THE VULNERABILITY OF IRAN'S NUCLEAR FACILITIES TO DRONE STRIKES

BY DR BAHRAM GHIASSEE, ASSOCIATE FELLOW

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Executive Summary

Unmanned aerial vehicles (UAVs), commonly known as drones, pose a significant threat to nuclear facilities across the globe. This report assesses the vulnerability of Iran's nuclear facilities to drone strikes, and the risk posed to each facility by their deployment.

As part of its advanced nuclear programme, Iran has acquired a number of nuclear-related facilities which are regarded as highly proliferation-sensitive, including uranium enrichment plants and heavy water reactors.

Iran's activities constitute a threat to the stability and security of the Middle East and North Africa (MENA), and these proliferation concerns, coupled with Iran's advanced missile programme, have provided the impetus for concerned States to mount cyberattacks, sabotage operations and drone strikes on Iran's nuclear-related facilities.

In this light, Iran's above-ground facilities represent a strategic weak point. They are highly vulnerable to aerial strikes, as are ancillary facilities (utilities) providing cooling water, gas, electricity, air and other critical services.

As elaborated in the report, should current diplomatic efforts fail in reviving the 'Iran Nuclear Accord' – formally known as the 'Joint Comprehensive Plan of Action' (JCPOA) – it is highly likely that attacks on Iran's nuclear facilities will escalate. Sporadic acts of sabotage may still occur, even if the JCPOA is successfully revived.

This escalation would not be without risk. As recent events in the Persian Gulf and Arabian Sea have demonstrated, Iran is capable of retaliation. Critical infrastructure in Bahrain, Saudi Arabia and the United Arab Emirates (UAE), including UAE's nuclear reactors, could be deemed suitable targets for retaliation, as could Israeli facilities through Iranian proxies in Iraq, Lebanon and Syria.

A preferable outcome would be for the International Atomic Energy Agency (IAEA) to resume its independent monitoring and verification activities in Iran, providing credible assurances to the international community that Iran's nuclear programme has no military dimensions.

Equally, concerted diplomatic efforts, at regional and international levels, need to succeed in averting a nuclear arms race in the MENA region, and to restore peace, stability and security in an already turbulent region. Diplomacy must prevail.

Glossary

AEOI	Atomic Energy Organisation of Iran
CENTO	Central Treaty Organization
CNI	Critical National Infrastructure
CSA	Comprehensive Safeguards Agreement between IAEA and Iran
CSIS	Center for Strategic & International Studies
HEU	Highly Enriched Uranium; used in submarines and nuclear weapons
IAEA	International Atomic Energy Agency
ISR	Intelligence, Surveillance and Reconnaissance
JCPOA	Iran Nuclear Accord, or the Joint Comprehensive Plan of Action
LEU	Low Enriched Uranium; used as fuel in nuclear reactors
MENA	Middle East and North Africa
NATO	North Atlantic Treaty Organization
NPP	Nuclear Power Plant
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NTI	Nuclear Threat Initiative
Pu	Plutonium; used in 'Fast Reactors' and nuclear weapons
PWR	Pressurised Light Water Reactor
U-235	Uranium-235 comprises 0.7% of natura uranium
U-238	Uranium-238 comprises 99.3% of natura uranium
UAE	United Arab Emirates
UAV	Unmanned Aerial Vehicle, commonly known as a drone
UF6	Uranium Hexafluoride; used as feedstock in uranium enrichment plants
UMV	Unmanned Marine Vehicle, or a marine drone
UNSC	United Nations Security Council
UO_2	Uranium Dioxide; used in reactor fuel rods
WNA	World Nuclear Association

Chapter 1: Introduction

Unmanned aerial vehicles (UAVs), commonly known as 'drones', pose a significant threat to nuclear facilities and other critical national infrastructure [1] across the globe. This report provides an assessment of the vulnerability of nuclear facilities in the Islamic Republic of Iran (Iran) to drone strikes, and the risk posed to these facilities.

Iran has acquired the full spectrum of facilities associated with the nuclear fuel cycle, including proliferation-sensitive uranium enrichment technology and heavy water nuclear reactors. The dual-use nature of nuclear technology is well established, and proliferation concerns have provided the impetus for concerned States to mount sabotage attacks on Iran's critical infrastructure, including its nuclear facilities.

In June 2021, a drone attack on the centrifuge component manufacturing workshop at the TESA Karaj complex near Tehran caused extensive damage, which Iran attributed to Israel. [2] [3] In 2010, cyberattacks on the Natanz uranium enrichment facility resulted in significant disruption and damage to the 6000 centrifuges operating at the time. These cyberattacks and the Stuxnet malware used were attributed to Israel and the US. [4]

Since clandestinely acquiring centrifuge technology in 1987, [5] Iran has developed the capability to produce highly enriched uranium (HEU), [6] with dual-use applications in civilian and nuclear weapons programmes. These nuclear capabilities, coupled with Iran's advanced missile programme, have alarmed countries in the Middle East and North Africa (MENA) region and beyond. Saudi Arabia has declared that it will consider embarking on a nuclear weapons programme if the international community allows Iran to do so, while successive Israeli administrations [7] have declared that military action would be an option in meeting the policy objective of preventing any hostile State in the MENA region from acquiring nuclear weapons. [8] In similar vein, Washington has repeatedly stated as a matter of policy that it will not allow Iran to acquire nuclear weapons. It is noteworthy that amid the recent tensions in the Persian Gulf and the Arabian Sea, the US Navy is establishing a new drone task force in Bahrain, with aerial, surface and subsurface capabilities. [9]

Other actors – specifically the European Union (EU), France, Germany and the UK – have primarily addressed their concerns through multilateral fora, including the United Nations

1 Zachary Kallenborn, "A cascading catastrophe: The drone threat to critical infrastructure", *Bulletin of the Atomic Scientists*, 26 November 2021, https://thebulletin.org/2021/11/a-cascading-catastrophe-the-drone-threat-to-critical-infrastructure/?utm_source=Newsletter&utm_medium=Email&utm_campaign=MondayNewsletter11292021&utm_content=DisruptiveTech_DroneThreatsCriticalInfrastructure_11292021.

2 David Rose, "Drone attack on suspected Iranian nuclear production plant", *The Times*, 24 June 2021, https://www.thetimes.co.uk/article/drone-attack-on-suspected-iranian-nuclear-production-plant-3vvg52hbf.

3 ToI Staff, "Satellite photos said to show damage from attack on Iran centrifuge site", *The Times of Israel*, 4 July 2021, https://www.timesofisrael.com/satellite-photos-said-to-show-damage-from-attack-on-iran-centrifuge-site/amp/.

4 Ralph Langner, "Stuxnet's Secret Twin – The real program to sabotage Iran's nuclear facilities was far more sophisticated than anyone realized", *Foreign Policy (FP)*, 19 November 2013, https://foreignpolicy.com/2013/11/19/stuxnets-secret-twin/.

5 Paul K. Kerr, "Iran's Nuclear Program: Status", Congressional Research Service Report (20 December 2019): 82, https://crsreports.congress.gov/product/pdf/RL/RL34544.

6 "Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015)", IAEA, *GOV/2021/28* (31 May 2021): 5, https://www.iaea.org/sites/default/files/21/06/gov2021-28.pdf.

7 Judah Ari Gross, "As Bennett meets Biden, IDF ramps up plans for strike on Iran's nuke program'', *The Times of Israel*, 24 August 2021, https://www.timesofisrael.com/as-bennett-meets-biden-idf-ramps-up-plans-for-strike-on-irans-nuke-program/?utm_source=The+Weekend+Edition&utm_campaign=weekend-edition-2021-08-29&utm_medium=email.

8 Trevor Hunnicutt and Matt Spetalnick, "Biden to Israeli PM: U.S. has options if Iran nuclear diplomacy fails'', *Reuters*, 28 August 2021, https://www.reuters.com/world/biden-due-talk-iran-with-israels-bennett-after-afghan-bombing-delay-2021-08-27/.

9 Jon Gambrell, "US Navy launches Mideast drone task force amid Iran tensions'', *Associated Press (AP)*, 8 September 2021, https://apnews.com/article/middle-east-iran-dubai-united-arab-emirates-bahrain-fe5517a7979e037ae6e266b885cc7719.

Security Council (UNSC), striving towards a diplomatic resolution to the potential threat to stability and security in the region.

This report assesses the potential vulnerability of Iran's nuclear facilities to drone strikes, and the extent to which such action could damage the Iranian nuclear programme. It also assesses the vulnerability of 'ancillary facilities' (utilities). Disruption to the normal functioning of facilities providing process water, cooling water, gas, electricity or other critical services to nuclear facilities could lead to extensive damage. It is worth noting that it was disruption to external electricity and cooling water supplies to the Fukushima nuclear power plant (NPP) in March 2011 that resulted in its destruction.

The methodology adopted in the preparation of this report was based on a detailed review of the open literature in the public domain, encompassing the following: (i) drones, and their destructive capabilities; (ii) cases of drone attacks on critical infrastructure, including nuclear facilities; and (iii) Iran's nuclear fuel cycle facilities under IAEA safeguards. A critical assessment of the vulnerabilities, threats and risks posed to nuclear facilities and their ancillary facilities (utilities) was then carried out.

This report is structured into five chapters. Following this introduction, Chapter 2 reviews the global threat posed by drones, and examines recent cases of drone attacks by State and non-State actors on critical infrastructure, including nuclear facilities. Chapter 3 provides a detailed review of Iran's declared nuclear facilities under IAEA safeguards. Chapter 4 assesses the vulnerability of each nuclear or ancillary facility to drone attacks, and the degree of risk posed to each facility. Chapter 5 presents the concluding remarks and recommendations. Finally, Appendix 1 provides a list of Iran's nuclear facilities.

Chapter 2. Threat to Nuclear Facilities and Other Critical Infrastructure

Critical national infrastructure (CNI)[10] consists of systems viewed as being vital to the effective functioning of a given country, and which accordingly require the highest level of protection against physical and electronic threats. Commercial drones have the potential to carry out operations on CNI for espionage and sabotage purposes. The increasing frequency of incidents involving drones is indicative of the significant threat posed to CNI, including nuclear facilities, across the globe.

Military drones have been in operation for a few decades conducting intelligence, surveillance and reconnaissance (ISR), and also combat missions. However, the proliferation of recreational and commercial aerial drones in recent years is posing a major threat to CNI. Equally, the developments in hardware, navigation systems, image processing and target recognition, and the cost reductions, have rendered commercial drones suitable for use for malicious purposes by State and non-State actors.[11][12]

Moreover, market availability, coupled with enhanced flight duration, increased payload capacity and ease of weaponisation, have allowed both State and non-State actors to exploit the potentially disruptive capabilities of commercial drones.[13][14] Commercial off-the-shelf drones may be easily loaded with explosives, and also programmed to fly to a particular point, thus becoming highly effective in disrupting and damaging critical infrastructure. Due to their small size and low altitude of flight, they are difficult to detect with radars, and equally difficult to destroy with air defence systems.[15] Commercial drones may also be anonymously procured, rendering the identification of the operator and the owner difficult, if not impossible, and the launch site difficult to establish.[16]

Small commercial drones, or drone parts, may be smuggled into a given country, weaponised by proxy groups or agents, and positioned close to their targets for malicious purposes. These tactics significantly reduce the possibility of identifying the drone, the owner, the operator and the launch site, and were deployed in a recent attack on the centrifuge component manufacturing workshop at the TESA Karaj complex near Tehran. Iran attributed the strike to Israel, without providing evidence.[17][18]

Both State and non-State actors, including proxy groups, militants, terrorists, criminals and individuals, have launched drone attacks on critical infrastructure sites including power

[10] The US Cybersecurity and Infrastructure Security Agency (CISA) refers to critical infrastructure as those vital to the US, the incapacitation or destruction of which would have a debilitating impact, https://www.cisa.gov/critical-infrastructure-sectors. It classifies the US civilian nuclear infrastructure as one of the 16 critical infrastructure sectors, updated 21 October 2020, https://www.cisa.gov/nuclear-reactors-materials-and-waste-sector.

[11] Alexander Solodov et al., "Analyzing the threat of unmanned aerial vehicles (UAV) to nuclear facilities", *Security Journal* 31, no.1 (2017): 305-324, https://www.osti.gov/pages/servlets/purl/1356834.

[12] Nickolas Roth, "The Risks and Rewards of Emerging Technology in Nuclear Security", Belfer Center for Science and International Affairs, Harvard Kennedy School, February 2020, https://www.belfercenter.org/publication/risks-and-rewards-emerging-technology-nuclear-security.

[13] Chris Abbott et al., "Hostile Drones: The Hostile Use of Drones by Non-State Actors Against British Targets", Remote Control Project (January 2016): 1-7, https://www.openbriefing.org/docs/Hostile-use-of-drones-report_open-briefing.pdf.

[14] Kerry Chavez and Ori Swed, "The proliferation of drones to violent nonstate actors", *Defense Studies* 21, no.1 (2021), https://www.tandfonline.com/doi/full/10.1080/14702436.2020.1848426.

[15] "Counter-Small Unmanned Aircraft Systems Strategy", U.S. Department of Defense, 7 January 2021, https://media.defense.gov/2021/Jan/07/2002561080/-1/-1/1/DEPARTMENT-OF-DEFENSE-COUNTER-SMALL-UNMANNED-AIRCRAFT-SYSTEMS-STRATEGY.PDF.

[16] "A Comprehensive Approach to Countering Unmanned Aircraft Systems – And Why Current Initiatives Fall Short", Joint Air Power Competence Centre, 2019, https://www.japcc.org/wp-content/uploads/JAPCC-Flyer_C_UAS_FG_screen.pdf.

[17] Rose, "Drone attack".

[18] Tol Staff, "Satellite photos".

stations, electricity grids, petrochemical plants, oil refineries, ships and nuclear facilities. The so-called Islamic State has used aerial drones for battlefield intelligence gathering and reconnaissance in both Iraq and Syria, and also tried attacking Kurdish fighters using aerial drones and ground unmanned vehicles laden with explosives. [19] In Japan in 2015, a protestor opposed to the government's nuclear energy policy landed a drone carrying radioactive sand from the Fukushima site on the roof of the Prime Minister's office in Tokyo. [20]

In September 2021, explosive-laden drones hit Erbil International Airport in northern Iraq, where the US forces are stationed, [21] and in February and September 2019, drones disrupted the air traffic at Dubai International Airport. A year earlier, in July 2018, the United Arab Emirates (UAE) denied reports that Abu Dhabi Airport had been attacked by a drone. [22] The 2019 destructive attack on the world's largest oil processing facility, in Saudi Arabia, involved a number of cruise missiles and a swarm of some 20 suicide drones loaded with munition. [23]

Unmanned marine vehicles (UMVs) pose a similar threat to nuclear facilities, in particular NPPs, which are commonly built on the shores of rivers, lakes and seas for ease of access to large supplies of cooling water. They are commercially available as 'Surface UMVs' and 'Submersible UMVs' and have an operating range of some 120 kilometres. [24] Iran's Bushehr NPP is located on the northern shores of the Persian Gulf and is, thus, vulnerable to UMV attacks by hostile State and non-State actors.

Some UMVs are designed to carry payloads of up to 1000kg. This is three times the quantity of explosives used by Al-Qaida in the fatal bombing of the destroyer *USS Cole* off the coast of Yemen in October 2000, resulting in the death of 17 US sailors and injury to 39 others. Two suicide terrorists had detonated a small fibreglass boat, laden with explosives, creating a 12x18 metre gash on the side of the destroyer. [25]

The MENA region in particular has seen a large number of drone attacks, attributed to Israel and Iran, and Iran's proxy forces in Iraq, Lebanon, Syria and Yemen. The July 2021 drone attack on the Israeli-managed tanker *Mercer Street*, in the Gulf of Oman, led to the deaths of British and Romanian nationals, and further heightened tensions in the region. The Foreign Ministers of Canada, France, Germany, Italy, Japan, the UK and the US, and the High Representative of the EU, all condemned the attack as a blatant violation of international law. The G7 also noted that available evidence manifestly pointed to Iran, and that its behaviour and support for proxy forces and armed non-State actors threatens international peace and security. [26]

Moreover, the North Atlantic Treaty Organization (NATO) military alliance added its voice to the chorus of condemnation, holding Iran responsible for the fatal incident. [27] Tel Aviv went

[19] Chris Abbott and Mathew Clarke, "How to respond to the threat from hostile drones in the UK", *Open Briefing* (14 March 2016): 1-2, https://www.openbriefing.org/publications/report-and-articles/how-to-respond-to-the-threat-from-hostile-drones-in-the-uk/.

[20] Ibid.

[21] Ali Sultan and John Davison, "Drone attack hits near U.S. forces in Erbil, northern Iraq – officials,", *Reuters*, 11 September 2021, https://www.reuters.com/world/middle-east/rockets-land-near-us-forces-erbil-airport-northern-iraq-officials-2021-09-11/.

[22] Reuters Staff, "Two flights diverted from Dubai due to suspected drones", *Reuters*, 22 September 2019, https://www.reuters.com/article/us-emirates-security-airport-idUSKBN1W70GM.

[23] Natasha Turak, "Detailed satellite photos show extent of 'surgical' attack damage to Saudi Aramco oil facilities", *CNBC*, 17 September 2019, https://www.cnbc.com/2019/09/17/satellite-photos-show-extent-of-damage-to-saudi-aramco-plants.html.

[24] Abbott et al., "Hostile Drones".

[25] J.D. Simkins, "Terrorist behind 2000 destroyer Cole bombing killed in airstrike", *NavyTimes*, 4 January 2019, https://www.navytimes.com/news/your-navy/2019/01/04/terrorist-behind-2000-uss-cole-bombing-killed-in-airstrike/.

[26] "G7 Foreign Ministers' Statement on the MV Mercer Street Attack", U.S. Department of State, 6 August 2021, https://www.state.gov/g7-foreign-ministers-statement-on-the-mv-mercer-street-attack/.

[27] "Statement by the acting NATO Spokesperson on the Mercer Street vessel attack", NATO, 3 August 2021, https://www.nato.int/cps/en/natohq/news_186010.htm.

further by threatening Iran with military action.[28] Iran's Foreign Ministry equivocally refuted the allegations,prompting the UK to refer the issue to the UNSC.[29] Such localised incidents have the potential to escalate into armed conflict, and pose a major threat to peace and prosperity in the MENA region and beyond.

2.1 Drone incidents near nuclear facilities

Incidents involving commercial drones around nuclear facilities have also increased in frequency. In 2014, drones repeatedly breached the restricted airspace of 13 of France's 19 NPPs, housing 56 nuclear reactors.[30][31] Disruption to the normal operation of NPPs in France, which account for 70% of the electricity generation, would have constituted a major breach of the security of its energy infrastructure.[32]

In 2016, a drone crashed into an NPP in Koberg in South Africa, hitting the exterior shield of the power plant.[33] In South Korea, the Nuclear Safety and Security Commission (NSSC) reported 13 incidents of drones flying illegally near NPPs during the period 2015 to 2019. Six of the incidents took place near the Kori NPP in August 2019.[34][35]

In June 2016, drones were observed over the Savannah River Site in South Carolina in the US, where substantial quantities of plutonium (Pu), used in nuclear weapons, are stored.[36] In September 2019, drones twice trespassed the airspace of the Palo Verde NPP in Arizona, remaining in the airspace for more than an hour, unchallenged by the security personnel. This plant is the largest in the US, generating 35% of Arizona's total power needs.[37]

Iran's critical infrastructure, including nuclear facilities, have also been the subject of sabotage, cyberattacks and drone strikes in recent years, as discussed below.

2.2 Drone attacks on Iran's nuclear facilities

In 2014, the Islamic Revolutionary Guards claimed their missiles had shot down an Israeli stealth drone near the Natanz uranium enrichment site. This is Iran's main enrichment facility, which, at the time, housed more than 16,000 centrifuges. Israel had previously threatened to attack Iran's nuclear facilities on a number of occasions.[38] At the time of the incident, Iran, the five

[28] Laurie Kellman, "Israeli defense minister threatens Iran with military action", *Associated Press (AP)*, 5 August 2021, https://apnews.com/article/joe-biden-business-iran-middle-east-united-nations-16666e8d97ed6e4571ae6d01785c00fc.

[29] Alisa Odenheimer, Verity Ratcliffe and David Wainer, "Israel Flags Evidence Iran Hit Ship as Mideast Tensions Rise", *Bloomberg*, 3 August 2021, https://www.bloomberg.com/news/articles/2021-08-03/israel-has-provided-hard-evidence-tying-iran-to-ship-attack.

[30] "EDF France: Inquiry after drones buzz nuclear sites", *BBC News*, 30 October 2014, https://www.bbc.co.uk/news/world-europe-29831897.

[31] Michael Stothard, "Drones fly into French nuclear debate", *Financial Times (FT)*, 7 November 2014, https://www.ft.com/content/54da14b4-64ea-11e4-ab2d-00144feabdc0.

[32] "Nuclear Power in France", World Nuclear Association (WNA), updated January 2021, https://world-nuclear.org/information-library/country-profiles/countries-a-f/france.aspx.

[33] Jae San Kim, "A Study on the Possibility of Unmanned Aerial Vehicles (UAV)' Threat in Nuclear Facilities", *Transactions of the Korean Nuclear Society Autumn Meeting*, Goyang, Korea, 24-25 October 2019, https://www.kns.org/files/pre_paper/42/19A-202-김재산.pdf.

[34] Baek Byung-yeul, "Nuclear power plants 'vulnerable to drone attacks'," *The Korea Times*, 16 October 2019, https://www.koreatimes.co.kr/www/tech/2021/05/129_276717.html.

[35] Jung Suk-yee, "Fear of Drone-based Terrorist Attacks Spreading in South Korea – Nuclear Plants Not Protected from Potential Drone Attacks", *BusinessKorea*, 18 September 2019, http://www.businesskorea.co.kr/news/articleView.html?idxno=36087.

[36] Kathleen Araújo and Jose Gomera, "Disruptive Change in Unmanned Aerial Systems, Nuclear Facilities, and Radiological Protection: A Review of US and French Developments", Nonproliferation and National Security Department, Brookhaven National Laboratory, November 2016, https://www.bnl.gov/isd/documents/94219.pdf.

[37] David Hambling, "'Drone Swarm' Invaded Palo Verde Nuclear Power Plant Last September – Twice", *Forbes*, 30 July 2020, https://www.forbes.com/sites/davidhambling/2020/07/30/drone-swarm-invaded-palo-verde-nuclear-power-plant/?sh=16004ed243de.

[38] "Iran 'shoots down Israeli drone' near Natanz nuclear site", *BBC News*, 24 August 2014, https://www.bbc.co.uk/news/world-middle-east-28920361.

permanent members of the UNSC (China, France, Russia, the UK and the US), Germany and the EU were negotiating over the future status of its nuclear programme.

Mr Abbasi-Davani, a former head of the Atomic Energy Organization of Iran (AEOI) and current Chair of the Iranian Parliament's Energy Committee, has claimed that the Natanz nuclear site has been hit five times in the past 15 years, without specifying whether these were drone attacks. [39]

In April 2021, an attack on the Natanz uranium enrichment facility caused extensive damage to some of the 6000 centrifuges spinning at the time. Iran has not officially announced the cause of the sabotage, but has attributed it to Israel, prompting demand for retaliatory action by the conservative elements in Iran. The ultraconservative newspaper *Keyhan Daily*, affiliated with the country's supreme leader, promptly called on the government to strike Israel's Dimona Nuclear Research Centre, in the Negev desert. [40] [41] Indeed, less than a week later, on 22 April 2021, Israel confirmed that a missile had landed some 30km from the Dimona nuclear reactor after air defence systems failed to intercept it. [42] This incident was indicative of the vulnerability of Israel's nuclear facilities and other critical infrastructure to drone, rocket and missile attacks by Iran's proxies in the countries neighbouring Israel. [43] Most recently, on 22 June 2021, a sabotage attack on the TESA Karaj site (near Tehran) involving one or more small rotor-powered drones caused extensive damage. The drones were flown from a short distance away. The aluminium blades and other centrifuge components produced at the site are used in the first-generation (IR-1) and advanced centrifuges installed at the Natanz and Fordow uranium enrichment facilities. Iran attributed the attack to Israel, which has repeatedly declared that it will not allow Iran to acquire nuclear material for nuclear weapons. [44] [45] Iran relies solely on centrifuges for its comprehensive uranium enrichment programme. Enriched uranium, as noted previously, has dual-use civilian and weapons applications. It is used in NPPs at below 5% enrichment; in research reactors (below 20%); and in nuclear submarines and nuclear warheads (above 90%).

[39] Tzvi Joffre, "Fmr. Iran nuke chief: Natanz explosion was 5th in recent years", *The Jerusalem Post*, 2 May 2021, https://www.jpost.com/middle-east/fmr-iran-nuke-chief-natanz-explosion-was-5th-in-recent-years-666965.

[40] ToI Staff, "'Eye for an eye': Iran editorial urges retaliatory attack on Dimona reactor", *The Times of Israel*, 17 April 2021, https://www.timesofisrael.com/eye-for-an-eye-iran-editorial-urges-retaliatory-attack-on-dimona-reactor/amp/.

[41] S. Zarrei, "Negotiating against National Interest" (in Farsi), *Keyhan*, 17 April 2021 (24/1/1400), https://kayhan.ir/files/fa/publication/pages/1400/1/27/2116_25279.pdf.

[42] Martin Chulov and Oliver Holmes, "Israel confirms Syrian missile landed near Dimona nuclear reactor", *The Guardian*, 22 April 2021, https://www.theguardian.com/world/2021/apr/22/israel-confirms-syrian-missile-landed-near-dimona-nuclear-reactor.

[43] Abbott, "Hostile Drones", 11, https://www.openbriefing.org/docs/Hostile-use-of-drones-report_open-briefing.pdf.

[44] Rose, "Drone attack".

[45] ToI Staff, "Satellite photos".

Chapter 3. Iran's Nuclear Facilities

Over the past six decades, Iran has acquired the full spectrum of nuclear facilities [46] associated with the nuclear fuel cycle, [47] [48] as listed in Appendix I. The nuclear fuel cycle encompasses a number of operations directly related to the production of electricity from nuclear reactors, the key stages of which are listed below:

(i) Mining, milling and purification of uranium ore are caried out using physical and chemical processes to produce uranium concentrate, U_3O_8 (yellowcake, as it is commonly known), containing up to 80% uranium;

(ii) Conversion of uranium concentrate (yellowcake) to uranium dioxide (UO_2) for direct fuel fabrication for heavy water reactors, or to hexafluoride gas (UF_6), for the enrichment stage;

(iii) Natural uranium contains 99.3% uranium-238 (U-238) and 0.7% uranium-235 (U-235). The enrichment process increases the U-235 content of the UF_6 gas stream from 0.7% to below 5% for commercial NPPs; to 20% for research reactors; and, generally, above 90% for nuclear-powered submarines and nuclear weapons;

(iv) Fuel fabrication, involving the chemical conversion of UF_6 gas to UO_2, or uranium metal, and construction of fuel rods for commercial reactors and fuel plates for research reactors;

(v) Electricity generation in an NPP, using uranium fuel rods containing up to 5% U-235. The splitting (fission) of U-235 in the fuel rods generates heat, which converts water into steam. As in conventional power plants, including coal-fired plants, the steam is then used to rotate the 'turbines', the rotation of which generates electricity in the 'generators';

(vi) Spent (irradiated) fuel storage, where spent fuel rods are removed from the reactor and stored in cooling pools inside the concrete biological confinement of the NPP. The circulating water in the pool removes the residual heat generated due to radioactivity. The water also shields the personnel from high levels of radiation, and allows radiation levels to drop sufficiently for the transfer of the spent fuel for permanent storage, or for subsequent reprocessing;

(vii) The reprocessing of spent fuel rods may be undertaken to recover the unused U-235, and also to extract the plutonium (Pu) generated during the operation of the nuclear reactor. Pu is used in the construction of nuclear weapons, and was first used in the atomic (nuclear) bomb dropped on Nagasaki in August 1945;

(viii) Long-term storage of radioactive waste, away from the NPP, is required for the safe storage of the highly radioactive waste generated in the reprocessing stage, and for the disposal of unprocessed spent fuel rods.

Iran has also established a number of nuclear-related research and development (R&D) programmes at a number of State-run establishments, laboratories and academic institutions. This is to support its nuclear fuel cycle activities, and to advance the applications of nuclear science and technology in industry, agriculture and the medical field. IAEA had previously

[46] IAEA defines a 'nuclear facility' as "A facility (including associated buildings and equipment) in which nuclear material is produced, processed, used, handled, stored or disposed of." See, "IAEA Safety Glossary – Terminology Used in Nuclear Safety and Radiation Protection", IAEA (June 2019): 152, https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1830_web.pdf.

[47] Ibid., 153.

[48] "Getting to the Core of the Nuclear Fuel Cycle", IAEA (undated): 1-12, https://www.iaea.org/sites/default/files/18/10/nuclearfuelcycle.pdf.

declared its concerns regarding "possible military dimensions to Iran's nuclear programme" prior to the end of 2003. [49]

Certain aspects of Iran's nuclear fuel cycle, and associated R&D activities, are regarded as highly proliferation sensitive, including (i) U-235 enrichment technology, which could be used to produce highly enriched U-235 (HEU) to levels above 90%; (ii) Heavy water reactors, which generate Pu during their normal operations; (iii) Research reactors, which are used for the production of medical radioisotopes, but could generate Pu; and (iv) The reprocessing technology, which may be used for extracting Pu from the spent uranium fuel rods. As noted previously, enriched U-235 and Pu are used in nuclear (atomic) weapons. The 'atomic bombs' dropped on Hiroshima and Nagasaki in August 1945 contained 64kg of HEU (95%) and 6.2kg of Pu, respectively. [50]

Iran's current and past activities in relation to enrichment, heavy water reactors, research reactors and reprocessing have proved to be of nuclear proliferation concern for a number of countries in the MENA region, in Western Europe and in North America. As a result, Iran's nuclear facilities and other critical infrastructure facilities have been the subject of drone strikes, cyberattacks and sabotage operations, in order to curtail Iran's expansion of its proliferation sensitive nuclear activities and accumulation of nuclear material. [51]

3.1 Development of nuclear power in Iran

Iran was, paradoxically, one of the key beneficiaries of President Eisenhower's 1953 'Atoms for Peace' programme, which provided the foundation for Iran's nuclear programme. Following the signing of the 1957 'Agreement for Co-operation Concerning Civil Uses of Atomic Energy' [52], the US, in 1960, provided Iran with a research reactor, nuclear fuel and several kilograms of HEU (weapons-grade) uranium. The 'Tehran Research Reactor', as it was known, became operational in 1967, and has been providing valuable training in nuclear science and technology for Iranian scientists ever since. [53] [54]

Iran was also a key beneficiary of yet another US initiative, the 1955 Baghdad Pact. Under this arrangement, the US took an indirect role, offering economic, military and technical support to the Pact members, namely, Iran, Iraq, Pakistan and Turkey. In 1957, the Baghdad Pact Nuclear Training Centre was established in Baghdad, training scientists from Iran and other member states under the scientific direction of British nuclear scientist and Nobel Laureate Sir John Cockcroft. The Baghdad Pact was renamed the 'Central Treaty Organization' (CENTO) following the 1958 coup in Iraq, and the nation's subsequent withdrawal. In 1959, the CENTO Institute of Nuclear Science was established at Tehran University, providing training to scientists from Iran, Pakistan and Turkey. [55] [56] [57]

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[49] See, "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran", IAEA, *GOV/2011/65*, Annex, 8 November 2011, https://www.iaea.org/sites/default/files/gov2011-65.pdf.

[50] "Hiroshima, Nagasaki, and Subsequent Weapons Testing", World Nuclear Association, March 2016, https://www.world-nuclear.org/information-library/safety-and-security/non-proliferation/hiroshima,-nagasaki,-and-subsequent-weapons-testin.aspx.

[51] Nuclear material includes natural uranium (excluding ore), enriched uranium and plutonium. See, "IAEA Safety Glossary".

[52] See, "Agreement for Co-Operation Between the Government of the United States of America and the Government of Iran Concerning Civil Uses of Atomic Energy, 5 March 1957", *United Nations Treaty Series* 342, no. 11 (1959): 29, https://treaties.un.org/doc/Publication/UNTS/Volume%20342/v342.pdf.

[53] See, "U.S. Relations with Iran:1953-2021", Council on Foreign Relations (updated April 2021), https://www.cfr.org/timeline/us-relations-iran-1953-2021.

[54] "Tehran Research Reactor (TRR)", Nuclear Threat Initiative (updated 23 August 2013), https://www.nti.org/learn/facilities/182/.

[55] "The Baghdad Pact (1955) and the Central Treaty Organization (CENTO)", U.S. Department of State, 20 January 2009, https://2001-2009.state.gov/r/pa/ho/time/lw/98683.htm.

[56] R. Roberts, "Scientific co-operation under CENTO", *Journal of The Royal Central Asian Society* 52, no. 2 (1965): 141-145; published online 2011, https://www.tandfonline.com/doi/abs/10.1080/03068376508731905.

[57] Merlin W. Anderson, "Turkey, CENTO vs. NATO – Mutually Supporting or a Conflict of Interest?", (Dissertation, US Army War College, Carlisle Barracks, Pennsylvania, 8 April 1966): 9-13, https://apps.dtic.mil/dtic/tr/fulltext/u2/a510152.pdf.

In 1973, the AEOI was established to oversee the development of an ambitious nuclear power programme. The AEOI concluded a number of agreements with Western contractors for the eventual construction of 23 NPPs, including contracts with Kraftwerk Union of Germany, a subsidiary of Siemens, to build two pressurised water (PWR) nuclear reactors at Bushehr. [58]

The 1979 Iranian revolution, which replaced the monarchy with a theocratic regime, coupled with the start of the Iran–Iraq war in September 1980, put an end to Iran's ambitious quest for nuclear power. [59] The Islamic Republic halted the nuclear power programme and, following repeated rocket attacks by Iraq on the partially completed Bushehr NPP, Kraftwerk Union abandoned the project.

Iran's nuclear programme was rekindled in mid-1980s. The Bushehr International Nuclear Technology Conference was convened in November 1985. Following the end of the Iran–Iraq war in August 1988, collaboration with China, Pakistan and the Soviet Union (as it was then), which had already begun, gathered pace.

As regards Pakistan, in 1987, Iran received technical drawings, centrifuge components and centrifuge machines for uranium enrichment process through the clandestine nuclear supply network of Abdul Qadeer Khan, the leading Pakistani metallurgist, known as the father of Pakistan's atomic bomb. [60] Also, in 1993, Iran reportedly received 500 unassembled P-1 centrifuges, P-2 centrifuge design information and related materials. [61] [62] The clandestine collaboration underpinned the development and advancement of Iran's centrifuge enrichment programme, which is capable of producing low enriched uranium (LEU) for nuclear energy applications, and HEU for non-civilian programmes, if required. [63]

China has been Iran's major nuclear partner since the mid-1980s, providing Iran with nuclear fuel cycle-related expertise, including exploration and mining of uranium, production of yellowcake, conversion of yellowcake to UF_6 gas, manufacture of uranium fuel rods, and construction of uranium fuel plates for research reactors in Esfahan and Tehran.

China has also collaborated closely with Iran in the development of the Esfahan Nuclear Technology Centre, established by France in mid-1970s, [64] supplying it with research reactors and other nuclear-related facilities. [65] [66] Also, in 1991, China supplied Iran with large quantities of UF_6, 500kg of UF_4 and 400kg of UO_2. China, at the time, was not party to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), and did not declare the transactions to the IAEA. [67]

In 1995, Russia started construction of the Bushehr NPP and began training personnel. The NPP became fully operational 16 years later in 2011. As noted previously, Kraftwerk Union of

[58] "Bushehr Nuclear Power Plant (BNPP)", NTI (updated October 2021), https://www.nti.org/education-center/facilities/bushehr-nuclear-power-plant-bnpp/.

[59] William Burr, "A brief history of U.S.-Iranian nuclear negotiations", *Bulletin of the Atomic Scientists* 65, no.1 (January/February 2009): 21-34, https://journals.sagepub.com/doi/pdf/10.2968/065001004.

[60] "Timeline of Nuclear Diplomacy With Iran", Arms Control Association (updated November 2021), https://www.armscontrol.org/factsheets/Timeline-of-Nuclear-Diplomacy-With-Iran.

[61] "Iranian Centrifuge Model Collection", NTI (updated 2021), https://www.nti.org/analysis/articles/iranian-centrifuge-model-collection/.

[62] "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran", IAEA, *GOV/2005/57*, 2 September 2005, https://www.iaea.org/sites/default/files/gov2005-67.pdf.

[63] Kerr, "Iran's Nuclear Program", 82.

[64] "Isfahan (Esfahan) Nuclear Fuel Research and Production Center (NFRPC)", NTI (updated 1 January 2011), https://www.nti.org/learn/facilities/235/.

[65] Kerr, "Iran's Nuclear Program", 83.

[66] "Isfahan (Esfahan) Nuclear Technology Center (INTC)", NTI (updated July 2017), https://www.nti.org/learn/facilities/237/.

[67] Ariana Rowberry, "Sixty Years of 'Atoms for Peace' and Iran's Nuclear Program", The Brookings Institution, 18 December 2013, https://www.brookings.edu/blog/up-front/2013/12/18/sixty-years-of-atoms-for-peace-and-irans-nuclear-program/.

Germany had initially started the construction of the NPP in 1975, but had to abandon the project during the Iran–Iraq war. Under a contract with Iran, Atomstroyexport, a subsidiary of the leading Russian Rosatom State Corporation, has been loading nuclear fuel into the Bushehr NPP and taking back the spent fuel which contains Pu. [68] The nuclear fuel is supplied by TVEL, another subsidiary of Rosatom. [69]

In the 1990s, a number of Russian entities reportedly provided Iran with expertise relating to heavy water production, the design of the Arak Heavy Water Reactor and the design of the fuel rods. In 1999, the US sanctioned the NIKIET Institute in Moscow for its alleged assistance. [70] [71] [72] The Arak Reactor is considered a proliferation sensitive facility, as heavy water reactors, generally, have the potential to produce weapons-grade plutonium. The reactor is currently undergoing re-modification to reduce its plutonium-generating capabilities.

3.2 'The Iran Nuclear Accord' (JCPOA)

Iran's nuclear programme, and the accelerated expansion of its nuclear fuel cycle facilities, finally came under close international scrutiny, monitoring and inspection in 2015, following 13 years of diplomatic endeavour. The diplomatic efforts were prompted following the revelations of the National Council of Resistance of Iran in August 2002. At a press conference in Washington DC, it reported the existence of a number of previously undeclared sites in Iran, where clandestine nuclear-related activities were being undertaken near Natanz and near Arak. [73] [74]

On 16 July 2015, Iran, the EU, the five permanent members of the UNSC and Germany (P5+1) concluded the 'Iran Nuclear Accord', formally known as the Joint Comprehensive Plan of Action (JCPOA). [75] The international community agreed to lift the sanctions first imposed on Iran in 2006, and Iran, at the time, pledged full transparency in relation to its nuclear programme.

On 20 July 2020, the UNSC unanimously endorsed the JCPOA, adopting resolution 2231 (2015) and mandating the IAEA to monitor the implementation of Iran's nuclear commitments under the JCPOA. [76] The UNSC further affirmed, inter alia, "that full implementation of the JCPOA would contribute to building confidence in the exclusively peaceful nature of Iran's nuclear programme". [77]

Under the provisions of the JCPOA, Iran has, inter alia, pledged to provisionally implement the 'Additional Protocol' to its Comprehensive Safeguards Agreement (CSA) with the IAEA.

Iran signed the original CSA in 1974, [78] as required under Article III of the NPT, [79] enabling the IAEA to provide assurance to the international community that Iran's 'declared' nuclear material,

[68] Kerr, "Iran's Nuclear Program", 31.

[69] TVEL – Rosatom News, "TVEL Fuel Company statement on cooperation with Iran", 23 July 2020, https://tvel.ru/en/press-center/news/?ELEMENT_ID=8403.

[70] "Nuclear Power in Iran – Arak IR-40 heavy water reactor", World Nuclear Association (WNA), January 2021, https://world-nuclear.org/information-library/country-profiles/countries-g-n/iran.aspx.

[71] Rowberry, "Atoms for Peace".

[72] "Mysteries Deepen Over Status of Arak Reactor Project", Institute for Science and International Security (11 August 2009): 3, https://isis-online.org/uploads/isis-reports/documents/ArakFuelElement.pdf.

[73] "Timeline of Nuclear Diplomacy with Iran".

[74] Kerr, "Iran's Nuclear Program".

[75] See, UNSC, "JCPOA document", *S/2015/544*, 16 July 2015, https://www.undocs.org/pdf?symbol=en/S/2015/544.

[76] See, UNSC, "Resolution 2231 (2015)", *S/RES/2231*, 20 July 2015, https://undocs.org/S/RES/2231(2015).

[77] See, UNSC, "Resolution 2231 (2015) on Iran Nuclear Issue – Background", Undated, https://www.un.org/securitycouncil/content/2231/background.

[78] IAEA, "The Text of the Agreement Between Iran and the Agency for the Application of Safeguards in Connection with the Treaty on the Non-proliferation of Nuclear Weapons", IAEA, *INFCIRC/214*, 13 December 1974, https://www.iaea.org/sites/default/files/publications/documents/infcircs/1974/infcirc214.pdf.

[79] See, "Treaty on the Non-Proliferation of Nuclear Weapons (NPT)", UN Office for Disarmament Affairs, https://www.un.org/disarmament/wmd/nuclear/npt/.

facilities and activities are not being diverted for military objectives. More importantly, the highly intrusive inspection and monitoring regime under the 'Additional Protocol' [80] enables the IAEA to provide assurance as to the 'undeclared' nuclear material and facilities in Iran.

However, following the US's unilateral withdrawal from the JCPOA in May 2018, and the reimposition of sanctions, [81] [82] Iran has reciprocated by embarking on a number of proliferation sensitive activities, including enrichment of U-235 to 60%; increase of its stockpiles of enriched uranium; operation of advanced centrifuges; and production of uranium metal. [83] Iran's recent nuclear-related activities are construed by some of the JCPOA participant States as being contrary to the pledges it had made under the JCPOA.

The recent nuclear advancements noted above have proved to be of proliferation concern to a number of countries in the MENA region and beyond. Foreign Ministers of France, Germany and the UK – the three European participants in the JCPOA – have also expressed their "grave concern". [84]

Israel has warned, notwithstanding its own nuclear weapons capabilities, that it is prepared to strike Iran's nuclear facilities, "in light of the Islamic Republic's ongoing march toward the technology needed for an atomic weapon, and the stalled negotiations between Washington and Tehran on the matter". [85]

Washington also expressed its dismay during the recent visit of the newly elected president of Israel to the Whitehouse, reiterating the US commitment to ensuring that "Iran never develops a nuclear weapon", and that the US is ready to turn to other options, should diplomacy fail in relation to Iran's nuclear programme. [86]

[80] "Protocol Additional to the Agreement between the Islamic Republic of Iran and the International Atomic Energy Agency for the Application of Safeguards in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons", IAEA, *INFCIRC/214/Add.1*, 4 March 2016, https://www.iaea.org/sites/default/files/infcirc214a1.pdf.

[81] "On President Trump's Decision to Withdraw From the JCPOA", U.S. Department of State, 8 May 2018, https://2017-2021.state.gov/on-president-trumps-decision-to-withdraw-from-the-jcpoa/index.html.

[82] Bahram Ghiassee, "Update on the Iran Nuclear Accord (JCPOA), Post U.S. Unilateral Withdrawal", *International Energy Law Review (IELR)* 37, no.3 (2019): 56-5.

[83] "Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015)", IAEA, *GOV/2021/28*, 31 May 2021, https://www.iaea.org/sites/default/files/21/06/gov2021-28.pdf.

[84] "Europeans express 'grave concern' over IAEA report on Iran", *The Independent*, 19 August 2021, https://www.independent.co.uk/news/world/europe/iran-germany-iaea-france-joint-comprehensive-plan-of-action-b1905344.html.

[85] Gross, "As Bennett meets Biden".

[86] Hunnicutt and Spetalnick, "Biden to Israeli PM".

Chapter 4. Assessment of Vulnerabilities

As noted previously, the vulnerability of Iran's nuclear facilities stems from the fact that a number of countries in the MENA region and beyond find Iran's advanced nuclear programme an issue of proliferation concern, and a threat to stability and security at national and transnational levels. On 9 September 2021, Bahrain, Egypt, Saudi Arabia and the UAE called for a "rapid and comprehensive" inspection of all Iranian nuclear sites. [87]

The call was prompted by two IAEA reports, dated 7 September 2021, the first of which concerned the unresolved issue of traces of uranium found in three undeclared locations in Iran, and the location of a uranium metal disk. [88] The second report was critical of Iran's decision not to implement its nuclear-related commitments under the JCPOA, and its impeding of the IAEA's full inspection and verification activities, including not providing full access to its monitoring equipment. [89]

Israel, as a matter of policy, has been opposed to the development of nuclear programmes in the MENA region which could be used in conjunction with weapons programmes. In 1981, Israeli jets destroyed the Osirak nuclear research reactor [90] in Iraq [91] and in 2007 destroyed a Syrian research reactor.

The latter reactor had not been declared to the IAEA and was about to come into operation. [92] As noted previously, cyberattacks, sabotage and drone strikes on Iran's nuclear-related facilities, and assassination of Iranian nuclear scientists on Iran's soil, have been attributed to Israel, which it has neither confirmed nor denied.

Physical threats posed to nuclear and radiological facilities from State and non-State actors fall into four general categories: [93] (i) Attack on, or sabotage of, NPPs and other nuclear fuel cycle facilities; (ii) Attacks on transport systems carrying nuclear and other radioactive materials in transport; (iii) Theft of existing nuclear weapons, or construction of crude explosive devices (improvised nuclear devices), using illicitly acquired nuclear material; and (iv) Use of radioactive substances in a radiological dispersive device (dirty bomb).

Categories iii and iv fall outside the remit of this report, and are not discussed further. The vulnerability of 'radiological facilities', where radioisotopes are generated or used for medical, industrial or research purposes, also falls outside the scope of this report. Such facilities are not part of the nuclear fuel cycle, do not directly support nuclear weapons programmes and, hence, pose limited nuclear proliferation concerns.

Drone attacks by hostile State and non-State actors on radiological facilities, however, could result in the release of radioactivity, causing significant ecological, social and economic harm.

87 "Arab Countries call for inspection of all Iranian nuclear sites", *Arab News*, 9 September 2021, https://www.arabnews.com/node/1925856/middle-east.

88 "NPT Safeguards agreement with the Islamic Republic of Iran", IAEA, *GOV/2021/42*, 7 September 2021, https://www.iaea.org/sites/default/files/21/09/gov2021-42.pdf.

89 "Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015)", IAEA, *GOV/2021/39*, 7 September 2021, https://www.iaea.org/sites/default/files/21/09/gov2021-39.pdf.

90 Donal G. Boudreau, "The Bombing of the Osirak Reactor", *International Journal on World Peace* 10, no.2 (June 1993): 21-37, https://www.jstor.org/stable/20751886.

91 Ruth Eglash, "Israel finally admitted it destroyed a Syrian reactor in 2007 – and set off a battle of egos", *The Washington Post*, 22 March 2018, https://www.washingtonpost.com/news/worldviews/wp/2018/03/22/israel-finally-admitted-it-destroyed-a-syrian-reactor-in-2007-and-set-off-a-battle-of-egos/.

92 "IAEA Safeguards Serving Nuclear Non-Proliferation", IAEA (June 2015): 12, https://www.iaea.org/sites/default/files/safeguards_web_june_2015_1.pdf.

93 Mohamed ElBaradei, "Nuclear Proliferation and the Threat of Nuclear Terrorism", *Nuclear Future* 1, no.1 (2005): 32-36.

Drones may also be used maliciously for dispersion of radioactivity in populated areas, or for the deployment of dirty bombs. [94] [95]

4.1 Vulnerability of Iran's nuclear facilities

In assessing the vulnerability of Iran's nuclear fuel cycle facilities to commercial and military drone strikes, both the threat and the risk posed to each facility are considered, noting that the likelihood of an attack, and its impact, are different for each facility. [96] [97]

Iran's uranium mining and milling operations are carried out at Saghand in Yazd and Gachine in Bandar Abbas. Threats posed to such facilities from drone strikes are limited, as they are not regarded as critical to the nuclear fuel cycle. It is highly unlikely that these facilities would be attacked, and the impact on Iran's nuclear programme, in the short and medium term, would be limited.

Iran operates two yellowcake production plants in Ardakan and in Bandar Abbas. The yellowcake facilities are built overground and, hence, are vulnerable to direct drone strikes. The likelihood (probability) of an attack may be regarded as limited, and the impact on the nuclear programme would be limited in the short term.

The conversion plant at the Esfahan Nuclear Technology Centre converts the yellowcake to UF_6 as feedstock for centrifuges, and also to UO_2. Iran has previously used UO_2 to manufacture natural uranium fuel rods for the Arak Heavy Water Reactor – a proliferation sensitive facility.

The facilities at the Esfahan Centre are located overground, and are highly vulnerable to drone strikes. The threat posed to the conversion plant, in particular, may be regarded as significant, as it constitutes a critical element of the nuclear fuel cycle. The likelihood (probability) of drone attacks by hostile State or non-State actors is high, and the consequent impact accordingly high. The risk may, thus, be regarded as equally significant. The disruptions to these above-ground facilities could impede Iran's nuclear programme in the medium term. [98] [99]

It is noteworthy that the Esfahan Nuclear Technology Centre is the most advanced nuclear science and technology complex in Iran. As noted previously, France embarked on the construction of the Centre in the 1970s, and China extensively expanded and equipped it in the late 1980s and early 1990s. In addition to nuclear research reactors, the Centre houses a number of proliferation sensitive technologies critical to Iran's nuclear programme, including UF_6 production, small-scale uranium metal production, fabrication of fuel rods for the Arak Heavy Water Reactor, and fabrication of fuel plates for the Tehran and Esfahan research reactors. The proliferation concerns, and the fact that these facilities are constructed above ground, renders the Centre highly vulnerable to aerial strikes. Explosive-laden drones, in particular, pose a serious threat to the Centre, as they could be launched from a short distance

[94] Bahram Ghiassee, "Nuclear Terrorism and the Environment", *UK Environmental Law Association e-Journal*, no. 8 (March 2002): 15-18.

[95] See, "Assessing the risk of terrorist attacks on nuclear facilities", Parliamentary Office of Science and Technology, Report 222, July 2004, https://www.parliament.uk/globalassets/documents/post/postpr222.pdf.

[96] 'Threat' may be defined as 'Capability x Intent', and 'Risk' as 'Likelihood x Impact', i.e., the likelihood of an attack occurring multiplied by the likely impact it could have. See, "Hostile drones – Supplementary risk assessment", *Open Briefing*, Appendix 1, 12 January 2016, https://www.openbriefing.org/docs/Hostile-drones-Supplementary-risk-assessment.pdf.

[97] Bahram Ghiassee, "Nuclear Terrorism and Environmental Protection under International Law", *International Journal of Nuclear Governance, Economy and Ecology* 4, no. 2 (2014): 83-99, https://www.inderscienceonline.com/doi/abs/10.1504/IJNGEE.2014.065931.

[98] Abdullah Toukan and Anthony H. Cordesman, "Options in Dealing with Iran's Nuclear Program", Center for Strategic & International Studies (March 2010): 39, https://csis-website-prod.s3.amazonaws.com/s3fs-public/legacy_files/files/publication/100323_Options_todealwith_Iran.pdf.

[99] Kerr, "Iran's Nuclear Program", 32.

away, could easily evade the air defence systems, and could not be identified as belonging to a specific State or non-State actor.

Specially designed container flasks (casks) are used for the transfer of UF6 from Esfahan to the enrichment plants at Natanz and Fordow. The containers are vulnerable to drone attack during transport, and possible targets for malicious activity by hostile State and non-State actors. However, the degree of risk posed is very limited, as the probability of an attack would be low and the disruption caused insignificant.

The Pilot Fuel Enrichment Plant and the Fuel Enrichment Plant, both at Natanz, are considered as critical elements of Iran's nuclear fuel cycle. The facilities have been the subject of cyberattacks, explosions and sabotage over the past decade. In April 2021, a cyberattack on the internal power supply system caused an explosion and damage to some of the roughly 6000 centrifuges spinning at the time. Iran blamed Israel for the sabotage, calling it an act of "nuclear terrorism". [100]

Built a few metres underground, the Natanz Enrichment Plant centrifuges are not considered vulnerable to weaponised commercial drones or military drones. However, the threat posed to the ancillary facilities (utility systems) – the external power (electricity) supply, the gas supplies, the auxiliary electricity generators, the air-conditioning and the water supply systems – which are built overground may be regarded as high. The risk posed to these utility services from air strikes, including commercial drones, is equally high, as it is likely that drones would target them, and the impact of an attack would be significant, disrupting the production of enriched uranium.

The Fordow Enrichment Facility, near the city of Qom, is built at a depth of some 60 metres inside a mountain, and thus not vulnerable to aerial attacks by drones, rockets, missiles or US 'bunker-busting' precision-guided bombs. [101] It is designed to hold approximately 3000 centrifuges. [102] According to the latest IAEA Verification and Monitoring report, [103] 1044 IR-1 centrifuges and 166 IR-6 centrifuges are currently enriching UF_6 up to 20%, with a capacity to produce more than 25kg of HEU per annum, sufficient for one implosion-type nuclear weapon.[104] The facility's entry ways, airshafts, air supply and other external supply systems are highly vulnerable to aerial attacks, including drones. It is likely that a hostile State would consider launching strikes on these soft targets, thus causing disruption to the production of enriched uranium for prolonged periods.

Iran's enrichment-related facilities, where centrifuge parts are manufactured, assembled or tested, are highly vulnerable, and have been the target of aerial attacks and sabotage. In July 2020, an explosion extensively damaged an overground building at Natanz, where advanced centrifuges were being assembled. To date, Iran has not confirmed the cause of the explosion, but has attributed it to Israel. [105] The facility is being rebuilt inside a mountain near Natanz. [106]

[100] "Iran Natanz nuclear site suffered major damage, official says", *BBC News*, 13 April 2021, https://www.bbc.co.uk/news/world-middle-east-56734657.

[101] Frank Gardner, "Why Iran's nuclear facilities are still vulnerable to attack", *BBC News*, 19 January 2021, https://www.bbc.co.uk/news/world-middle-east-55271429.

[102] "Fordow Fuel Enrichment Plant", Nuclear Threat Initiative, updated 25 October 2021, https://www.nti.org/education-center/facilities/fordow-fuel-enrichment-plant/.

[103] "Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015)", IAEA, *GOV/2021/51*, 17 November 2021, https://www.iaea.org/sites/default/files/21/11/gov2021-51.pdf.

[104] Toukan and Cordesman, "Dealing with Iran", 45.

[105] Julia Masterson and Kelsey Davenport, "Explosion at Natanz Damages Centrifuge Production Building", Arms Control Association, 16 July 2020, https://www.armscontrol.org/blog/2020-07/p4-1-iran-nuclear-deal-alert.

[106] Richard Spencer, "Iran rebuilding nuclear plant at Natanz after blast", *The Times*, 29 October 2020, https://www.thetimes.co.uk/article/iran-rebuilding-nuclear-plant-at-natanz-after-blast-g5mbdz2j3.

In June 2021, a drone attack on a facility manufacturing centrifuge components caused extensive damage. [107] [108] The IAEA monitoring and recording devices installed at the TESA Karaj site were also damaged. The attack was attributed to Israel. [109]

Some of the UF_6 enriched at Natanz and at Fordow is transported back to Esfahan in specially designed container flasks (casks), for conversion to uranium fuel rods, plates and, if need be, uranium metal. The containers are vulnerable to drone attack during transport. The threat exists, but the degree of risk posed is limited, as the probability of an attack would be low, and the disruption caused to the nuclear fuel cycle operations would be limited.

NPPs are generally designed and constructed to withstand airborne attacks by light aircraft, and Bushehr NPP is no exception. The plant, which was partially completed by Kraftwerk Union of Germany, was bombarded by Iraq in the 1980s. The external containment structure, made of reinforced concrete, was damaged, but not destroyed. However, the ancillary facilities (utilities) are highly vulnerable to aerial attacks, including drone strikes. Built on the northern shores of the Persian Gulf, the NPP is also vulnerable to attacks by UMVs. UMVs, as noted previously, are commercially available as 'Surface UMVs' and 'Submersible UMVs', with an operating range of some 120 kilometres.

UMVs could attack the water inlet and outlet systems, forcing the power plant to shut down. UAVs (drones) could damage the water treatment facilities which supply cooling water to the NPP, and also to the 'spent fuel ponds (pools)'. A synchronised attack on the cooling water facilities, external electricity supply and electricity distribution systems could lead to the overheating of the reactor core and the spent fuel ponds (pools). Under such circumstances, as in the Fukushima nuclear accident, the reactor core could melt down, followed by hydrogen explosions and uncontrolled release of radioactivity into the air and the marine environment. Fatalities and extensive ecological, social and economic harm could ensue. Oil extraction, gas production and shipping in the Persian Gulf could also be disrupted.

Moreover, the massive turbine halls and electricity generators at Bushehr NPP – a common feature of all power plants – could come under aerial drone attack, forcing the NPP to shut down and causing severe disruption to electricity supplies.

The heavy water plant at Arak, which started operating in 2006, produces 20 tonnes of heavy water per annum. Heavy water is neither a nuclear material nor a radioactive substance. Hence, it is not of proliferation or radiological security concern *per se*. However, it is used as a 'coolant' and 'moderator' in the Arak (Khondab) Heavy Water Research Reactor. The heavy water plant is highly vulnerable to aerial attacks, including drones, as the key components of the plant are tall columns built outdoors. The reactor is currently undergoing modification to reduce the proliferation risks associated with it, as required under the provisions of the JCPOA. Heavy water reactors generate Pu during normal operation, which could be extracted and diverted for non-civilian uses. [110] All nine nuclear-capable States have used Pu in their weapons programmes.

The heavy water reactor is not operational as yet. However, it could come under pre-emptive drone attack due to its proliferation sensitive nature. Once operational, it could become a target for hostile State and non-State actors. As noted previously, in 1981, Israeli jets destroyed

[107] Rose, "Drone attack".

[108] Arie Egozi, "Iranian Nuke Centrifuge Plant Badly Damaged By Drones", *Breaking Defense*, 25 June 2021, https://breakingdefense.com/2021/06/iranian-nuke-centrifuge-plant-madly-damaged-by-drones/.

[109] ToI Staff, "IAEA says its equipment in Iran was damaged in blast associated with Israel", *The Times of Israel*, 8 September 2021, https://www.timesofisrael.com/iaea-says-its-equipment-in-iran-was-damaged-in-blast-associated-with-israel/.

[110] Kerr, "Iran's Nuclear Program", 28-30.

Iraq's Osirak nuclear research reactor, which was under construction.[111] Also, in 2007, Israel carried out a pre-emptive air raid on Syria's research reactor. The reactor, the construction of which was not declared to the IAEA, was about to come into operation.[112]

Spent (irradiated) nuclear fuel from NPPs and research reactors is temporarily stored close to where it is generated, in order for the radioactivity levels to diminish in intensity. The spent fuel is subsequently sent to long-term storage facilities. Countries with nuclear weapons programmes reprocess the spent fuel rods to extract the Pu generated. In relation to Bushehr NPP, Russia, under a contract with Iran, supplies the fresh fuel and takes back the spent fuel. Hence, Iran has no access to the spent fuel. In the past, however, Iran has conducted small-scale reprocessing at the Tehran Nuclear Research Centre and at the Esfahan Nuclear Technology Centre.

Iran also operates two small radioactive waste storage facilities – in Karaj, near Tehran, and at Anarak, in Yazd. These facilities are not considered proliferation sensitive and, thus, are unlikely to be the target of aerial attacks, including drone strikes.

In the remote and unlikely event of an all-out strike, Iran's research reactors, nuclear research laboratories (based in academic institutions), radioactive waste storage tanks and waste storage ponds could be targeted. This could have severe radiological and environmental implications, as these facilities are not generally designed and constructed as robustly as NPPs. Release of radioactivity could result in loss of life, injury, psychological damage, economic loss, disruption to public amenities and ecological harm. Under the circumstances, Iran could decide to retaliate directly against critical infrastructure targets in the Middle East, including the NPP in the UAE. It could also mobilise its proxies to launch drones, rockets and missiles against Israel's nuclear research centres and reactors.

[111] Borzou Daragahi, "Israel's 1981 bombing of Iraq nuclear reactor may have fuelled Saddam's nuclear ambitions", *The Independent*, 7 June 2021, https://www.independent.co.uk/news/world/israel-iraq-nuclear-osirak-military-b1861255.html.

[112] Eglash, "Syrian reactor".

Chapter 5. Concluding Remarks and Recommendations

Iran has established a comprehensive nuclear programme, aspects of which are highly proliferation sensitive and of concern to a number of countries in the MENA region and beyond.

Iran's lack of transparency in its past nuclear activities, and lack of full cooperation with the IAEA, has generated distrust in the nature of its nuclear programme.

Iran's centrifuge enrichment capabilities have reached the stage where it could produce weapon-grade uranium (90%) in less than two months. Equally, Iran's heavy water reactor, which is undergoing modifications, could have the potential to generate weapon-grade plutonium if not reconfigured. These proliferation sensitive facilities are, consequently, vulnerable to sabotage, cyberattacks and drone strikes.

Iran's other facilities, including the hydrogen fluoride (HF) plants and uranium hexafluoride plants (UF_6), which are regarded as critical elements of its nuclear fuel cycle, are also of proliferation concern, and equally vulnerable to attacks by hostile State and non-State actors. Drones, in particular, pose a major threat to these facilities which are built above ground. The degree of risk posed is high, as these facilities constitute likely targets for drone strikes, and any disruptions would have significant impact on other fuel cycle operations. Commercial drones, laden with explosives, may be launched from a few kilometres away. They generally evade air defence systems, due to their size and low altitude of flight, and their origin and identity cannot be easily ascertained.

Explosive-laden drones also pose a significant threat to Iran's ancillary facilities (utilities), which are built above ground, including cooling water, external electricity and air supplies to underground facilities. They are highly vulnerable, and have been the target of drone strikes, sabotage and explosions in the past 15 years.

Should current diplomatic efforts to revive the 'Iran Nuclear Accord' (JCPOA) fail, an increase in the frequency of cyberattacks, sabotage and drone strikes against Iran's nuclear-related facilities would be likely. A successful conclusion of the negotiations may not prevent sporadic sabotage attacks, as Israel has reiterated that it will try to sabotage, delay or destroy Iran's nuclear program.[113] However, as recent events in the Persian Gulf have demonstrated, Iran could decide to retaliate by attacking critical infrastructure in Bahrain, Saudi Arabia and the UAE, including the UAE's NPP.

Also, Iran, through its proxies in Iraq, Lebanon and Syria, could launch strikes against Israel's nuclear sites and other critical infrastructure. Israel's 'Iron Dome' has been penetrated a number of times in recent years, and has proved not to be infallible.

In de-escalating hostilities and tension in the region, the international community needs to lend its full support to the IAEA, to provide assurance that Iran's nuclear programme has no military dimensions and that there are no undeclared nuclear facilities and nuclear materials in Iran.

Equally, diplomatic efforts, at regional and international levels, need to succeed in averting a nuclear arms race in the MENA region, and in restoring peace, stability and security in an already turbulent region. Diplomacy must prevail.

[113] Steven Erlanger, "Iran Insists on Immediate Lifting of Sanctions as Nuclear Talks Resume", *The New York Times*, 29 November 2021, https://www.nytimes.com/2021/11/29/world/europe/iran-sanctions-nuclear-talks.html.

Appendix 1. Iran's Nuclear Facilities under IAEA Safeguards [A B C D E]

Facility/Site	Function	Location	Status
Saghand Uranium Mine	Uranium Ore Extraction	Saghand, Yazd	Operational
Gchine Uranium Mine	Uranium Ore Extraction	Bandar Abbas	Operational
Ardakan Uranium Ore Concentrate Plant	Yellowcake Production	Ardakan, Yazd	Operational
Bandar Abbas Uranium Ore Concentrate Plant	Yellowcake Production	Bandar Abbas	Operational
Tehran Research Reactor (TRR)	Nuclear Research	Tehran	Operational
MIX Production Facility	Molybdenum, Iodine and Xenon Radioisotope	Tehran	Operational
Jabr Ibn Hayan Multipurpose Lab (JHL)	Nuclear Fuel Cycle-Related Research	Tehran	Operational
Miniature Neutron Source Reactor	Nuclear Research Reactor (30KWth)	Esfahan	Operational
Light Water Sub-Critical Reactor	Nuclear Research Reactor	Esfahan	Operational
Heavy Water Zero Power Reactor	Nuclear Research Reactor	Esfahan	Operational
Uranium Conversion Facility (UCF)	Converting Yellowcake to UO_2 and UF_6 gas	Esfahan	Operational
Fuel Manufacturing Plant (FMP)	Production of Uranium Fuel Rods	Esfahan	Operational
Fuel Plate Fabrication Plant (FPFP)	Production of Uranium Fuel Plates	Esfahan	Operational
Enriched UO_2 Powder Plant	Production of Uranium Oxide Powder	Esfahan	Operational
Zirconium Production Plant	Production of Tubes to Encase the Fuel Rods	Esfahan	Operational
Pilot Fuel Enrichment Plant (PFEP)	R&D and U-235 Enrichment, using Centrifuges, 2003	Natanz	Operational
Fuel Enrichment Plant (FEP)	U-235 Enrichment, using Centrifuges, 2007	Natanz	Operational
Fordow Fuel Enrichment Plant (FFEP)	U-235 Enrichment, using Centrifuges, 2011	Fordow, near Qom	Operational
Arak Heavy Water Plant (HWPP)	Production of Heavy Water (D_2O)	Arak	Operational

Arak (Khondab) Heavy Water Reactor (IR-40)	Nuclear Research Reactor (20MWth)	Arak	Under Modification
Bushehr Nuclear Power Plant (BNPP)	Power Reactor (1000MWe)	Bushehr	Operational
Karaj Waste Storage	Nuclear (Radioactive) Waste Storage Facility	Karaj	Operational
Anarak Nuclear Waste Repository	Storage of Radioactive Waste	Anarak, Yazd	Operational

A "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran", IAEA, *GOV/2015/50*, Annex I, 27 August 2015, https://www.iaea.org/sites/default/files/gov-2015-50-derestr.pdf.

B "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran", IAEA, *Annex II*, *GOV/2015/65*, 18 November 2015, https://www.iaea.org/sites/default/files/gov-2015-65.pdf.

C "Protocol Additional to the Agreement".

D The above list excludes the four undeclared sites which the IAEA has recently reported as being contaminated with uranium. "NPT Safeguards Agreement with the Islamic Republic of Iran", IAEA, *GOV/2021/15*, 23 February 2021, https://www.iaea.org/sites/default/files/21/03/gov2021-15.pdf.

E Also see, Hussein D. Hassan, "Iranian Nuclear Sites", Congressional Research Service, *CRS Report*, 9 August 2007, https://sgp.fas.org/crs/nuke/RS22531.pdf; "Iran watch, 'Table of Iranian Nuclear Sites and Related Facilities'", Wisconsin Project on Nuclear Arms Control, 23 March 2021, https://www.iranwatch.org/our-publications/weapon-program-background-report/table-iranian-nuclear-sites-related-facilities; "Nuclear Power in Iran", World Nuclear Association, updated January 2021, https://world-nuclear.org/information-library/country-profiles/countries-g-n/iran.aspx; Kerr, "Iran's Nuclear Program."

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