease their decay heat generation. Through reprocessing, spent fuel discharged from a reactor can be cleared from unnecessary fission products and minor actinides. Those are generally labeled as high level waste and they cannot be used as a fuel in a reactor again. However, spent fuel also contains reusable elements such as uranium, plutonium, and some of other minor actinides. In proliferation terms, reprocessing of spent fuel becomes a matter of concern when fissile content, especially Pu239, of the spent fuel is taken back through a customized method.[227] For such a purpose, PUREX (plutonium uranium reduction extraction), which is the method used for extraction of uranium and plutonium purely by reduction processes, can be used.[228] Historically, this was experienced during the Manhattan Project, by which the U.S. benefitted from reprocessing of spent fuel to retrieve weapon grade plutonium in addition to the enrichment of natural uranium.[229] In this respect, reprocessing of spent fuel can be very proliferation sensitive in the back end of the nuclear fuel cycle.

In contrast to the military application, reprocessing of spent fuel can also be conducted through several methods, such as COEX, UREX, and TRUEX, for the peaceful use of nuclear energy.[230] For example, COEX is a co-extraction method in which uranium and plutonium extracted together while UREX is used to extract only uranium from the irradiated fuel. By TRUEX, transuranics, such as Am and Cm, are removed from the

---

[225] Manson Benedict, Thomas H. Pigford, and Levi, 457.
[226] Jean-Paul Glatz, P. Souček, and R. Malmbeck, "3 - Key Challenges in Advanced Reprocessing of Spent Nuclear Fuels A2 - Taylor, Robin," in *Reprocessing and Recycling of Spent Nuclear Fuel* (Oxford: Woodhead Publishing, 2015).
[227] Helmut Rauch and Michael Schneeberger, "Fundamentals of the Nuclear Fuel Cycle," *Elektrotech Maschinenbau* 94, no. 2 (1977).
[228] E. R.; Reas Irish, W. H. , *The Purex Process - a Solvent Extraction Reprocessing Method for Irradiated Uranium* (Richland, Washington: U.S. Atomic Energy Commission, 1957).
[229] Gosling.
[230] M. C. Regalbuto, "7 - Alternative Separation and Extraction: Urex+ Processes for Actinide and Targeted Fission Product Recovery," in *Advanced Separation Techniques for Nuclear Fuel Reprocessing and Radioactive Waste Treatment*, ed. Kenneth L. Nash and Gregg J. Lumetta (Woodhead Publishing, 2011).

spent fuel to facilitate the spent fuel management.[231] To put it bluntly, all of these methods are designed to prevent the extraction of pure or weapon grade plutonium from the irradiated fuel. Therefore, in peaceful terms, reprocessing of spent fuel using these methods has several advantages.[232] For example, retrieving fissile and fertile content of the spent fuel provides with the conversation of natural uranium resources by recycling the spent nuclear fuel. Additionally, spent fuel management and waste management issues become more sustainable by removing unusable minor actinides and fission products from the irradiated fuel.[233]

From the perspective of diversion, uranium based nuclear fuel cycle, whether it is once through or closed, has a weakness to prevent proliferation because of the plutonium production in the irradiated fuel. Since plutonium has a very low significant quantity, there can be enough amount of plutonium to make several nuclear weapons even in the spent fuel of a traditional nuclear power reactor. In more technical terms, for example, a 1000 MWth nuclear power reactor can produce around 164.25 kg of weapon grade plutonium in one year operation.[234] When the significant quantity of 2 kg for weapon grade plutonium is considered, 164.25 kg can be enough to make almost 83 nuclear weapons. Given these points, as long as uranium based nuclear fuel cycle is used, the weapon grade plutonium will continue to be bred by the irradiation of uranium in the nuclear reactors.

2.2.3. Advanced Routes

After the WWII, the search for more power have taken states into the development of more advanced systems of nuclear weapons. As they advanced fission-based nuclear weapons, next step would be to create fusion-based nuclear weapons. Through fusion

---

[231] Paulenova, in *Advanced Separation Techniques for Nuclear Fuel Reprocessing and Radioactive Waste Treatment*.
[232] Kenneth L. Nash and Mikael Nilsson, "1 - Introduction to the Reprocessing and Recycling of Spent Nuclear Fuels A2 - Taylor, Robin," in *Reprocessing and Recycling of Spent Nuclear Fuel* (Oxford: Woodhead Publishing, 2015).
[233] B. Taebi, *Moral Dilemmas of Uranium and Thorium Fuel Cycles*, vol. 19, *Radioactivity in the Environment* (Elsevier Ltd, 2013).
[234] OECD/NEA, *Spent Nuclear Fuel Assay Data for Isotopic Validation* (France: Nuclear Energy Agency, 2011).

reaction, it was clear that much more destructive nuclear weapons in yield could be produced.[235] Theoretically, nuclear fusion reaction needs external heat at very high temperatures to fuse two small atom numbered elements.[236] Therefore, the amount of energy released from fission reactions turns out to be an initiator for the nuclear fusion reactions. In this respect, a proliferator state should firstly ensure its nuclear capability regarding fission reactions related systems. Without advancing in fission related weapons, it is not a case for a state that the boosting of its nuclear weapons could be achievable.[237] So, this thesis assumes that producing fusion weapons or hydrogen bombs require more advanced capabilities other than conventional nuclear fission weapons. Specifically, these capabilities range from weapons design to used explosive materials. Hence, following subsections will explore those materials in detail.

2.2.3.1. Deuterium and Tritium

As being isotopes of hydrogen, deuterium and tritium are two small elements in atomic weight. Deuterium has one proton and one neutron while tritium has one proton and two neutrons. Here, it is important to note that deuterium is a stable element in oxide forms (D2O) named as heavy water.[238] Since it naturally exists in nature with a fraction of 0.01% of the light water (H2O), it can be produced by an enrichment method specific to the separation of heavy water from light water, which is called Girdler sulfide (GS) process.[239] Tritium, on the other hand, can be produced by either fission or capture reactions. For example, lithium and boron can fission under fast neutron flux to produce tritium. Additionally, in the nuclear reactors, heavy water also has a potential to capture a neutron to produce tritium.[240]

Since the fusion reaction occurs when two small nuclei come together under certain conditions, deuterium and tritium can be used as the fuel for fusion reactions. In the early

---

[235] NTI, "Thermonuclear Weapon."
[236] NTI, "Fusion," last modified -not available-, accessed 01.02.2021. https://tutorials.nti.org/glossary/?term=Fusion.
[237] Feiveson et al., 41.
[238] IAEA, *Safeguards Glossary 2001 Edition*.
[239] Manson Benedict, Thomas H. Pigford, and Levi, 708-10.
[240] Martin B. Kalinowski, *International Control of Tritium for Nuclear Nonproliferation and Disarmament*, vol. IV, *Science and Global Security Monograph Series* (United States of America: CRC Press LLC, 2004).

generation of hydrogen bombs, these two nuclei were used as a booster for fission based nuclear weapons.[241] For a hydrogen bomb, required heat to initiate fusion reaction is supplied by the fission reaction. Then, fusion reaction takes place by producing helium and releasing more neutrons. If more nuclear material, such as U235, U238, and Pu239, exist in the medium, those neutrons cause more fissions and the boosting can be achieved through these successive fission, fusion, and fission reactions.

In nuclear nonproliferation terms, deuterium and tritium can pose a proliferation threat in the context of the fission and fusion reactions. Besides being a fusion fuel, deuterium, which becomes heavy water in oxide form (D2O), can also be used in the nuclear reactors as a moderator to slow down neutrons. Especially, due to its moderation ratio, heavy water does not require the enrichment of uranium and can make natural uranium fueled reactors operate. This, however, causes the production of weapons grade plutonium in the back end. Unlike deuterium, tritium should be produced continuously to fuel hydrogen bombs since it is radioactive with a half-life of 12.3 years. This has created the major problem for the sustainability of the early hydrogen bombs. However, this problem has been solved by the usage of lithium deuteride. As a result, deuterium and tritium still have a potential to cause diversion of the peaceful use.

2.2.3.2. Lithium Deuteride Salt

Since tritium decays by time, it is important to replace it with a more stable element. Capable of producing tritium under fast neutron flux, this element is lithium deuteride. In a thermonuclear weapon, fission reactions release fast neutrons that irradiates lithium deuteride. And, this makes lithium deuteride split into deuterium and tritium.[242] By the way, the heat produced during the fission reactions makes those produced deuterium and tritium fuse together. After these fusion reactions, helium and a neutron come out. As a result, these reactions increase the yield of the nuclear weapons. In this context, thermonuclear weapons can be stored for a long time if they are fueled with lithium deuteride.

[241] NTI, "Thermonuclear Weapon."
[242] Manson Benedict, Thomas H. Pigford, and Levi, 23.

2.3. CONVENTIONAL BARRIERS TO PREVENT PROLIFERATION

During the course of nuclear nonproliferation efforts, both internal and external barriers have been developed to prevent proliferation of nuclear weapons or diversion of peaceful use of nuclear energy.[243] Since the fissile material production is primarily a technical issue, these barriers mainly focus on the internal or technical characteristics of nuclear energy. In other words, many of the barriers have been primarily embedded in the technical aspects of nuclear technologies. Accordingly, these technical features determine the quantity and quality of nuclear material utilized in a nuclear energy system, and then, how those materials should be handled within the peaceful purposes before and after utilization.[244] As being complementary to the internal barriers, external barriers are basically sort of regulatory or legal instruments. These kind of barriers range from being party to the international conventions to adopting those conventions in domestic legal and regulatory system.[245] Consequently, a well-functioning combination of both internal and external barriers is expected to be more successful in preventing diversion of peaceful applications.

Accordingly, internal and external barriers can be extrapolated into many types of deployment in various nuclear energy systems.[246] However, these extrapolations may cause a complexity to understand them neatly. Therefore, this thesis adopts the analogy of barriers suggested by the IAEA. Especially, "defense in depth" approach developed by the IAEA explains very well how these barriers functions within the safety, security and safeguards measures.[247] Hence, following subsections will scrutinize these barriers in detail from the lenses of the international nuclear nonproliferation efforts.

---

[243] IAEA, *Technical Features to Enhance Proliferation Resistance of Nuclear Energy Systems*.
[244] IAEA, *Inpro Collaborative Project: Proliferation Resistance: Acquisition/Diversion Pathway Analysis (Prada)*.
[245] Montgomery and Sagan.
[246] IAEA, *Inpro Collaborative Project: Proliferation Resistance: Acquisition/Diversion Pathway Analysis (Prada)*.
[247] IAEA, *Safeguards Glossary 2001 Edition*.

2.3.1. Intrinsic Barriers

Intrinsic barriers are such measures encompassing both material and technical aspects of nuclear energy. In other words, these barriers deal with the quantity and quality of the nuclear material for a certain type of nuclear energy system. Considering the intrinsic point of view, these barriers are not only a complementary to each other, but also they are planned to supplement the external barriers. In this respect, nuclear material is managed according to its features such as isotopic, chemical, radiological, mass and bulk, and detectability.[248] Related with the material barriers, technical barriers focus on the features of the facilities in which nuclear material is produced, used, reprocessed, and storaged. Considering these points, design of these barriers is required to be conducted in a way in which there exists no possible way to diversion.

2.3.1.1. Material Barriers

From the point of nonproliferation of nuclear weapons, the significant quantities of each fissile material can be the first step to examine the role of the material barriers. At first glance, these fissile materials can be U233, U235, and Pu239. Here, there is an imperative to make a distinction among them with respect to their existence in nature. As has been noted, naturally occurring fissile material is only U235. However, U233 and Pu239 are artificial fissile materials. This means that they are produced during the irradiation of nuclear fuels such as thorium (Th232) and uranium (U238), respectively. As a result, isotopic quantities of these fissile isotopes can constitute a proliferation risk after a significant quantity of one of them is acquired by a proliferator.

In the context of nuclear weapons proliferation, their production methods and related routes are also important for the acquirement of their significant quantities. For example, enrichment of uranium is a requirement to increase the isotopic concentration of U235 in the front end of nuclear fuel cycle.[249] Therefore, quantity and quality (or grade) of enriched uranium should be kept within the peaceful boundaries. On the other hand, taking place in the back end of nuclear fuel cycle, the case for the production of artificial

[248] IAEA, *Technical Features to Enhance Proliferation Resistance of Nuclear Energy Systems*.
[249] NTI, "Uranium Enrichment."

fissile elements is a bit more complex than the enrichment of uranium since it requires a set of chemical extraction methods. For instance, the production rate and amount of these fissile materials can be predetermined by the “conversion ratio” embedded in the design features of a nuclear power reactor. In technical terms, conversion ratio simply equals to the ratio of final fissile inventory of the spent (or discharged) fuel to the initial fissile inventory of fresh fuel. For example, this ratio, in practice, ranges from 0.5 to 0.7 for a conventional LWR. But, for breeder reactors, such as FBRs, this ratio is adjusted to be bigger than 1.0 since their aim is to produce more fissile material than they consume.[250] Moreover, these design features can be modulated with respect to the usage of natural uranium or enriched uranium in a nuclear reactor moderated with heavy water, graphite or light water. However, following such modulations may end up with different quantities and qualities of the fissile materials produced in the spent fuel. In other words, irradiation time of the fuel in a nuclear reactor, which is generally defined in terms of burnup (MWd/tHM) as a function of reactor thermal power, duration of operation, and mass of fuel, is an important indicator of the degradation of weapons grade plutonium.[251] For a simple comparison, spent fuel of a CANDU reactor contains more weapons grade plutonium (Pu239) than the spent fuel of a LWR. In technical terms, nuclear fuel spends less time in a CANDU reactor, which means lower burnup for the fuel. Therefore, Pu239 can be removed from the core of CANDU without further irradiation of the fuel to let the production of Pu240 and 241. Since LWRs have higher burnups in contrast to the CANDUs, Pu240 and Pu241 exist in the spent fuel inventory, which decrease the possibility of Pu239 to be used in a nuclear weapon.[252] As previously mentioned, artificially produced fissile materials can be retrieved from the irradiated fuel by using one of the several actinide extraction methods. In this respect, using COEX or TRUEX method would be more proliferation resistant than using PUREX method.[253]

In conclusion, these are chiefly considered aspects of material barriers. For each fissile material, these barriers come into the scene regarding their significant quantities. In many

---

[250] OECD/NEA.
[251] Manson Benedict, Thomas H. Pigford, and Levi, 88.
[252] S. K. Aghara and C. A. Beard, "Feasibility Study of a Proliferation-Resistant Fuel Form for Plutonium Recycling," *Nuclear Technology* 137, no. 1 (2002).
[253] IAEA, *Technical Features to Enhance Proliferation Resistance of Nuclear Energy Systems*.

respects, these barriers are designed to create an environment in which safety, security, and safeguards of the nuclear material can be performed harmoniously.[254]

2.3.1.2. Technical Barriers

Technical barriers encompass quite a wide range of barriers both in the front and back end of the nuclear fuel cycle. In nonproliferation terms, nuclear facilities, where nuclear material produced, used, reprocessed, and storaged, should be primarily kept away from troubles regarding safety and security.[255] Moreover, safeguards measures at each of these stages should be maintained so that the misuse of nuclear energy and its related systems can be detected and prevented. In this regard, access control systems of nuclear facilities is important to deter, detect, and respond to any unauthorized attempt.[256] Therefore, nuclear facilities should be designed to be unattractive for the diversion. While doing this, main aspects of nuclear energy such as neutronic, thermal hydraulic, and material can be blended with each other to strengthen the technical barriers of the peaceful use of nuclear energy.[257]

To create efficient and effective barriers, it is always considered that these features of nuclear energy are closely related with each other. Since they affect each other, a modulation into the one of them may inherently cause a modulation into others.[258] In technical terms, these modulations can be possible in every stage of nuclear fuel cycle. To take a case in point in the front end of the nuclear fuel cycle, enrichment of uranium, as previously mentioned, can be performed by the gas centrifugation. In a gas centrifugation plant, there exist so many centrifuges ordered in cascades in proportional to the planned enrichment levels. As being a proliferation barrier, number of centrifuges in an enrichment plant should be kept lower to prevent further enrichment of the natural

---

[254] IAEA, *Nuclear Energy Basic Principles, Iaea Nuclear Energy Series No. Ne-Bp* (Vienna: International Atomic Energy Agency, 2008).
[255] IAEA, *Design Measures to Facilitate Implementation of Safeguards at Future Water Cooled Nuclear Power Plants, Technical Reports Series No. 392* (Vienna: International Atomic Energy Agency, 1998).
[256] IAEA, *Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (Infcirc/225/Revision 5), Nuclear Security Series No. 13* (Vienna: International Atomic Energy Agency, 2011).
[257] IAEA, *Facility Design and Plant Operation Features That Facilitate the Implementation of Iaea Safeguards, Str-360* (Vienna: International Atomic Energy Agency, 2009).
[258] Trond Bjornard et al., "Achieving the Benefits of Safeguards by Design," (01/01 2008).

uranium. Related with the requirement for the enrichment, nuclear reactor types can also be designed according to the moderator types in line with the proliferation barriers. If the enrichment of uranium is not planned for a reactor, heavy water or graphite can be chosen as moderator to operate the reactor with the natural uranium. However, while this can be a proliferation barrier in the front end in terms of uranium enrichment, it can constitute a proliferation risk in the back end in terms of producing plutonium with lower burnup. Actually, this is a case for CANDU reactors, which makes them less proliferation resistant in comparison to the LWRs since a CANDU reactor has a relatively lower burnup rate than a LWR. Here, it is also important to emphasize that LWRs use enriched uranium with less than 5% enrichment to achieve higher burnups. As a result of high burnup, produced Pu239 in the reactor can be prevented not to be used directly as a weapon material since Pu240 and Pu241 are also produced. In sum, it can be inferred from these points that LWRs are more proliferation resistant than CANDUs both in the front and back end of the nuclear fuel cycle.[259]

In nonproliferation terms, all of these aspects of nuclear energy, such as neutronics, thermal hydraulics, and material, should be well-balanced with each other. In other words, focusing too much on one of them should not cause a compromise for others. Since the complexity of a system can prevent a potential proliferator from reaching its goal, it is important to find an optimum implementation within a complex manner so that the highest efficiency and effectiveness of technical barriers could be achieved.[260] In sum, a technical barrier can be the first barrier that can limit the capability before the consideration of the intention.

2.3.2. External Barriers

While internal barriers deal with the safety, external barriers tackle with the security and safeguards. Within the international nuclear nonproliferation regime, external barriers encompass mainly policy level efforts to prevent diversion. In more general terms, these

[259] Z. Xu, M. S. Kazimi, and M. J. Driscoll, "Impact of High Burnup on Pwr Spent Fuel Characteristics," *Nuclear Science and Engineering* 151, no. 3 (2005).
[260] IAEA, *Inpro Collaborative Project: Proliferation Resistance: Acquisition/Diversion Pathway Analysis (Prada)*.

barriers include bilateral, regional, and international efforts through initiatives, treaties, conventions, and agreements, which ultimately contribute to the international nuclear nonproliferation regime.[261] In this respect, state level commitments lay at the core of the external barriers.

In the context of this thesis, the connection between the IAEA and the NPT is very important in terms of the safeguarding of the peaceful use of nuclear energy. Indeed, the IAEA safeguards system has started by the establishment of the IAEA. And then, this safeguards system is adopted by the NPT to accompany to the promotion of peaceful use, as reflected in the Article IV of the NPT.[262] In this way, quantification processes of nuclear materials and facilities can be conducted systematically. In other words, quantification of nuclear materials and activities through safeguards makes NNWS deterred from diversion since the accountability can provide early detection of any diversion or misuse.[263]

Throughout the nuclear nonproliferation efforts, external barriers have evolved and expanded remarkably as a result of emerging threats to the nuclear nonproliferation regime. After the NPT entered into force, the Zangger Committee (ZAC) emerged in 1971 and offered clarifications for different interpretations of nuclear material and related technologies, reflected in the NPT, by coming up with the Trigger List.[264] Later, a nuclear explosive test in 1974 by a Non-NPT state, which is India, caused troubles about the effectiveness of the NPT. In response to this behavior, Nuclear Suppliers Group (NSG) was established in 1975 to control the import and export of nuclear material.[265] For the case of South Africa, nuclear nonproliferation efforts helped South Africa give up its nuclear weapons and became a party to the NPT.[266] Upon this success, the NPT was decided to continue in force indefinitely at the Review and Extension Conference on 11

---

[261] Carlson and Leslie.
[262] UNODA, "Treaty on the Non-Proliferation of Nuclear Weapons (Npt)," UNODA, accessed 16.05.2021, 2021. https://www.un.org/disarmament/wmd/nuclear/npt/.
[263] M. Stein and M. Morichi, "Safety, Security, and Safeguards by Design: An Industrial Approach," *Nuclear Technology* 179, no. 1 (2012).
[264] NTI, "Zangger Committee (Zac)," last modified July 14, 2020, accessed 27.03.2021. https://www.nti.org/learn/treaties-and-regimes/zangger-committee-zac/.
[265] I. Anstey, "Negotiating Nuclear Control: The Zangger Committee and the Nuclear Suppliers' Group in the 1970s," *International History Review* 40, no. 5 (2018).
[266] F. V. Pabian, "The South African Denuclearization Exemplar: Insights for Nonproliferation Monitoring and Verification," *Nonproliferation Review* 22, no. 1 (2015).

May 1995.[267] In 1997, the scope of the IAEA safeguards system was expanded with the introduction of Additional Protocol to include undeclared nuclear facilities and activities that exist in NNWS. These can be regarded as the major enhancements of external barriers within the context of this thesis.

The motivations of the states for the nuclear weapons may vary from power and prestige to meet their energy needs.[268] However, external barriers have a great political impact on the behaviors of the states to keep their will within which their expectations converge. Here, it is important to note that the sustainability of the nuclear nonproliferation regime depends verily on the commitments of the states. Because, if one of the states does not follow the rules, principles, norms, and procedures regarding internal and external barriers, then it means that that state will potentially divert from peaceful use to military use of nuclear energy. Furthermore, this diversion can happen in various forms in various stages of nuclear fuel cycle.[269] For example, as mentioned earlier, most sensitive stages of uranium based nuclear fuel cycle are enrichment of uranium and reprocessing of spent fuel. Apart from NWS, states not party to the NPT –India, Israel, and Pakistan– searched for the nuclear weapons, and they obtained it. However, the nuclear nonproliferation regime created solutions to control export and import of nuclear material and related technologies to those countries through the ZAC and NSG.[270] On the other hand, some of the NNWS tried to divert peaceful use or directly obtain nuclear weapons through purchase. For example, Libya tried to buy nuclear weapons from China, but China refused to sell nuclear weapons. Therefore, Libya bought natural uranium from Niger and planned to enrich it by collecting parts of enrichment technologies. In the end, Libya was deterred from obtaining nuclear weapons.[271] On the other hand, Iran also takes attention with its efforts to enrich uranium for its nuclear power plants. However, its efforts possibly goes beyond the %5 enrichment level for the peaceful use of nuclear energy.[272] The most striking case for the nuclear nonproliferation regime is North Korea. It was a state party

---

[267] UNODA, "Treaty on the Non-Proliferation of Nuclear Weapons (Npt)," UNODA, accessed 16.05.2021, 2021. https://www.un.org/disarmament/wmd/nuclear/npt/.
[268] D. J. Jo and E. Gartzke, "Determinants of Nuclear Weapons Proliferation," *Journal of Conflict Resolution* 51, no. 1 (2007).
[269] IAEA, *Inpro Collaborative Project: Proliferation Resistance: Acquisition/Diversion Pathway Analysis (Prada)*.
[270] Anstey.
[271] G. Bahgat, "Nonproliferation Success: The Libyan Model," *World Affairs* 168, no. 1 (2005).
[272] G. Bahgat, "Nuclear Proliferation: The Islamic Republic of Iran," *Iranian Studies* 39, no. 3 (2006).

to the NPT, but it left NPT in 2003 to continue its nuclear weapon program and it obtained nuclear weapons.[273] Table 2 reflects the diversion routes of those states.

Table 2: Examples of Diversion Routes for Some Countries

Country	Initial Purpose	Diversion Route	Cause of Proliferation	Party to the NPT	Result
India	Peaceful	Reprocessing (CANDU - Pu)	Security Dilemma	No	Obtained
Iran	Peaceful	Enrichment	Prestige	Yes	Deterred
Israel	Peaceful	Reprocessing	Self-help	No	Obtained
Libya	Peaceful	Enrichment	Prestige / Security Dilemma	Yes	Deterred
North Korea	Peaceful	Enrichment / Reprocessing	Prestige	No (Since 2003)	Obtained
Pakistan	Peaceful	Enrichment / Reprocessing	Security Dilemma	No	Obtained

[273] Ahn and Wit, in *Routledge Handbook of Nuclear Proliferation and Policy*.

It can be inferred from Table 2 that all of those states have misused or diverted from the most sensitive stages of uranium based nuclear fuel cycle; enrichment of uranium or reprocessing of spent fuel. Within the purpose of nuclear nonproliferation regime, nuclear energy systems should be developed to increase the efficiency and effectiveness of internal and external barriers in line with the internationally standardized and safeguardable characteristics so that the misuse or diversion of peaceful use can be prevented.[274] At his point, thorium, as a proliferation resistant nuclear fuel, can play an important role in dealing with these diversion routes besides contributing to the peaceful use of nuclear energy. In the following chapter, it will be analyzed how an option like thorium can provide internal barriers with sound improvements, which inherently improves the efficiency and efficacy of external barriers.

[274] IAEA, *Technical Features to Enhance Proliferation Resistance of Nuclear Energy Systems*.

CHAPTER III: THORIUM AS AN ALTERNATIVE TO PREVENT DIVERSION

During the efforts of nonproliferation of nuclear weapons, as has mentioned in previous chapter, there have been developed many kind of barriers within uranium based nuclear fuel cycle. However, these barriers are not enough to prevent the capabilities of a proliferator in terms of enrichment and reprocessing. Since uranium intrinsically cannot support those barriers as much as thorium, a state may have a potential to divert peaceful use of nuclear energy into the military use of nuclear energy by using uranium based fuel cycle. This latency effect, in terms of nuclear weapons proliferation, can have a potential to occur both in the front end and back end of uranium based nuclear fuel cycle. Given that its technical barriers are almost established in many respects, uranium based nuclear energy systems are still unable to decrease the concerns of NWS.[275] Therefore, spread of peaceful use of nuclear energy has faced many challenges, which cause concerns between NWSs and NNWSs.[276] In some cases, these challenges have threatened the future of the NPT regime. For example, some of the states, as the cases for India and Pakistan, have not become parties to the NPT and obtained nuclear weapons capabilities. Additionally, NNWS as parties to the NPT have not widely benefitted the peaceful use of nuclear energy, especially in power generation. Additionally, concerns between NWS and NNWS has not been solved due to the uncertainty stemming from the dual use aspects of uranium based nuclear fuel cycle.[277]

In the course of nuclear power generation efforts, especially in the 1960s, thorium based nuclear power reactors were examined for their applicability. At that time, the interest in thorium was mainly due to the scarcity of uranium. Therefore, adding thorium fueled reactors to the power generation fleet was intended to support the sustainability of the nuclear power generation. However, this trend changed due to the discovery of new uranium ores around the world. Although thorium fueled reactors has never grown as much as uranium in commercial scale, there were experimental and power reactors fueled

---

[275] M. S. Yim, "Nuclear Nonproliferation and the Future Expansion of Nuclear Power," *Progress in Nuclear Energy* 48, no. 6 (2006).
[276] Jorge Morales Pedraza, "Is the Npt an Effective International Instrument to Stop Nuclear Proliferation without the Establishment of an International Organisation to Supervise the Implementation of Its Provision?," *Public Organization Review* 15, no. 2 (2015).
[277] Yim.

with thorium operated until the late 1980s.[278] These reactor types included high temperature gas cooled reactors (HTGRs), light water reactors (LWRs), pressurized heavy water reactors (PHWRs), liquid metal cooled fast breeder reactors (LMFBRs), and molten salt breeder reactors (MSBRs). As a result, these demonstrations verified that thorium could also be used as a nuclear fuel.[279]

After 2000, the interest in nuclear energy has revived due to the increasing energy need of the world. Along with renewable energy sources, nuclear energy also becomes another important option.[280] In contrast to the renewables, it is important to emphasize that nuclear energy can provide with much more energy production in amount. However, expansion of the current uranium based nuclear power reactors has a potential to cause a problem of proliferation of the nuclear weapons that can also threaten the world.[281] In this regard, the spread of nuclear energy to meet the growing energy demand should be conducted cautiously considering the dual use of nuclear energy. In terms of internal and external barriers, thorium, in contrast to uranium, can assist the proliferation resistant nuclear reactor technologies to achieve the spread of nuclear power reactors for peaceful purposes without diversion. Given these points, following sub-sections will examine the thorium fuel cycle with all details ranging from benefits to challenges and alternative approaches to proposed deployments.

3.1. THORIUM AS A NUCLEAR FUEL

Thorium is a radioactive element existing in the Earth’s crust, generally, in the form of monazite and thorite. It was discovered by Jons Berzellus in 1828, and taken its name from the Scandinavian God “Thor”.[282] After its discovery, it has been used for many purposes such as manufacturing mantles and arc lamps, optical coatings, crucibles, and

---

[278] IAEA, *Thorium Fuel Cycle - Potential Benefits and Challenges*.
[279] Ibid.
[280] OECD/IEA, *Nuclear Energy in a Clean Energy System* (France: 2019), www.iea.org.
[281] I. N. Kessides, "The Future of the Nuclear Industry Reconsidered: Risks, Uncertainties, and Continued Promise," *Energy Policy* 48 (2012).
[282] TEA, "1.0 Introduction," last modified -not available-, accessed 26.03.2021. https://thoriumenergyalliance.com/1-0-introduction/.

thorium alloys.[283] In the nuclear field, it made significant contribution to the discovery of radioactivity with respect to the attention to its radioactive properties. When compared to uranium, however, thorium has no fissile isotope naturally. It is a fertile element with atomic weight of 232 g/mol and chemical symbol Th. Since it is fertile, Th232 cannot sustain a fission chain reaction.[284] Therefore, it needs a fissile driver such as U235, Pu239, or U233. From the experiences gained from the demonstration reactors, it has been cleared that thorium accompanied by a fissile driver performs very well within the wide range of neutron energies such as thermal, epithermal, and fast.[285] Most importantly, as being a fertile element, irradiated thorium can produce Uranium-233, which is also another artificial fissile element. In technical terms, to reach U233, Th232 absorbs an energetic neutron and becomes Protactinium-233 (Pa233). After 29 days, Pa233 makes a beta decay to become U233. Unlike U235 and Pu239, U233 carries out very productive fission reactions by releasing more than 2 neutrons per fission within a wide range of thermal spectrum.[286] Promisingly, this means that thorium fuel can be utilized in thermal breeder reactors. Since U233 can be produced from the irradiation of Th232, a self-sustaining thorium fuel cycle is possible in the long term.[287]

3.2. POTENTIAL BENEFITS AND CHALLENGES OF THORIUM

Using thorium as a nuclear fuel inevitably creates some benefits and challenges in the nuclear fuel cycle. In line with this thesis's argument, a fuel cycle depending on thorium can create a nuclear environment in which more proliferation resistant barriers can be implemented. In such a case of the nuclear fuel cycle, NNWS cannot divert peaceful use of nuclear energy into the military use to produce nuclear weapons. Therefore, prolonging concerns between NWS and NNWS can be mitigated considerably. Since the historical record verifies the implementation of thorium in the nuclear power reactors, benefits and

---

[283] TEA, "5.0 General Uses," last modified -not available-, accessed 26.03.2021. https://thoriumenergyalliance.com/5-0-general-uses/.
[284] IAEA, *Thorium Fuel Utilization: Options and Trends*.
[285] Ibid.
[286] C. W. Forsberg, *Uses for Uranium-233: What Should Be Kept for Future Needs?* (Oak Ridge, Tennessee: Chemical Technology Division, Oak Ridge National Laboratory, 1999).
[287] IAEA, *Role of Thorium to Supplement Fuel Cycles of Future Nuclear Energy Systems*, *Iaea Nuclear Energy Series No. Nf-T-2.4* (Vienna: International Atomic Energy Agency, 2012).

challenges of thorium will be explained in more detail by making comparison with uranium based nuclear fuel cycle.

3.2.1. Benefits

At first glance, it has been known that thorium exists in nature in large amounts in contrast to uranium. So, this abundancy of thorium has always been regarded as an advantage for the nuclear fuel industry in case of a uranium scarcity.[288] Additionally, there are other benefits of thorium, which can be achievable both in the front and back end of its fuel cycle. First of all, thorium cannot produce long-lived minor actinides such as Neptunium, Americium, and Curium.[289] Additionally, higher burnup rates can be achievable via thorium fuel cycle. As a result of these, thorium fuel cycle has a potential to produce less nuclear waste and low radiotoxicity without long-lived minor actinides.[290] As a comparison, a CANDU reactor fueled with natural uranium produces much waste than a PWR since it has relatively low burnup. The significant increase in the burnup provided by the use of thorium inherently contributes to the spent fuel management. Moreover, thorium dioxide (ThO2) is chemically more stable and inert than uranium dioxide (UO2), which makes it difficult for ThO2 to behave in a way like UO2 oxidizes to UO3 and U3O8. Technically, this oxidization problem of uranium has been an extremely important issue in the front and back end of uranium based nuclear fuel cycle. In terms of fuel performance, ThO2 has better thermal conductivity and lower coefficient of thermal expansion, which makes thorium favorable to produce more accident-tolerant fuels. The neutronic properties of thorium fuel, in terms of absorption cross-section for thermal neutrons, can provide with higher conversion ratios, which means that fertility of thorium can be higher than uranium in the thermal region of the neutron energies.[291]

In nonproliferation terms, thorium fuel cycle can be proliferation resistant intrinsically due to the production of U232 as a result of (n, 2n) reactions with Th232, Pa233, and

---

[288] OECD/NEA, *Introduction of Thorium in the Nuclear Fuel Cycle: Short- to Long-Term Considerations, Nea No. 7224* (France: Nuclear Energy Agency, 2015).
[289] M. Todosow et al., "Use of Thorium in Light Water Reactors," *Nuclear Technology* 151, no. 2 (2005).
[290] J. Uhlíř, *Fuel Cycle Aspects of Molten Salt Reactor System*, vol. 3, *International Congress on Advances in Nuclear Power Plants 2009, ICAPP 2009* (Atomic Energy Society of Japan, 2009).
[291] IAEA, *Thorium Fuel Cycle - Potential Benefits and Challenges*.

U233.[292] The importance of U232 production is that the daughter elements produced in the decay chain of U232 are bismuth (Bi212) and thallium (Tl208). These daughter elements are strong gamma emitters which makes handling of U233 for the military purposes difficult. Furthermore, it is important to emphasize that this radiation barrier for U233 exists for a long time since the half-life of U232 is about 74 years. As a result, safeguarding of U233 is much easier than safeguarding of Pu239. Therefore, the possible misuse of U233 can be detected easily in contrast to Pu239.[293] The other role of thorium in the nonproliferation of nuclear weapons can be the use of thorium blended with weapons grade plutonium, reactor grade plutonium, and highly enriched uranium. Following such a route would significantly contribute to the international nuclear nonproliferation efforts since the stockpiles of nuclear weapons material can decrease.[294]

3.2.2. Challenges

Introduction of thorium into the nuclear fuel cycle can create some challenges stemming mainly from unique properties of thorium. First of all, thorium has a very high melting point of 3350 ^{0}C. Therefore, solid fuel production from thorium requires very high temperatures above 2000 ^{0}C. Since ThO2 is chemically inert, reprocessing of spent thorium fuel is not as easy as reprocessing of spent uranium fuel. This challenge can be overcome by adding HF into the HNO3 to dissolve ThO2. However, adding HF can result in the corrosion of the stainless steel parts of reprocessing plant. Additionally, it is important to note that THOREX is a solvent extraction method to reprocess spent thorium fuel.[295] In terms of daughter elements, irradiation of thorium fuel in the reactors produces significant amount of U232. As previously mentioned, U232 emits strong gamma rays because of Bi212 and Tl208, and this requires heavy shielding measures supported by the remote and automated control systems. In this respect, U232 increases the cost of reprocessing and refabrication of thorium fuels. However, this is a supportive aspect for

---

[292] Jungmin Kang and Frank N. von Hippel, "U-232 and the Proliferation-Resistance of U-233 in Spent Fuel," *Science & Global Security* 9, no. 1 (2001/01/01 2001).
[293] A. Wojciechowski, "The U-232 Production in Thorium Cycle," *Progress in Nuclear Energy* 106 (2018).
[294] Todosow et al.
[295] V. K. Manchanda and P. N. Pathak, "Amides and Diamides as Promising Extractants in the Back End of the Nuclear Fuel Cycle: An Overview," *Separation and Purification Technology* 35, no. 2 (2004/02/15/ 2004).

nonproliferation of nuclear weapons. Another challenge is the production of Pa233 during the conversion of Th232 to U233, which has a 27 days of half-life. Therefore, around a year of time frame is required for Pa233 to cool down and complete its decay to U233. Also, reactor control mechanisms including safety should be updated to adapt changes regarding this time frame of half-life. The existence of Pa233 can also create a problem for processes in THOREX while separating U233 and Th232. Furthermore, thorium has a potential to be utilized in different forms of fuel such as solid and fluid. However, data base and experiments for thorium should also be developed for new types of reactors in the light of past experiences so that thorium fuels and fuel cycles could be utilized commercially.[296]

3.3. UTILIZATION OF THORIUM IN POWER REACTORS

In the course of nuclear power generation, there have been several approaches to the utilization of thorium as a fuel in the nuclear reactors.[297] In this context, most of the routes regarding the implementations for the utilization of thorium in a reactor core can be divided mainly into two categories; homogeneous and heterogeneous fuel distribution of thorium fuel.[298] By the way, this thesis assumes that this separation cannot be applied to the fuel option of (Th232+U233)O2 since it is the final purpose of the thorium fuel cycle. In technical terms, homogeneous fuel distribution means that thorium is blended with other fissile nuclear fuels homogeneously. In contrast to the homogeneous fuel distribution, heterogeneous fuel distribution means that thorium is located into the reactor core without blending with other nuclear fuels such as enriched uranium or MOX fuel. In terms of engineering, it is expected that these two main implementations can alter the current requirements for the reactor core designs.[299] Also, following homogeneous or heterogeneous fuel distribution also requires different treatments in the back end.[300] For

---

[296] OECD/NEA, *Introduction of Thorium in the Nuclear Fuel Cycle: Short- to Long-Term Considerations*.
[297] Ibid.
[298] IAEA, *Thorium Fuel Utilization: Options and Trends*.
[299] S. S. Mustafa and E. A. Amin, "Feasibility Study of Thorium-Plutonium Mixed Oxide Assembly in Light Water Reactors," *Scientific Reports* 9, no. 1 (2019).
[300] E. Zimmer and J. Borchardt, *Thorex Process Studies*, trans., Chemistry Int Committee for Solvent Extraction, Technology, and Engineering European Federation of Chemical, vol. 1, *ISEC '86 International Solvent Extraction Conference - Preprints.* (West Ger
Munich, W Ger: DECHEMA, 1986).

example, two different fuel cycle can be possible by the utilization of thorium and uranium separately in a reactor core. Given these points, it is clear that introduction of thorium into the nuclear fuel cycle is possible with practical and proposed applications. So, following sub-sections will examine these possibilities thoroughly from the lenses of international nuclear nonproliferation efforts in addition to nuclear engineering.

3.3.1. Alternative Approaches for the Utilization of Thorium

In the context of the nuclear engineering, a reactor core needs fissile and fertile mix of nuclear fuel with an appropriate moderator in order to operate and produce heat for a predetermined span of time. In the light of this mechanism, thorium has to be mixed with a fissile driver, whether it is a natural or an artificial fissile element, so that the nuclear chain reaction can be sustained.[301] For this purpose, there are complementary fissile fuel options for thorium that include fissile drivers such as U233, U235, and Pu239. Technically, Th232 can be blended with each of these fissile materials individually with respect to the fuel types (solid or fluid), core designs (homogeneous or heterogeneous) and moderator types (light water, heavy water, or graphite). However, it is important to note that each of these components cannot be isolated from each other and potentially affect each other. For example, moderation through light water increases the required enrichment level or amount of fissile material to be mixed with thorium. Conversely, moderation through heavy water or graphite decreases the required enrichment level or amount of fissile material for a reactor core.

In the context of this thesis, here, the following fuel options are selected and examined for thorium utilization in terms of technical applicability; a) (Th232, U235+238)O2, b) (Th232, Pu239)O2, c) (Th232, U233)O2.[302] For the first option, thorium is to be mixed with enriched uranium. In this case, HEU can be an important option to decrease the amount of weapons grade uranium. For the second option, weapons grade plutonium or reactor grade plutonium can be mixed with thorium. In these two cases, once through fuel cycle can be implemented due to the high burnup rate achievable by thorium fuel. In this

---

[301] Kazimi.
[302] IAEA, *Thorium Fuel Utilization: Options and Trends*.

way, weapons grade plutonium and HEU stocks can be incinerated and the produced amount of plutonium and other long-lived minor actinides in the spent fuel would relatively be decreased in contrast to the uranium based fuel cycle. For the third option, thorium can be used with its own artificial fissile element U233. Indeed, this case is the final stage of thorium fuel cycle, in which breeding and reprocessing of U233 is required. In this case, it is important to emphasize that U232 produced by the irradiation of thorium can prevent the misuse of U233 and relatedly the production of the nuclear weapons.[303] As a result, all of these options of the utilization of thorium can make considerable contributions to the international nuclear nonproliferation efforts.

3.3.2. Proposed Utilization of Thorium as a Nuclear Fuel

In the past, it was demonstrated that thorium could be utilized as a nuclear fuel in various types of nuclear reactors such as LWRs, HWRs, HTGRs, and MSBRs. However, its utilization has never been commercialized on an expected scale and almost abandoned by the end of 1980s. There exist several views about why thorium has not been deployed like uranium. Some of them are on the opinion that there is no need for thorium since uranium is not scarce yet; while others put emphasize on the fertile aspect of thorium, which means that it cannot sustain fission chain reaction by itself.[304] Therefore, this thesis chooses to examine those arguments within their starting points. On the one hand, it is conceivable that new discoveries of uranium ores might have decreased the possibility of thorium utilization. On the other hand, it might be difficult to find fissile drivers for fertile thorium in the early days of the commercialization of nuclear power generation. In this regard, during 1960s and 1970s, it would not be a viable option for NWSs to incinerate their weapons grade plutonium or highly enriched uranium to develop a thorium fuel cycle. Consequently, it is important to note that the policies of NWSs against the reprocessing of spent nuclear fuel have changed considerably after the newly established NPT regime. For example, the U.S. has abandoned the reprocessing of spent nuclear fuel in case of a proliferation threat stemming from the possible retrieval of weapons grade

---

303 Kang and von Hippel.

304 OECD/NEA, *Perspectives on the Use of Thorium in the Nuclear Fuel Cycle* (France: Nuclear Energy Agency, 2015).

plutonium.[305] Therefore, NWSs have followed the uranium based once through fuel cycle, which has been seen as the main obstacle for the closed thorium fuel cycle.[306] In technical terms, it is important to mention that reprocessing of spent fuel is not performed in the back end of the once through fuel cycle. As a result, U233 production by the irradiation of thorium would be useless without reprocessing since the retrieval of U233 and Th232 do not happen in the back end.

After 2000, interest in energy sources with zero carbon emissions has increased remarkably to cope with the climate change. According the OECD-NEA, almost 40% of all carbon emissions comes from the power generation because of its dependence heavily on the fossil fuels.[307] In this context, the role and potential of nuclear energy in the power generation has come back to the scene since the nuclear power reactors never produce CO2.[308] As of 2019, according to IEA, global share of nuclear energy in the electricity generation is around 11%.[309] Accordingly, there were 443 nuclear power reactors operating with a capacity of 392.1 GWe for the same year. However, this share of nuclear power is not enough to meet and contribute to the Sustainable Development Goals (SDG) to keep the global temperature rise below 1.5 ^{0}C by 2050.[310] In order to achieve such a goal, it is projected that the net capacity of nuclear power within the current power generation should be doubled. When considering the aging nuclear power plants, this means that more than 15 GWe capacity should be added to the grid in every year up to 2050.[311] For the purpose of meeting this demand, it is promising that nuclear power generation will potentially increase across the world. But, this increase should be conducted cautiously in the international scale. In line with the argument of this thesis, it is potential that the proliferation of nuclear weapons can threaten the world if this much increment in the capacity is met with the uranium based fuel cycle.

---

[305] J. M. Martinez, "The Carter Administration and the Evolution of American Nuclear Nonproliferation Policy, 1977–1981," *Journal of Policy History* 14, no. 3 (2002).
[306] OECD/NEA, *Introduction of Thorium in the Nuclear Fuel Cycle: Short- to Long-Term Considerations*.
[307] OECD/NEA, *Projected Costs of Generating Electricity* ed. International Energy Agency (France: OECD/Nuclear Energy Agency, 2020).
[308] A. Adamantiades and I. Kessides, "Nuclear Power for Sustainable Development: Current Status and Future Prospects," *Energy Policy* 37, no. 12 (2009).
[309] OECD/IEA.
[310] IAEA, *Climate Change and Nuclear Power 2020* (Vienna: International Atomic Energy Agency, 2020).
[311] OECD/NEA, *Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders, Nuclear Technology Development and Economics* (OECD/Nuclear Energy Agency, 2020).

At this point, introduction of thorium into the nuclear fuel cycle can help nuclear power generation grow more peacefully in terms of both proliferation resistance and technical benefits for the peaceful use. In the past, thorium was utilized in many types of reactors ranging from experimental to power reactors. Today, there exist recent studies which propose that thorium can also be utilized in the new generation reactor types such as Generation IV (GenIV) and small modular reactors (SMRs).[312] In the light of past and recent demonstrations of thorium utilization, there are several perspectives on the application of thorium in the nuclear power reactors. These perspectives can be examined for and divided into the short, mid, and long term applications of thorium.

In the short term, uranium scarcity does not seem to happen, however, addition of thorium into the fuel cycle can be supplementary to the nuclear fuel. Additionally, thorium can be inserted into the nuclear reactors to make modifications in the core power profile without using other burnable poisons like gadolinium. However, direct introduction of thorium into the conventional reactors can decrease the design powers.[313] Therefore, this can make nuclear reactor operators to hesitate from the utilization of thorium. Nevertheless, these kind of applications can considerably contribute to the policies regarding both front and back end of the proposed thorium fuel cycles.[314]

In the midterm, scarcity of uranium resources can start to challenge the sustainability of the nuclear power generation if the proposed increment happens year by year in the nuclear capacity. And, in such a case, the reprocessing of the spent nuclear fuel will potentially come back to the agenda to supply the nuclear fuel demand if thorium utilization does not start in the nuclear power reactors.[315] As a reminder, the purpose of reprocessing is that reusable contents of the spent nuclear fuel can be retrieved. Especially, retrieval of plutonium can fuel the fast breeder reactors (FBRs). In this context, FBRs will potentially challenge the existence of closed thorium fuel cycle. In

---

[312] GIF, "Gif Annual Report 2019," last modified 30.07.2020, accessed 01.02.2021. https://www.gen-4.org/gif/jcms/c_119034/gif-2019-annual-report; OECD/NEA, *Perspectives on the Use of Thorium in the Nuclear Fuel Cycle*.
[313] M. Todosow and G. Raitses, *Thorium Based Fuel Cycle Options for Pwrs*, trans., Society American Nuclear et al., vol. 3, *International Congress on Advances in Nuclear Power Plants 2010, ICAPP 2010* (San Diego, CA: 2010).
[314] OECD/NEA, *Introduction of Thorium in the Nuclear Fuel Cycle: Short- to Long-Term Considerations*.
[315] A. V. Zrodnikov, "Fast Reactors in the Energy Security for the Stable Development of Russia," *Atomic Energy* 108, no. 4 (2010).

case of the FBRs, plutonium production will have to increase since they produce more plutonium than they consumed. Also, the amount of long-lived actinides will also be present in the spent nuclear fuel with much higher amounts than it is now. More importantly, as being a potential proliferation route in the back end of the uranium fuel cycle, reprocessing may end up with the increased plutonium stockpile whether it is weapons grade or reactor grade. During this period, there are certain utilization options for thorium. First of all, thorium can be homogeneously mixed with other fuel elements in the reactor core.[316] For example, it can be used to incinerate reactor and weapons grade plutonium. In such a case, inertness and chemical stability of thorium can also be used to produce more accident-tolerant fuels. For the cases in which thorium is not mixed with other fuel elements in the reactor core, two separate fuel cycles can be developed for both uranium and thorium.[317] As a result, this latter option can potentially create an opportunity for the closed thorium fuel cycle in the long term.

Finally, in the long term, thorium fuel cycle is expected to complete its maturity as Th232+U233 fuel cycle. For this case, thermal reactors whose conversion ratios are greater than 1.0 can be designed so that the sustainability of thorium fuel cycle can be ensured. In contrast to uranium fuel cycle, much higher burnup values and high operational temperatures can be achievable due to the intrinsic properties of thorium. Additionally, higher burnup in thorium fuel cycle means that less spent nuclear fuel will be produced in terms of both quantity and long-lived actinides. Consequently, the spent fuel management, waste management, and storage problems can be mitigated in the back end. In nonproliferation terms, radiation barriers provided by U232 can provide significant contributions to the conventional barriers to prevent diversion of peaceful use.

Given these points, the future of uranium based once through fuel cycle will play primary role in the utilization of thorium in the nuclear reactors. Although it is not clear that how much time is left to introduce thorium in the nuclear fuel cycle, this situation is bound to change mainly by the drivers such as scarcity of uranium and growing energy demand.[318]

---

[316] K. D. Weaver and J. S. Herring, "Performance of Thorium-Based Mixed-Oxide Fuels for the Consumption of Plutonium in Current and Advanced Reactors," *Nuclear Technology* 143, no. 1 (2003).
[317] Todosow and Raitses.
[318] IAEA, *Thorium Fuel Utilization: Options and Trends*.

3.4. EVALUATION

In the light of international nuclear nonproliferation efforts, this thesis tried to answer the following research question; “Can thorium become an alternative fuel to prevent diversion?” As an answer to the research question, this thesis suggested that thorium fuel cycle, which is proposed to be used in nuclear reactors, is resistant to proliferation since its intrinsic features has a potential to strengthen the connection between internal and external measures of nuclear nonproliferation puzzle, which eventually contributes to the prevention of diversion and the nonproliferation of nuclear weapons. Accordingly, introduction of thorium into the nuclear power reactors will reduce the proliferation concerns and consequently the security dilemma in the international system.

Nuclear energy is a unique form of energy that can be used for civilian or military purposes. Considering these aspects, it was explained in the second chapter that the risk of diversion from peaceful to military use can occur in various stages of the existing uranium based nuclear fuel cycle. Among those stages, enrichment of uranium and reprocessing of spent nuclear fuel overlap up to a point both for peaceful and military activities. So, this technically means that peaceful activities can be intentionally diverted into military activities if certain thresholds or barriers, given in the third part of the second chapter, are exceeded. Accordingly, it was demonstrated that these barriers can be challenged by the nuclear activities depending on uranium based nuclear fuel cycle. In order to prevent the exploitation of the peaceful use of nuclear energy, therefore, it was given in the third chapter that the thorium fuel cycle can significantly contribute to the international nuclear nonproliferation efforts to strengthen the nuclear nonproliferation regime.

While answering the research question, the thesis benefitted from the theories of International Relations to explain the root causes of the diversion and the international nuclear nonproliferation efforts. According to Realism, international system is anarchic since there is no higher authority that governs the states. So, states pursue power to survive in the anarchic international system. Since nuclear weapons are enormously destructive and powerful, states want to obtain them to increase their military power. Given that the intentions of states cannot be known exactly, states can start to increase their capabilities militarily to help themselves in a self-help system.[319] However, any increase in the capability of a state can be perceived as a threat by others, and this creates a security dilemma in the international system.[320] As a result of security dilemma, states end up with an arms race with each other. As mentioned before, arms race due to the proliferation of nuclear weapons was an important issue in the international system after the WWII. However, the Cuban missile crisis illustrated that nuclear weapons cannot be easily used in a war time since both sides have the nuclear capability to destroy each other due to their second strike capabilities.[321] This crisis showed that proliferation of nuclear weapons would end up with the total destruction the world in the case of a nuclear war. Therefore, in order to prevent the further proliferation of nuclear weapons, the UK, USSR, and the US came together and drafted an international treaty on the nonproliferation of nuclear weapons, the NPT, which was opened to signature in 1968, entered into force in 1970. And, this Treaty has been the cornerstone of the nuclear nonproliferation regime.

In contrast to Realism, Liberalism claims that "harmony and balance amongst competing interests" can be possible and they can reach an equilibrium where conflicts can be resolved.[322] When the balance of interests is sustained, possibility of peace and cooperation increases among the actors of the international community. As liberals suggest, international institutions and regimes can contribute to reduce the impact of anarchy, which in fact constitutes the obstacles for morality, peace, and cooperation to prevail. Through international institutions, states create an environment in which they come together and make negotiations and bargaining on the important issues of international politics.[323] In this way, they can determine boundaries of acceptable behaviors for the achievement of collective goals. As a result, the fear of being exploited can be reduced thanks to the determined punishment mechanisms within institutions.[324] Along with international institutions, international regimes also contribute to resolve

[319] Dunne, Kurki, and Smith, 79.
[320] Schweller.
[321] Waltz, *Theory of International Politics*, 202.
[322] Heywood, 61-62.
[323] H. Nasu and K. Rubenstein, "Introduction: The Expanded Conception of Security and Institutions," *Legal Perspectives on Security Institutions* (2015).
[324] Dunne, Kurki, and Smith, 123.

conflicts by creating "rules, norms, principles and decision making procedures around which actors' expectations converge in a given area of international relations."[325]

Since the threat posed by the proliferation of nuclear weapons endangers all the actors of the international system, the thesis agrees that the expectations of the actors can converge in the nuclear nonproliferation regime; nonproliferation of nuclear weapons, nuclear disarmament, and peaceful use of nuclear energy. Thanks to the nuclear nonproliferation regime, the impact of anarchy and its results can be reduced through the cooperation and commitment of the states. Within the nuclear nonproliferation regime, as Sebnem Udum reflects, states are required to follow "various rules and regulations" if they want to benefit from the peaceful use of nuclear energy.[326] By involving in the nuclear nonproliferation regime, in this regard, NNWS have been able to benefit from the peaceful use of nuclear energy by complying with the IAEA safeguards system. In this way, compliance of the NNWS to their commitments can be verified and the early detection of any misuse or diversion of peaceful activities can be possible.[327] However, during this course, peaceful use of nuclear energy has been challenged by the risk of diversion because of the certain stages of uranium based nuclear fuel cycle; which are enrichment of uranium and reprocessing of spent fuel. By misusing or diverting these stages, proliferators can covertly obtain fissile materials such as enriched uranium and plutonium to acquire nuclear weapons. Therefore, the thesis examined these points that the peaceful use pillar of the nonproliferation regime has not been effective and efficient due to the proliferation concerns stemming from dual use aspects of the uranium based nuclear fuel cycle.

Considering these points, the thesis proposed that the utilization of thorium in nuclear power reactors can primarily contribute to the peaceful use pillar of the nuclear nonproliferation regime. Unlike uranium based nuclear fuel cycle, thorium fuel cycle considerably limits the risks of diversion by proliferation resistant enhancements to nuclear power reactors. These enhancements can be implemented both in the front and the back end of thorium fuel cycle. In the front end, weapons and reactor grade plutonium

---

[325] Krasner.
[326] Udum.
[327] IAEA, *Inpro Collaborative Project: Proliferation Resistance: Acquisition/Diversion Pathway Analysis (Prada).*

or highly enriched uranium can be used as a fissile driver for thorium. In this way, stockpile of fissile materials in the front end and the amount of plutonium and long-lived actinides in the back end can be decreased considerably. In addition, strong gamma radiation provided by U232 can reinforce safeguarding of nuclear material and related activities. In contrast to uranium, thorium can be utilized in thermal breeder reactors, which enables to reach high burnup rates since conversion ratio more than 1.0 can be achievable. This is especially important in terms of the conservation of fuel reserves and decreasing the spent fuel amount and radiotoxicity.

While answering the sub-questions, the thesis illustrated in the third chapter that the utilization of thorium in nuclear reactors including LWRs, HWRs, HTGRs, and MSBRs has been studied for decades. In terms of commercialization, India has considerably progressed on Advanced Heavy Water Reactor (AHWR), which uses thorium-based nuclear fuel cycles. India's interest in thorium mainly stems from its scarce resources of uranium. Having almost a quarter of world thorium reserves, India plans to implement a full scope thorium fuel cycle in the long term.[328] Additionally, China has research and development program on Liquid Fluoride Thorium Reactor (LFTR) for the utilization of thorium at the China's Academy of Sciences. The results and commercialization of these studies would impact the utilization of thorium as a nuclear fuel in the following decades. On the other hand, the U.S., Russia, Japan, and France have small scale studies for the utilization of thorium.[329] This mainly stems from the proposed fast breeder reactors to be fueled through possible reprocessing of spent fuels.

Given that thorium is abundant than uranium, there would be opportunities for states having vast resources of thorium. For example, India and China can meet their growing energy demand from their indigenous resources. If the number of states utilizing thorium increases especially in the states having thorium reserves, change in the energy dependency may consequently effect the behavior of the states. In such a case, new rules, regulations, norms, and procedures regarding utilization of thorium can be introduced into the nuclear nonproliferation regime to deal with possible problems.

---

[328] J. E. Platte, "Indian Nuclear Fuel Cycle Decision-Making: An Analysis of Influences," *Journal of Risk Research* 17, no. 1 (2014).
[329] IAEA, *World Thorium Occurrences, Deposits and Resources, Iaea-Tecdoc-1877* (Vienna: International Atomic Energy Agency, 2019).

The above evaluations demonstrated that concerns of the NWS about the proliferation of nuclear weapons stemming from the dual use aspects of nuclear energy can be mitigated by the utilization of thorium since NNWS technically cannot divert or misuse the nuclear materials and activities as in the case of uranium based nuclear fuel cycle. In this regard, it can be deduced that the pillar of peaceful use of nuclear energy can be strengthened within the nuclear nonproliferation regime. In the same lines, proliferation of nuclear weapons can be prevented due to the technical enhancements provided by the thorium fuel cycle while the use of nuclear energy can grow peacefully. Therefore, the nuclear nonproliferation regime, as the Regime theory claims, can be efficient and effective in decreasing the impact of anarchy and security dilemma in the international system. In addition to the nuclear nonproliferation and peaceful use of nuclear energy, utilization of thorium can contribute to the nuclear disarmament pillar of the nuclear nonproliferation regime. For this purpose, thorium fuel cycle can be utilized to consume highly enriched uranium and weapon grade plutonium. Since these outcomes help build trust between NWS and NNWS, nuclear nonproliferation regime can prevail to maintain peace and security in the international system.

CONCLUSION

This thesis tackled with the possible contributions of thorium fuel cycle to the international nuclear nonproliferation efforts. When compared to the uranium fuel cycle, thorium fuel cycle has a potential to strengthen the intrinsic features of nuclear reactors to be more proliferation resistant. In other words, intrinsic features provided by thorium fuel cycle can significantly limit the capabilities of a potential proliferator. Therefore, diversion of peaceful use of nuclear energy becomes almost impossible. In this respect, nuclear nonproliferation regime can be further strengthened by a technical or internal measure.

In an anarchic system, as realists suppose, states have to be very powerful militarily to ensure their survival. However, search for the power creates a security dilemma in the international system. Especially, pursuing nuclear weapons to increase military power, as experienced at the beginning of the Cold War, can imminently be disastrous for the international system. In this respect, prevention of the proliferation of nuclear weapons is beneficial for all of the states. So, in order to achieve nonproliferation of nuclear weapons, states are urged to cooperate within the nuclear nonproliferation regime. For cooperation, international institutions and regimes are important instruments in which rules, principles, and decision making procedures can be cultivated to meet the expectations of the actors. In this way, the impact of anarchy can be reduced and states understand the intentions of each other to continue cooperation in the future. In this respect, international nuclear nonproliferation efforts can make up the nuclear nonproliferation regime which consists of treaties, conventions, agreements, and institutions.

As being the core object of this thesis, prevention of diversion requires sound internal and external measures, which are implemented under the nuclear nonproliferation regime. For this purpose, the NPT is an important treaty that determines the main rules of the nuclear nonproliferation regime, which couple the internal and external measures. Therefore, the NPT is called as the cornerstone of the nuclear nonproliferation regime. Particularly, international nuclear nonproliferation efforts depend on the pillars of the NPT; nonproliferation of nuclear weapons, nuclear disarmament, and peaceful use of nuclear energy. Here, the NPT requires NNWS to comply with the IAEA safeguards system to benefit from the peaceful use of nuclear energy. However, some of the NNWS attempted to misuse the latter pillar and tried to obtain nuclear weapons by diversion from peaceful use. This kind of attempts have caused NWS to concern about proliferation of nuclear weapons. So, this thesis explained that these concerns occur due to the sensitive stages of uranium based nuclear fuel cycle. While doing this, possible proliferation routes within uranium fuel cycle was examined in detail, including both front and back end of its fuel cycle. Additionally, it was explained how conventional barriers –internal and external– work to prevent proliferation of nuclear weapons. Lastly, potential benefits and challenges of thorium fuel cycle was comprehensively analyzed, and the scenarios and approaches for the utilization of thorium were evaluated for the short, mid, and long terms.

In conclusion, answer of the main research question of the thesis is concluded that thorium can become an alternative nuclear fuel to prevent diversion. To put it succinctly, thorium fuel cycle can prevent diversion by decreasing the overlap of the peaceful and military uses of the nuclear energy. As a result of this separation, the intrinsic and extrinsic barriers together can make the proliferation routes useless for potential proliferators by limiting their capabilities regardless of their intentions. Therefore, thorium fuel cycle can help the nuclear nonproliferation regime function harmoniously with its pillars. As a result of well-functioning nuclear nonproliferation regime, concerns for the proliferation of nuclear weapons disappear, security dilemma among states mitigates, peaceful use of nuclear energy can be available for all states, and the eventual disarmament of nuclear weapons can be achieved.

BIBLIOGRAPHY

Nuclear Nonproliferation: The Spent Fuel Problem. Edited by Frederick C. Williams and David A. Deese. Pergamon Policy Studies on Energy and Environment. New York: Pergamon Press, 1979.

Nuclear Safeguards, Security, and Nonproliferation: Achieving Security with Technology and Policy. Edited by James E. Doyle. Burlington, USA: Elsevier Inc., 2008.

Fusion Physics. edited by Mitsuru Kikuchi; Karl Lackner; Minh Quang Tran. Vienna: International Atomic Energy Agency, 2012.

"Treaty on the Non-Proliferation of Nuclear Weapons (Npt)." UNODA. Last modified 2018. Accessed 10.04.2018, 2018. https://www.un.org/disarmament/wmd/nuclear/npt/text.

U.S. Department of Energy. *Safety Data Sheet Uranium Hexafluoride (Uf6)*, 2020.

Acton, J. M. "Strengthening Safeguards and Nuclear Disarmament." *Nonproliferation Review* 14, no. 3 (2007): 525-35.

Adamantiades, A. and I. Kessides. "Nuclear Power for Sustainable Development: Current Status and Future Prospects." *Energy Policy* 37, no. 12 (2009): 5149-66.

Aghara, S. K. and C. A. Beard. "Feasibility Study of a Proliferation-Resistant Fuel Form for Plutonium Recycling." *Nuclear Technology* 137, no. 1 (2002): 1-9.

Ahn, S. Y. and J. S. Wit. "North Korea's Nuclear-Weapon Program: Implications for the Nonproliferation Regime." In *Routledge Handbook of Nuclear Proliferation and Policy*, 70-85: Taylor and Francis, 2015.

Anstey, I. "Negotiating Nuclear Control: The Zangger Committee and the Nuclear Suppliers' Group in the 1970s." *International History Review* 40, no. 5 (2018): 975-95.

Asada, M. "The Treaty on the Non-Proliferation of Nuclear Weapons and the Universalization of the Additional Protocol." *Journal of Conflict and Security Law* 16, no. 1 (2011): 3-34.

Axelrod, Robert. "The Emergence of Cooperation among Egoists." *The American Political Science Review* 75, no. 2 (1981): 306-18.

Bahgat, G. "Nonproliferation Success: The Libyan Model." *World Affairs* 168, no. 1 (2005): 3-12.

Bahgat, G. "Nuclear Proliferation: The Islamic Republic of Iran." *Iranian Studies* 39, no. 3 (2006): 307-27.

Barré, B. "Fundamentals of Nuclear Fission." In *Energy from the Nucleus: The Science and Engineering of Fission and Fusion*, 1-21: World Scientific Publishing Co. Pte. Ltd., 2016.

Bjornard, Trond, Robert Bean, David Hebditch, Jim Morgan, Bruce Meppen, Scott Demuth, Michael Ehinger, and John Hockert. "Achieving the Benefits of Safeguards by Design." (01/01 2008).

Brooks, Stephen G. "Dueling Realisms." *International Organization* 51, no. 3 (1997): 445-77.

Brzoska, Michael. "Is the Nuclear Non-Proliferation System a Regime? A Comment on Trevor Mcmorris Tate." *Journal of Peace Research* 29, no. 2 (1992): 215-20.

Bull, Hedley. "Rethinking Non-Proliferation." *International Affairs* 51, no. 2 (1975): 175-89.

Carlson, J. and R. Leslie. "Nuclear Nonproliferation: The Role of Complementary Regimes." *Journal of Nuclear Materials Management* 30, no. 4 (2002): 4-9.

Carter, L. J. "Nuclear Weapons: Nonproliferation and Test-Ban Talks to Be Resumed." *Science* 151, no. 3706 (1966): 57-60.

Clausewitz, Carl von. *On War*. Edited by Beatrice Heuser. Translated by Michael Howard and Peter Paret. Oxford University Press, 2007.

Dunne, T., M. Kurki, and S. Smith. *International Relations Theories*. OUP Oxford, 2013.

Eisenhower, Dwight D. "Atoms for Peace Speech." IAEA. Last modified 1953. Accessed 24.04.2021. https://www.iaea.org/about/history/atoms-for-peace-speech.

Eklund, S. "Iaea Safeguards in Perspective." *JNMM, Journal of the Institute of Nuclear Materials Management* 15, no. 4 (1987).

Epstein, William. "Why States Go -- and Don't Go -- Nuclear." *Annals of the American Academy of Political and Social Science* 430 (1977): 16-28.

Feiveson, H. A., A. Glaser, Z. Mian, and F. N. Von Hippel. *Unmaking the Bomb: A Fissile Material Approach to Nuclear Disarmament and Nonproliferation*. The MIT Press, 2014.

Feng, Liu and Zhang Ruizhuang. "The Typologies of Realism." *The Chinese Journal of International Politics* 1, no. 1 (2006): 109-34.

Forsberg, C. W. *Uses for Uranium-233: What Should Be Kept for Future Needs?* Oak Ridge, Tennessee: Chemical Technology Division, Oak Ridge National Laboratory, 1999.

Gartzke, E. and M. Kroenig. "A Strategic Approach to Nuclear Proliferation." *Journal of Conflict Resolution* 53, no. 2 (2009): 151-60.

GIF. "Gif Annual Report 2019." Last modified 30.07.2020, Accessed 01.02.2021. https://www.gen-4.org/gif/jcms/c_119034/gif-2019-annual-report.

Gilinsky, V. and H. Sokolski. "Serious Rules for Nuclear Power without Proliferation." *Nonproliferation Review* 21, no. 1 (2014): 77-98.

Glatz, Jean-Paul, P. Souček, and R. Malmbeck. "3 - Key Challenges in Advanced Reprocessing of Spent Nuclear Fuels A2 - Taylor, Robin." In *Reprocessing and Recycling of Spent Nuclear Fuel*, 49-62. Oxford: Woodhead Publishing, 2015.

Gosling, F. G. *The Manhattan Project: Making the Atomic Bomb*. National Security History Series: United States Department of Energy, 2010.

Heywood, A. *Global Politics*. Palgrave Macmillan, 2011.

IAEA. "Reactor-Years of Operation." Last modified 13.05.2021, Accessed 21.04.2021. https://pris.iaea.org/PRIS/home.aspx.

IAEA. *Design Measures to Facilitate Implementation of Safeguards at Future Water Cooled Nuclear Power Plants*. Technical Reports Series No. 392. Vienna: International Atomic Energy Agency, 1998.

IAEA. *Safeguards Glossary 2001 Edition*. Vienna: International Atomic Energy Agency, 2002.

IAEA. *Thorium Fuel Utilization: Options and Trends*. Vienna: International Atomic Energy Agency, 2002.

IAEA. *Thorium Fuel Cycle - Potential Benefits and Challenges*. Vienna: International Atomic Energy Agency, 2005.

IAEA. *Nuclear Energy Basic Principles*. Iaea Nuclear Energy Series No. Ne-Bp. Vienna: International Atomic Energy Agency, 2008.

IAEA. *Facility Design and Plant Operation Features That Facilitate the Implementation of Iaea Safeguards*. Str-360. Vienna: International Atomic Energy Agency, 2009.

IAEA. *Technical Features to Enhance Proliferation Resistance of Nuclear Energy Systems*. Vienna: International Atomic Energy Agency, 2010.

IAEA. *Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (Infcirc/225/Revision 5)*. Nuclear Security Series No. 13, edited by IAEA. Vienna: International Atomic Energy Agency, 2011.

IAEA. *Inpro Collaborative Project: Proliferation Resistance: Acquisition/Diversion Pathway Analysis (Prada)*. Vienna: International Atomic Energy Agency, 2012.

IAEA. *Role of Thorium to Supplement Fuel Cycles of Future Nuclear Energy Systems*. Iaea Nuclear Energy Series No. Nf-T-2.4. Vienna: International Atomic Energy Agency, 2012.

IAEA. *Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (Uram-2009)*. Vienna: International Atomic Energy Agency, 2014.

IAEA. *Iaea Safeguards 2016: Serving Nuclear Non-Proliferation*. Vienna: International Atomic Energy Agency, 2016.

IAEA. *World Thorium Occurrences, Deposits and Resources*. Iaea-Tecdoc-1877. Vienna: International Atomic Energy Agency, 2019.

IAEA. *Climate Change and Nuclear Power 2020*. Vienna: International Atomic Energy Agency, 2020.

Irish, E. R.; Reas, W. H. . *The Purex Process - a Solvent Extraction Reprocessing Method for Irradiated Uranium*. Richland, Washington: U.S. Atomic Energy Commission, 1957.

Jervis, Robert. "Cooperation under the Security Dilemma." *World Politics* 30, no. 2 (1978): 167-214.

Jervis, Robert. "The Political Effects of Nuclear Weapons: A Comment." *International Security* 13, no. 2 (1988): 80-90.

Jervis, Robert. "Realism in the Study of World Politics." *International Organization* 52, no. 4 (1998): 971-91.

Jervis, Robert. "Realism, Neoliberalism, and Cooperation: Understanding the Debate." *International Security* 24, no. 1 (1999): 42-63.

Jo, D. J. and E. Gartzke. "Determinants of Nuclear Weapons Proliferation." *Journal of Conflict Resolution* 51, no. 1 (2007): 167-94.

John, Simpson. "Nuclear Non-Proliferation in the Post-Cold War Era." *International Affairs (Royal Institute of International Affairs 1944-)* 70, no. 1 (1994): 17-39.

Kalinowski, Martin B. *International Control of Tritium for Nuclear Nonproliferation and Disarmament*. Vol. IV. Science and Global Security Monograph Series, edited by Harold Feiveson. United States of America: CRC Press LLC, 2004.

Kang, Jungmin and Frank N. von Hippel. "U-232 and the Proliferation-Resistance of U-233 in Spent Fuel." *Science & Global Security* 9, no. 1 (2001/01/01 2001): 1-32.

Kazimi, Mujid S. "Thorium Fuel for Nuclear Energy: An Unconventional Tactic Might One Day Ease Concerns That Spent Fuel Could Be Used to Make a Bomb." *American Scientist* 91, no. 5 (2003): 408-15.

Keohane, Robert O. *After Hegemony: Cooperation and Discord in the World Political Economy*. Princeton University Press, 1984.

Kessides, I. N. "The Future of the Nuclear Industry Reconsidered: Risks, Uncertainties, and Continued Promise." *Energy Policy* 48 (2012): 185-208.

Krasner, Stephen D. "Structural Causes and Regime Consequences: Regimes as Intervening Variables." *International Organization* 36, no. 2 (1982): 185-205.

Lantis, J. S. "Economic Competition and Nuclear Cooperation: The "Nuclear Renaissance" Revisited." *Nonproliferation Review* 21, no. 1 (2014): 21-41.

Larson, L. N. "The Front End of the Nuclear Fuel Cycle: Current Issues." In *Key Congressional Reports for July 2019: Part Iv*, 35-76: Nova Science Publishers, Inc., 2019.

Lehtveer, M. and F. Hedenus. "Nuclear Power as a Climate Mitigation Strategy - Technology and Proliferation Risk." *Journal of Risk Research* 18, no. 3 (2014): 273-90.

Levy, Jack S. "The Causes of War and the Conditions of Peace." *Annual Review of Political Science* 1, no. 1 (1998): 139-65.

Manchanda, V. K. and P. N. Pathak. "Amides and Diamides as Promising Extractants in the Back End of the Nuclear Fuel Cycle: An Overview." *Separation and Purification Technology* 35, no. 2 (2004/02/15/ 2004): 85-103.

Manson Benedict, Thomas H. Pigford, and Hans Wolfgang Levi. *Nuclear Chemical Engineering*. Second ed. New York: McGraw-Hill Education, 1981.

Martinez, J. M. "The Carter Administration and the Evolution of American Nuclear Nonproliferation Policy, 1977–1981." *Journal of Policy History* 14, no. 3 (2002): 261-92.

Mearsheimer, John J. "The False Promise of International Institutions." *International Security* 19, no. 3 (1994): 5-49.

Mearsheimer, John J. *The Tragedy of Great Power Politics*. New York: Norton, 2002.

Montgomery, A. H. and S. D. Sagan. "The Perils of Predicting Proliferation." *Journal of Conflict Resolution* 53, no. 2 (2009): 302-28.

Mustafa, S. S. and E. A. Amin. "Feasibility Study of Thorium-Plutonium Mixed Oxide Assembly in Light Water Reactors." *Scientific Reports* 9, no. 1 (2019).

Nagaratnam, A. "Nuclear Fuels." *Energy Management (New Delhi)* 4, no. 2 (1980): 177-83.

Nash, Kenneth L. and Mikael Nilsson. "1 - Introduction to the Reprocessing and Recycling of Spent Nuclear Fuels A2 - Taylor, Robin." In *Reprocessing and Recycling of Spent Nuclear Fuel*, 3-25. Oxford: Woodhead Publishing, 2015.

Nasu, H. and K. Rubenstein. "Introduction: The Expanded Conception of Security and Institutions." *Legal Perspectives on Security Institutions* (2015): 1-24.

NTI. "Fission." Last modified -not available-, Accessed 01.02.2021. https://tutorials.nti.org/glossary/?term=Fission.

NTI. "Fusion." Last modified -not available-, Accessed 01.02.2021. https://tutorials.nti.org/glossary/?term=Fusion.

NTI. "Highly Enriched Uranium." Last modified -not available-, Accessed 01.02.2021. https://tutorials.nti.org/glossary/?term=Highly%20enriched%20uranium%20(HEU).

NTI. "Reprocessing." Last modified -not available-, Accessed 01.02.2021. https://tutorials.nti.org/glossary/?term=Reprocessing.

NTI. "Thermonuclear Weapon." Last modified -not available-, Accessed 01.02.2021. https://tutorials.nti.org/glossary/?term=Thermonuclear%20weapon.

NTI. "Uranium Enrichment." Last modified -not available-, Accessed 01.02.2021. https://tutorials.nti.org/glossary/?term=Enriched%20uranium.

NTI. "Weapons Grade Material." Last modified -not available-, Accessed 01.02.2021. https://tutorials.nti.org/glossary/?term=Weapons-grade%20material.

NTI. "Zangger Committee (Zac)." Last modified July 14, 2020, Accessed 27.03.2021. https://www.nti.org/learn/treaties-and-regimes/zangger-committee-zac/.

Nye, Joseph S. "Maintaining a Nonproliferation Regime." *International Organization* 35, no. 1 (1981): 15-38.

OECD/IEA. *Nuclear Energy in a Clean Energy System*. France, 2019.

OECD/NEA. *Spent Nuclear Fuel Assay Data for Isotopic Validation*. France: Nuclear Energy Agency, 2011.

OECD/NEA. *Introduction of Thorium in the Nuclear Fuel Cycle: Short- to Long-Term Considerations*. Nea No. 7224. France: Nuclear Energy Agency, 2015.

OECD/NEA. *Perspectives on the Use of Thorium in the Nuclear Fuel Cycle*. France: Nuclear Energy Agency, 2015.

OECD/NEA. *Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders*. Nuclear Technology Development and Economics: OECD/Nuclear Energy Agency, 2020.

OECD/NEA. *Projected Costs of Generating Electricity* Edited by International Energy Agency. France: OECD/Nuclear Energy Agency, 2020

Pabian, F. V. "The South African Denuclearization Exemplar: Insights for Nonproliferation Monitoring and Verification." *Nonproliferation Review* 22, no. 1 (2015): 27-52.

Paulenova, A. "2 - Physical and Chemical Properties of Actinides in Nuclear Fuel Reprocessing." In *Advanced Separation Techniques for Nuclear Fuel Reprocessing and Radioactive Waste Treatment*, edited by Kenneth L. Nash and Gregg J. Lumetta, 23-57: Woodhead Publishing, 2011.

Pedraza, Jorge Morales. "Is the Npt an Effective International Instrument to Stop Nuclear Proliferation without the Establishment of an International Organisation to Supervise the Implementation of Its Provision?" *Public Organization Review* 15, no. 2 (2015): 227-36.

Perkovich, George. "Nuclear Proliferation." *Foreign Policy*, no. 112 (1998): 12-23.

Permana, S., G. Saputra, M. Suzuki, and M. Saito. *Analysis on Reactor Criticality Condition and Fuel Conversion Capability Based on Different Loaded Plutonium Composition in Fbr Core*. Vol. 799. 1 ed. 5th International Conference on Advances in Nuclear Science and Engineering, ICANSE 2015: Institute of Physics Publishing, 2017.

Platte, J. E. "Indian Nuclear Fuel Cycle Decision-Making: An Analysis of Influences." *Journal of Risk Research* 17, no. 1 (2014): 7-21.

Poinssot, Ch, S. Bourg, N. Ouvrier, N. Combernoux, C. Rostaing, M. Vargas-Gonzalez, and J. Bruno. "Assessment of the Environmental Footprint of Nuclear Energy Systems. Comparison between Closed and Open Fuel Cycles." *Energy* 69 (2014): 199-211.

Prăvălie, R. and G. Bandoc. "Nuclear Energy: Between Global Electricity Demand, Worldwide Decarbonisation Imperativeness, and Planetary Environmental Implications." *Journal of Environmental Management* 209 (2018): 81-92.

Quester, G. H. "The Nuclear Nonproliferation Treaty and the International Atomic Energy Agency." *International Organization* 24, no. 2 (1970): 163-82.

R. Wigeland, T. Taiwo, H. Ludewig, M. Todosow, W. Halsey, J. Gehin, R. Jubin, J. Buelt, S. Stockinger, K. Jenni, and B. Oakley. *Nuclear Fuel Cycle Evaluation and Screening - Final Report*. Idaho National Laboratory, 2014.

Rauch, Helmut and Michael Schneeberger. "Fundamentals of the Nuclear Fuel Cycle." *Elektrotech Maschinenbau* 94, no. 2 (1977): 70-82.

Regalbuto, M. C. "7 - Alternative Separation and Extraction: Urex+ Processes for Actinide and Targeted Fission Product Recovery." In *Advanced Separation Techniques for Nuclear Fuel Reprocessing and Radioactive Waste Treatment*, edited by Kenneth L. Nash and Gregg J. Lumetta, 176-200: Woodhead Publishing, 2011.

Robinson, T. C. "What Do We Mean by Nuclear Proliferation?" *Nonproliferation Review* 22, no. 1 (2015): 53-70.

Rockwood, L. "Safeguards and Nonproliferation: The First Half-Century from a Legal Perspective." *Journal of Nuclear Materials Management* 35, no. 4 (2007): 7-17.

Rose, Gideon. "Neoclassical Realism and Theories of Foreign Policy." *World Politics* 51, no. 1 (1998): 144-72.

Sagan, Scott D. "Why Do States Build Nuclear Weapons?: Three Models in Search of a Bomb." *International Security* 21, no. 3 (1996): 54-86.

Schriefer, D. "Safeguards, Security, Safety and the Nuclear Fuel Cycle." In *Nuclear Fuel Cycle Science and Engineering*, 52-79: Elsevier Inc., 2012.

Schweller, Randall L. "Neorealism's Status-Quo Bias: What Security Dilemma?" *Security Studies* 5, no. 3 (1996/03/01 1996): 90-121.

Shenasaei, H. and F. Shirvani. "Article Iv of the Npt Treaty and Legitimacy of Sensitive Nuclear Activities." *Asian Social Science* 10, no. 3 (2014): 120-28.

Shils, Edward A. "The Failure of the Unaec: An Interpretation." *Bulletin of the Atomic Scientists* 4, no. 7 (1948/07/01 1948): 205-10.

Sobek, D., D. M. Foster, and S. B. Robison. "Conventional Wisdom? The Effect of Nuclear Proliferation on Armed Conflict, 1945-2001." *International Studies Quarterly* 56, no. 1 (2012): 149-62.

Squassoni, S. "Nuclear Energy and Nonproliferation: Todays Challenges." In *Business and Nonproliferation*, 17-30: Brookings Institution Press, 2011.

Stacey, Weston M. *Nuclear Reactor Physics*. Second Edition, Completely Revised and Enlarged ed. Weinheim: WILEY-VCH Verlag GmbH & Co. KGaA, 2007.

Stein, M. and M. Morichi. "Safety, Security, and Safeguards by Design: An Industrial Approach." *Nuclear Technology* 179, no. 1 (2012): 150-55.

Taebi, B. *Moral Dilemmas of Uranium and Thorium Fuel Cycles*. Vol. 19. Radioactivity in the Environment: Elsevier Ltd, 2013.

TEA. "1.0 Introduction." Last modified -not available-, Accessed 26.03.2021. https://thoriumenergyalliance.com/1-0-introduction/.

TEA. "5.0 General Uses." Last modified -not available-, Accessed 26.03.2021. https://thoriumenergyalliance.com/5-0-general-uses/.

Thayer, B. A. "The Causes of Nuclear Proliferation and the Utility of the Nuclear Nonproliferation Regime." *Security Studies* 4, no. 3 (1995): 463-519.

Todosow, M., A. Galperin, S. Herring, M. Kazimi, T. Downar, and A. Morozov. "Use of Thorium in Light Water Reactors." *Nuclear Technology* 151, no. 2 (2005): 168-76.

Todosow, M. and G. Raitses. *Thorium Based Fuel Cycle Options for Pwrs*. Translated by Society American Nuclear, Society French Nuclear, Society Korean Nuclear, and Japan Atomic Energy Society of. Vol. 3. International Congress on Advances in Nuclear Power Plants 2010, ICAPP 2010. San Diego, CA, 2010.

U.S.NRC. "Fertile Material." Last modified December 2, 2020, Accessed 03.03.2021. https://www.nrc.gov/reading-rm/basic-ref/glossary/fertile-material.html.

U.S.NRC. "Uranium Enrichment." Last modified December 2, 2020, Accessed 20.02.2021. https://www.nrc.gov/materials/fuel-cycle-fac/ur-enrichment.html.

Udum, Şebnem. "Peaceful Use of Nuclear Energy and the International Nuclear Nonproliferation Regime." *Energy and Diplomacy Journal* vol.1, no. 4 (2015): 94-115.

Uhlíř, J. *Fuel Cycle Aspects of Molten Salt Reactor System*. Vol. 3. International Congress on Advances in Nuclear Power Plants 2009, ICAPP 2009: Atomic Energy Society of Japan, 2009.

UNODA. "Fissile Material." Last modified -not available-, Accessed 03.03.2021. https://www.un.org/disarmament/fissile-material/#:~:text=Fissile%20materials%20are%20materials%20that,%2D239%20isotope%20of%20plutonium.

UNODA. "Treaty on the Non-Proliferation of Nuclear Weapons (Npt)." UNODA. Last modified Accessed 22.04.2021. https://www.un.org/disarmament/wmd/nuclear/npt/.

UNODA. "Treaty on the Non-Proliferation of Nuclear Weapons (Npt)." UNODA. Last modified 2016. Accessed 16.05.2021, 2021. https://www.un.org/disarmament/wmd/nuclear/npt/.

UNODA. "Treaty on the Non-Proliferation of Nuclear Weapons (Npt)." UNODA. Last modified 2021. Accessed 16.05.2021, 2021. https://www.un.org/disarmament/wmd/nuclear/npt/.

van Evera, Stephen. "Offense, Defense, and the Causes of War." *International Security* 22, no. 4 (1998): 5-43.

Waldrop, M. "The Technology Behind Nuclear Proliferation." *Chemical and Engineering News* 55, no. 30 (1977): 17-23.

Walker, J. S. "Nuclear Power and Nonproliferation: The Controversy over Nuclear Exports, 1974-1980." *Diplomatic History* 25, no. 2 (2001): 215-49.

Waltz, Kenneth N. "The Emerging Structure of International Politics." *International Security* 18, no. 2 (1993): 44-79.

Waltz, Kenneth N. *Theory of International Politics*. Waveland Press, 2010.

Weaver, K. D. and J. S. Herring. "Performance of Thorium-Based Mixed-Oxide Fuels for the Consumption of Plutonium in Current and Advanced Reactors." *Nuclear Technology* 143, no. 1 (2003): 22-36.

WNA. "Uranium Enrichment." World Nuclear Association. Last modified September 2020, Accessed 20.04.2021. http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx.

Wojciechowski, A. "The U-232 Production in Thorium Cycle." *Progress in Nuclear Energy* 106 (2018): 204-14.

Xu, Z., M. S. Kazimi, and M. J. Driscoll. "Impact of High Burnup on Pwr Spent Fuel Characteristics." *Nuclear Science and Engineering* 151, no. 3 (2005): 261-73.

Yim, M. S. "Nuclear Nonproliferation and the Future Expansion of Nuclear Power." *Progress in Nuclear Energy* 48, no. 6 (2006): 504-24.

York, D. L., G. Rochau, and C. Mendez. *Enhancing Nonproliferation through Nuclear Fuel Cycle Transparency*. Vol. 95. 2006 Winter Meeting of the American Nuclear Society. Albuquerque, NM, 2006.

Yudin, Y. "Nuclear Energy and Non-Proliferation." In *The Handbook of Global Energy Policy*, 205-23: Wiley Blackwell, 2013.

Zimmer, E. and J. Borchardt. *Thorex Process Studies*. Translated by Chemistry Int Committee for Solvent Extraction, Technology, and Engineering European Federation of Chemical. Vol. 1. ISEC '86 International Solvent Extraction Conference - Preprints. West Ger

Munich, W Ger: DECHEMA, 1986.

Zrodnikov, A. V. "Fast Reactors in the Energy Security for the Stable Development of Russia." *Atomic Energy* 108, no. 4 (2010): 230-33.

APPENDIX I: ETHICS COMMISSION FORM FOR THESIS

HACETTEPE UNIVERSITY
GRADUATE SCHOOL OF SOCIAL SCIENCES
ETHICS COMMISSION FORM FOR THESIS

HACETTEPE UNIVERSITY
GRADUATE SCHOOL OF SOCIAL SCIENCES
INTERNATIONAL RELATIONS DEPARTMENT

Date: 21/09/2021

Thesis Title: INTERNATIONAL NUCLEAR NONPROLIFERATION EFFORTS: THORIUM AS A VIABLE ALTERNATIVE TO PREVENT DIVERSION

My thesis work related to the title above:

1. Does not perform experimentation on animals or people.
2. Does not necessitate the use of biological material (blood, urine, biological fluids and samples, etc.).
3. Does not involve any interference of the body's integrity.
4. Is not based on observational and descriptive research (survey, interview, measures/scales, data scanning, system-model development).

I declare, I have carefully read Hacettepe University's Ethics Regulations and the Commission's Guidelines, and in order to proceed with my thesis according to these regulations I do not have to get permission from the Ethics Board/Commission for anything; in any infringement of the regulations I accept all legal responsibility and I declare that all the information I have provided is true.

I respectfully submit this for approval.

21.09.2021

Name Surname: AHMET BİÇER
Student No:
Department: INTERNATIONAL RELATIONS
Program: INTERNATIONAL RELATIONS
Status: ☒ MA ☐ Ph.D. ☐ Combined MA/ Ph.D.

ADVISER COMMENTS AND APPROVAL

Approved

ASSOC. PROF. DR. ŞEBNEM UDUM

APPENDIX II: MASTER'S THESIS ORIGINALITY REPORT

HACETTEPE UNIVERSITY
GRADUATE SCHOOL OF SOCIAL SCIENCES
MASTER'S THESIS ORIGINALITY REPORT

HACETTEPE UNIVERSITY
GRADUATE SCHOOL OF SOCIAL SCIENCES
INTERNATIONAL RELATIONS DEPARTMENT

Date: 21/09/2021

Thesis Title : INTERNATIONAL NUCLEAR NONPROLIFERATION EFFORTS: THORIUM AS A VIABLE ALTERNATIVE TO PREVENT DIVERSION

According to the originality report obtained by myself/my thesis advisor by using the Turnitin plagiarism detection software and by applying the filtering options checked below on 9/19/2021 for the total of 73 pages including the a) Title Page, b) Introduction, c) Main Chapters, and d) Conclusion sections of my thesis entitled as above, the similarity index of my thesis is 14 %.

Filtering options applied:

1. ☒ Approval and Decleration sections excluded
2. ☒ Bibliography/Works Cited excluded
3. ☐ Quotes excluded
4. ☒ Quotes included
5. ☒ Match size up to 5 words excluded

I declare that I have carefully read Hacettepe University Graduate School of Social Sciences Guidelines for Obtaining and Using Thesis Originality Reports; that according to the maximum similarity index values specified in the Guidelines, my thesis does not include any form of plagiarism; that in any future detection of possible infringement of the regulations I accept all legal responsibility; and that all the information I have provided is correct to the best of my knowledge.

I respectfully submit this for approval.

21.09.2021

Name Surname: AHMET BİÇER

Student No:

Department: INTERNATIONAL RELATIONS

Program: GRADUATE (WITH THESIS)

ADVISOR APPROVAL

APPROVED.

ASSOC. PROF. DR. ŞEBNEM UDUM