Institute for Science and International Security

Report

Iran's Likely Violations of Section T: Computer Modeling Relevant to Nuclear Weapons Development

By, Mark Gorwitz, Mohammadreza Giveh, and David Albright

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Highlights

Iran has developed elaborate cover stories for its nuclear weapons development activities, as seen in the Nuclear Archive and elsewhere.[1] It is a strategy that evolved from the Amad Plan, Iran's crash nuclear weapons program in the early 2000s. Iran conducts work that continues Iran's nuclear weapons development by calling it civilian or non-nuclear military work. Over the years, studying Iran's open-source scientific and engineering literature has revealed work related to nuclear weapons development with varying foci and fluctuating intensity and relevance to nuclear weapons, serving as an important indicator of Iran's priorities.

This report concentrates on computer modeling related to nuclear weapons development. It is based on a survey of several hundred recent Iranian academic scientific publications, of which 157 articles were selected for detailed scrutiny. These publications were selected because they discussed weaponization-related technology with an emphasis on computer modeling potentially relevant to nuclear weapons development. Computer modeling is an intrinsic part of nuclear weapons development and thus of high value for Iran, while being easily disguised with cover stories that are often difficult to assess or see through.

Although Iran has a long history of hiding nuclear weapons work across a broad spectrum, this report focuses on computer modeling related to nuclear weapons development conducted recently, specifically after 2016 when the Joint Comprehensive Plan of Action (JCPOA) was implemented. Through section T of its Annex 1, this plan attempted to address concerns about activities relevant to potential nuclear weaponization. That section requires Iran not to engage in specific activities, which could "contribute to the design and development of a nuclear explosive device." The first article of Section T prohibits the "designing, developing, acquiring, or using computer models to simulate nuclear explosive devices."

[1] David Albright with Sarah Burkhard and the Good ISIS Team, *Iran's Perilous Pursuit of Nuclear Weapons* (Washington, D.C.: Institute for Science and International Security Press, 2021).

Despite the prohibition, a large number of recent Iranian scientific studies demonstrate that Iran is disregarding, likely violating, the modeling aspects of Section T. It has advanced its nuclear weaponization efforts in a decentralized manner with academic covers. Through this, the regime is acquiring additional knowledge and capabilities in regard to "designing and developing" nuclear weapons.

Iran has used computer codes to evaluate and simulate many scenarios, materials, properties, parameters, and reactions that may be relevant to nuclear weapons development, allegedly for, or under the cover of, civilian nuclear applications or non-nuclear military applications.

These studies collectively also reveal that Iran has established an extensive civilian and military scientific and engineering research and development infrastructure that can contribute significantly to building nuclear weapons and aiding in advancing the program, once initiated. Its infrastructure and personnel capabilities can significantly shorten the time needed to build nuclear weapons and better ensure their reliability, once the Iranian regime makes the decision to build nuclear weapons.

At the heart of any Iranian nuclear weapons effort is SPND, a DARPA-like Defense entity, which evolved from the Amad Plan and still holds many of the personnel and material assets of the Amad Plan. According to the Defense Ministry's spokesman, "SPND has contractual cooperation with 100 universities and 1,200 knowledge enterprises and provides service to all branches of military forces."[2]

In addition, this survey of Iranian scientific publications demonstrates:

- Iran's use of computer modeling to advance its nuclear weaponization capabilities is ongoing today.
- Iran's ability to modify open-source computer codes has helped shorten and improve its simulation work associated with nuclear design efforts.
- Iran has the ability to integrate experimental results into current design codes, and the revised codes can further advance both the accuracy of these codes and the ability to undertake simulations. These simulations are likely to lead to new improvements in codes, leading to conducting additional experiments, whose results can be incorporated into the computer modeling, leading to further improvements.
- Iran's work on supercomputers, as seen in these studies, opens a way to port existing codes into a supercomputing environment, a step leading to even further advances in nuclear weapons design.
- The government's network in universities is growing. While a portion of the detected weapons-related work has been conducted at facilities and by people previously known to be related to the regime's weapons program, new facilities and departments are participating, possibly to scatter the work and obstruct visibility even further.

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[2] "The Parliament's gift to the Ministry of Defense/How does the SPND help the armed forces", [Translated from Farsi], *KhabarOnline*, April 2, 2024, khabaronline.ir/xm8sQ

Introduction

Computer modeling plays a critical role in designing, testing, and finalizing a workable nuclear weapon. These models can advance the Islamic Republic's nuclear weaponization efforts under a well-developed cover, making detectability difficult. This work is especially sensitive, because Iran has already learned so much about nuclear weapons designs and component testing during its earlier nuclear weapons programs, particularly its crash nuclear weapons program in the early 2000s, codenamed the Amad Plan. The experimental data collected during that time can play a role in further guiding and verifying simulation work today.

Figure 1 is a schematic produced by the Amad Plan in the early 2000s showing the basic design of a levitated, solid-core nuclear implosion weapon and its major components, including a multipoint initiation system, called the shock wave generator, and a neutron source placed at the center of the core. Figure 2 shows a hydrodynamic simulation. Figure 3 is a chart showing the organizational structure of the Amad Plan's Project 110, which was responsible for designing, developing, and building deliverable nuclear weapons. The Operating System was code for the nuclear weapon itself and extensively used theoretical calculations and computer modeling.

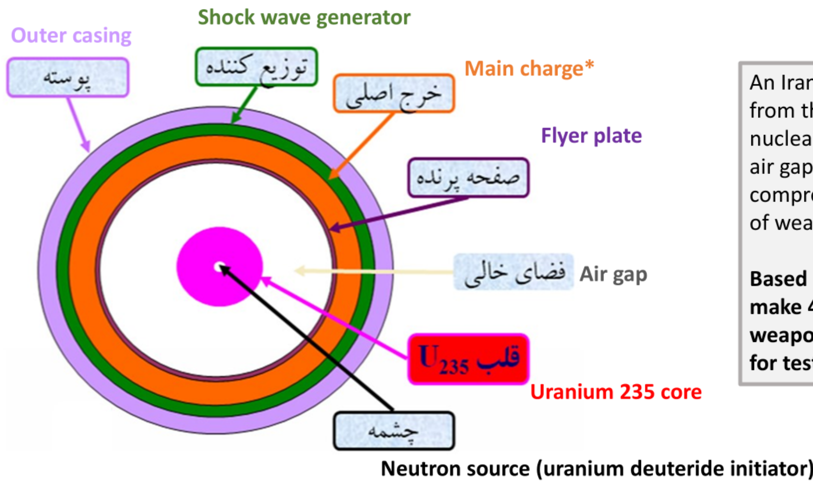
Because of Iran's experience, additional computer modeling and resulting simulations can shorten the time needed to iron out any problems in existing nuclear weapons designs, and help improve and finalize these designs. Modeling can also guide and even reduce the number of physical tests required of individual components and serves to help improve or certify individual components.

Modeling and associated simulations are also important in ensuring the weapon's reliability over longer periods of time and understanding the aging processes of the various components of the weapon design. In addition, mathematical descriptions of how materials behave under different conditions such as under high pressure and temperature need to be calculated and checked against existing databases.

This paper categorizes Iran's research, as gleaned from open scientific studies relevant to Section T and nuclear weaponization relevant computer modeling, into three sections: neutronic calculations calculating the neutronic behavior of the fissile reaction at the core of a nuclear device or during a reactor accident; hydrodynamic studies simulating behavior of materials under extremely high pressures and temperatures of a bomb; high explosive charges; and the work related to the simulation of the behavior of the multipoint initiation of the main explosive charge in the device. At the end, the paper briefly discusses simulation work related to fissile material production as prerequisites of a device and Iran's supercomputing capabilities to run these codes.

The 157 papers assessed by the Institute ranged from as recently as three months ago and included many from 2022 and 2023. There were no indications that the work discussed in the paper has stopped.

Iranian Nuclear Weapon Schematic Developed During the Amad Plan



An Iranian schematic (with translation), from the Nuclear Archive, of a levitated nuclear weapon design, i.e. one with an air gap and flyer plate to increase compression of the core, based on the use of weapon-grade uranium.

Based on this design, Iran was planning to make 4 missile-deliverable nuclear weapons and a nuclear explosive device for testing.

Figure 1. A schematic of a levitated nuclear weapon design from the Nuclear Archives.

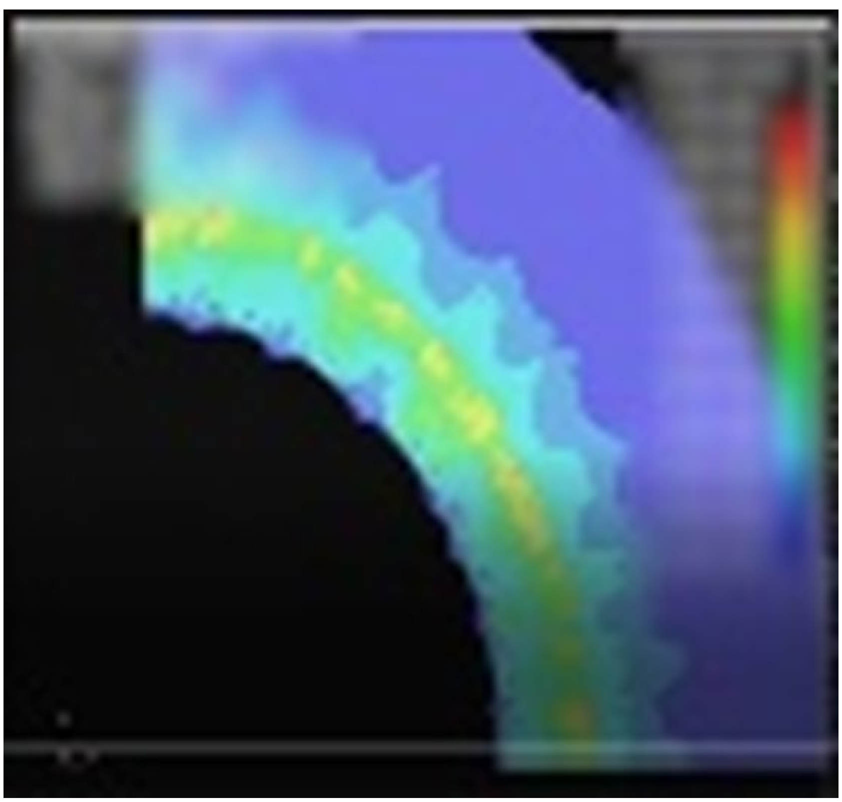


Figure 2. Simulation from the hydrodynamic modeling of a nuclear explosion from the Nuclear Archives.

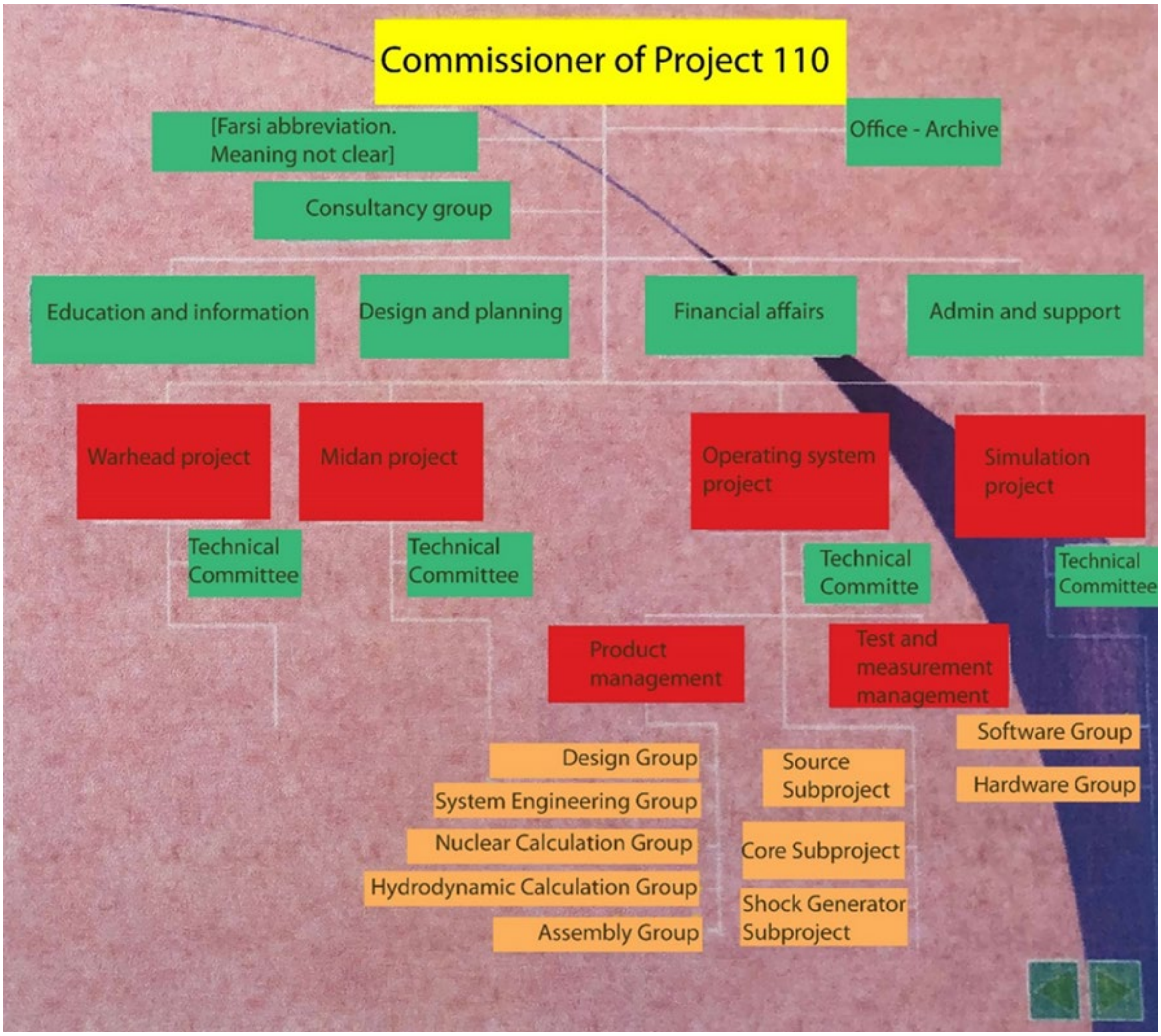


Figure 3. Translation of a Nuclear Archive chart depicting the organizational structure of the Amad Plan's Project 110, which was responsible for designing, developing, and building deliverable nuclear weapons. The Operating System was code for the nuclear weapon itself. As can be seen, theoretical work, including calculations, software, and simulations, was central to the Operating System Project. Note: The Farsi word for "commissioner" can also be translated as "commander." The extra white lines on the mid-left of the chart are from the original diagram. For a more detailed discussion of this document, see *Iran's Perilous Pursuit of Nuclear Weapons, Chapter 3.*

Section T

Section T was an innovative section of the JCPOA that aimed to plug a hole in limits on Iran's work on nuclear weapons-related work. However, it was never implemented in any serious way, and some of the designers of the section believed it was not verifiable. Nonetheless, Iran agreed to this section, and it remains a benchmark by which to judge Iran's actions and potential work on nuclear weapons.

Under Section T, Iran committed that it will not engage in the following activities, which could contribute to the design and development of a nuclear explosive device:

- Designing, developing, acquiring, or using computer models to simulate nuclear explosive devices.
- Designing, developing, fabricating, acquiring, or using multi-point explosive detonation systems suitable for a nuclear explosive device, unless approved by the Joint Commission for non-nuclear purposes and subject to monitoring.
- Designing, developing, fabricating, acquiring, or using explosive diagnostic systems (streak cameras, framing cameras, and flash x-ray cameras) suitable for the development of a nuclear explosive device, unless approved by the Joint Commission for non-nuclear purposes and subject to monitoring.
- Designing, developing, fabricating, acquiring, or using explosively driven neutron sources or specialized materials for explosively driven neutron sources.

As can be seen, some activities are outright banned, while others can be done with the approval of the executive arm established under the JCPOA. Computer modeling related to simulating a nuclear explosive is banned.

In addition to the use of computer modeling to simulate nuclear explosives, Section T also prohibits the use of certain equipment in experimental studies unless approved by the JCPOA's executive organization, the joint commission, such as the use of high-speed cameras. It is known that Iran has many suitable high-speed cameras, and there are indications that Iran may be using them absent of approval or IAEA monitoring. However, the use of computer codes is so abundant in the recent open-source literature, and has become a subject of recent public debates, that it is the main focus of the paper.

Cover Stories

Beyond Section T consideration, Iran has developed elaborate cover stories for its nuclear weapons development activities, as evidenced in the Nuclear Archive and elsewhere.[3] It presents some work that aids nuclear weapons development by calling it civilian or non-nuclear

[3] David Albright with Sarah Burkhard and the Good ISIS Team, *Iran's Perilous Pursuit of Nuclear Weapons* (Washington, D.C.: Institute for Science and International Security Press, 2021).

military work. Because of this past behavior, studying open-source scientific and engineering literature can reveal work related to nuclear weapons development.

These open studies can represent only the tip of the iceberg, since nuclear weapons personnel would greatly protect their nuclear weapons design related codes. But these open studies can indicate the contracting out of aspects of nuclear weapons development and involving more personnel in developing and improving relevant modeling under an academic or civilian cover. This can both advance nuclear weapons modeling and create a pool of talented individuals that can be recruited into the nuclear weapon program, when necessary.

The Iranian nuclear weapons program has a record of distributing sensitive work to universities and maintaining close relationships with them. Many Amad Plan members held key positions at Iranian universities; a practice that continued after the end of the Amad Plan and the shrinkage of the nuclear weapons program. In 2009, for example, the *Times of London* revealed a document titled "Outlook for special neutron-related activities over the next four years" describing Iran's plan to build a neutron generator and the government's use of academic covers to assist that effort which was key to furthering the nuclear weapons program. The document talks about supplementing the weapons program's capabilities through "ordinary project arrangements" and moving equipment (in this case a neutron generator) to universities under an agreement and with the supervision of the weapons program's personnel to disguise the nature of the research.

One of the goals stated for performing experiments in this document is for the personnel "to gain more knowledge of the subject." It is stated that the program needs trustworthy experts, as well as temporary hires, to perform neutronic calculations. To serve this purpose, the document provisions recalling exports who have been involved in similar projects in the past as well temporarily hiring a combination of graduate students (who might not be fully aware of what they are involved in) to perform parts of the neutronic calculations.

Today, as in the past, disseminating weaponization-related work to universities can also help support a nuclear weapons program, making it more ready to build nuclear weapons, if the regime decides to do so. It serves as a way to put a relatively large number of technically competent persons on a "hot standby" without them knowing that their work would contribute to building nuclear weapons in the future.

Neutronic Calculations

To design a nuclear weapon, it is crucial to understand the behavior of the fissile material (weapon-grade uranium or plutonium) used in the weapon, particularly in terms of its criticality. Calculating neutronic parameters such as neutron cross-section, neutron multiplication factor, and neutron transport in specific materials such as beryllium is essential for determining the criticality of the fissile material. A number of recently published scientific papers were found in the open scientific literature where Iranian scientists applied sophisticated computer codes to calculate these neutronic parameters. Specifically, the MCNP code and its variants/family of codes are the most common. Developed by the U.S. Nuclear Weapons Laboratory at Los Alamos, MCNP has numerous civilian applications and is used by many universities and research institutes in the West. However, the code's application in nuclear weapon effects modeling has made it subject to rigorous export control and can qualify it for Section T restrictions.[4]

Neutron Interactions with Matter - Cross Sections

Searching the open-source Iranian scientific literature, recent papers of interest were found related to the use of computer codes to determine neutron cross sections. Calculating neutron cross sections in the context of nuclear fission assesses the probability of a neutron causing a nucleus to undergo fission. Calculating the neutron cross section is vital in assessing the conditions under which a specific fissile (highly enriched uranium or plutonium) material becomes critical and may then proceed to a supercritical state.

One specific paper, written in 2021 by researchers at Islamic Azad University, combined the MCNP code with another code, NJOY, to develop new software used to calculate the neutron cross section of different isotopes, including uranium. The abstract from the paper titled "Development of Two Software Packages for Connecting with the MCNPX and NJOY Nuclear Codes to Directly Obtain and Extract Multi-Group Nuclear Cross Sections for Any Isotope" reads: "MCNPX can be combined with the NJOY nuclear cross section code to 'obtain and extract Multi-Group Nuclear Cross for Any Isotope'. In this research, two software packages are developed to be connected with MCNP and NJOY to obtain and extract nuclear cross sections. The first (main) software package was coupled with the MCNPX code to automatically run it to obtain cross sections of isotopes for multi-group and a wide range of incident neutron energies. [...] It was observed that from the thermal neutron range to the fast, the cross sections of isotopes obtained by the AutoNJOY were nearly similar to the results obtained by the first software package, and the derived graphs of both methods approved with each other."[5]

MCNP is the most relevant code, but there are additional nuclear reactor codes, which may date back years but are still being used, such as WIMS. Calculating the effective neutron multiplication factor using MCNP/WIMS & CITATION codes is standard in nuclear reactor design. NJOY and ENDF/B-VII.1 are two of the most popular codes used to calculate neutron population in a fissile medium to predict neutron fission, capture, and scattering in a fissile material.[6] See footnote 7 for additional examples of studies using relevant codes for commercial applications.[7]

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[4] T. Goorley, "MCNP for Nuclear Weapons Effects Modeling," presented at the HEART Conference, Orlando, FL, Apr. 1, 2011.

[5] S. A. M. Shirazi, "Development of Two Software Packages for Connecting with the MCNPX and NJOY Nuclear Codes to Directly Obtain and Extract Multi-Group Nuclear Cross Sections for Any Isotope," *Arab Journal of Nuclear Sciences and Applications*, vol. 54, no. 1, pp. 120–133, Jan. 2021, doi: 10.21608/ajnsa.2021.34629.1377.

[6] Barroso, D.E.G., *Physics of Nuclear Explosives,* (Rio de Janeiro, Brazil, 2021).

[7] M. G. Rahmati, M. Hasanzadeh, and S. A. H. Feghhi, "Calculation of neutronic and kinetic parameters of Isfahan Miniature Neutron Source Reactor using slope fit and perturbation methods," Radiation Physics and Engineering

In another paper from 2022, an Iranian researcher at Islamic Azad University examined various plutonium isotopes and calculated important parameters related to the fission of plutonium isotopes, including plutonium 239, the isotope desired for plutonium-based nuclear weapons. The paper determined the total kinetic energy values of neutron fragments of plutonium isotopes using the scission point model. The paper reads: "The deformation parameters were obtained for neutron fission of plutonium 239, 241, and 242 by comparing the calculated results with experiments in the scission point model…Using the results of the fission deformation parameters, the average kinetic energy of all neutron fragments for the rest of the plutonium isotopes is calculated. The average kinetic energy of all neutron fission fragments for plutonium isotopes is 185 MeV."[8] This process relates to nuclear cross section and the neutron multiplication factor.

Neutron Transport Equation

A number of recent papers were found in the open-source scientific literature using the Monte Carlo method via MCNP codes (such as Iran's own version, the MCPS-Explicit code) to determine neutron transport equations, relevant to calculating the criticality of different fissile materials under different parameters, such as varying density and complex three-dimensional geometry.[9,10]

In one 2018 paper written by an Iranian scientist, MCNP was used to determine the alpha-eigenvalue coefficient, an important part of the time-dependent neutron transport equation. The paper states that this approach "can only show a rather quantitative measure for the distance of a system from criticality […]. This article proposes a direct physical relationship to adjust the alpha-eigenvalue in the Monte Carlo alpha-k interaction method."[11] This is an

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vol. 1, no. 4, pp. 1–8, Oct. 2020, doi: 10.22034/rpe.2020.104838; H. Khaameh, S. Zare Ganjaroudi, A. Pazirandeh, and Y. Kasehsaz, "Neutronic Analysis of V-1000 Zero Power Reactor Core Mock-Up using MCNPX2.7.0, WIMS & CITATION Codes and Advanced SuperMC3.2.0 Program," in The International Conference on Interdisciplinary Studies in Management and Engineering, Tehran, 2019; and M. Hasanzadeh, F. Khoshahval, M. Amin Mozafari, M. Amirkhani, A. Lashkari, and M. Rajaei, "Neutronic conceptual design of Tehran Research Reactor using tubular fuel," *Journal of Nuclear Science, Engineering and Technology (JONSAT)*, vol. 43, no. 1, pp. 146-155, 2022, doi: 10.24200/nst.2022.1359.

[8] M. Jamiati, "Calculation of the total kinetic energy distributions for neutron fission of plutonium isotopes," *Journal of Nuclear Science, Engineering and Technology*, vol. 43, no. 1, pp. 156-164, 2022.

[9] M. G. Mazaher, A. A. Salehi, and N. Vosoughi, "Modification of a Dynamic Monte Carlo Technique to Simplify and Accelerate Transient Analysis with Feedback," *Nuclear Science and Engineering*, vol. 196, no. 4, pp. 395–408, Nov. 2021, doi: 10.1080/00295639.2021.1989932.

[10] On April 25, 2016 Matthew McKinzie (NRDC) gave an NPEC Dinner Seminar at the Capitol Hill Club entitled "East Asian Nuclearization - Is Trump Wrong," H MCNP5 was listed as an example of nuclear engineering software that could be applied to nuclear weapons design. He stated that MCNP can be used to calculate parameters in the theoretical design of nuclear explosive devices, such as the efficiency constant Keff and critical masses "for arbitrary, fixed configurations of fissile material, neutron-reflecting materials and other components."

[11] H. A. Kia, M. Zangian, A. Minuchehr, and A. Zolfaghari, "An improved convergence rate for the prompt alpha eigenvalue calculation in the alpha-k iteration methods," *Annals of Nuclear Energy*, vol. 118, pp. 15-25, 2018.

important concept in weapons design as it is necessary to determine the value of alpha (neutron chain development) in the system as it approaches criticality.[12]

In another paper, an Iranian scientist used MCNP in a way that is related to neutron multiplication rates in critical systems. The paper reads: "Simulation of a direct geometry spectrometer for neutron time-of-flight (nTOF) is performed based on the Monte Carlo method to calculate the energy spectrum of the neutron source […]. The simulation of the nTOF measurements gives the opportunity to investigate the effect of the parameters such as distance, angle, and detector type on the results." The simulations were done using a modified MCNPX code and simulating the energy spectrum of a 241Am-9Be source (see notes on this neutron source below).[13]

In two 2021 papers, Ali Akbar Salehi, former head of the AEOI indicated that progress was made using the MCSP-Explicit codes to calculate neutron population growth more precisely, for more generations of neutron multiplication and larger quantities of neutron populations. He writes a "simpler approach compared to the existing approaches is developed to analyze nuclear reactor dynamics based on the explicit Monte Carlo method. A new population control method is also introduced to prevent neutron population growth and consequent memory shortages, which increases memory speed […]. A number of benchmark problems are studied at the end to evaluate the performance of the proposed approach in various situations."[14] He further stated in another paper, "Poor memory management can be considered as the first restrictive barrier to the implementation of the neutron transport equation for large reactors. The current research presents a new MRT with the ability to reduce the required memory and increase cache coherency." MCPS-Explicit can be run with multigroup libraries, and processing can be sped up by the use of parallel processing.[15]

Of note, Salehi had been previously associated with Iranian physicists from Iran's nuclear weaponization program, such as Majid Shahriari (assassinated in 2010 for his involvement in code development and flash x-ray aspects of the weaponization efforts) on the development of multi-dimensional neutron transport codes.

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[12] "The direct solution of the time dependent neutron equation coupled to the radiation hydrodynamic allows a more reliable determination of the time evolution of neutron flux, and hence the energy released in a nuclear explosion computer simulation," Barroso, D.E.G., Physics of Nuclear Explosives, (Rio de Janeiro, Brazil, 2021).

[13] S. A. Hosseini and M. Mehrabi, "Simulation of the direct geometry spectrometer for neutron time of flight based on the Monte Carlo method to calculate the energy spectrum of the neutron source," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 949, p. 162872, 2020.

[14] M. G. Mazaher, A. A. Salehi, and N. Vosoughi, "Modification of a Dynamic Monte Carlo Technique to Simplify and Accelerate Transient Analysis with Feedback," *Nuclear Science and Engineering*, vol. 196, no. 4, pp. 395–408, Nov. 2021, doi: 10.1080/00295639.2021.1989932.

[15] M. Porhemmat, M. Mahzoon, A. A. Salehi, K. Hadad, and K. Hosseinipour, "Improved memory management for solving neutron transport via a novel Modular Ray Tracing (MRT) approach embedded in parallel method of characteristic (MOC) framework," *Progress in Nuclear Energy*, vol. 132, p. 103590, Feb. 2021, doi: 10.1016/j.pnucene.2020.103590.

Simulating Effects of Radiation Exposure

For a nuclear weapons context it is important to know how the electronic components and other material components degrade under the effect of radiation. Multiple papers were found relevant to this aspect, using the MCNP and SRIM codes.

Two Imam Hussain University researchers, Davood Ghasemabadi and Massoud Abdolahzadeh, published an article in 2020 in which they experimented with applications of MCNP codes to investigate the penetration depth of beta particles emitted from Nickel-63 into a silicon target.[16] The silicon target may have been part of a fast switch used to trigger components of a nuclear weapons system. The specific isotope investigated, Nickel-63, has been employed in krytrons and sprytron triggers, which are more sophisticated generations of triggered spark gaps used in the firing and detonation systems of nuclear weapons.

A more recent publication from 2024 looked at "Structural properties, such as mechanical and electrical properties of materials irradiated with *γ*-rays are affected by displacement damage. Successive processes with different behaviors ultimately lead to the formation of sets of 'defects' within the material, and as an example, it may cause the substance to become brittle. In this study, Monte Carlo codes provide information using a code-based simulation method on primary knock-on atoms, or PKAs, that cause damage."[17]

Another recent investigation looked at the effect of gamma rays from a Cobalt 60 source on the electrical properties of transistors and silicon diodes for application in high dose dosimetry. "Transistors and silicon diodes are the best tools for use as detectors in the individual gamma active dosimeter due to their small volume, low weight, low operating voltage, good energy resolution, simple operation and ease of transport."[18]

Most recently, in 2024, four NSTRI researchers used MCNPX codes to evaluate nitrile butadiene rubber for use in neutron shielding, in their paper titled "Assessment of shielding performance of nitrile butadiene rubber through simulation and experiments at MNSR (Miniature Neutron Source Reactor) beam line."[19] In a nuclear weapons context, aligning components, i.e. those holding the major components in place, may be made out of polymer and must be able to withstand the radiation exposures.

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[16] D. Ghasemabadi and M. Abdolahzadeh, "Investigation of the Penetration Depth of the Nickel-63 Beta Spectrum in Silicon Using the Monte Carlo Method with the MCNPX Code," *Journal of Radiation Safety and Measurement*, vol. 9, no. 4, pp. 347–352, Jun. 2020.

[17] M. Hoseini, S. Hamidi, and A. Mohammadi, "The use of the SRIM code for calculating radiation damage induced by γ-rays," Pramāna, vol. 98, no. 1, Feb. 2024, doi: 10.1007/s12043-023-02708-9.

[18] Z. Daram, B. Shirani Bidabadi, and S. Golshah, "An investigation of the effect of Gamma irradiation on the electrical properties of transistors and silicon diodes for application in high dose dosimetry," *Journal of Radiation Safety and Measurement*, vol. 11, no. 5, pp. 89-92, 2023.

[19] Z. Gholamzadeh, R. Ebrahimzadeh, M. H. Choopan Dastjerdi, and J. Mokhtari, "Assessment of shielding performance of nitrile butadiene rubber through simulation and experiments at MNSR beam line," *Radiation Physics and Engineering*, vol. 5, no. 2, pp. 43-50, 2024, doi: 10.22034/rpe.2024.420403.1167.

In 2022, a former co-author of Eta'ati[20] along with a researcher from the Nuclear Science and Technology Research Institute (NSTRI) published a paper focusing on the impact of shielding materials on the radiation dose received by a breast cancer tumor and surrounding healthy tissues, particularly the heart and lungs in which they used MCNPX codes to simulate the process.[21] Neutron shielding, which is a dual-use technology, is directly relevant in a nuclear weaponization context to ensure personnel safety.

Physics facilities located at various Iranian universities may be used to study electromagnetic interference testing and the transient response of vital military and nuclear components to HEMP (high-altitude electromagnetic pulses). This type of computer simulation has been openly reported by researchers from Sharif, Imam Khomeini, and Amirkabir Universities.

Nuclear Reactor Accident Simulations

Nuclear reactor accident codes can be modified to benchmark and improve nuclear weapons codes (see Figure 4). Nuclear reactor accident modeling is relevant to developing nuclear weapons, particularly when it concerns rapid fissioning of uranium or plutonium in the nuclear reactor core, the core melting, and then disassembly of the core due to the extreme temperature rise during a sudden increase in reactor power. This is achieved by modifying the code to predict fully uncontrolled fission chain reactions and simulate the behavior of materials specific to nuclear devices, and then comparing the results to that achieved from early reactor accident codes. Taiwan has previously used reactor safety computer codes (AX-1) to study the dynamic simulation of a nuclear explosion.[22]

Iran may use openly available data to improve its codes in this area. Specifically, the data available from a set of Russian experiments in which an enriched uranium core surrounded by a beryllium tamper (also used in a nuclear weapon as a neutron reflector) was allowed to reach a supercritical state. The "device" in those experiments was contained in an explosion proof chamber and was initiated by a burst of 14 MeV neutrons. Furthermore, information has been declassified regarding U.S. reactor criticality studies, known as the Kiwi-TNT experiments, which provided data on neutron flux and core dynamics under critical conditions. These sources can be leveraged for advanced nuclear simulation and weapon development.
There are notable recent publications by Iranian scientists using the MCNP codes to calculate nuclear criticality and neutron population growth in nuclear reactors, directly relevant to calculating uncontrolled neutron population growth in a nuclear reactor accident or a nuclear

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[20] Gholam Reza Eta'ati has been associated with Iran's Organization of Defensive Innovation and Research (SPND) and weaponization activities. Wisconsin Project on Nuclear Arms Control, "Gholam Reza Eta'ati," Iran Watch, August 2, 2019, https://www.iranwatch.org/iranian-entities/gholam-reza-etaati.
[21] M. Tajik and H. Ranjbar, "A simulation based dosimetric study for electron therapy during breast surgery," *Journal of Radiation Safety and Measurement*, vol. 11, no. 2, pp. 85-93, 2022, doi: 10.22052/rsm.2022.113644.
[22] Taiwan has previously used reactor safety computer codes (AX-1) to study the dynamic simulation of a nuclear explosion. See, David Albright and Andrea Stricker, *Taiwan's Former Nuclear Weapons Program: Nuclear Weapons On-Demand* (Washington, D.C.: Institute for Science and International Security Press, 2018).

device.[23] Available abstracts found in the open-source literature indicate that multiple calculations of these nuclear reactor accident applications using the MCNP codes were conducted recently.[24]

One of the more straightforward cases where the dual-use nature of Iran's nuclear reactor related research can be seen is a 2016 conference presentation by three Iranian scientists in Saint Petersburg, Russia. Different types of neutron reflectors were evaluated to determine the minimum critical mass of uranium metal in a spherical shape, enriched at different levels, including weapon-grade uranium (90 and 95 percent enriched uranium). The different types of neutron reflector material included beryllium; an ideal neutron reflector in small, sophisticated research reactors, but also a known neutron reflector material in nuclear weapons.

Noorani (co-authors Zolfagharpour and Azimkhani), affiliated with University of Mohaghegh Ardabili, presented the paper titled "The influence of the presence or absence of a neutron reflector on the critical mass of uranium." An extract from the abstract reads, "To increase productivity and improve the neutron economy in the reactor, neutron reflection is used. These reflectors cause a lack of neutron leakage and reactor fuel can reach critical mass faster […]. In this paper, by using the MCNP code, critical mass of uranium in the term of enrichment for different reflectors is obtained. The results show beryllium, carbon and deuterium are an excellent choice for this purpose. Also increasing the thickness of the neutron reflector causes an increase in neutron multiplication factor."[25]

As noted above, interestingly, the authors picked a spherical geometry for their simulation, and decided to run the simulations for a wide range of enrichment levels, ranging from 15 percent enriched uranium to 96 percent enriched uranium. The paper states, "The MCNP code is one of the most important multipurpose computational codes […] that is in the base of the Monte Carlo method. The distinguishing feature of this code is the possibility of three-dimensional simulation of different issues […] We choose to simulate spherical geometry because this geometry quickly makes the material critical."

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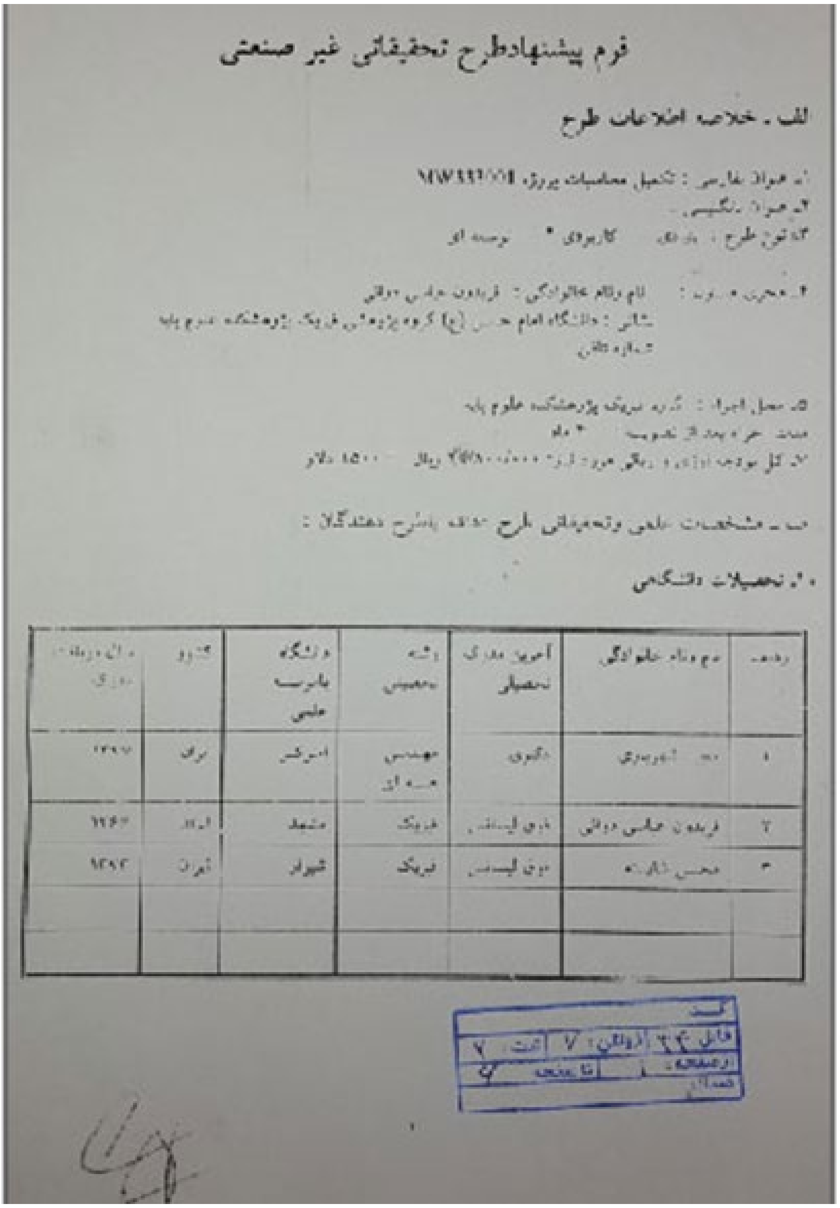
[23] B. Salmassian, A. Rabiee, M. R. Nematollahi, F. Faghihi, and A. Pirouzmand, "Transient Parameter Analysis of Non-Scrammed Local Melting Accidents – A VVER-1000 Case Study," *Frontiers in Energy Research*, vol. 9, 2021, Art. no. 666032; B. Salmassian, A. Rabiee, M. R. Nematollahi, and A. Pirouzmand, "Transient parameters analysis of non-scrammed local melting accident scenarios using MCNPX and COBRA/EN," *Journal of Nuclear Science, Engineering and Technology*, vol. 43, no. 2, pp. 148-157, 2022; B. Salmassian, A. Rabiee, M. R. Nematollahi, and A. Pirouzmand, "Diagnosing core local flow blockages in a VVER-1000/446 reactor using ex-core detectors and neural networks," *Progress in Nuclear Energy*, vol. 161, 2023, Art. no. 104736.

[24] M. G. Mazaher, A. A. Salehi, and N. Vosoughi, "Investigation of a dynamic Monte Carlo method for transients analysis with thermal-hydraulic feedbacks using MCNPX code," *Annals of Nuclear Energy*, vol. 130, pp. 240-249, 2019, https://www.sciencedirect.com/science/article/pii/S0306454919301203; E. Boustani, M. Hassanzadeh, and Ahangari, "Investigation of under-containment gamma dose after total core uncovering accident in Tehran Research Reactor," *Radiation Physics and Engineering*, vol. 2, no. 4, pp. 47-56, 2021, https://rpe.kntu.ac.ir/article_145206.html.

[25] M. Noorani, Zolfagharpour, and S. Azimkhani, "The influence of the presence or absence of a neutron reflector on the critical mass of uranium," in *International Conference on Research in Science and Technology*, Saint Petersburg, Russia, July 28, 2016.



فرم پیشنهادطرح تحقیقاتی غیر صنعتی

الف ـ خلاصه اطلاعات طرح

Figure 4. First page of a six-page research proposal from the Nuclear Archive, dated to the late 1990s or early 2000s, innocuously entitled “Proposal for Non-Industrial Research Project,” submitted by its project leader Fereydoun Abbasi-Davani, who was a key leader the Amad Plan. The proposal summarizes the project’s scientific and technical principles: *“*The principles of the project are based on nuclear reactor theories. It will examine issues related to turning the system into a super-critical system and the system’s dynamic behavior. The technical issues this project will focus on involve designing a system without the control measures commonly used in reactors and involve releasing maximum energy.” Abbasi-Davani noted the project’s importance: “Since this information will play a key role in the operational stage of the *operating system* [code for nuclear weapon], the importance of this project is clear” (emphasis added). The work was slated to occur at Imam Hussein University, demonstrating its link to the nuclear weapons program, a link which likely continues today. For a more detailed discussion of this document, see ***Iran’s Perilous Pursuit of Nuclear Weapons, Chapter 3.***

Neutron Detection

A handful of recent papers used the MCNP codes and a variant, the SRIM codes, for fast neutron detection and measurement.[26] Fast neutron detection is directly relevant in a nuclear weapons context, because fast neutrons are needed to initiate and sustain the chain fission reaction. As such, simulations can aid in the development of neutron sources and the evaluation of important parameters of the chain fission reaction, such as multiplication factor, an important predictor of a workable weapons design and yield.

The SRIM code was used in the development of a low-cost fission chamber neutron detector and its performance was evaluated in the radiation field of the Isfahan miniature reactor neutron beam line.[27] This development effort was performed by researchers from Islamic Azad University working with researchers from the Reactor and Nuclear Safety Research School, part of the AEOI's NSTRI.

Americium-Beryllium Neutron Source Evaluation

In at least two papers, computer codes were used to evaluate an Americium-Beryllium neutron source.[28] One of the studies used the GEANT4 code to measure the spectrum of 241Am-Be neutron source by developing and using a neutron spectrometer system based on Superheated Drop Detectors (SDDs) operating under various external pressures. Of note, the 241Am-Be neutron source can be used to simulate the neutron spectrum of a low-yield nuclear device.[29]

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[26] A. Zabihi, Gh. Forozani, F. Semsarha, A. Moslehi, and P. Rezaeian, "Study of biological effects of fast neutrons (2-14 MeV) using Monte Carlo method on DNA atomic model," *Journal of Nuclear Science and Technology*, vol. 91, no. 1, pp. 50-59, 2020.

[27] E. Teimoory, M. A. Allaf, J. Mokhtari, and M. H. C. Dastjerdi, "Development and characterization of fission chamber neutron detectors in Isfahan miniature neutron source reactor," *Radiation Physics and Chemistry*, vol. 215, p. 111360, Feb. 2024, doi: 10.1016/j.radphyschem.2023.111360.

[28] F. Rahmani and H. Darvish Motevalli, "Optimization of 241Am-Be emission direction in neutron porosity tools for improving the precision in determining the porosity in calcite formation," *Iranian Journal of Physics Research*, vol. 19, no. 1, pp. 61-68, 2019, doi: 10.29252/ijpr.19.1.7.
S. Badiei, G. Raisali, M. Kardan, P. Rezaeian, and A. Moslehi, "Development and experimental validation of a fast neutron spectrometry system based on Superheated Drop Detectors (SDDs) operating under different external pressures," *Nuclear Instruments and Methods in Physics Research Section A Accelerators Spectrometers Detectors and Associated Equipment*, vol. 1010, p. 165569, Sep. 2021, doi: 10.1016/j.nima.2021.165569.

[29] Waller (University of Ontario Institute of Technology, Faculty of Energy Systems and Nuclear Science) published that "A simple and low-cost device was designed to perform testing of commercial off-the-shelf neutron detection equipment to the expected spectral shape from a low-yield nuclear weapon. By enclosing a 241Am-Be neutron source within a heavy-water moderated sphere, the general shape of a 1-kiloton standard fission weapon was generated…The design of the low-yield nuclear weapon simulator required assessment of the reference neutron spectrum, performing simulations of various shield configurations utilizing the MCNPX radiation transport code and the simulated spectra with the reference spectra," E. J. Waller, "Representation of a Low-Yield Nuclear Weapon Neutron Spectrum Using an (α,n) Neutron Source," *Nuclear Technology*, vol. 175, no. 1, pp. 89–92, Jul. 2011, doi: 10.13182/nt11-a12275; "The MCNPX Monte Carlo radiation transport code was used to design a moderator arrangement for a 207.2 GBq 241Am-Be source, and it was determined that both polyethylene and heavy water would be investigated as moderators for the raw neutron spectra and that an outer covering of lead would be used to attenuate the gamma emissions."

Development of Small Neutron Generators

Iran's nuclear weapon design in the Amad Plan used a D-D reaction which occurs in a uranium metal deuteride pellet under the effects of intense heat and compression to produce neutrons to initiate the chain reaction, to occur in a uranium metal deuteride pellet. The effects of porosity on the neutron yield of the UD3 composite are a very important parameter that may have been studied during the implosion tests conducted years earlier at Taleghan 1. Any post-Amad direct work on this type of internal D-D neutron initiator was slated to be done in secret, but different aspects were being contracted out to universities and research centers.[30]

The use of these types of neutron initiators was previously classified by the United States.[31]

The titanium deuteride mentioned in those studies may have been for a small neutron generator tube similar to what Abbasi Davani reported on openly in later years. Research done at Mound Laboratory Miamisburg (MLM) in the United States has been declassified, and a number of different metal hydrides have been reported on for use in internal nuclear device neutron generators. The United States and other countries tested these neutron sources in a number of actual nuclear tests.[32]

Moreover, post-Amad nuclear weapons work reportedly included work on pulsed neutron generators, which in nuclear weapons are placed outside the nuclear core.[33] A pulsed neutron generator could be an alternative to a uranium deuteride pellet for a crude nuclear device or one slated for underground testing, if problems develop in the use of the uranium deuteride initiator. It could also be used in other alternative nuclear weapon designs.

Multiple recent studies simulating D-D or D-T neutron generators were found in the open-source Iranian scientific literature.

Most notably, two studies, dating 2020 and 2021, continue the development of a high yield compact neutron generator using D-T or D-D. The "compact" device is a key component, as the neutron generator needs to be small enough to fit in a nuclear device.[34]

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30 *Iran's Perilous Pursuit of Nuclear Weapons.*

31 The United States has declassified the following facts regarding TN initiator experiments:
1. That a thermonuclear initiator is an initiator that produces neutrons by TN reactions
2. That the United States has explored initiators that produce neutrons with TN reactions
3. That the United States explored TN initiators.

32 Mark Gorwitz, unpublished report.

33 *Iran's Perilous Pursuit of Nuclear Weapons.*

34 H. Jarahi, T. A. Chiniforoush, and Y. Kasesaz, "MCNP Dose evaluation around D-D and D-T neutron generators and shielding design," *Journal of Instrumentation*, vol. 16, no. 10, p. P10001, Oct. 2021, doi: 10.1088/1748-0221/16/10/p10001; H. Jarahi and Y. Kasesaz, "Estimation of neutron effective dose from DD and DT neutron generators and the design of appropriate shield for standing user," *Journal of Radiation Safety and Measurement*, vol. 9, no. 4, pp. 33-42, 2020.

A 2022 paper looks further at the development of the target inside a neutron generator, i.e. Tritium or Deuterium targets. Relevant in a nuclear weapons context are the yield and the lifespan of the neutron generator, both of which were evaluated in these recent simulations. The paper evaluated important parameters of the target, such as the material and "thickness of the layers and substrates suitable for use as solid targets for industrial neutron generators, using SRIM-code simulations. Then using the simulation results, samples of the target were constructed by the sputtering coating method."[35]

An undated paper, but written by the same author and likely from a similar timeframe, gives further details regarding the design and simulation of a small D-D neutron generator. The paper states, "The target assembly including solid deuterium target sheet, target cooling system and high voltage feedthrough suitable for the neutron production in the compact D-D neutron generators was designed and constructed. The deuterium targets were constructed by using the sputtering coating method after determining the optimum thickness of the layer and substrate using SRIM-code simulations […] Choosing an optimum thickness of target is very significant to access the suitable lifetime and maximum neutron yield. Moreover, the efficiency of neutron production depends mainly on the target capacity to retain the deuterium and tritium ions and also on the stopping power of the targets…The widely (*sic*) research on neutron generator targets illustrate that some materials such as scandium and titanium layers on high thermal conductivity substrate like copper and molybdenum can forms suitable targets for neutron production from the D–T reactions."[36]

These experiments can be useful in designing and simulating a small, long-lasting neutron generator source suitable for use in a nuclear weapon.

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[35] A. Kargaryan, M. Ghapanvari, M. Sedaghat, A. Aslezaeem, and A. Bagheri, "Design and construction of a solid target with a cooling system to investigate the surface fusion phenomenon," *Journal of Nuclear Science and Technology*, vol. 101, no. 4, pp. 113-123, 2022.

[36] A. Kargaryan and M. Ghapanvari, "Design and construction of deuterium targets with cooling system and high-voltage feedthrough for compact D-D neutron generators." No publication or date is given on the pdf version of this report.

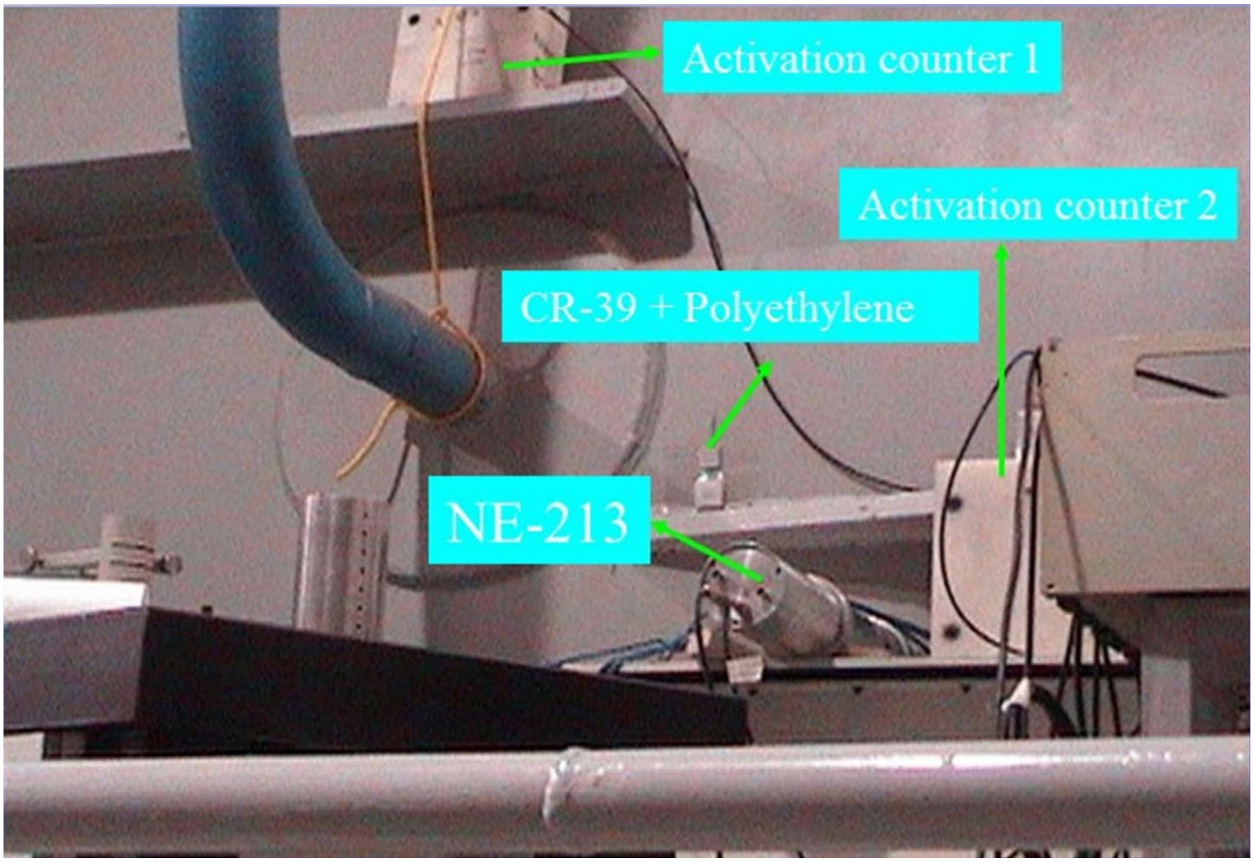

Figure 5. A NE-213 liquid-scintillator detector in an image of a portion of the Parchin high explosive chamber. Image is from the Nuclear Archives.

Tritium Breeding

In a 2016 paper, an Iranian researcher used MCNP codes to examine the possibility of producing tritium by irradiating enriched lithium 6 targets in the Tehran research reactor. Tritium production is relevant to nuclear weapons, because it could be used in a neutron initiator and thermonuclear weapons, although there is currently no evidence, such as in the Nuclear Archive, that Iran has been or is working on thermonuclear weapons.

Iran has conducted research on the separation of lithium via the amalgam method and is believed to have developed and operated a pilot plant for this at Sharif University.[37]

An extract from the 2016 paper reads, "Neutron flux in the eight irradiation boxes of the 5 MW Tehran low power research reactor computes by MCNP Monte Carlo N-Particle transport code. The lithium orthosilicate, an interesting material in fusion engineering, encapsulated by quartz cylindrical containers positioned in the irradiation boxes to produce tritium. According to the weight of the tritium produced in the Tehran research reactor in comparison with reference

[37] Mark Gorwitz, "Lithium 6 report," unpublished, personal communication.

reactor, this type of low power reactor can be used as a source of external tritium supplier in the fusion research facility [...] MCNP code had been verified for tritium production evaluation procedure in fusion engineering. Therefore, Tehran research reactor (TRR), a fission research reactor, modeled using the MCNP code which the lithium orthosilicate targets positioned in the irradiation boxes. The number of neutrons calculated in the empty irradiation boxes to find the irradiation box with highest neutron flux. Moreover, the number of neutrons calculated in the irradiation boxes which containing quartz tubes. Finally, the mass and density of the hydrogen-3 can be calculated analytically in the irradiation boxes."[38]

Iranian researchers have also looked at the production of tritium from a lithium blanket in a tokamak fusion reactor. An advanced breeding concept using lithium orthosilicate in the form of pebble beds was simulated. The 2019 paper written by researchers at Amirkabir University reads, "With the MCNPX code, the efficiency of this proposed model for the production and self-sufficiency of tritium was investigated."[39]

Hydrodynamic Codes

MULTI Family of Codes and Fusion Related Research

In a thermonuclear weapon, fusion happens through irradiating a fusion capsule by X-ray typically containing deuterium and tritium. A process similar to both direct and indirect inertial confinement fusion (ICF). The MULTI family of codes can be used to simulate their targets. During the indirect drive process, high energy laser beams or heavy ions enter a small gold or uranium hohlraum producing x-rays which then compress the fusion capsule.[40] These capsule implosion experiments are designed by researchers from the current nuclear weapons powers to model processes that occur in the implosion (compression) of a secondary component of a thermonuclear weapon. The indirect drive process can be used to model the implosion of a fusion capsule in a nuclear weapon.

Researching the open literature, a number of articles and conference papers using the MULTI family of codes were found during the last three years. The MULTI system of codes are an openly available numerical tool used to simulate Inertial Fusion Energy microcapsules.[41] In recent years, Iranian physicists have published a series of scientific journal articles describing indirect drive target physics and target design. These studies were conducted by Babak

[38] K. Hadad, M. Jabbari, Z. Tabadar, and M. Hashemi-Tilehnoee, "Producing Hydrogen-3 by irradiating lithium orthosilicate targets in a fission research reactor," *International Journal of Hydrogen Energy*, vol. 41, no. 17, pp. 7181-7184, 2016.
[39] H. Sadeghi and M. Habibi, "Design and simulation of a blanket module for TOKAMAK reactors," *Modern Physics Letters A*, vol. 34, no. 13, p. 1950103, 2019.
[40] A. Schaper, "Arms Control at the Stage of Research and Development? – The Case of Inertial Confinement Fusion," *Science and Global Security*, vol. 2, pp. 279-299, 1991.
[41] R. Ramis and J. Meyer-ter-Vehn, "MULTI-IFE – A one-dimensional computer code for Inertial Fusion Energy (IFE) target simulation," *Computer Physics Communications*, vol. 203, pp. 226-237, 2016.

Khanbabaei and his co-authors mainly at the Department of Physics at the University of Damghan.[42]

Most of the studies found looked at indirect-drive targets using laser beams, although research has also been published on direct-drive fusion. In direct-drive fusion, the target is illuminated symmetrically and uniformly by either lasers or heavy ions.

One recent example that used heavy ions for direct-drive fusion is a paper from 2024. An excerpt reads: “Researchers have shown interest in direct-drive heavy ion beams due to their high efficiency in accelerating particles. To ensure the consistent operation of fusion reactors, it is essential to achieve robustness in target implosion. As a proposed solution, this paper investigates the impact of beam radius variation and wobbling frequency on target gain in heavy ion beam illumination. The study specifically examines the effects of beam radius variation and wobbling frequency on target gain.”[43]

A facility at the University of Isfahan’s Department of Physics houses an inertial confinement fusion device which has been used for fusion related experiments. A recent paper from one of the researchers at the facility reads: “Our goals in this research are firstly to find suitable materials for neutron and gamma shielding for IECF [Inertial electrostatically confinement fusion] device of University of Isfahan, and secondly to simulate the best geometry for shielding and doing dosimetry calculations to guarantee the safety of different users’ workplace with

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[42] S. M. Hosseini and B. Khanbabaei, “Study of ignition and burn dynamics of inertial fusion target with diamond ablator using MULTI-IFE hydrodynamic code,” *Journal of Nuclear Science, Engineering and Technology*, vol. 43, no. 10, pp. 10-18, 2022.
M. Naserian and B. Khanbabaei, “Study of the double-layer high-density carbon-polystyrene ablator in the ignition of inertial fusion targets,” *Journal of Nuclear Science, Engineering and Technology*, vol. 44, no. 2, pp. 116-126, 2023.
B. Khanbabaei, "Enhancing inertial confinement fusion with doped beryllium ablator layer in indirect drive scheme," *Radiation Physics and Engineering*, vol. 4, no. 4, pp. 35-42, 2023, doi: 10.22034/rpe.2023.395904.1133.
M. Azizi and B. Khanbabaei, “Study of antiprotons as drivers in inertial confinement fusion by fast ignition method,” *Physica Scripta*, vol. 98, no. 9, p. 095609, Aug. 2023, doi: 10.1088/1402-4896/acf011.
B. Khanbabaei and A. Naghidokht, “Enhancing ICF Target Design: The Impact of Gold Particles as Pusher on Ignition and Burn,” *Iranian Journal of Science*, vol. 48, pp. 1019-1029, Jun. 2024, doi: 10.1007/s40995-024-01645-5.
B. Kaleji, B. Khanbabaei, and M. Kasayian, “An Investigation of Effective Parameters in Deuterium-Tritium Fuel Gains in Shock Ignition Method Driven by Laser Beams,” *Karafan Quarterly Scientific Journal*, vol. 18, pp. 201–211, Aug. 2021, doi: 10.48301/kssa.2021.256945.1272.
M. Nazirzadeh, B. Khanbabaei, and H. Alborznia, “Study of the effect of Au impurity on the ignition conditions of DT fuel in fusion plasma using the inertial confinement method,” *Journal of Nuclear Science, Engineering and Technology (JONSAT)*, vol. 44, no. 4, pp. 148-154, 2023, doi: 10.24200/nst.2022.1214.1788.
S. Ghasemi, S. Faghih, and B. Khanbabaei, “The effect of electron characteristics on the optimum transport into the dense pre-plasma for fast-shock ignition concept,” *Journal of Nuclear Science, Engineering and Technology (JONSAT)*, vol. 41, no. 1, pp. 60-73, 2020, doi: 10.24200/nst.2020.1096.
[43] A. Naghidokht and B. Khanbabaei, “Effects of beam radius and wobbling frequency on the uniformity of target implosion in direct-drive heavy ion fusion approach,” *Indian Journal of Physics*, vol. 98, no. 1, pp. 327–337, Jun. 2023, doi: 10.1007/s12648-023-02827-4.

MCNPX code, and finally to prepare the conditions for setting up and using this device."[44] Modeling of the IECF in that paper was done for the 3He-3He interactions. Neutrons have been modeled as a result of nuclear fusion reactions such as D-T.

Opacity Calculations

Opacities control the transport of radiative energy in nuclear weapons and affect many important aspects of weapons performance. Opacity models are complex and time consuming, requiring detailed knowledge of atomic structure, level populations, spectral-line shapes, and plasma interactions.[45] Determining the radiative opacity of uranium plasma is an extremely complex process which needs large computing capacity.

Because there is less unclassified information about this aspect of nuclear weapons development, Iran would need to do a large number of calculations, making work with other materials also important. Iran would also be motivated to seek out interaction with the foreign fusion community. In a 2017 paper, researchers from the University of Mazandaran wrote in a paper, "Opacity is dependent on the radiation temperature, material temperature, and density of the material […] The purpose of this work is to obtain a more detailed structure of opacity in regards with broadening effects […] Calculations were done for the element silicon […] Thus, the success of these capsule designs depends on accurate knowledge of the dopant opacity in the temperature range, at a variety of densities."[46]

Shock Wave Codes

PAM Software. In researching the open literature, one paper dating to 2023 was found in which an Iranian scientist used the PAM software in collaboration with other researchers from a Canadian University. There is concern that the PAM family of software can be used to model impact studies in the design of nuclear weapon components, such as simulating the collision of the various layers of a nuclear implosion weapon. The study is titled, "An advancement in truck-tire–road interaction using the finite element analysis."[47]

Demonstrating the dual-use potential of the software, the IAEA in their February 22, 2008 report briefly reported questioning Iran about its use of PAM "shock" software.[48]

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[44] S. A. Ghorashi and M. Mahdavi, "Opacity structure of glass ablator in ICF target design," *Journal of Fusion Energy*, vol. 36, pp. 80-86, 2017.
[45] T. S. Perry and B. H. Wilde, "NIF System-Design Requirements for Nuclear-Weapons Physics Experiments," UCRL-ID-120738, 1995.
[46] S. A. Ghorashi and M. Mahdavi, "Opacity structure of glass ablator in ICF target design," *Journal of Fusion Energy*, vol. 36, pp. 80-86, 2017.
[47] H. Fathi, M. Khosravi, Z. El-Sayegh, and M. El-Gindy, "An Advancement in Truck-Tire–Road Interaction Using the Finite Element Analysis," *Mathematics*, vol. 11, no. 11, p. 2462, May 2023, doi: 10.3390/math11112462.
[48] Report by the Director General, "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions 1737 (2006) and 1747 (2007) in the Islamic Republic of Iran," February 22, 2008.

LS-DYNA Code. Numerous papers using the LS-DYNA code conducted in recent years were found in the open literature. Just like the PAM software, there is concern that this code can be used to model impact studies and as such allows for the study of explosively-propelled liners.[49]

Further, there are more recent papers using LS-DYNA.[50] Of note, some were co-authored by Gholamhossein Liaghat, at Tarbiat Modares University, who co-authored papers with scientists at the Islamic Revolutionary Guard Corps (IRGC) controlled Malek Ashtar University. He is a recognized researcher in the armor and ballistic impact areas.

AUTODYN. Another simulation code being used is AUTODYN. It is different code but of interest in simulating explosions. Recently, researchers primarily affiliated with Imam Hussein University and Malek Ashtar University used AUTODYN to simulate explosions with high explosive materials.[51]

A deformation experiment on metal sheets by accelerating a polyester sheet from a planar shockwave is illustrated in the article "Plastic Deformation of Multi-Layer Metallic Sheets of Similar and Dissimilar Metals with Constant Surface Density under Repeated Impulsive

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[49] LS-DYNA was developed by LLNL and is used to model hypervelocity impacts in areas such as armor, and the 3D version has been used in modeling nuclear weapon reentry body (Mk4) impact research.

[50] A. Manouchehri, G. Liaghat, and H. Ahmadi, "Investigating on the energy absorption of PA/GF6 thermoplastic composite produced by hot pressing method under low-velocity impact test," *Journal of Solid and Fluid Mechanics*, vol. 13, no. 1, pp. 1-13, 2023, doi: 10.22044/jsfm.2023.12675.3693.
J. Nikzare, G. Liaghat, and H. Ahmadi, "Experimental and numerical analysis of the effect of using perforated plates in front of the target against ballistic impact," *Iranian Journal of Manufacturing Engineering*, vol. 9, no. 7, pp. 9-21, 2022, doi: 10.22034/ijme.2022.163348.
N. Zahedan, H. Ahmadi, and G. Liaghat, "Numerical study of composite sandwich panels with compound cellular core of auxetic lattice structure and foam under low velocity impact load," in *17th National Conference and 6th International Conference on Manufacturing Engineering*, Tehran, 2020.
N. Zahedan, H. Ahmadi, and G. Liaghat, "Experimental and Numerical Investigation on the Flexural Behavior of Composite-Reinforced Top-Hat Shape Beam," 2021.
M. Haghgoo, H. Babaei, and T. M. Mostofi, "Numerical simulation of the influence of confined multi-point ignited H2–O2 mixture on the propagation of shock waves towards a deformable plate," *International Journal of Hydrogen Energy*, vol. 47, no. 63, pp. 27080–27095, Jul. 2022, doi: 10.1016/j.ijhydene.2022.06.051.
H. Shanazari, G. Liaghat, S. Feli, and H. Hadavinia, "Analytical and experimental study of high-velocity impact on ceramic/nanocomposite targets," *Journal of Composite Materials*, vol. 51, no. 27, pp. 3743–3756, Feb. 2017, doi: 10.1177/0021998317692658.

[51] See, for example, B. Yasemi, H. Soleimanimehr, H. Khodarahmi, S. Rahmati, and N. Khazraiyan, "Numerical Analysis of the Crater Diameter and Penetration Depth of the Target Due to the Impact of Short-Rod Segmented Projectiles at High Velocity," *Advanced Design and Manufacturing Technology*, vol. 15, no. 3, pp. 39–46, Sep. 2022. Other university researchers that were notably active in this field include Hossein Mehmannavaz, Sadegh Rahmati, and Mohammad Najafi from the Islamic Azad University. See, M. H. Navaz, G. H. Liaghat, S. Rahmati, M. Najafi, and H. Fazeli, "Numerical analysis of shaped charge bimetallic liners effects on diameter and depth of penetration into steel targets," *Scientific Journal of Aerospace Mechanics*, vol. 15, no. 30, pp. 93-105, 2019.

Loading."[52] Experimental data were compared to results from simulations, which likely were done using AUTODYN or a similar code, but it is not specified in the paper. Of note, the experiments used aluminum and steel sheets, but if they used uranium, important data on uranium deformation could be collected in such an experimental setup.

Modeling Explosive Welding

The AUTODYN code has been used to model explosive welding. Recent studies show that Iran is using the code for this purpose. Examples of studies were presented at two recent conferences in Iran. Explosive welding is of concern, because it provides ample experience with, and opportunities to simulate, high explosives and metal acceleration.

At least six papers were identified simulating explosive welding of metals, four of which are cited below. For example, two papers by Malek Ashtar University researchers on explosive welding of stainless steel to aluminum pipes used AUTODYN simulation.[53]

The author of at least two relevant, recent papers is Gholamhossein Liaghat. Notably, one of the papers indicated that Iran was using a simulation involving metal acceleration at high velocities.[54] Another paper calculated parameters of relevance for a levitated nuclear weapon design, such as standoff distance.[55]

In addition, there are other relevant experimental studies on explosive welding that are not discussed here, since we are focusing on the use of computer modeling.[56]

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[52] M. Zia Shamami, H. Babaei, T. Mirzababaei Mostofi, and H. Khodarahmi, "Plastic Deformation of Multi-Layer Metallic Sheets of Similar and Dissimilar Metals with Constant Surface Density under Repeated Impulsive Loading," *Aerospace Mechanics Journal*, vol. 18, no. 1, pp. 137-159, 2022.

[53] M. Ayaz, M. Khandaei, and Y. Vahidshad, "Investigation of sheet thickness in the electromagnetic welding of aluminum-stainless steel," *Materialwissenschaft und Werkstofftechnik*, vol. 53, no. 6, pp. 732–749, Jun. 2022, doi: 10.1002/mawe.202100278.

H. Arabi, "Investigation of explosive welding of 304 stainless steel pipe to 5083 aluminum pipe using simulation in AUTODYN finite element software," in *5th International Conference on Welding and Non-Destructive Testing & 23rd National Conference on Welding & Inspection & 12th National Conference on NDT*, Isfahan, 2022.

[54] M. Amani, G. Liaghat, and A. Firoozi Lotf Abadi, "Numerical optimization of parameters affecting the explosive welding process," in *9th International Conference & Exhibition on Materials Science & Metallurgical Engineering (iMat2020)*, 2020.

[55] M. Amani, G. Liaghat, and A. Firoozi Lotf Abadi, "Numerical study of the explosive welding process of dissimilar sheets," in *3rd International Conference on Mechanical Engineering, Materials and Metallurgy*, 2020.

[56] I. Mohammadi and S. A. A. Mosavi, "Investigation of the Interface of Dissimilar Joining of Copper and St52 Steel Using Explosive Welding Process," in *11th International Conference on Material Engineering and Metallurgy (iMat2022)*, 2022.

H. Nikbakht, M. Khanzadeh, and H. Bakhtiari, "Investigation of the effect of explosive welding variables on the corrosion behavior of the joint of two explosive layers of 5000 series copper-copper sheets," *Journal of Welding Science and Technology of Iran (JWSTI)*, vol. 7, no. 2, pp. 13-24, 2022; G. Khalaj and A. Fadaei, "Effect of post weld heat treatment on the structure and mechanical properties of explosive welding of austenitic steel 321 - aluminum 1050 - aluminum 5083," Journal of Welding Science and Technology of Iran (JWSTI), vol. 9, no. 1, pp. 101-112, 2023; M. Rastgoo, Z. S. Seyed Raoufi, and M. Ghanbari Haghighi, "Effect of rolling process on the copper-aluminum

Equation of state (EOS)

The Iranian scientific open literature was searched for articles on equation of state experiments and codes involving metals of interest, particularly involving high temperatures and pressures relevant to nuclear weapons. Many papers on equation of state simulations were found, indicating that Iran has gained ample experience with the process, but not many of those studies involved metals of interest.

One 2019 journal article co-authored by an Iranian scientist (Hallajisany) at the K. N. Toosi University of Technology (KNTU), entitled "Numerical and theoretical determination of various materials Hugoniot relations based on the equation of state in high-temperature shock loading," makes a specific reference to nuclear explosions and to the "various investigations" of materials at high temperature and pressure that were conducted. The authors stated that, "One of the important objects of a material behavior is the shock loading response. The simplest equation of the shock loading is the shock wave velocity-particle relation. There are different methods such as incident plate test, techniques based on high explosives, simple gas gun, multistage gas gun loading, and nuclear explosions to obtain this relation for materials […] So far, various investigations have been performed to recognize the shock behavior of materials at high temperatures."[57]

The calculations were not made for uranium, but for various other metals such as aluminum, gold, copper, tantalum, and tungsten. The journal article does reference experiments carried out at Los Alamos that include uranium put under pressure of up to two megabars and Russian measurements up to even higher pressure levels.

As indicated in the paper's quote, EOS experiments can be conducted using gas guns and high explosives. At least three Iranian universities have suitable light gas guns: Imam Hussein University, K. N. Toosi University, and Bu-Ali Sina University. In the past, Iran also used a gas gun at the Nour-Abad site; it is unknown where that gas gun is located today.[58]

One paper written in 2019, titled "Performance of a Two-stages Gas Gun: Experimental, Analytical and Numerical Analysis," uses the deployment of a gas gun at Bu-Ali Sina University to characterize materials at high rates of deformation. Numerical simulations were done using the AUTODYN commercial code. Predicted projectile velocity for any state of pump and chamber pressure were calculated.[59]

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interface of explosive welding," in *5th International Conference on Welding and Non Destructive Testing & 23rd National Conference on Welding & Inspection & 12th National Conference on NDT*, Isfahan, 2022.

[57] M. Hallajisany, J. Zamani, and J. A. Vitoria, "Numerical and theoretical determination of various materials Hugoniot relations based on the equation of state in high-temperature shock loading," *High Pressure Research*, vol. 39, no. 4, pp. 666-690, 2019.

[58] *Iran's Perilous Pursuit of Nuclear Weapons*.

[59] G. H. Majzoobi, M. H. Rahmati, and M. Kashfi, "Performance of a two-stage gas gun: Experimental, analytical and numerical analysis," International Journal of Engineering, vol. 32, no. 5, pp. 759-768, 2019.

Imam Hussein University researchers conducted impact experiments for the University of Tehran. These experiments looked at shock wave damping in aluminum sandwich panels.[60]

For experimental data collection, Iran may be developing additional methods for equation of state experiments, avoiding the use of high explosives and opting for laser impact studies such as those developed at Los Alamos and BARC (India) instead.[61] Explosives, gas guns, and lasers all are used to determine different pressure ranges of EOS.

Recent design studies conducted in 2020 simulated the design of a laser that might be suitable for these EOS type of experiments.[62] For example, researchers at Malek Ashtar University simulated the design of a 10-KW solid state slab laser in which two different schemes for optical pumping with high-power laser diodes were investigated.[63] Further, another powerful laser setup, a Nd:YAG end-pumped zigzag multipass slab amplifier, was simulated and may have the power to carry out these types of experiments.[64] Unpublished research done by the Institute revealed a long list of laser equipment that the Lashkar Ab'ad site was trying to import. Whether these laser systems and components were actually imported remains unclear.

Although equation of state (EOS) tables are openly available from both U.S. and Russian sources, Iran will need to verify that data through its own experiments.[65]

Explosive Studies

The BKS Equation of State codes can be used to model explosives performance, initiation, impact, and velocity studies. In a 2024 journal article, researchers at Malek Ashtar University used the code to model Gurney velocity, which is used to measure the velocity of the impact of

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[60] M. Rahmani and A. M. Petrudi, "Experimental and numerical optimization study of shock wave damping in aluminum," *Frattura ed Integrita Strutturale*, vol. 15, no. 55, 2020.
[61] M. Shukla, S. Sawant, A. Agrawal, Y. Kashyap, T. Roy, and A. Sinha, "Laser produced thin metallic planar mini-flyer generation using fiber optic plate," *Laser and Particle Beams*, vol. 31, pp. 289-300, 2013.
R. H. Warnes, D. L. Paisley, and D. L. Tonka, "Hugoniot and spall data from the laser-driven miniflyer," in *American Physical Society Topical Conference*, 1995.
[62] N. S. Mousavi, P. Parvin, and M. Ilchi-Ghazani, "Modeling of a Q-switched master oscillator power amplifier fiber laser and gain saturation properties," *Laser Physics*, vol. 30, no. 8, p. 085101, 2020.
[63] H. Ebadian, M. M. Moslem, and N. Azarpoor, "Design of a high power 10-KW solid-state heat capacity laser and the thermal management," *International Journal of Optics and Photonics*, vol. 17, no. 1, pp. 47-56, 2023.
[64] M. Najafi, M. Shayganmanesh, M. M. Majidof, A. Sepehr, E. Tanhaee, and H. S. Nabavi, "Nd end-pumped zigzag multi-pass slab amplifier optimization: numerical and experimental study regarding the saturation effects," *Optics Express*, vol. 30, no. 10, p. 16184, 2022.
[65] Los Alamos National Laboratory, "SESAME Database," ALDSC, Los Alamos.
P. R. Levashov, K. V. Khishchenko, I. V. Lomonosov, and V. E. Fortov, "Database of shock-wave experiments and experiments available via the Internet," *AIP Conference Proceedings*, vol. 706, no. 1, 2004.

two metals colliding. The main author, Keshavarz, has been involved in the development of codes that are used in designing and predicting properties of energetic materials.[66]

The authors reported that "Organic energetic compounds containing aluminum (OECAl) are hazardous materials, which have extensive applications in industries. For military and commercial high explosives, Gurney velocity is the terminal velocity of explosively-propelled metal liner on the basis of the ratio of the mass of metal to the mass of explosive. A novel approach is introduced to use laser-induced breakdown spectroscopy (LIBS) as a highly energetic laser pulse to atomize and excite samples (a plasma) for assessment of the Gurney velocity of OECAl."[67] Aiding in the diagnostics for these types of experiments are high-speed cameras. The diagnostic equipment is not specified in this paper, so it is possible that the study used a high-speed camera covered by Section T without specifying it.

It is known that Iran acquired high-speed cameras subject to Section T, via documented illicit procurement efforts.[68] However, the researchers and papers encountered in the Institute's survey did not provide details about high-speed cameras, although they did publish pictures showing that they had used them.

Multi-Point Initiation (MPI)

There are multiple computer codes that can be used for the modeling of explosives initiation and performance, such as the DYNA3D, which was developed by Lawrence Livermore National Laboratory (LLNL) and is commercially available. There are many studies using these codes, but not all are relevant to MPI. At least two recent papers were found in the open literature that included mentioning of multi-point initiation to create a shock wave.[69] As such, these codes can be used to simulate the initiation sequence of an implosion device.

Another 2020 paper titled "Numerical Simulation of the Heat Transfer in the Electric Hot Bridgewire Initiator" discussed the development of a mathematical model to "investigate the effective parameters on the electrical initiator performance." An extract from the paper reads, "Comparison of numerical results by the finite difference method and experimental data showed that this model has the ability of the prediction of the ignition time and determine the transient temperature profile in axial and radial direction. The model showed that the

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[66] M. H. Keshavarz, R. Ebadpour, and M. Jafari, "Assessment of the terminal velocity of explosively-propelled metal liner using laser-induced breakdown spectroscopy," *Journal of Energetic Materials*, pp. 1–13, Oct. 2023, doi: 10.1080/07370652.2023.2275214.

[67] "Assessment of the terminal velocity of explosively-propelled metal liner using laser-induced breakdown spectroscopy."

[68] David Albright and Olli Heinonen, "Verifying Section T of the Iran Nuclear Deal: Iranian Military Site Access Essential to JCPOA Section T Verification," *Institute for Science and International Security*, August 31, 2017.

[69] A 2018 journal article looked at the multi-point initiation for an explosively formed penetrator (EFP). The paper examines the effect of multi-point initiation on the formation and penetration of EFPs by using the finite element method and LS-DYNA code. The high explosive (Comp-B) burn was modeled using both the JWL and DYNA3D codes. M. Kozehgaran, H. Khodarahmi, V. Afshari, and R. Kasaee, "Numerical and experimental analysis of multi-point initiation EFP performance," *Journal of Energetic Materials*, vol. 13, no. 1, serial no. 37, pp. 1-14, Spring 2018.

reduction of the contact heat transfer coefficient between the bridgewire and the primer compared to its increase has a greater effect on the heat transfer rate."[70] This refers to the ability of the bridgewire to initiate an explosive charge as part of the initiation sequence. This research is of concern, because it simulates the entire process of the ignition of the chemical explosives in a nuclear weapon.

Main Charge Studies

Other recent papers were found documenting the simulation of the burn of the explosives in order to look at the performance of the explosives, especially the performance of insensitive high explosives, which are used in nuclear weapons.

For example, a 2018 study by Kasaie used the LS-DYNA code to "compare the influence of Octol and PBXN-110 on the performance of a specific shaped charge warhead…PBXN-110 exhibited a weak penetration effect due to its lower density and detonation velocity compared to Octol." Studies with Octol are of interest, as it was a main explosive used in and mass produced for Iran's AMAD program.[71]

Figure 6. A high explosive casting mold from the Nuclear Archives.

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[70] R. Sohrabi and M. Abolghasemi, "Numerical Simulation of the Heat Transfer in the Electric Hot Bridgewire Initiator," Journal of Energetic Materials, vol. 15, no. 2, Serial No. 46, pp. 123-135, Summer 2020.
[71] R. Kasaie, A. Mollaie, and A. Kheyrabadia, "Performance comparison of Octol and PBXN-110 in a shaped charge," Journal of Energetic Materials, vol. 13, no. 2, pp. 105-112, 2018.

Furthermore, a 2020 journal article by Pourandarabi analyzed and then simulated the one-dimensional direct initiation of Comp-B. "The purpose of this article is to develop a one-dimensional computer for the simulation of the direct initiation of energetic materials. The Fortran SIN hydrocode was used for this purpose and the I&G burn model was added to this code. The developed code was used to simulate the direct initiation of Comp-B by sustained shock bursts…In the simulation of the initiation of Comp-B by 3.78 GPa shock, the run distance to detonation was 14.8mm, which the difference between this value and the reported experimental data is 5.7%."[72]

In that paper, experimental data were collected on the planar impact of the Comp-B by a projectile fired from a gas gun. In the set-up of the experiment, the exploding bridgewire was initiated by a spark gap. The multi-point bridgewire was then used to initiate a prime charge.[73] These results were compared to initiation data collected earlier on LX17, PBX9404, and C-4 in the United States, and data from previous experiments on Comp-B conducted in the UK. PBX9404 is known to be an especially insensitive high explosive, and thus is of main interest.

Other Relevant Capabilities

Isotope Production

Multiple papers on isotope production were found, which can be relevant to producing plutonium and tritium for a nuclear weapon, but also relevant for neutron studies, specifically, the development of neutron sources.

Isotope production in a 1GBq D-D dense plasma focus device using Geant4 was simulated. Geant4 collaboration is a toolkit for the simulation of transport of particles through matter and was used to estimate the number of desired radionuclides produced in the target. Deuterons with energy around 1.5 MeV - 2.0 MeV have the highest interaction rate in the target for the production of isotopes such as F-18, N-13, and O-15.[74]

A 2024 article describes the design of a hot cell for the reprocessing of Mo-99 from LEU. The overall size of the hot cell is 3.3 meters x 8.2 meters x 3.8 meters (height), and MCNP6 was used to calculate the radiation dose rate of the irradiated fuel. The holster containing the fuel targets was irradiated in the D6 channel of the Tehran Research Reactor (4 MWth) for six days and then allowed to cool for one day in the reactor pool.[75]

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[72] E. Pourandarabi, S. Soury, and P. Taghavi Eishkooh, "One-Dimensional Simulation of Direct Initiation of Comp-B and Comparison with Experimental Data," *Journal of Energetic Materials*, vol. 14, no. 4, pp. 217-226, 2020.
[73] Section T prohibits the use of multipoint initiation suitable for a nuclear device related system.
[74] F. Tabbakh, S. M. S. Kiai, and M. Pashaei, "Conceptual achievement of 1GBq activity in a plasma focus driven system," *Applied Radiation and Isotopes*, vol. 129, pp. 211-214, 2017.
[75] A. Kiyani, A. B. Samani, R. Pourimani, and S. M. Miremad, "Shielding design and analysis of the hot cell used to produce fission molybdenum-99," *Radiation Physics and Chemistry*, vol. 222, p. 111856, 2024.

MCNPX 2.6 code was used to simulate the reactor core, irradiating beam tubes and radiological shields of the Tehran Research Reactor. The lead author of this study (Hedayat) has written a series of journal articles that evaluate various parameters such as fuel management optimization of the Tehran Research Reactor open pool reactor with rated power of 5 MW.[76]

A study done at the Institute of Nuclear Science and Technology, Plasma and Nuclear Fusion Research School, used the Geant4 code to simulate production of radioisotopes using plasma focus as the neutron source. Geant4 was found to be a reliable Monte Carlo method for simulating the beam-target mechanism and radioisotopes production in plasma focus driven systems, according to the experimental data.[77]

Using a plasma focus source to irradiate a target could also be used for Tritium or Plutonium production if the neutron production rate was high enough and focused on the proper targets.

Fissile Material Production

Fissile material production related simulations are relevant to developing new processes for producing fissile materials including materials such as uranium 233 from the thorium cycle being studied by Iranian scientists, and thus not limited to weaponization, but they can also be relevant for alternative neutron initiator studies.

Iranian scientists have published a conceptual design for a high flux research reactor with a low enriched uranium fuel and low plutonium production. Fuel pins from a WWER reactor fuel pin type similar to that used in the Bushehr nuclear power plant were used in these simulations. Light water was selected as the coolant, while heavy water was used as the moderator.[78]

The reactor was rated at 22 MW, and the total fuel loading in the core was 334.774 kg. Plutonium production at the end of the cycle was estimated to be 0.9487 kg using an initial fuel enrichment of 3.7% uranium.

“In order to perform fast and accurate calculations, neutronic codes (WIMS-D5 and CITATION) and thermal hydraulic code (COBRA-EN) are coupled by a FORTRAN program…This designed

[76] A. Hedayat, J. Emani, and R. Salartash, “Determination of the neutron and gamma dose rates of the irradiating beam tubes of a pool-type research reactor by using Monte Carlo simulation and experimental detectors regarding protection issues,” *International Journal of Advanced Nuclear Reactor Design and Technology*, vol. 3, pp. 27-43, 2021.
[77] F. Tabbakh, S. M. S. Kiai, and M. Pashaei, “Conceptual achievement of 1GBq activity in a Plasma Focus driven system,” *Applied Radiation and Isotopes*, vol. 129, pp. 211–214, Nov. 2017, doi: 10.1016/j.apradiso.2017.08.028.
[78] G. Rahimi, M. R. Nematollahi, K. Hadad, and A. Rabiee, “Conceptual design of a high flux research reactor with low enriched uranium fuel and low plutonium production,” *Nuclear Engineering and Technology*, vol. 52, no. 3, pp. 499-507, 2020.

reactor has a Central Beam Channel located at the center of the core which can be used for irradiation purposes and isotopes production."[79]

A conference presentation from 2023 looks at the Pu production from a heavy water reactor and states, "Westerners know that the type of plutonium in the heart of the reactor will be different based on the time the fuel is kept in the water pit after leaving the heart of the reactor, and despite the clear technical arguments that the plutonium produced in the reactor will not be used for use in atomic weapons."[80]

This Iranian's statement is well known to be false, and likely just a cover story, as many government studies since the 1960s have shown that plutonium with a lower fraction of plutonium 239 can be used in nuclear weapons. The main constraint in a first-generation weapon is that the explosive yield will be lower than the case where the plutonium 239 fraction is maximized.

Supercomputing

All of the computer simulations above are only as good as the computing capabilities. As such, improvements in Iran's supercomputing capabilities are of major importance. While Iran was limited by its computing capabilities in the past, open-source literature indicates that it has made significant progress, despite international export controls and sanctions and Iran's reliance on Western microchips.

For example, an international computer science journal discusses, among the latest developments, a supercomputer designed by Amirkabir University (AUT) researchers, claimed to deliver 1 petaflop of performance. It further claims that Iran is currently developing a new generation computer called Maryam that will be 100 times more powerful than this current generation, called Simorgh.[81]

Further details of the Simorgh supercomputer were given in a 2024 article which stated, "The supercomputer runs at a speed of 0.56 to 1 Petaflops. Over time, this performance is expected to increase to 10 Petaflops. Currently, it comprises 42 racks, which will be expanded to 84 racks in the future."[82]

According to the same source, Textbook.com, "Iran has been a contender in the supercomputer race since 2001. From the 192 GigaFlops supercomputer made by the Aerospace Research

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[79] "Conceptual design of a high flux research reactor with low enriched uranium fuel and low plutonium production."

[80] M. A. Afroozi, "Investigating the increase of plutonium extraction from heavy water reactors," in *2023 8th International Conference on Technology and Energy Management (ICTEM)*, 2023.

[81] T. Trader, "Iran gains HPC capabilities with launch of 'Simorgh' Supercomputer," HPCwire, May 18, 2021. https://www.hpcwire.com/2021/05/18/iran-launches-simorgh-supercomputer.

[82] "Iran's Simorgh Supercomputer - All You Need to Know," Testbook, Jan. 29, 2024. [Online]. Available: https://testbook.com/static-gk/simorgh-supercomputer. [Accessed: Aug. 8, 2024].

Institute to the 860 GigaFlops scale made by the Info-Tech Development Company, Iran has consistently progressed in the field. Now, with the Ptescale Simorgh supercomputer, the country has significantly advanced in becoming a significant soft power."

It is reasonable to conclude that Iran now has supercomputing capabilities comparable or more advanced to what the United States had in the late 1980s. At that time, by way of example, Bruce Weinke (from Los Alamos) estimated that an average of 8,000 hours of supercomputer time are spent on the design of a new nuclear explosive.[83] However, Weinke was referring to advanced nuclear weapons; Iran would likely need far fewer hours for its current levitated nuclear weapon designs. The current generation of Iranian supercomputers has far faster and greater computing power than the U.S. supercomputers from the late 1980s to which Weinke was referring.

[83] B. R. Weinke and B. L. Buzbee, "Supercomputing Applications," Physics Teacher, 1989.