Interdicting Iran?

Examining military strikes on nuclear infrastructure in light of JCPOA decertification

Jack Davidson

Professor Daryl Press

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Abstract

This paper analyzes the United States' ability to launch a successful surprise interdiction strike on the Iranian nuclear program should the Trump Administration decertify Iran's compliance with the Joint Comprehensive Plan of Action (JCPOA). In analyzing a strike, this paper prioritizes specific targets, and assesses the resources needed to destroy them, U.S. capability to meet those resource demands, and its ability to defeat Iranian air defenses. I find that the United States is more than capable of launching such an attack on Iran successfully, although the air defense military balance has continued to shift in Iran's favor since the last comprehensive analyses were done over five years ago.

I. Introduction

Historical Background

Iran has had a nuclear program since the 1950s, operated a nuclear reactor since the 1960s, and been seen by the United States as a potential proliferant since the 1970s.[1] Iran shuttered its nuclear program following the 1979 Revolution but quickly restarted it in 1982 during the Iran-Iraq War. Although Iran signed the Non-Proliferation Treaty (NPT) in 1968 and is subject to International Atomic Energy Agency (IAEA) inspections and safeguards, throughout the 1980s and 1990s the U.S. tracked the time that it would take Iran to produce a nuclear weapon. Following the revelation of secret nuclear facilities in 2002, which were not disclosed to the IAEA, Iran became one of the world's primary proliferation threats. Since then, various world powers have negotiated agreements with Iran attempting to limit its nuclear program, including the "E3" (the United Kingdom, France, and Germany) in 2003 and the "P5+1" (the United States, China, Russia, and the E3 countries) in 2013. These negotiations culminated with the Joint Comprehensive Plan of Action (JCPOA) in 2015 between Iran and the P5+1, which was meant to be a comprehensive and long-term solution to the proliferation risk posed by Iran. The deal, on a broad level, exchanges sanctions relief by the P5+1 for restrictions on Iran's nuclear program and increases IAEA monitoring rights.

A military strike on Iran's nuclear program has become increasingly relevant as the Trump administration has threatened to "decertify" Iran's compliance with JCPOA, although the Atlantic Council, a think tank, notes that Iran has not been found to be out of compliance with its obligations by the JCPOA.[2] The administration's likely goal is negotiating a better deal with Iran, If Trump decertifies Iran's compliance with JCPOA and an alternative agreement cannot be reached, the United States could turn to a military strike on Iran's nuclear facilities to set back the timeline of Iran's proliferation or attempt to weaken Iran's leverage at the negotiating table. The United States has implicitly threatened military action in the past,[3] and such action has at points been supported

[1] See Kerr, P. K. (2017). *Iran's Nuclear Program: Status*. Congressional Research Service. for information in this section unless otherwise cited.
[2] Sen, A. K. (2017, October 10). What are the Implications of Decertification of the Iran Nuclear Deal? Retrieved December 05, 2017, from http://www.atlanticcouncil.org/blogs/new-atlanticist/what-are-the-implications-of-decertification-of-the-iran-nuclear-deal
[3] See Hersh, S. M. (2006, April 17). The Iran Plans. Retrieved December 05, 2017, from https://www.newyorker.com/magazine/2006/04/17/the-iran-plans Cornwell, S. (2007, November 2). Iran letter sparks new fight between Clinton, Obama. Retrieved December 05, 2017, from

by public opinion.[4] Israel has conducted military strikes on Iraqi and Syrian nuclear facilities,[5] although conventional military force has not been used by anyone so far in the case of Iran's nuclear program.[6] This paper seeks to present a clear picture of U.S. capabilities to carry out such an attack, and the potential implications.

Literature Review and Questions Posed

Two key questions bear upon the effectiveness of a U.S. interdiction strike on Iran's nuclear program. The first is one of power projection: can the U.S. successfully strike hardened facilities that are halfway around the world and as well defended as any sites in Iran? The second question is one of information, strategy, and timelines: how much time could a U.S. interdiction strike add before Iran could produce a nuclear weapon?

The conventional wisdom on the first question is clear. A review of the literature, both news[7] and academic, indicate that the United States has the military capabilities necessary to strike almost anywhere in the world, including Iran's nuclear sites. Historically, U.S. power projection has been somewhat assumed in much of the nuclear interdiction literature, with far more attention paid to potential strikes on nuclear infrastructure by Israel on the assumption that the military competitiveness is far closer in that case.[8] While the assumption that the United States is far better equipped for such a strike is correct, this assumption and the conventional wisdom that the United

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https://www.reuters.com/article/idUSIndia-30287620071102 and Kerr (2017). *Iran's Nuclear Program: Status*. 21. for discussion of "military threats" against Natanz.

[4] Mason, J. (2012, March 13). Most Americans would back U.S. strike over Iran nuclear weapon: poll. Retrieved December 05, 2017, from https://www.reuters.com/article/us-usa-iran-poll/most-americans-would-back-u-s-strike-over-iran-nuclear-weapon-poll-idUSBRE82C19Y20120313

[5] For summaries of Operations Opera (1981) and Orchard (2007), see BBC. 1981: Israel bombs Baghdad nuclear reactor. (2005, June 07). Retrieved December 05, 2017, from http://news.bbc.co.uk/onthisday/hi/dates/stories/june/7/newsid_3014000/3014623.stm and Follath, E., & Stark, H. (2009, November 02). The Story of 'Operation Orchard': How Israel Destroyed Syria's Al Kibar Nuclear Reactor. Retrieved December 05, 2017, from http://www.spiegel.de/international/world/the-story-of-operation-orchard-how-israel-destroyed-syria-s-al-kibar-nuclear-reactor-a-658663.html

[6] It is worth noting that Israel has been accused of assassinating Iranian nuclear scientists and the U.S. and Israel were accused of orchestrating the 2010 Stuxnet cyberattack on Iranian centrifuge enrichment. For examples and more information see Staff. (2015, August 07). Israel behind assassinations of Iran nuclear scientists, Ya'alon hints. Retrieved December 05, 2017, from http://www.jpost.com/Middle-East/Iran/Israel-behind-assassinations-of-Iran-nuclear-scientists-Yaalon-hints-411473 and Zetter, K. (2014, November 03). An Unprecedented Look at Stuxnet, the World's First Digital Weapon. Retrieved December 05, 2017, from https://www.wired.com/2014/11/countdown-to-zero-day-stuxnet/

[7] See Kazianis, H. J. (2017, April 10). How the U.S. Military Could Strike Iran. Retrieved December 05, 2017, from http://nationalinterest.org/blog/the-buzz/how-the-us-military-could-strike-iran-20102, Crowley, M. (2015, June 24). Plan B for Iran. Retrieved December 05, 2017, from https://www.politico.com/magazine/story/2015/06/plan-b-for-iran-119344#.VYw9YRNriu4, and Thompson, M. (2015, July 8). Iran Nuclear Deal: How the U.S. Military Would Attack. Retrieved December 05, 2017, from http://time.com/3945020/iran-nuclear-deal-military/

[8] See Cordesman, A. H., & Toukan, A. (2010). *Options in Dealing with Iran's Nuclear Program*. Center for Strategic and International Studies., Long, A., & Rass, W. (2007). Osirak Redux?: Assessing Israeli Capabilities to Destroy Iranian Nuclear Facilities. *International Security, 31*(4), 7-33. Retrieved from http://www.jstor.org/stable/4137564, Zanotti, J., Katzman, K., Gertler, J., & Hildreth, S. A. (2012). *Israel: Possible Military Strike Against Iran's Nuclear Facilities*. Congressional Research Service., Bergman, R. (2012, January 25). Will Israel Attack Iran? Retrieved December 05, 2017, from http://www.nytimes.com/2012/01/29/magazine/will-israel-attack-iran.html, and DePetris, D. R. (2015, July 22). Israel's Master Plan to Crush Iran's Nuclear Program. Retrieved December 05, 2017, from http://nationalinterest.org/feature/israels-master-plan-crush-irans-nuclear-program-13392 for examples.

States could strike Iran's nuclear sites at will is worth exploring. In examining whether or not conventional wisdom on the power projection is correct, this paper will seek to answer three key questions: whether the United States has weaponry capable of defeating Iran's hardened facilities; given resource constraints,[9] whether the U.S. would be able to muster enough forces to defeat all targets of interest; and whether recent changes to the air defense environment has shifted the balance sufficiently in Iran's favor for a successful defense against a strike on its nuclear facilities.

There is less conventional wisdom on the second question of delay, something that this paper seeks to address. In doing so, it both looks at the time it might take Iran to reconstruct essential facilities and takes a more in-depth look at Iranian centrifuge enrichment. Although there is minimal data on the time it would take Iran to rebuild its facilities or produce new centrifuges, numbers have been extrapolated from historical construction times and production numbers.

Outline of the Attack

The attack conceived and analyzed in this paper is a surprise interdiction strike intended to delay Iran's ability to acquire a first nuclear weapon for as long as possible. Such an attack is assumed to use surprise and attempt to defeat Iranian air defenses using a combination of B-2 stealth bombers, and air- and sea-launched cruise missiles for reasons described in subsequent sections. Carrier-based naval aviation would likely play some supporting role in an attack but due to weapons' range constraints, would likely be prevented from direct strikes on facilities. This attack assumes that the United States wishes to destroy Iranian nuclear facilities without initiating a Suppression of Enemy Air Defenses (SEAD) campaign, which could increase escalatory pressures on Teheran and heighten global tensions. The attack as envisioned in this paper also assumes that the United States will not use locally based forces (those stationed at bases in the region) due to political concerns. The United States also could attempt to use other methods, such as low-altitude terrain-masked flights by B-1Bs, to bring more fire power to the table, although as we shall see below, the United States has more munitions available from the less risky and more effective combined stealth and cruise missile attack than are likely necessary for an interdiction strike, making a gamble such as low-flying B-1Bs unnecessary. Permutations of attacks on Iran other than a surprise attack limited to bombing of Iranian nuclear facilities by non-locally-based forces are not considered here, and this analysis should not be treated as predictive of outcomes in an interdiction strike different from the one described above.

Geography

Although a detailed understanding of Iran's geography is not vital for understanding a U.S. strike on its nuclear program, several geographic features of Iran do place constraints on the United States. First, Iran is large, approximately 1,500 from where an attack might be launched in the Gulf of Oman to Teheran. This limits which weapons systems the United States can use in an attack as many do not have the range to hit targets deep within Iran. Second, Iran is surrounded on almost all sides by other countries, from which the United States would have to ask permission to conduct an attack transiting their airspace. The only exception is a small segment of Iran's southeast coast (around 450 km) on the Gulf of Oman in the Indian Ocean. Iran also has around 1,000 miles of southern coastline on the Persian Gulf, but it would be difficult to enter or exit the Persian Gulf or

[9] For example, the number of bombers that would likely be available for such a mission.

its airspace to conduct a surprise attack such as the one envisioned in this paper. Operating naval ships in the Persian Gulf would require that the United States transit them through the Strait of Hormuz, a dicey task in normal times[10] and highly risky to U.S. warships after a U.S. surprise attack.

Other Topics of Concern

While this paper does not address a potential Iranian response to a strike on its nuclear facilities, Anthony Cordesman and Abdullah Toukan provide a good overview in their presentation on "Options in Dealing with Iran's Nuclear Program."[11] This paper also omits potential U.S. interdiction targets related to Iran's ballistic missile program, which would require a similar length analysis of Iran's ballistic missile sites, progress, and prioritization for a strike as that presented in this paper for Iran's nuclear program. Finally, this paper largely assumes the circumstances of a strike. The political and international circumstances of a strike on Iran would help shape how it is conducted. Relative animosity in the international community towards Iran or between Iran and the United States might either lead to countries assisting the United States. in an attack or Iran anticipating and better preparing for an attack, negating surprise advantages. Different political circumstances leading up to a strike could have an impact on the military balance described here. As the analysis presented here only applies to the case of a U.S. interdiction strike that is meant to surprise and delay the current Iranian nuclear program following decertification of the JCPOA and a decision by U.S. political leaders that limited use of military force against Iran's nuclear sites *only* is the best course of action, it may not be applicable to all situations.

Structure of Analysis

This paper looks at the different sites in the Iranian nuclear program that the United States would like to target, prioritizes them based on criteria that the United States might use to determine their value to an interdiction strike, and then assesses the force requirements and likely U.S. deployment in the context of the Iranian air defense environment. Information on Iran's nuclear sites is drawn largely from the unfortunately named Institute for Science in International Studies (ISIS), International Atomic Energy Agency (IAEA), Congressional Research Service (CRS), and Department of Defense (DOD) documents. Information on United States and Iranian forces is drawn from military sources, industry publications such as *IHS Janes Land Warfare Platforms: Artillery and Air Defence*, think tanks such as *Air Power Australia*, and news sources. This analysis has been limited to public sources, which have been sufficient for much of the work, although classified knowledge of exact locations and activities at Iran's nuclear sites and U.S. confidence in the ability to disable or avoid SAM defenses by nonconventional means such as electronic warfare could further elucidate this analysis. The prioritization of Iranian nuclear sites with respect to criteria and execution is my original analysis, as is the discussion of force employment strategies and requirements for the destruction of specific targets.

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[10] See Aboudi, S. (2017, March 22). Iranian navy endangering international navigation in Gulf: U.S. commanders. Retrieved December 05, 2017, from https://www.reuters.com/article/us-mideast-security-carrier/iranian-navy-endangering-international-navigation-in-gulf-u-s-commanders-idUSKBN16T2CZ

[11] Cordesman, A. H., & Toukan, A. (2010).

Implications

The main implications of the analysis presented below are threefold. First, the United States has the capabilities necessary to destroy a wide range of targets in the Iranian nuclear program, although the balance of power has shifted towards the defender over the last five years and likely will continue to do so. U.S. attack capabilities rely on tools that are only available to the United States, which may make a similar strike more difficult or impossible for other countries. To shift the military balance definitively into a competitive state, Iran would need to invest in anti-stealth and anti-cruise missile capabilities that would allow it to counter U.S. power projection strengths. Second, such an attack could set back Iran's nuclear program by up to three years. This number is an estimate due to information gaps, but it provides an indication of the potential magnitude of the delay to Iranian nuclear capabilities that could be caused by a successful strike. Third, the continued ability of the United States to execute such an attack and the potential for significantly extending Iranian breakout time has broad implications for U.S. and Iranian foreign policies and negotiating postures. Such implications could fill an entire paper such as this one if discussed in depth, but are described briefly in Sections IX and X below.

Roadmap

The remainder of this paper is divided into eight main sections. In Section II, "Anatomy of a Nuclear Program," I will examine the different routes states can take to acquiring a first nuclear weapon and the steps on each route. In Section III, "The Iranian Nuclear Program," I will describe and provide context for the Iranian nuclear facilities within the weapons production chain. Section IV, "Target Criteria," describes three criteria (strategic value, target difficulty, and political considerations) that I use to evaluate Iran's nuclear sites and prioritize them for a strike. Sections V and VI, "U.S. Offensive Strike Capabilities" and "Iranian Air Defenses" look at the forces available to the United States and Iran that would likely be involved in an interdiction strike or defense against one. Section VII, "Prioritizing Targets," synthesizes the information of Sections III through VI to create a ranked list of targets for the United States to strike. In Section VIII, "Potential Strikes," I examine the resource allocation question of how many targets the United States could strike. Section IX, "Timelines," discusses how long such a strike could set Iran back if successful. Finally, Section X, "Conclusion" summarizes and discusses implications.

II. Anatomy of a Nuclear Program

Design

To understand how the United States might disrupt the Iranian nuclear program through a military strike, one must first understand the basics of modern nuclear weapons and their production. Atomic weapons, such as those created by the Manhattan Project during World War II and dropped on Hiroshima and Nagasaki in 1945, use nuclear fission to split the nuclei of heavy elements, in the process releasing significant amounts of binding energy that hold the nuclei together.[12] Basic atomic bombs are designed to bring together "subcritical" masses of fissile

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[12] Office of the Under Secretary of Defense for Acquisition and Technology. (1998). *Weapons of Mass Destruction Technologies* (Vol. II, The Militarily Critical Technologies List). Washington, D.C.: Department of Defense. II-5-6.

material (those that cannot sustain a chain reaction) to create a larger "supercritical" mass (where a runaway chain reaction can occur) in a very short period of time, leading to a nuclear explosion.[13]

The weapons used on Japan and those that a modern "proliferant," a nation looking to acquire a first nuclear weapon, would seek to acquire are similar in design.[14] The two designs used on Japan, a "gun-type" weapon and an "implosion" weapon, have key differences, both in terms of difficulty of design and the amount of nuclear material required to make a functioning weapon.

A gun-type weapon, like the *Little Boy* bomb dropped on Hiroshima, is considered the "easiest of all nuclear devices to construct and the most foolproof"[15] as evidenced by the story that "Manhattan Project scientists were so confident in the performance of the [design] that the device was not even tested before it was dropped on Hiroshima."[16] The gun-type design works by firing a projectile at a target, both of which are made of ^{235}U, to create a supercritical mass and trigger a nuclear explosion. This simple design is significantly less efficient than the implosion design, requiring more nuclear material to achieve a similar explosive yield.[17] The gun-type bomb is also restricted to use in uranium weapons due to the danger of premature detonation as a result of spontaneous neutron emission in weapons containing too much of a specific plutonium isotope, ^{240}Pu.[18]

The implosion design, by contrast, can be used for both uranium and plutonium weapons. Implosion devices, such as those used in the Trinity nuclear test and *Fatman* weapon dropped on Nagasaki, use conventional high explosives "to form an imploding shock wave which compresses the fissile material to supercriticality."[19] There is some degree of complexity in detonating and positioning the explosives in order to form the desired imploding shock wave but this complexity is repaid by lower nuclear material requirements and higher weapon yield for implosion devices.[20]

Research and Testing

The basic gun-type and implosion designs that would be used by a proliferant are well known and documented in the open literature, and a relatively modest amount of additional research beyond what is publically available is required to construct such a weapon. Despite the major challenges that the original developers of atomic weapons faced, the introduction of modern computers, the advancement in physics and chemistry, and the broad availability of basic knowledge related to nuclear weapons have significantly reduced the cost and difficulty of building a first nuclear weapon.[21] As a result,

> Although talented people are essential to the success of any nuclear weapons program, the fundamental physics, chemistry, and engineering involved are widely understood; no basic research is required to construct a nuclear weapon.[22]

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13 Ibid.
14 Ibid, II-5-5.
15 Ibid, II-5-6.
16 Ibid,
17 Ibid, II-5-(60-61).
18 Ibid, II-5-42.
19 Ibid, II-5-6.
20 Ibid, II-5-61.
21 Ibid, II-5-3.
22 Ibid, II-5-2.

While “detailed design information, and particularly the knowledge gleaned by the nuclear weapons states from decades of design and testing, remains classified” and thus must be reconstructed through independent research and testing by a proliferant,[23] on the whole, acquiring know-how seems to be thought of as a secondary challenge to proliferants.

Although a full-yield nuclear detonation test may be unnecessary to have confidence in a device, many smaller tests are still needed in order to construct a nuclear weapon.[24] “Moderately complex” testing is required to ensure a properly functioning gun-type bomb, but that testing focuses on the conventional components of the weapon, and none of the tests requires the use of nuclear material.[25] As an implosion weapon is more complex, such a weapon would likely require tests of both conventional components and hydrodynamic testing to ensure proper timing of components and compression of nuclear material.[26] However, both the track record of the nuclear weapons powers, which all were able successfully to achieve nuclear detonations on their first tests,[27] and the ability to validate most aspects of an implosion design using non-nuclear or low-yield tests, make a full-scale nuclear test more of a guideline than a requirement for an implosion-design proliferant.[28]

Despite the need of a proliferant to conduct research and testing to gain some of the classified knowledge required to construct a nuclear weapon, “obtaining nuclear weapon materials—plutonium or highly enriched uranium—[is] the greatest single obstacle most countries would face in pursuing nuclear weapons”[29] and thus the main focus of our discussion of nuclear weapons programs.

The Two Pathways

A potential proliferant has two potential pathways to acquire a first nuclear weapon, the uranium pathway, which requires the ^{235}U isotope (a specific type of an element with a certain number of protons and neutrons in the nucleus), and the plutonium pathway, which requires ^{239}Pu. The two pathways require distinct facilities but are in many ways related. The ability of a proliferant to switch relatively easily between the uranium and plutonium paths as Iraq did after the destruction of the Osirak reactor by switching from plutonium production to a focus on uranium enrichment[30] means that both paths warrant consideration in determining which targets to strike. The following subsections help the reader to understand how a proliferant choosing each pathway would go about procuring a nuclear weapon and the types of facilities required.

As both the uranium and plutonium pathways require some uranium as an input, it is worth understanding the terminology used to discuss uranium and its different forms. Two major isotopes of uranium exist in significant qualities in nature: ^{235}U, which is the type that is used for nuclear weapons and makes up 0.72% of naturally occurring uranium, and ^{238}U, which is slightly heavier and cannot sustain the chain reaction necessary for atomic explosion.[31] For nuclear weapons and

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[23] Office of Technology Assessment. (1993). *Technologies underlying weapons of mass destruction*. Washington, DC: U.S. Congress. 5.
[24] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-92.
[25] Ibid.
[26] Ibid.
[27] Ibid, II-5-91.
[28] Office of Technology Assessment. (1993), 152.
[29] Ibid, 3.
[30] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-44.
[31] Ibid, II-5-3.

in some nuclear reactors, natural uranium must be "enriched," which means using one of several processes to increase concentration of ^{235}U that in natural uranium.[32] Several terms of art are used to describe uranium with varying concentrations of ^{235}U. Uranium with higher concentrations of ^{235}U than natural uranium is called "enriched uranium" (>0.72% ^{235}U), which can be divided into "low-enriched uranium" (LEU), generally thought of as between 5% and 20% ^{235}U, and "high-enriched uranium" (HEU), which contains greater than 20% ^{235}U.[33] Very highly enriched uranium (>90% ^{235}U) is suitable for use in nuclear weapons and is thus called "weapons-grade," while uranium that is enriched between 3% and 5% is used as fuel for most nuclear power reactors and is thus called "reactor grade."[34] Uranium with concentrations of ^{235}U lower than that of natural uranium, usually found as a byproduct of the enrichment process, is called "depleted."[35]

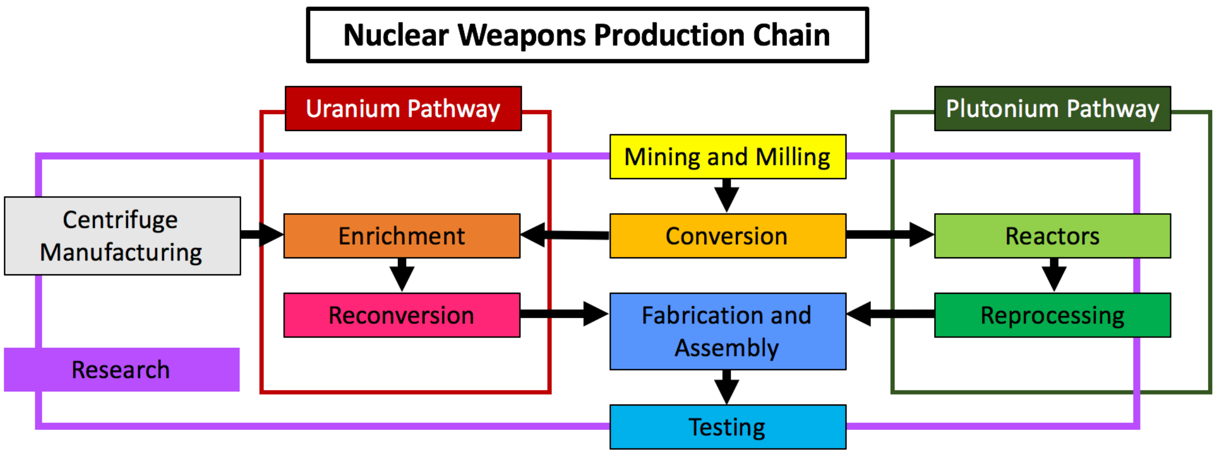

Figure 1: Diagram of the interlocking components of the nuclear weapons production chain.[36]

Uranium Pathway

For the uranium pathway, the amount of 90% ^{235}U weapons-grade uranium required to build a weapon depends on the design. For the less complex and less efficient gun-type design, between 40 and 50 kgs of weapons-grade uranium would be required, while a simple implosion weapon would require only 15 kgs of weapons-grade uranium.[37] The IAEA defines a "significant

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[32] Ibid, II-5-13.
[33] Ibid.
[34] Henderson, S., & Heinonen, O. (2015). *Nuclear Iran: A Glossary*. The Washington Institute for Near East Policy & The Belfer Center for International Affairs, 7.
[35] World Nuclear Association. (2017, May). Uranium Enrichment. Retrieved December 05, 2017, from http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx
[36] Based on graphic from Albright, D., & Hibbs, M. (1992). Iraqs Shop-Till-You-Drop Nuclear Program. *Bulletin of the Atomic Scientists, 48*(3), 27-37. doi:10.1080/00963402.1992.11460079
[37] Union of Concerned Scientists. (2004, August 01). Weapon Materials Basics (2009). Retrieved December 05, 2017, from http://www.ucsusa.org/nuclear-weapons/nuclear-terrorism/fissile-materials-basics

quantity" of HEU, "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded," to be 25 kg.[38]

Acquisition

Uranium, while rare, occurs naturally in a variety of mineral and rocky sources around the world and can be mined or extracted for use in nuclear weapons.[39] Uranium deposits vary in concentration with "high-grade" deposits containing up to 20% uranium and "low-grade" deposits containing generally 0.1% uranium.[40] To feed either an enrichment program or a nuclear reactor, uranium must be extracted and processed into more concentrated form of uranium known as yellowcake (60-80% U) through a process called milling.[41]

As described in *Technologies Underlying Weapons of Mass Destruction*, there are three main ways that a proliferant could acquire nuclear material for its weapons program. A proliferant could attempt to divert uranium from its civilian nuclear program in violation of IAEA safeguards, purchase or steal uranium, or develop an indigenous, non-safeguarded production capacity.[42] Of the three, "the surest path to a nuclear-weapons program leads through the development of a uranium-enrichment capability fed by" indigenous uranium production due to the lack of safeguards on uranium mining and milling and the significant difficulties posed by attempting to acquire uranium covertly through either of the other two means.[43]

Conversion

Following acquisition of yellowcake uranium, a proliferant must convert the uranium into gaseous form in order to enrich it to weapons-grade quality. For most enrichment processes including centrifuges (the primary method used by Iran), this form is uranium hexafluoride (UF_6), which is useful because it exists in a gaseous state if heated slightly above room temperature, and because fluorine has only one isotope (^{19}F) meaning that mass discrepancies in UF_6 are a result of the different uranium isotopes in each molecule.[44] The techniques to convert yellowcake into UF_6 are "straightforward industrial chemistry" and "are unclassified and widely known."[45]

Centrifuge Enrichment

Several methods have been developed for enriching UF_6 to obtain high concentrations of ^{235}U suitable for use in nuclear reactors and atomic bombs. The most helpful in understanding the

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[38] Although it is worth noting that the IAEA cutoff is the traditional HEU 20% ^{235}U cutoff instead of the 90% weapons-grade cutoff. INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safeguards Glossary, International Nuclear Verification Series No. 3, IAEA, Vienna (2002), 23.
[39] Federation of American Scientists. (n.d.). Uranium Production. Retrieved December 5, 2017, from https://fas.org/programs/ssp/nukes/fuelcycle/centrifuges/U_production.html
[40] Albright, D., Shire, J., & Brannan, P. (2009). *Is Iran running out of yellowcake?* Institute for Science in International Studies, 2.
[41] Federation of American Scientists. (n.d.). Uranium Production.
[42] Office of Technology Assessment. (1993), 129.
[43] Brown, G., Carlyle, M., Harney, R., Skroch, E., & Wood, K. (2007). Interdicting a Nuclear-Weapons Project. *Operations Research, 57*(4). doi:10.21236/ada486685, 869.
[44] Federation of American Scientists [Federation of American Scientists]. (2009, April 3). *CentrifugeVideoFAS* [Video file]. Retrieved from https://youtu.be/vPZP_q7WMcY
[45] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-10.

nuclear program of a potential proliferant is gaseous centrifuges, though gaseous diffusion, electromagnetic isotope separation, and laser isotope separation also deserve mention.

Using gas centrifuges for isotope separation such as uranium enrichment was first proposed in 1919 and first successfully demonstrated in 1934.[46] Although abandoned by the Manhattan Project due to technology constraints,[47] DOD describes it as "likely to be the preferred [enrichment] technology of the future due to its relatively low-energy consumption, short equilibrium time, and modular design features."[48] Centrifuges consist of hollow, capped cylindrical tubes, called "rotors" that are "between 1 and 4 meters long and between 10 and 30 centimeters in diameter."[49] The rotors are mounted vertically, filled with UF_6, and induced to spin along the axis of the rotor at speeds greater than 500 meters per second.[50] The rotors are spun within a casing, which is used both to create a vacuum around the rotor to reduce friction and "to contain the rapidly spinning components in the event of a failure."[51] Without the casing, failure in one centrifuge could destroy large numbers of the devices, which are generally mounted in close proximity for reasons explored below.

Centrifuges use the different masses of ^{235}U and ^{238}U to separate the two isotopes contained in UF_6. The high speed of rotation of centrifuges means that the effective force near the wall of the rotor can be incredibly strong, allowing the centrifuge to separate the slightly heavier and slightly lighter forms of UF_6. This separation process can be accelerated by either heating one end of the centrifuge or using baffles to create a "relatively slow axial countercurrent flow of gas within the centrifuge that concentrates enriched gas at one end and depleted gas at the other."[52]

Several potential weak points in centrifuge enrichment are worth considering for our purpose of interdicting a proliferant's nuclear weapons program. A centrifuge's ability to separate uranium isotopes is proportional to "the length of the rotor and the rotor wall speed."[53] The level of technological advancement in centrifuge materials and design has a direct impact on the separation ability of the centrifuges and thus the speed at which a proliferant is able to enrich uranium. This linkage makes disruption of a centrifuge research and development program a way of potentially imposing a delay on enrichment throughput.[54] Another vulnerability is the reliance of gas centrifuges on very high-frequency alternating current, which requires the conversion of "input at the 50- or 60-Hz line frequency available from the electric power grid [to an] output at a much higher frequency (typically 600 Hz or more)."[55] This conversion is required as "the speed of an alternating current motor is proportional to the frequency of the supplied current," meaning that the very high speed centrifuges necessitate correspondingly high frequency current.[56] This precise requirement makes the power supply a potential target for disruption of a centrifuge operation.

Although centrifuges are relatively more efficient than most of the other enrichment techniques discussed below, because "the throughput of a single centrifuge is usually small,"

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[46] Ibid, II-5-15.
[47] Federation of American Scientists. (n.d.). Uranium Production.
[48] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-15.
[49] Federation of American Scientists [Federation of American Scientists]. (2009, April 3). *CentrifugeVideoFAS* [Video file]. Retrieved from https://youtu.be/vPZP_q7WMcY
[50] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-15.
[51] Ibid, II-5-16.
[52] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-15.
[53] Ibid.
[54] Ibid.
[55] Ibid.
[56] Ibid.

"several thousand centrifuges would be required" to produce only one nuclear weapon per year.[57] Because of efficiency considerations (separating uniformly enriched uranium is more efficient than running centrifuges for extended periods of time), the enrichment process requires multiple steps in order to reach "weapons-grade" or "reactor-grade" levels of enrichment.[58] In order to enrich a larger quantity of uranium at once, many centrifuges are operated "in parallel" performing the same task simultaneously.[59] As a single set of centrifuges (a "stage") cannot enrich uranium very much on its own, the partially enriched uranium (the "product") from one stage is usually used as input for another stage in an organization called a "cascade" while the slightly depleted uranium (the "tails") is usually recycled as input for an earlier stage.[60][61]

The number of stages determines how highly enriched the uranium output will be.[62] In general, nuclear programs that are designed to fuel power reactors require large quantities of LEU while those designed to produce nuclear weapons require small quantities of weapons-grade HEU. Although individual centrifuges can be used for either task, which is initially problematic for determining whether a country is trying to acquire weapons-grade uranium, the organization of the cascade and the number of stages varies depending on the goal. Countries enriching for civil programs will have a few very large stages for high throughput of LEU, while those enriching for weapons will have many, much smaller stages. Enrichment is a "progressively easier process" with 50% of the work to enrich a 90% ^{235}U isotope mix completed by the time 3% enrichment is achieved,[63] 75% by 5% enrichment, and 90% by 20% enrichment.[64] This means that most of the work required to enrich weapons-grade uranium can be done under the pretense of enriching for civilian purposes, making determining or verifying the intentions of potential proliferants challenging.

The relative ease of using centrifuges without detection as compared to most other enrichment methods represents one of the primary advantages of centrifuges for proliferants. Centrifuge enrichment in previously unknown facilities may not be detectable through heat signatures, although such signatures could potentially be used to determine the operational status of known facilities.[65] Signs of a centrifuge enrichment facility may also include "unexplained special security or military reinforcements around an industrial site" or "detectable acoustic or radiofrequency noise" at short range.[66] Other signatures of a centrifuge program include the import of high-strength and electronic materials required to construct centrifuges although these would likely be less helpful in detecting a new enrichment site in an existing centrifuge program than in monitoring the operation of known sites.

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57 Ibid, II-5-16.
58 Ibid.
59 Federation of American Scientists [Federation of American Scientists]. (2009, April 3). *CentrifugeVideoFAS* [Video file]. Retrieved from https://youtu.be/vPZP_q7WMcY
60 Ibid.
61 Office of Technology Assessment. (1993), 140.
62 Federation of American Scientists [Federation of American Scientists]. (2009, April 3). *CentrifugeVideoFAS* [Video file]. Retrieved from https://youtu.be/vPZP_q7WMcY
63 Office of Technology Assessment. (1993), 145.
64 Henderson, S., & Heinonen, O. (2015), 7.
65 Office of Technology Assessment. (1993), 163.
66 Ibid.

Other Enrichment Technologies

Other enrichment techniques have been used in the past, but all present specific problems in the context of a proliferant's nuclear weapons program.

Gaseous diffusion forces UF_6 through porous barriers through which ^{235}U moves more quickly due to its lighter weight.[67] Problems such as "difficulties associated with making and maintaining a suitable barrier, large energy consumption, [and] large in-process inventory requirements" combine to make gaseous diffusion less than ideal for a proliferant's enrichment operation.[68]

Electromagnetic isotope separation (EMIS) uses the same technique as a mass spectrometer to separate different uranium isotopes by running ionized particles through an electric field where they will follow circular paths of different radii.[69] Despite significant inefficiencies and challenges in the process, the Iraqis chose to use EMIS as their primary method of uranium enrichment in their nuclear program "because of its relative simplicity and their ability to procure the magnet material without encountering technology transfer obstacles."[70][71]

A more recent technology, laser isotope separation, takes advantage of the differing spectral properties of uranium isotopes to enrich uranium with a "high separation factor, low energy consumption (approximately the same as the centrifuge process), and a small volume of generated waste."[72] Despite the advantages that laser isotope separation could hold for an enrichment program, "the technology has proven to be extremely difficult to master and may be beyond the reach of even technically advanced states."[73]

Fabrication and Assembly

Following the production of highly enriched UF_6, a proliferant would have to convert the compound into uranium metal and mold it into the appropriate forms before it would be ready for use in a weapon. This process takes between one and three weeks, and the time to complete both the conversion to metal and the manufacture of bomb parts is known as the "conversion time."[74] This conversion requires facilities similar to those needed to convert yellowcake to UF_6. Once the uranium is in metal form, it takes only an estimated seven to ten days to shape it into components for a weapon.[75] As mentioned in the subsection above on weapons *Design*, these components can take the form of either a gun-type or an implosion bomb for the uranium pathway.

Working with nuclear materials requires skill and precautions but the fabrication of weapons components is not thought to be one of the major challenges to a proliferant. Many of the tools used to shape components \are widely available, as is the knowledge required to use them,[76]

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[67] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-15.
[68] Ibid.
[69] Ibid, II-5-14. Note that the EMIS process uses UCl_4 instead of UF_6.
[70] Federation of American Scientists. (n.d.). Uranium Production.
[71] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-14.
[72] Ibid, II-5-17.
[73] Federation of American Scientists. (n.d.). Uranium Production.
[74] Henderson, S., & Heinonen, O. (2015), 29.
[75] Ibid.
[76] Office of Technology Assessment. (1993), 13.

and the quality of these tools has increased significantly since the first nuclear weapons were produced.[77]

Plutonium Pathway

Acquisition

The obvious difference of the plutonium pathway is its use of ^{239}Pu instead of ^{235}U as its main fissile material. Plutonium does not occur naturally in large quantities.[78] As a result, plutonium used in nuclear weapons programs must be "bred" in nuclear reactors by hitting ^{238}U with neutrons to create ^{239}U, which then decays to ^{239}Pu.[79]

Like uranium, there are multiple isotopes of plutonium. The primary isotopes relevant to a nuclear program are ^{239}Pu, which is the fissile plutonium material desired for bombs and the plutonium equivalent of ^{235}U, and ^{240}Pu, which has one more neutron in its nucleus and "decays by spontaneous fission and should therefore be minimized in weapon fuel."[80] "Weapons-grade" plutonium contains greater than 93% ^{239}Pu, although unlike uranium "essentially all isotopic mixtures of plutonium—including reactor-grade plutonium (around 76% ^{239}Pu)—can be used for nuclear weapons."[81] Higher-grade plutonium is better for nuclear weapons due to the increased danger of pre-detonation due to spontaneous neutron emission from ^{240}Pu and the possibility of a "fizzle" causing smaller detonation than desired, although explosive yield in such a case will still be significant.[82]

Nuclear Reactor Types and Isotope Output

Although plutonium below weapons grade can be refined in a similar manner to uranium to obtain a mixture of primarily ^{239}Pu, "in practice, it is simpler to alter the reactor refueling cycle to reduce the fraction of plutonium which is ^{240}Pu."[83] Because altering reactor design and configuration is the primary method of calibrating the isotopic mix of plutonium for use in nuclear weapons, understanding different reactor types, their functions, and their isotope outputs is worthwhile. The list below closely parallels the categories defined by the Department of Defense (DOD) in their chapter on "Nuclear Fission Reactors" from *Weapons of Mass Destruction Technologies*.[84]

<u>Research reactors</u> typically produce minimal power and use relatively highly enriched uranium as fuel.[85] Research reactors are of proliferation concern because ^{238}U can be inserted into the reactor core or placed as a "blanket" in order to breed ^{239}Pu.[86] Research reactors that can be refueled during operation (on-line refueling) "are of special concern for plutonium production

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[77] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-79.
[78] Ibid, II-5-43.
[79] Ibid.
[80] Ibid.
[81] Union of Concerned Scientists. (2004, August 01).
[82] Ibid.
[83] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-13.
[84] See Ibid, II-5-(42-47).
[85] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-42.
[86] Ibid.

because they can limit fuel burnup, which enhances the quality of the plutonium compared to that obtained from reactors that require high burnup before shutdown and refueling."[87]

Power reactors are designed to generate electrical power and are usually fueled by LEU.[88] Although the skills required to design, build, and operate a power reactor are transferable to operating reactors that are of greater proliferation concern,[89] power reactors "provide little opportunity for the proliferant to obtain fuel for a weapon" as most types of power reactors cannot be refueled without "extended, easily detected shutdowns" and produce low-quality plutonium in spent fuel due to high burnup rates.[90] It is also "difficult to irradiate fertile material in power reactors and uneconomical to shut down frequently to extract the fuel at the low burnup levels that yield high-quality plutonium."[91] Thus, neither spent fuel nor inserted breeder materials are practical for producing high quality plutonium in power reactors.

Production reactors are "built for the express purpose of producing plutonium for nuclear weapons."[92] This is the type of reactor designed to produce plutonium for the Manhattan Project during World War II and presents the greatest proliferation threat. These reactors are configured to produce either high-grade plutonium or tritium for nuclear weapons and to do so relatively efficiently.[93] Such reactors often use either high-grade graphite or heavy water as a moderator.[94][95] Because of the desire to produce high-quality plutonium, "plutonium production reactors usually are designed with on-line refueling so that relatively little ^{240}Pu is found in the "spent" fuel."[96]

Heavy Water Production

Heavy water is "the key to one type of *production* reactor in which plutonium can be bred from natural uranium. (Emphasis added)"[97] Along with high-grade graphite, heavy water can be used to operate a natural-uranium-powered reactor. Heavy water has the same elemental makeup as regular water (H_2O) although both of the hydrogens in heavy water are the deuterium isotope that has a neutron as well as a proton in its nucleus.[98] Much as ^{235}U occurs in small quantities in nature and must be acquired through an enrichment program, heavy water is produced through enriching regular water, which contains 0.015% deuterium, to purity of greater than 99.75%.[99] Heavy water separates from natural water more easily than ^{235}U does from natural uranium, but higher purity requirements offset this somewhat. Although industrial-scale production of heavy water requires facilities and infrastructure, the requirements are similar to those of "common industrial processes" such as "ammonia production [and] alcohol distillation."[100]

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[87] Ibid.
[88] Ibid.
[89] Ibid, II-5-44.
[90] Ibid.
[91] Ibid.
[92] Spinrad, B. I., & Marcum, W. (2017, May 09). Nuclear reactor. Retrieved December 05, 2017, from https://www.britannica.com/technology/nuclear-reactor/Liquid-metal-reactors
[93] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-43.
[94] Ibid.
[95] Spinrad, B. I., & Marcum, W. (2017, May 09).
[96] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-43.
[97] Ibid, II-5-113.
[98] Ibid, II-5-112.
[99] Ibid.
[100] Ibid.

Reprocessing

To use plutonium in nuclear weapons, it must be separated from the rest of the spent fuel or breeder material that is output by a reactor. Although this process is well understood in principle as "the steps used in reprocessing are standard chemical operations and the literature on the chemistry and equipment required has been widely disseminated, the successful separation of uranium and plutonium is a formidable task."[101]

Reprocessing involves chopping up material containing plutonium and then dissolving of the material in hot acid followed by a separation system that is highly technically challenging to execute successfully.[102] The high radioactivity of the spent reactor fuel or breeder material requires serious precautions and skill, as well as specialized facilities with extensive radioactive shielding and equipment that allows technicians to handle the materials remotely.[103]

In the case of incomplete intelligence regarding a proliferant's nuclear facilities, "the plutonium-production route, which involves reprocessing of spent reactor-fuel to extract plutonium, would be easier to detect than would be a small-scale clandestine uranium enrichment facility."[104] Reprocessing facilities should be identifiable due to their use of highly radioactive materials and the requirement that they "vent radioactive gases (^{131}I, for example) to the atmosphere."[105]

Fabrication and Assembly

Fabrication and assembly concerns for plutonium weapons are similar to those for uranium ones.

Safing, Arming, Fuzing, and Firing (SAFF)

Proliferants trying to acquire nuclear weapons must have mechanisms to prevent unwanted detonations and command structures to ensure delivery when desired. The need to develop such structures is perhaps an obvious, but nevertheless important, step for all aspiring nuclear powers. According to DOD, "SAFF problems generally have simple engineering solutions."[106] While SAFF, due to its low time costs and potential redundancies, is not a particularly appealing target for an interdictor looking to target a pre-nuclear-weapons state, SAFF C4I mechanisms would likely be the target of counterforce strikes meant to disable the nuclear forces following the acquisition of nuclear weapons by a proliferant.

III. The Iranian Nuclear Program

Iran has had a nuclear program since the 1950s. According to a Congressional Research Service (CRS) report, "the United States has expressed concern since the mid-1970s that Tehran

[101] Ibid, II-5-48.
[102] Union of Concerned Scientists. (2004, August 01).
[103] Ibid.
[104] Office of Technology Assessment. (1993), 164.
[105] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-4.
[106] Ibid, II-5-67.

might develop nuclear weapons."[107] Consistent with conventional wisdom, in the unclassified "2007 National Intelligence Estimate on Iran's Nuclear Intentions and Capabilities," the CIA "assess[ed] with high confidence that Iran has the scientific, technical and industrial capacity eventually to produce nuclear weapons if it decides to do so."[108]

Prior to the 2015 Joint Comprehensive Plan of Action (JCPOA), there was significant discussion of how much progress Iran had made towards this goal. Iran has moved to solve the challenge of acquiring enough weapons-grade uranium or plutonium to build a nuclear weapon, bolstering key aspects of the nuclear production chain such as uranium enrichment capabilities and the acquisition of a nuclear reactor that could produce weapons-grade plutonium.

As pointed out by Anthony Cordesman in a heading from his 2015 book, "Fissile Material Does Not Mean Weaponization."[109] Questions surround "whether and to what extent Tehran had taken the other steps [beyond acquisition of nuclear material] necessary for producing a nuclear weapon."[110] According to a CRS report "the IAEA [in 2011 had] 'credible' information that Iran had carried out activities 'relevant to the development of a nuclear explosive device'" including the "acquisition of 'nuclear weapons development information and documentation' and work to develop 'an indigenous design of a nuclear weapon including the testing of components.'"[111] Such activities would mean that Iran went beyond the production of nuclear weapons material and included efforts to develop the technical capabilities to build a weapon.

How far this research and development program has progressed since is important to determining a target set for a U.S. interdiction strike, as sites where such research and testing take place would be higher priority targets if Iran's progress on nuclear weapons research remains relatively limited. However, the time it would take Iran to "break out" after acquiring enough fissile material for a weapon may be indeterminable from unclassified information (and perhaps even from the classified). In an October 2013 Senate Foreign Relations Committee hearing, former Undersecretary of State for Political Affairs Wendy Sherman said that it would take Iran up to a year to produce a nuclear weapon if it decided to do so, nine or ten months longer than it would take Iran to acquire the nuclear material necessary for a bomb.[112] The reason for this discrepancy was unclear, but it may signal Iran still had significant research, design, and testing barriers to overcome in order to construct a nuclear weapon. Cordesman states that "the U.S. has never publically addressed the question of Iran's real-world reaction time in moving from acquiring fissile material to actual weaponization and deployment."[113] The lack of definitive recent information on the subject makes it impossible to make well-grounded assumptions to that effect. Without clear assessment of the progress Iran has made on weapons research, development, and design, it is impossible to assign a definitive priority for targeting research facilities in a U.S. strike. This paper will assume (as a worst-case scenario) that Iran will be able to achieve a nuclear weapon as it acquires enough fissile material to build a bomb due to uncertainty in the amount of research

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[107] Kerr (2017). *Iran's Nuclear Program: Status,* summary 1.
[108] Treverton, G. F. (2007). *The 2007 National Intelligence Estimate on Iran's Nuclear Intentions and Capabilities*. Washington, D.C.: Center for the Study of Intelligence.
[109] Cordesman, A. H., & Peacock, M. (2015). *The Arab-U.S. Strategic Partnership and the Changing Security Balance in the Gulf: Joint and Asymmetric Warfare, Missiles and Missile Defense, Civil War and Non-State Actors, and Outside Powers*. Washington, DC: Center for Strategic & International Studies, 303.
[110] Kerr (2017). *Iran's Nuclear Program: Status,* 31.
[111] Ibid, 32.
[112] Ibid, 35.
[113] Ibid, 31.

and testing remaining for Iran, an assumption that relegates research facilities to lower priority as targets.

Concerns that Iran has failed to disclose some of its important nuclear facilities (as it has done in the past),[114] are likely unwarranted. According to a 2017 CRS report, "U.S. officials have argued that Iran currently does not appear to have any nuclear facilities of which the United States is unaware."[115] According to the report, "U.S. officials have expressed confidence in the ability of U.S. intelligence to detect Iranian covert nuclear facilities."[116] Statements from high level officials cited by the same report seem to corroborate this. In 2015, CIA Director John Brennan stated that the United States has "a good understanding of what the Iranian nuclear program entails," and U.S. Secretary of Energy Ernest Moniz declared, "we feel pretty confident that we know [the Iranian program's] current configuration."[117] This U.S. knowledge is compounded by Iranian disincentives under JCPOA for failing to disclose facilities. Given the effort that Iran put into negotiating the deal and its sacrifices in terms of restrictions on facilities and removal of nuclear material, it seems illogical that Iran would risk the sanctions relief that it gained to retain undisclosed facilities. While planners need to know the extent of Iran's nuclear program, something that this paper is unable to be certain of due to the lack of publically available information, it seems from the aforementioned report and disincentives to Iranian secrecy post-JCPOA that the United States likely does have confidence it understands the extent of the aspects of the program it is targeting.

Negotiations and JCPOA[118]

World powers have engaged Iran in negotiations meant to limit the proliferation potential of its nuclear program since the extent of the program was revealed in the early 2000s. These negotiations culminated with agreement of the Joint Comprehensive Plan of Action (JCPOA) in 2015. The JCPOA had three major effects on Iran's nuclear program that are important to the analysis here: it limited the quantities and qualities of nuclear material that Iran could possess, the enrichment activities it could engage in (and thus its breakout capabilities on the uranium pathway), and effectively ended the threat that Iran could quickly produce a nuclear weapon using the plutonium pathway. It had other impacts such as increased monitoring and transparency but for the purposes of target prioritization and increasing breakout time, the time it would take for Iran to produce enough weapons-grade material to make a nuclear weapon if it had the technical capability to do so, these were the three most important components. The extent to which the JCPOA affected Iran's nuclear program is controversial and has been written about extensively.[119]

The JCPOA limited Iranian stockpiles of enriched uranium, capping the enrichment level that Iran is allowed to possess at 3.67% ^{235}U and limiting stockpiles of this LEU to 300kg. Higher enriched uranium (Iran had stocks with up to 20% ^{235}U prior to the deal) were required to be either diluted, converted to reactor fuel, or shipped out of the country. Such requirements were meant to

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[114] See Kerr (2017). *Iran's Nuclear Program: Status,* for examples from the early 2000s.
[115] Ibid, 36.
[116] Ibid.
[117] Ibid.
[118] All information in this subsection comes from Katzman, K., & Kerr, P. K. (2017). *Iran Nuclear Agreement*. Congressional Research Service. unless otherwise cited.
[119] See Fallows, J. (2015, July 28). The Real Test of the Iran Deal. Retrieved December 05, 2017, from https://www.theatlantic.com/international/archive/2015/07/the-iran-debate-moves-on/399713/ for explanation of controversy.

place more space between Iran and a nuclear weapon and reduce Iran's capacity for a quick breakout.

Iran is restricted in both the enrichment activities it can engage in and the number of centrifuges that it can have installed under the JCPOA. As stated above, Iran cannot enrich uranium to high concentrations of ^{235}U (above 3.67%), and it is also limited to enriching uranium only at the Natanz nuclear facility (discussed later in this section). Under the agreement, Iran is also restricted to operating around one-third of the centrifuges it had installed at its enrichment facilities in 2013 and the other centrifuges must be disconnected from cascades and placed in storage. The agreement also places limits on the types and locations of centrifuge research and development. Although these limits on Iran's enrichment program hamper the speed at which it could acquire a nuclear weapon on the uranium pathway, the changes are not irreversible and the collapse of the JCPOA could see Iran very quickly revert to enrichment and attempt to construct a uranium weapon.

Finally, the JCPOA required that Iran disable the Arak IR-40 reactor, the most significant proliferation risk on the plutonium pathway in Iran, and rebuilt it with a design that is agreed to under the supervision of the P5+1. This disabling of the IR-40 seems to have effectively ended Iran's plutonium pathway proliferation risk as it is unlikely that Iran could replace the IR-40 in a short period of time, although caveats to that assumption are addressed in the discussion of Iran's nuclear reactors below.

Uranium Pathway

For this paper, I will assume that Iran's primary method for attempting to obtain a nuclear weapon is the acquisition of a weapons-grade uranium implosion device. This assumption largely reflects conventional wisdom that Iran "would seek to develop a simple implosion device" as its method of weaponizing HEU.[120] Although Iran has explored the plutonium pathway, it is not clear that this was ever the primary thrust of its nuclear program, and as we shall see below, current concerns about Iranian breakout are almost entirely restricted to the uranium pathway due to the JCPOA. As the uranium pathway is Iran's most likely method of attaining a nuclear weapons capability, it is similarly the prime target for an interdiction strike on Iran's nuclear program.

Mining and Milling

Although Iran's nuclear deposits are comparatively small, Iran operates two uranium mining and milling operations.[121] The uranium industry in Iran is state owned and operated by the Atomic Energy Organization of Iran (AEOI).[122]

Gachin (also known as Gchine) is a uranium mining and milling operation located near the southern Iranian city of Bandar Abbas, which has been operating since 2006.[123] Gachin is a "low-grade" (0.08%), open-pit mine designed to extract uranium contained in local salt plugs.[124] The

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[120] Samore, G. (Ed.). (2005). *Iran's Strategic Weapons Programmes: A Net Assessment*. London: International Institute for Strategic Studies.
[121] Brown, G., Carlyle, M., Harney, R., Skroch, E., & Wood, K. (2007), 869.
[122] International Atomic Energy Agency & OECD Nuclear Energy Agency. (2016). *Uranium 2016: Resources, Production and Demand*. Paris: OECD/NEA Publishing, 275.
[123] Ibid.
[124] Ibid.

Gachin mine and its corresponding mill on the same location have an annual production capacity of 21 tonnes of uranium per year with an estimated 100 tonnes of uranium recoverable from the site.[125] Gachin was notably controversial as it was initially not disclosed to the IAEA by Iran and its output of 21 tonnes per year was too low to fuel its civilian nuclear power reactor but enough to supply a uranium weapons program.[126] According to the Institute for Science in International Studies, "the information in the possession of the IAEA suggests that the [Gachin] mine was originally intended as a source of uranium for a military nuclear program" but was re-categorized as a civilian site when its existence was revealed in the early 2000s.[127]

The second uranium mining and milling operation of Saghand-Ardakan opened in 2015 and is located in the central Iranian province of Yazd.[128] The Saghand mine has two shafts that were sunk in 1999-2002 and began "underground development" in 2003.[129] The mine is very low-grade with only 0.0553% U deposits (553 ppm), below the threshold generally seen as economical to mine.[130] The Saghand mine and corresponding Ardakan mill have yearly throughput of 50 tonnes of uranium with an estimated 900 tonnes of uranium recoverable in total from the deposit.[131]

Together, these mining and milling facilities are unable fully to feed Iran's planned nuclear program, which must rely on existing stocks and purchases from other uranium producers for a portion of its fuel.[132] According to a CRS report, Iran's domestic "reserves are sufficient, however, to produce 250-300 nuclear weapons."[133] The Iranian government has plans to expand both the Gachin and Saghand-Ardakan mining-milling operations,[134] which would reduce or eliminate the need for imports.

Iran has imported yellowcake on several past occasions. In 1982, Iran imported 531 tonnes from South Africa,[135] which made up the stock of uranium that Iran relied on (along with minor indigenous production) prior to the conclusion of the JCPOA.[136] Since JCPOA, Iran has been importing yellowcake from Russia and, according to a March 2017 statement, had imported 382-384 tonnes since the agreement.[137] Current estimates of its stock of yellowcake uranium supplies as of January 2017 suggest that Iran possesses over two-hundred-thousand metric tons of yellowcake with plans to import more.[138] This quantity "significantly exceed Iran's needs for natural uranium over the next 15 years"[139] and is enough for around 50 nuclear weapons using the conversion ratio from the CRS report of the previous paragraph.

It is unclear how vulnerable Iran's mining and milling facilities are to an interdiction strike. It seems likely that at least the open-pit Gachin mine is relatively resistant to strikes though strikes

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125 Ibid.
126 ISIS - Nuclear Iran. (n.d.). Nuclear Sites. Retrieved December 5, 2017, from http://www.isisnucleariran.org/sites/
127 ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
128 International Atomic Energy Agency & OECD Nuclear Energy Agency. (2016), 275.
129 Ibid.
130 Albright, D., Shire, J., & Brannan, P. (2009), 2.
131 International Atomic Energy Agency & OECD Nuclear Energy Agency. (2016), 275.
132 See Kerr (2017). *Iran's Nuclear Program: Status,* footnote 182.
133 Kerr (2017). *Iran's Nuclear Program: Status,* 28.
134 International Atomic Energy Agency & OECD Nuclear Energy Agency. (2016), 275.
135 Kerr (2017). *Iran's Nuclear Program: Status,* footnote 150.
136 Ibid, 24.
137 Ibid.
138 Heinonen, O. (2017, January 10). Iran Stockpiling Uranium Far Above Current Needs. Retrieved December 05, 2017, from http://www.defenddemocracy.org/media-hit/olli-heinonen1-iran-stockpiling-uranium-far-above-current-needs/
139 Ibid.

on the Saghand mine could possibly collapse the mineshafts. If the U.S. wanted to strike early in the nuclear fuel cycle, Iran's milling operation, which has buildings and equipment that could be destroyed, is a more likely target. It is unclear whether the U.S. would want to attack targets so early in the fuel cycle as Iran would be able to continue to process the nuclear materials it has in its inventory.

Conversion

Iran's conversion operation is centered at the Uranium Conversion Facility (UCF), which is part of the Esfahan (Isfahan) Nuclear Technology Center.[140] The UCF has been operating since the mid-2000s and has an annual capacity of 200 metric tons (tonnes or roughly 1.1 tons) of UF_6.[141] From 2004 to 2009, it produced 541 tonnes of UF_6.[142] As of March 2015, Iran's UF_6 inventory would have been "sufficient to power Iran's planned enrichment facilities for several years."[143]The UCF can convert "yellowcake into uranium dioxide, uranium metal, and uranium hexafluoride" with its stated role being conversion for use in reactors.[144] The UCF appears to be Iran's only conversion facility.[145] It is not clear whether the UCF would be used to reconvert highly enriched UF_6 into uranium metal for casting but its importance as the dominant conversion facility in Iran's nuclear production chain makes it an appealing interdiction target regardless. If Iran did not have other conversion capabilities, which appears to be the case from past analyses of Iran's nuclear sites, "destroying [the UCF] could set back Iran's centrifuge program several years."[146] According to the 2017 CRS report on Iran's nuclear program, while able to "produce centrifuge feedstock of sufficient purity for light-water reactor fuel… whether Iran is currently able to produce feedstock pure enough for weapons-grade HEU is unclear, however."[147]

The IAEA's November 2017 report notes that Iran has kept its commitment to having less than 300 kg of 3.67% LEU UF_6 which according to the report is the equivalent of 202.8 kg of uranium.[148] As of November 5, 2017, Iran had 96.7 kg of 3.67% LEU.[149] Depending on whether this number is for pure uranium or UF_6, Iran would have enough uranium to produce roughly 3.95 kg of 90% enriched, weapons-grade uranium (insufficient for producing a weapon) assuming no ^{235}U remaining in tails and no loss of material during the enrichment process.[150] As such, Iran would need to convert and enrich more uranium to produce a first nuclear weapon. This is important to the U.S. strategic picture as disruption of conversion, mining, milling, uranium stockpiles, or other avenues for the Iranian nuclear program to obtain more uranium to enrich could stall Iran's pursuit of a weapon until rectified.

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140 Henderson, S., & Heinonen, O. (2015), 20.
141 Ibid.
142 Kerr (2017). *Iran's Nuclear Program: Status,* 23.
143 Henderson, S., & Heinonen, O. (2015), vii.
144 Ibid, 20.
145 Albright, D., & Hinderstein, C. (2003, March 14). The Iranian Gas Centrifuge Uranium Enrichment Plant at Natanz: Drawing from Commercial Satellite Images. Retrieved December 05, 2017, from http://www.isis-online.org/publications/iran/natanz03_02.html See discussion of no conversion at Natanz and enrichment being fed by UCF Esfahan.
146 Sokolski, H., & Clawson, P. (Eds.). (2004). *Checking Iran's Nuclear Ambitions*. Strategic Studies Institute, 120.
147 Kerr (2017). *Iran's Nuclear Program: Status,* 24-25.
148 IAEA (2017). GOV/2017/48, Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015).
149 GOV/2017/48
150 96.7 kg * (3.67% / 90%) = 3.94321 kg. These assumptions are unrealistic in favor of Iranian enrichment.

Enrichment

Iran has three significant known uranium enrichment facilities. Two, the Fuel Enrichment Plant (FEP) and the Pilot Fuel Enrichment Plant (PFEP), are located at Natanz, the "primary site of Iran's gas centrifuge program."[151] The Fordow Fuel Enrichment Plant (FFEP), located at Fordow (also known as Fordo), is smaller but better fortified, an important consideration for a potential attack to interdict Iran's military nuclear capability.[152]

Centrifuge enrichment activities at Natanz center primarily around FEP. FEP is a set of "three large underground buildings, two of which are designed to be cascade halls,"[153] which could hold "as many as 54,000 centrifuges" according to one estimate.[154] All three underground buildings are connected to the surface by a disguised vehicle access tunnel. In the original 2014 JPOA, Iran halted installing new centrifuges at the facility meaning that the facility peaked at around 9,000 IR-1 and 1,000 IR-2m centrifuges installed.[155] Under the JCPOA, Iran is limited in the number and type of centrifuges that can be installed at the facility as well as the enrichment that can occur there.[156] As of May 2016, Iran had only 5,060 IR-1 centrifuges, an older model, installed at FEP.[157] FEP is notably "protected by a cover of cement, rocks, and earth many feet deep to protect it from airstrikes"[158] with the cascade halls estimated to be approximately 20 meters (65 feet) underground.[159] Satellite imagery taken during the construction of FEP "showed the construction of thick concrete walls"[160] adding to the difficulty of destroying the facility. According to a *Reuters* report on the fortification of Iran's enrichment facilities,

> Mark Fitzpatrick, an Iran expert at London's International Institute for Strategic Studies, said that Natanz was buried under several layers of dirt and concrete but it was "nevertheless possible to damage it with precision bombing with one sortie to create a crater and second sortie to burst through the bottom of the crater to the facility below."[161]

Given the assumed depth of FEP's enrichment halls and the claimed depth of U.S. bunker-buster weapons (discussed in more detail below), theoretically FEP could be destroyed with just one bomb. It seems as though the separate underground enrichment halls, Production Halls A and B and the third underground building, would at a minimum require one bomb each to destroy all centrifuges fully if the halls are properly fortified and compartmentalized.

PFEP, which began operation in October 2003, is "Iran's centrifuge research and development facility that uses uranium hexafluoride."[162] Historically, PFEP has tested both

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[151] ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
[152] Ibid.
[153] Ibid.
[154] Henderson, S., & Heinonen, O. (2015), 8.
[155] Ibid, 11.
[156] Kerr (2017). *Iran's Nuclear Program: Status,* 17.
[157] Ibid.
[158] Henderson, S., & Heinonen, O. (2015), 8.
[159] Reuters Staff. (2012, January 12). Iran nuclear sites may be beyond reach of "bunker busters". Retrieved December 05, 2017, from https://www.reuters.com/article/us-iran-nuclear-strike/iran-nuclear-sites-may-be-beyond-reach-of-bunker-busters-idUSTRE80B22020120112
[160] ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
[161] Reuters Staff. (2012, January 12).
[162] ISIS - Nuclear Iran. (n.d.). Nuclear Sites.

individual centrifuge models and production-scale cascades.[163] While the test cascades usually combine the product and tails of the output such that no enrichment occurs as a result of the tests, PFEP can and has been operated to enrich uranium up to 20% ^{235}U.[164][165] PFEP "has a cascade hall that can accommodate six cascades" (likely around 1,000 centrifuges in total due to Iran's use of 174 centrifuge cascades), and in the past, two of the six cascades at PFEP were at points used for this 20% enrichment task.[166] A strike meant to eliminate all Iranian enrichment capabilities thus must destroy PFEP as well as FEP and the facility at Fordow (discussed below), despite PFEP's small potential throughput as compared to FEP. As an aboveground building, PFEP is far more vulnerable to an airstrike than the fortified FEP and thus would likely not require the bunker-buster weaponry that other facilities important to Iran's enrichment program would. Even though Iran's main enrichment capacity lies in other facilities (FEP), destruction of the PFEP could be a significant, long-term handicap to Iran's enrichment program. Most of Iran's other current centrifuges are the old and relatively inefficient IR-1 model, and the testing with nuclear materials that is required to design and introduce new models is restricted to the PFEP under JCPOA and mechanical testing occurs only at PFEP and the Tehran Research Center.[167]

A *GlobalSecurity.org* analysis of 2006 satellite imagery of the facility identifies other potential targets at the Natanz site, including an administration building. Iran also houses its centrifuge "research, development, and assembly" facilities in aboveground buildings at the site, a key target for the U.S. if it wanted to attack Iran's centrifuge enrichment program.[168] A 2003 Institute for Science in International Studies (ISIS) analysis found that six of the aboveground buildings were devoted to these functions with many other buildings having undetermined functions.[169] Such buildings would likely be prioritized in an attack although other buildings would likely be targeted as well due to uncertainty.

The Fordow Fuel Enrichment Plant (FFEP) began construction in 2006-2007 and was "fully outfitted" with centrifuges in late 2012 – early 2013.[170] FFEP has two cascade halls, which are "each designed to hold 8 cascades of 174 centrifuges per cascade" for a combined total of approximately 3,000.[171] Although it does not have the same enrichment throughput as Natanz, according to an American estimate FFEP "would be capable of producing approximately one weapon's worth" of HEU each year if operating at full capacity.[172] Although Iran originally stated it would install advanced centrifuges at FFEP, Iran instead installed 2,710 IR-1 centrifuges at the facility by November 2013.[173][174] From 2011 to 2013, Iran transitioned its program that enriched uranium up to nearly 20% ^{235}U from PFEP to FFEP using the 3.5% enriched UF_6 produced at Natanz as feed for this process.[175] Under JCPOA, FFEP was transformed into "a nuclear, physics,

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[163] Henderson, S., & Heinonen, O. (2015), 16.
[164] Kerr (2017). *Iran's Nuclear Program: Status,* 17.
[165] Ibid, 18.
[166] IAEA (2017). GOV/2011/65, Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran.
[167] Kerr (2017). *Iran's Nuclear Program: Status*, 19.
[168] Nuclear Threat Initiative. (n.d.). Facilities. Retrieved December 06, 2017, from http://www.nti.org/learn/facilities/ and ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
[169] Albright, D., & Hinderstein, C. (2003, March 14).
[170] ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
[171] Ibid.
[172] Kerr (2017). *Iran's Nuclear Program: Status,* 35.
[173] ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
[174] Kerr (2017). *Iran's Nuclear Program: Status,* 19.
[175] ISIS - Nuclear Iran. (n.d.). Nuclear Sites.

and technology centre," and the number of centrifuges installed at the facility was reduced to 1,044 IR-1s (likely six cascades of 174).[176] The facility no longer contains nuclear material, and the centrifuges are used currently for "'for the production of stable isotopes' for medical and industrial uses."[177] Iran told the IAEA in 2009 that FFEP was built as a "contingency enrichment plant, so that the enrichment activities shall not be suspended in the case of any military attack" due to the threat to enrichment operations at Natanz.[178] As such it is more strongly fortified than FEP, "believed buried up to 80 meters (260 feet) deep on a former missile base controlled by the elite Revolutionary Guards Corps"[179] "within a mountain in order to harden the facility against a potential military strike."[180] There is some question whether the United States could successfully destroy the plant using a conventional strike and the force employment that would be required to do so. Such concerns are discussed in Section VII below.

Ideally a strike on Iran's centrifuge enrichment capacity would also destroy centrifuges that have not been installed and are in storage, preventing Iran from replacing damaged or destroyed centrifuges without entirely new production. Some of the centrifuges that were previously operational at Natanz have been "dismantled and stored" at the site following the implementation of the JCPOA.[181] According to the Arms Control Association, "all of the dismantled machines will be stored at Natanz under IAEA surveillance"[182] which appears to include all centrifuges that were previously installed at Fordow other than the 1,044 allowed to remain at the facility under the JCPOA.[183] According to *World Nuclear News*, the Natanz centrifuges have been disconnected and removed from Production Hall A and are being stored in Production Hall B.[184]

Iran has also dabbled in laser isotope separation in the past at a facility called Lashkar Abad in south-central Iran. Although Iran ceased operation at the site in 2003 following its public disclosure and a 2007-2008 IAEA inspection confirmed the site was being used for commercial, non-nuclear laser activities, there are some signs that it could remain a potential enrichment risk. According to the inspection, some of the equipment used for laser enrichment remained at the site, and IAEA "reports have since [2011] reported on the inspectors unsuccessful efforts to determine if Iran's laser enrichment efforts have restarted."[185] In 2011, Iran's president Mahmoud

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[176] Kerr (2017). *Iran's Nuclear Program: Status,* 19.
[177] Ibid.
[178] Ibid, 21.
[179] Reuters Staff. (2012, January 12).
[180] ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
[181] See Albright, D., & Heinonen, O. (2017). *Is Iran Mass Producing Advanced Gas Centrifuge Components?* Washington, D.C.: Institute for Science in International Studies, 3. and Blair, D. (2015, November 02). Iran starts removing thousands of centrifuges in line with nuclear deal. Retrieved December 06, 2017, from http://www.telegraph.co.uk/news/worldnews/middleeast/iran/11970271/Iran-starts-removing-thousands-of-centrifuges-in-line-with-nuclear-deal.html
[182] Davenport, K. (2015, December). Arms Control Today. Retrieved December 06, 2017, from https://www.armscontrol.org/ACT/2015_12/News/Iran-Dismantling-Centrifuges-IAEA-Says
[183] Reuters Staff. (2017, January 16). Iran sticks to deadline of nuclear deal with centrifuge move: IAEA. Retrieved December 06, 2017, from https://www.reuters.com/article/us-iran-nuclear/iran-sticks-to-deadline-of-nuclear-deal-with-centrifuge-move-iaea-idUSKBN1501R5 and Iran Watch. (2016, August 09). A History of Iran's Nuclear Program. Retrieved December 06, 2017, from http://www.iranwatch.org/our-publications/weapon-program-background-report/history-irans-nuclear-program
[184] World Nuclear News. (2015, November 19). Iran removes centrifuges from enrichment plants. Retrieved December 06, 2017, from http://www.world-nuclear-news.org/NP-Iran-removes-centrifuges-from-enrichment-plants-1911157.html
[185] ISIS - Nuclear Iran. (n.d.). Nuclear Sites.

Ahmadinejad "stated that Iran 'possessed' uranium laser enrichment technology" according to the ISIS.[186] Although Iran has not focused on laser enrichment, the destruction of Lashkar Abad might be a component of a U.S. strike attempting to wipe out all of Iran's enrichment capabilities.

Centrifuge Manufacturing[187]

Iranian centrifuge manufacturing is an important target for a U.S. interdiction attack if the U.S. wants to maximize long-term damage to Iran's nuclear weapons program. Since the JCPOA, Iran has continued to manufacture components for its more advanced centrifuge models, and although it is unclear exactly where Iranian centrifuge manufacturing takes place, some potential targets include Kalaye Electric and subsidiaries (Pars Trash and Farayand Technique,) the Defense Industries Organization (DIO) and its many subsidiaries, and others.[188] Although writers in the open literature seem to have a general sense of the location and purpose of facilities used by Iran to produce centrifuges in the past, much of this information has not been updated since the early 2000s due to a lack of IAEA inspections of the sites.[189] Although the JCPOA has helped to clarify the picture of Iran's centrifuge manufacturing somewhat, it is uncertain whether U.S. military planners know the exact details of which facilities are operational and could be used to produce centrifuge components currently. It is worth noting as well that the JCPOA limits centrifuge research and development to PFEP at Natanz making it an important target for interdicting advanced centrifuge production, although it is possible that manufacturing is occurring elsewhere.[190]

According to a 2017 ISIS analysis of Iranian centrifuge production since the JCPOA, Iran "is known to have put together more than half a dozen IR-8 rotor assemblies at the Kalaye Electric facility in north Tehran."[191] Kalaye Electric was the location of Iran's IR-1 development, assembly, and testing programs from 1997-2002.[192] Although much of Kalaye Electric's function within Iran's nuclear program was transferred to PFEP following its revelation and the Nuclear Threat Initiative (NTI) lists its status as "Dismantled,"[193] "Kalaye Electric has remained an important centrifuge research and development site"[194] as evidenced by the continued manufacture of centrifuge components at the site. According to NTI, the site consists of "two large workshops and several office buildings" and appears to be relatively concentrated, making it an easy target. Kalaye Electric also has a subsidiary, Pars Trash, that is located nearby and "manufactured centrifuge outer casings," the part of the centrifuge that creates the vacuum and shields the cascade from individual malfunctions.[195] Pars Trash "is located in Tehran among warehouses and light industrial buildings about a kilometer west of the Kalaye Electric facility."[196] In 2003 when much of Iran's

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186 Ibid.
187 Kerr (2017). *Iran's Nuclear Program: Status,* Appendix D. for a complete list.
188 These are companies listed in UN Security Council Resolution 1737 (2006) as assisting in Iran's centrifuge production. UN Security Council, *Resolution 1737 (2006)*, 23 December 2006, S/RES/1737 (2006), available at: http://www.isisnucleariran.org/assets/pdf/_UNSC_1737.pdf [accessed 6 December 2017]
189 ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
190 Kerr (2017). *Iran's Nuclear Program: Status,* 19.
191 Albright, D., & Heinonen, O. (2017).
192 ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
193 Nuclear Threat Initiative. (n.d.). Facilities.
194 ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
195 Ibid.
196 Ibid.

centrifuge production program was disclosed, Farayand Technique was "an important subsidiary of Kalaye Electric" that "conducted quality control activities for centrifuge components, including rotors, and manufactured centrifuge components for the facilities at Natanz" and had facilities for other aspects of the centrifuge production process such as assembly on site.[197] From the ISIS description of centrifuge manufacturing sites:

> According to former senior United Nations officials close to the IAEA, there remain questions about the full intended role of [Farayand Technique]. It is also unclear today whether it continues to play a role in making and testing centrifuges, including advanced ones.[198]

The ISIS discussion of Farayand Technique notes that there was a large building under construction at the site in the early 2000s, which could be used as a pilot centrifuge plant serving the same role as PFEP, though it is larger than the PFEP building.[199] It is unclear from satellite imagery whether this building was completed and if so, which building this is.

Another important component of Iran's centrifuge production is the centrifuge-related subsidiaries of Iran's Defense Industries Organization (DIO). The DIO is a state-owned military contractor that, alongside its conventional military procurement activities, owns several companies that have been named as centrifuge manufacturers.[200] Of these, three are worthy of individual mention: Khorason Metallurgy, 7th of Tir, and Kaveh Cutting Tools. 7th of Tir Industries is the site where Iran manufactured the "bellows" for its centrifuges, a key component. The site likely holds the type of high-grade steel as well as the precision equipment required to make these bellows, and the destruction of this equipment would likely hamper Iran's ability to construct more centrifuges without the purchase of new equipment and steel.[201] It is almost impossible to estimate how long it would take Iran to reacquire these components as they would almost certainly fall under sanctions or safeguard protocols and thus be impossible to import legally. Kaveh Cutting Tools and its parent company, Khorasan Metallurgy Industries manufactured non-rotating components of centrifuges using precision equipment obtained from Western companies.[202] Such non-rotating components are easier to manufacture than other parts of the centrifuge, but the destruction of the precision equipment used and desire to destroy all of Iran's centrifuge production capabilities could make them an appealing target.

As discussed, Iran's centrifuge manufacturing is spread among many sites, although these sites have the advantage of being clustered in two main target sets. Both Farayand Technique (KE) and 7th of Tir Industries (DIO) are located in the area around Esfahan, Farayand within an industrial park and 7th of Tir outside the city. The remaining sites discussed above are clustered in or near Teheran, Kalaye Electric and Pars Trash in eastern Teheran. Other sites of note in Iran's centrifuge manufacturing program include Sanam Electronic Industries and TABA (formerly Iran Cutting Tools Manufacturing Company),[203] located in northern Teheran and 50 km west of the city,

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197 Ibid.
198 Ibid.
199 Ibid.
200 Ibid.
201 Ibid.
202 Ibid.
203 According to this ISIS report, "Iran declared centrifuge manufacturing activities at the TABA centrifuge production site." Albright, D., & Heinonen, O. (2017), 4.

respectively. The only site that is far from any other nuclear targets is Kaveh Cutting Tools, which is located in northeast Iran and could only be reached by TLAMs or B-2s.

Overall, uncertainties about Iran's centrifuge program and its dispersion among many sites may make it an unattractive target for military planners, potentially wasting resources that could be used elsewhere in a roll the of the dice in hope of eliminating all centrifuge production capacity. Although each of the facilities is relatively small and would only require a few munitions, their spread throughout the country might require tasking a disproportionate number of forces (B-2s) to destroy all of Iran's centrifuge manufacturing capabilities, or require one B-2 to fly a haphazard pattern around Iran to bomb all of the sites, limiting the element of surprise. This is compounded by the problem that several of the sites located near Teheran are out of range of cruise missiles and thus could *only* be attacked using a B-2, but mitigated by the ability to eliminate facilities around Esfahan with cruise missiles if desired. Classified information on Iranian centrifuge production may better inform military planners on the precise location and extent of Iran's current centrifuge manufacturing efforts allowing for more a detailed discussion of target sets and tradeoffs than is possible here.

Plutonium Pathway

Although Iran does not appear to be primarily using the plutonium pathway to acquire nuclear weapons, particularly after the changes of the JCPOA, it has several facilities related to the pathway that are important to its nuclear program and could pose some proliferation risk.

Reactors

Iran's only civilian nuclear power reactor, Bushehr-1 is located in the southwest near the Persian Gulf. Bushehr-1 is a pressurized light water reactor of Russian design.[204] Construction of a reactor began in 1975 but Bushehr-1 did not begin producing power until 2011 due an extended halt in construction result from the Iranian revolution.[205] The reactor has a capacity of 915 MW(e),[206] large enough to "produce enough plutonium for dozens of nuclear weapons per year."[207] The reactor is fueled by 3.62% LEU fuel supplied by Russia.[208] The power reactor at Bushehr is of some proliferation concern because "low-enriched uranium fuel earmarked for Bushehr could be diverted and further enriched to weapons-grade, or the reactor could be used to produce plutonium for weapons use."[209] According to Michael Eisenstadt, a fellow at The Washington Institute for Near East Policy:

> If Tehran were willing to violate its Nuclear Nonproliferation Treaty (NPT) commitments or withdraw from the NPT, Iran could separate truly prodigious quantities (scores of bombs worth) of weapons- or reactor-grade plutonium annually—depending on fuel burn-up. Although reactor-grade plutonium is not ideal for bombmaking (Heat and radioactivity makes it difficult and dangerous to work with, while its isotopic composition makes for an

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[204] Henderson, S., & Heinonen, O. (2015), 12.
[205] Ibid, 4.
[206] Ibid.
[207] Sokolski, H., & Clawson, P. (Eds.). (2004), 116.
[208] Kerr (2017). *Iran's Nuclear Program: Status,* 27 & 37.
[209] Sokolski, H., & Clawson, P. (Eds.). (2004), 116.

inefficient and unreliable bomb in rather crude weapons designs.), the United States demonstrated the military utility of reactor-grade plutonium in a 1962 underground nuclear explosive test.[210]

Despite the potential risks of the Bushehr power reactor, "it is worth noting that light-water reactors are generally regarded as more proliferation-resistant than other types of reactors."[211] Bushehr, like most power reactors, would be an inefficient source of plutonium as the reactor's high burnup rate would lead to higher than optimal quantities of ^{240}Pu in the output's isotopic mix and would require frequent shutdowns to remove spent fuel. As a 2004 article from *Iran Watch* notes, the Bushehr reactor would produce plutonium with less than 60% ^{240}Pu if operating normally, well under the 93% that is required for plutonium to be considered weapons grade.[212] Iran operates the Bushehr reactor under IAEA safeguards, and its deal with Russia to supply fuel for the reactor requires it to return spent fuel to Russia, making it difficult for Iran to divert uranium or acquire the plutonium needed for a weapon at Bushehr.[213]

Other reactors are planned at the Bushehr site and could be included in the same target set, with construction on two new light-water power reactors of a similar but updated design to Bushehr-1[214] beginning in September 2016 and expected to take ten years.[215] These reactors may have advantages over the operating nuclear reactor as airstrike targets due to the possibility of "exposing civilians downwind to fallout" in a strike on an operational power reactor.[216] The risk of fallout certainly makes Bushehr-1 a less appealing target politically and its suboptimal configuration for plutonium production makes it a less attractive target for an interdictor.

Prior to JCPOA, the reactor of primary proliferation concern in Iran's nuclear program was the 40 megawatt (thermal) IR-40 CANDU-type heavy-water reactor located at Arak.[217] CANDU (CANadian Deuterium Uranium) reactors are a type of pressurized heavy-water reactor that are able to operate using natural uranium as fuel, and unlike most reactors, CANDUs can be refueled while operating at full power.[218] Both aspects of the CANDU design assist a proliferator in producing plutonium for nuclear weapons. Use of natural uranium fuel means that CANDUs can operate without the need for enrichment, which would have made IR-40's plutonium production impervious to a strike on Iran's enrichment facilities. The capability of online refueling makes removal of spent fuel containing high-grade plutonium easier and possible without easily detectable reactor shutdowns.[219]

The existence of a nuclear facility at Arak was revealed by an opposition group in 2002, and in 2006 the AEOI stated that the IR-40 reactor at Arak was meant to replace the TRR that was built in the 1960s.[220] The original CANDU design of the IR-40 reactor posed significant

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[210] Ibid.
[211] Kerr (2017). *Iran's Nuclear Program: Status,* 27.
[212] Iran Watch. (2004, March 01). Assessing Iran's Plutonium Reprocessing Capabilities: A Way to Obtaining Nuclear Weapons Material. Retrieved December 06, 2017, from http://www.iranwatch.org/library/private-viewpoints/assessing-irans-plutonium-reprocessing-capabilities-way-obtaining-nuclear-weapons-material
[213] Kerr (2017). *Iran's Nuclear Program: Status,* 27.
[214] Nuclear Threat Initiative. (n.d.). Facilities.
[215] Kerr (2017). *Iran's Nuclear Program: Status,* 28.
[216] Sokolski, H., & Clawson, P. (Eds.). (2004), 120.
[217] Ibid, 117.
[218] Canadian nuclear association. (n.d.). CANDU technology. Retrieved December 06, 2017, from https://cna.ca/technology/energy/candu-technology/
[219] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-(42-44).
[220] CRS Iranian Nuclear Sites 2-3

international concern that the IR-40 could be used by Iran to acquire a plutonium weapon for the reasons described above. Estimates of the plutonium that could have been produced by the IR-40 reactor suggest that if operating at full capacity it likely could have supplied enough weapons-grade material for one to two nuclear weapons per year.[221][222][223] The Arak IR-40 was fueled by natural uranium oxide supplied by the Eshfahan conversion and fuel fabrication facilities[224] and heavy water supplied by the HWPP at Arak (see below).[225]

Under the JCPOA, Iran was required "to render the Arak reactor's original core inoperable," which it has done.[226] According to the *BBC,* this was done by removing the IR-40's reactor core and filling it with cement,[227][228] which according to *The Diplomat* "will effectively bar the production of weapons-grade plutonium in the country for what is certain to be decades."[229] Should a reconstruction of its core and restart of the reactor be possible (although this appears not to be the case), the IR-40 would likely be a prime target due to its ability to produce weapons-grade plutonium and its lack of dependence on enrichment capabilities that would likely be targeted in a strike. The JCPOA also commits Iran and the P5+1 to working together to redesign and rebuild the Arak reactor in order to produce lower-grade plutonium, and in January 2016, Iran said it is "trying to complete the project in five years."[230] Given this timeline, it will likely take until 2021 for the new reactor to become operational. An under-construction reactor could provide a target for an interdiction strike if the United States believes that the new reactor with updated configuration still presents a materials proliferation risk.

The Tehran Research Reactor (TRR) is a 5 MW(t) reactor located at the Tehran Nuclear Research Center in the Iranian capital of Tehran.[231] It was built by the United States and began operation in 1967 using weapons-grade 93%-enriched uranium supplied by the United States.[232] Following the Iranian Revolution, the United States ended its supply of HEU fuel for the TRR, and in 1987, the Iranian government contracted the Argentina's Applied Research Institute to convert the reactor to using just under 20% ^{235}U LEU supplied by Argentina, a process that was completed in 1994.[233] According to the Nuclear Threat Initiative, the TRR is capable of producing 600 grams of plutonium annually, which is not enough for a nuclear weapon,[234] and it is also unclear whether this plutonium is reactor- or weapons-grade. If Iran were to rely only on the 600 grams of plutonium from the TRR to reach the IAEA-defined "significant quantity" of 8 kg Pu, it

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[221] Henderson, S., & Heinonen, O. (2015).
[222] Kerr (2017). *Iran's Nuclear Program: Status,* 26.
[223] Sokolski, H., & Clawson, P. (Eds.). (2004), 117.
[224] ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
[225] Ibid.
[226] Kerr (2017). *Iran's Nuclear Program: Status,* 26.
[227] BBC. (2016, January 11). Iran 'fills Arak nuclear reactor core with concrete'. Retrieved December 06, 2017, from http://www.bbc.co.uk/news/world-middle-east-35285095
[228] Conca, J. (2016, January 17). Iran Measures Up To The Nuclear Deal. Retrieved December 06, 2017, from https://www.forbes.com/sites/jamesconca/2016/01/14/iran-measures-up-to-the-nuclear-deal/#2f8d41b11f1b
[229] Panda, A. (2016, January 12). With Arak Reactor Core Filled, 'Implementation Day' of the Iran Deal Approaches. Retrieved December 06, 2017, from https://thediplomat.com/2016/01/with-arak-reactor-core-filled-implementation-day-of-the-iran-deal-approaches/
[230] Kerr (2017). *Iran's Nuclear Program: Status,* 26.
[231] CRS Iranian Nuclear Sites 2-3
[232] ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
[233] Kerr (2017). *Iran's Nuclear Program: Status,* 18.
[234] Nuclear Threat Initiative. (n.d.). Facilities.

would take over 13 years.[235] Around 1990, Iran engaged in activities at the TRR that indicated attempts to acquire a nuclear weapon, including production of a polonium isotope that is used as a trigger for a plutonium weapon[236] and some plutonium reprocessing experiments.[237] According to the Institute for Science in International Studies (ISIS), "of the original U.S.-supplied fuel, about 7 kilograms of irradiated HEU remains stored at the reactor site [and] Iran likewise is storing irradiated Argentine-supplied LEU."[238] It is unclear whether this irradiated material could pose a proliferation threat.

Iran has several other operational or planned nuclear reactors. Iran has been building a new 360 MW power reactor at a second site in southwestern Iran, Darkhovin, since 2008.[239] That reactor likely has similar considerations Bushehr-1 as a potential target, although it is still under construction and thus does not have the downside of potential nuclear fallout from destroying an active power reactor like Bushehr-1. There are also several smaller research reactors at Esfahan that could be included in the larger Esfahan target set but probably are too small to pose a significant proliferation risk.[240]

Reprocessing

Iran's progress on reprocessing capabilities is uncertain. According to a CRS report, "Iran acknowledged to the IAEA in 2003 that it had conducted plutonium-separation experiments" although by 2007, the IAEA "had resolved its questions about Iran's plutonium activities."[241] Iran denied that it would reprocess spent fuel from the IR-40 reactor (which could have produced high-grade plutonium) at its Arak facility. However, ISIS stated that "Iran originally declared to the IAEA that there were plans to construct a building at the Arak site with hot cells,"[242] which are the primary containment area for radiation in a nuclear reprocessing operation,[243] to facilitate "the production of long-lived radioisotopes, [which was] interpreted to mean plutonium."[244] In May 2004, Iran reversed course and "eliminated plans to construct any hot cells for long-lived isotopes."[245] It is unclear, however, how long it would take Iran to construct such reprocessing facilities if it decided to do so. Historical examples suggest construction time for a reprocessing facility to take under three years, significantly less time than it would take Iran to construct a new reactor.[246]

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[235] IAEA Safeguards Glossary (2002), 23.
[236] ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
[237] Nuclear Threat Initiative. (n.d.). Facilities.
[238] ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
[239] Reuters Staff. (2008, February 08). Iran starts second atomic power plant: report. Retrieved December 06, 2017, from https://www.reuters.com/article/us-iran-nuclear-plant/iran-starts-second-atomic-power-plant-report-idUSL0812863720080208 Unclear whether MW are thermal or electric.
[240] Pike, J. (n.d.). Esfahan (Isfahan) Nuclear Technology Center. Retrieved December 06, 2017, from https://www.globalsecurity.org/wmd/world/iran/esfahan.htm
[241] Kerr (2017). *Iran's Nuclear Program: Status,* 25.
[242] ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
[243] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-48.
[244] ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
[245] Ibid.
[246] Dey, P. K. (n.d.). Spent Fuel Reprocessing; An Overview. Retrieved December 6, 2017, from http://fissilematerials.org/library/barc03.pdf

Heavy Water Production

Also located at the Arak complex is Iran's Heavy Water Production Plant (HWPP) which began operation in 2006 and "can produce sixteen metric tons of heavy water per year [which would have been used] in the IR-40 heavy-water reactor" prior to the JCPOA requirement of redesigning that reactor and restriction on Iranian use of heavy-water reactors in the future.[247][248] According to a 2017 CRS report on Iran's nuclear program, IAEA reports "since the start of JCPOA implementation indicate that the plant… is operating."[249] While Iran has committed not to maintain an inventory of heavy water "beyond Iran's needs" and to "sell any remaining heavy water on the international market for 15 years,"[250] the HWPP could be a target for a strike that looks to disrupt the potential for a future Iranian heavy-water reactor. Such a strike could be inefficient due to Iran having "render[ed] the Arak reactor's original core inoperable"[251] and the time that would likely be required to construct a new heavy-water reactor or clear the Arak IR-40's original core. Due to these time constraints on facilities that use heavy water as an input, it is possible that a new heavy-water production plant could be built before the loss of the HWPP would be felt with significant impact on Iran's plutonium production. If so, a strike on the HWPP would be a minor inconvenience and would not actually delay Iran's nuclear program as it rests off the "critical path" described by project management theorists as the set of activities whose disruption would delay a proliferant's nuclear project.[252]

Research

Iran has conducted some explosive experiments at the military site at Parchin, which may have been related to the development of nuclear weapons.[253] As discussed above, constructing an implosion weapon requires extensive testing beforehand in order to ensure a properly functioning final design, and some have suggested that Iran has conducted this testing at Parchin.[254] Though the Parchin site is not explicitly nuclear and is officially a site for "research, development, and production of ammunition, rockets, and high explosives," such implosion-related tests "can be hidden among the conventional high explosive activities," a strategy "pursued by other proliferant states seeking to hide nuclear weapons development work" according to ISIS.[255] It is unclear whether attacking the Parchin site or implosion testing facilities in general would actually set back Iran significantly as its seems likely those facilities could likely be reconstructed or activities carried out elsewhere relatively easily compared to most nuclear facilities.

Iran also has several research facilities that have historically been connected to its nuclear program including not only the Teheran Nuclear Research Center (TNRC) where the TRR is located and the Esfahan Nuclear Technology Center (ENTC) where the UCF is located, but also other less obviously military sites including several Iranian universities.[256] This paper largely

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[247] Kerr (2017). *Iran's Nuclear Program: Status,* 26.
[248] Henderson, S., & Heinonen, O. (2015), 9.
[249] Kerr (2017). *Iran's Nuclear Program: Status,* 26.
[250] Ibid.
[251] Ibid.
[252] Brown, G., Carlyle, M., Harney, R., Skroch, E., & Wood, K. (2007), 867.
[253] ISIS - Nuclear Iran. (n.d.). Nuclear Sites.
[254] Ibid.
[255] Ibid.
[256] For list see Henderson, S., & Heinonen, O. (2015).

assumes that the United States would not deliberately target these universities for reasons described in Section VII and groups potential research targets at TNRC and ENTC in with other targets at those sites when describing the attack.

Other

Beyond facilities specific to the production of Iranian nuclear weapons, it is worth considering whether an American interdiction strike on Iran's military nuclear program should include related non-nuclear programs such as Iran's ballistic missile program and sites. That question requires a separate, and parallel, prioritization of targets that is beyond the scope of our discussion here. It also seems likely that the time to replace missile sites is shorter than the time to replace production of weapons-grade nuclear material due to the significant and specific challenges in producing nuclear material, so it is unclear whether strikes against related non-nuclear sites would increase disruption meaningfully.

IV. Target Criteria

In prioritizing targets for a strike on Iranian nuclear facilities, U.S. considerations can be grouped into three broad categories: strategic value, target difficulty, and political concerns. While strategic value focuses on the strategic mission of pushing back Iran's nuclear time table, target difficulty considers the operational challenges of executing a disabling or destructive strike, and political considerations attempt to limit escalation and legitimacy of an Iranian response.

Strategic Value

Strategic value relates to the importance of the site within the Iranian nuclear program and the extent to which destruction of a facility would delay Iran's efforts to construct a first nuclear weapon. In calculating a site's strategic value, the United States' primary considerations would likely be the time and resources required to replace lost production, a target's potential throughput, and its place within the nuclear production chain. Destruction of a nuclear site that cannot be reconstructed without significant time and effort would require that Iran either forfeit the facility's production or invest significant resources in repairing or replacing that segment of the nuclear production chain. As such, *ceteris paribus*, a facility that is harder to replace due to uniqueness within the Iranian nuclear program, difficulty acquiring factors of production for that element of the production chain, or other factors provides a more appealing target. Similarly, a strike on a facility with a higher throughput (the amount of nuclear materially that can be processed in a given timespan) would be preferable, as delaying the Iranian nuclear weapons program through a military strike is only effective if a sufficient portion of the throughput as a percentage of total capacity at that link in the production chain is affected. Ideally, an attacker would be able to locate a difficult-to-replace link in the production chain where a proliferant had its entire operation in a single facility, for instance only having one conversion facility, where a strike would effectively stall the entire chain while the missing link is replaced. Even in the case of multiple, redundant facilities working on the same link in the production chain, a strike that is able to knock out all facilities in any one activity is an ideal outcome for an interdiction strike. A final consideration is that facilities later in the production cycle are more valuable for a strike than those earlier due to the continuum of in-progress inventory within a weapons program. While a strike on a milling operation will reduce the input of nuclear materials to later stages of the weapons process, existing stocks of yellowcake and UF_6 could still be enriched and molded into weapons, while a strike later in the process, such as one targeting refining, would serve as a chokepoint that traps materials at earlier stages.

A historical example aids understanding of why prioritizing for strategic value is important and why differently structured nuclear production chains are more or less vulnerable to military strike. Israel's 1981 strike on the Osirak reactor at the center of Iraq's nuclear program is commonly used as an example of a successful strike that effectively ended a nuclear program and is the example that a modern interdiction strike on Iran would likely try to emulate.[257] The destruction of Osirak plutonium production capacity "set [Iraq's nuclear] effort several years back"[258] and led Iraq to abandon the plutonium path and focus instead on uranium enrichment.[259] Vital to the success of the mission was Osirak's visibility, vulnerability, and centrality to the production chain. Envisioning the production of a nuclear weapon along either the uranium or plutonium pathway as both vertical (from inputs procurement to assembly) and horizontal (as a percentage of the program's throughput for any vertical segment), we see that Osirak was ideally placed for its destruction to set back the Iraqi nuclear program. As the only nuclear reactor site that Iraq operated,[260] Osirak accounted for an entire horizontal segment in the production chain. The long time to construct a replacement plutonium-producing nuclear reactor effectively stalled Iraq's work on the plutonium pathway and likely led to Iraq's decision to reverse course and pursue the uranium pathway by severing Iraq's production of any plutonium and thus any plutonium weapons until a new reactor could be built. Iran has incorporated many lessons from Osirak, opting for a program that "is large, carefully concealed, and spread extensively throughout the country, with multiple pathways to a nuclear weapons capability."[261] Because Iran has created redundancies in its production chain, divided each segment horizontally into different, geographically separate facilities, and operates some capabilities on both the uranium and plutonium pathways, a careful prioritization and grouping of targets by strategic value is necessary in order to achieve the same success as Israel's Osirak strike.

Target Difficulty

Challenges to a successful military strike on specific targets consist of three key types: fortification, range required to reach the target, and air defenses (SAM sites and radar installations). First, hardened facilities require an attacker to use bunker-buster bombs, which are heavier and can require the commitment of specialized forces (such as stealthy B-2s that are able to overfly the target) to ensure destruction of the facility.[262] In the case of Iranian enrichment facilities, their fortifications require specialized weaponry including a significant commitment of forces executing a relatively difficult mission. In the case of Fordow, this can be seen through the common view that FFEP's enrichment hall is at the limit of the U.S. MOP's penetration range and in order to ensure destruction, the U.S. would likely have to commit multiple bombers carrying

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[257] See Long, A., & Rass, W. (2007) and Air attack Iran
[258] Sokolski, H., & Clawson, P. (Eds.). (2004), 113.
[259] Office of the Under Secretary of Defense for Acquisition and Technology. (1998), II-5-44.
[260] Federation of American Scientists. (2000, October 9). Osiraq / Tammuz - 33°12'30"N 44°31'30"E. Retrieved December 06, 2017, from https://fas.org/nuke/guide/iraq/facility/osiraq.htm
[261] Long, A., & Rass, W. (2007), 13.
[262] See discussion of Fordow facility and the MOP

MOPs and attempting to achieve a "consecutive miracle," a difficult mission of dropping a second bomb down a hole created by the first.[263] Such considerations are addressed below in more detail, within the context of the individual nuclear sites. As the United States would be choosing how to allocate its bomber resources, which are limited by the desire to hold some in reserve for operations in other theaters, the high cost of destroying a heavily fortified facility in terms of the forces that must be committed to do so must be weighed against its strategic value in order to determine its priority as a target. Similarly, the range to a target imposes restrictions on U.S. strike capabilities. Finally, Iran's SAM defenses limit operational freedom for non-stealth planes and thus restrict bombers such as the B-1Bs and B-52s that are equipped to carry bunker buster bombs primarily to using cruise missiles to attack targets on the periphery of Iran. Limitations that air defenses place on the use of non-stealth aircraft affect primarily the usage pattern of different platforms, making B-2s strikes more efficient in destruction of hardened facilities requiring bunker-buster weapons and those towards the interior of Iran that may be outside cruise missile range, and a long-range cruise missile strike from naval vessels and traditional bombers that are out of range of Iranian air defenses to destroy targets on the coast or close to Iran's borders.

Political Concerns

A final major consideration for a potential strike is the political implications of different targets. Since the First Gulf War, the United States has prioritized minimizing the collateral damage and political backlash of airstrikes.[264] Under Air Force doctrine, America prefers clearly military targets due to the reduced political risk of civilian casualties, and hard targets such as enrichment facilities to soft ones such as research universities due to the potential political implications of a strike. Other political concerns include symbolic considerations such as the religious significance of the city of Qom near Fordow, and scale-related considerations that might see the United States limiting the overall scope of the bombing campaign in an attempt to reduce Iranian cause for retaliation or retribution against the United States or other international political fallout. Scale considerations could restrict not only the target set but also the overall number of targets beyond resource restrictions. While such concerns are important for political decision makers, this paper deals with the potential delay that an American interdiction strike *could* have on Iran's nuclear program and thus largely ignores the political scale-based concerns. Such political considerations do likely further discourage the United States from attacking inactive nuclear facilities for fear of minimal gain in delaying Iran while incurring greater risk of political and military consequences and this discouraging effect will be accounted for here. Although the prioritization calculus is likely dominated by evaluations of strategic value and target difficulty, particularly in the case of a comprehensive strike, focusing only on these two criteria will largely lead to similar target prioritization as a comprehensive approach, although political considerations might constrain the potential target set in a more limited strike.

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[263] Air Force News. (1998, May 19). B-2 achieves 'consecutive miracle'. Retrieved December 06, 2017, from https://fas.org/nuke/guide/usa/bomber/n19980519_980693.html
[264] See for example: Gibbons-Neff, T. (2017, March 31). To understand how the U.S. approaches airstrikes in Mosul, look to Russia's war in Chechnya. Retrieved December 06, 2017, from https://www.washingtonpost.com/news/checkpoint/wp/2017/03/31/to-understand-how-the-u-s-approaches-airstrikes-in-mosul-look-to-russias-war-in-chechnya/

V. United States Offensive Strike Capabilities

The United States would likely employ several combinations of strike forces in a surprise attack on Iran's nuclear facilities. Due to the political issues of conducting such a strike from an allied base in the region and the difficulty of maintaining surprise after informing an ally, such a strike would be unlikely to rely on locally deployed forces. Because the United States is limited by political considerations to forces it can bring in from outside the region in its planning, such a strike would likely rely on long-range aerially refueled bombers, carrier-based naval aviation in the region, and ship- or submarine-launched land-attack cruise missiles.[265]

Long Range Airpower

America's known long-ranged air capabilities are provided by three bombers operated by the United States Air Force: the B-52 "Stratofortress," the B-1B "Lancer," and the B-2 "Spirit."[266] The B-52 is one of the oldest plane designs still in use by the United States Air Force. Originally produced in the 1950s and early 1960s as a strategic bomber for nuclear deterrence, the B-52 has proven effective and versatile enough that it is projected to remain in service through 2040.[267] As of December 2015, the U.S. Air Force had 58 active and 18 reserve B-52s.[268] In a strike on Iran, B-52s would likely be kept out of range of Iranian air defenses and used to launch cruise missiles at targets near the border or coastline of the country due to their large radar cross sections (RCS), high payload capacity (around 70,000 pounds), and relatively low top speed (650 mph).[269]

The B-1B "Lancer," more commonly called the B-1B, was built in the 1980s as a replacement for the aging B-52 bomber fleet. The U.S. Air Force had an active force of 62 B-1Bs as of September 2016.[270] The B-1B has a maximum speed of around 900 mph (Mach 1.2) and a payload capacity of 75,000 pounds.[271] Although the B-1B's lack of true stealth capability may limit it to a similar role to that of the B-52, its higher speed and RCS reduction might allow it to strike targets in central Iran by flying at low enough altitude that the curvature of the earth blocks detection by Iranian air defenses.[272] Deployment of air-launched cruise missiles would likely involve the B-1B and B-52 forces assigned to the mission flying low under radar horizon of Iran's SAM defenses and launching approximately 50-100 km off the coast of Iran.[273]

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[265] Sokolski, H., & Clawson, P. (Eds.). (2004), 123.
[266] United States Air Force. (n.d.). Air Force Fact Sheets. Retrieved December 06, 2017, from http://www.af.mil/About-Us/Fact-Sheets/. It is worth noting that the U.S. could have other air capabilities that it has kept secret as it did for an extended period of time in the case of the B-117 Nighthawk. See Roblin, S. (2016, October 8). America's First Stealth Fighter: The Legend of the F-117 Nighthawk. Retrieved December 06, 2017, from http://nationalinterest.org/blog/americas-first-stealth-fighter-the-legend-the-f-117-17976
[267] United States Air Force. (n.d.). Air Force Fact Sheets.
[268] Ibid.
[269] Ibid.
[270] Ibid.
[271] Ibid.
[272] See Wikipedia. (2017, December 01). Rockwell B-1 Lancer. Retrieved December 06, 2017, from https://en.wikipedia.org/wiki/Rockwell_B-1_Lancer
[273] Depending on mast height and altitude floor for pilots, this range could shift. For the 40V6 family of masts and floors between 500-1000 feet above ground level, the range is 71-98km. See Kopp, C. (2014, January 27). Almaz S-300P/PT/PS/PMU/PMU1/PMU2 / Almaz-Antey S-400 Triumf / SA-10/20/21 Grumble / Gargoyle. Retrieved December 06, 2017, from http://www.ausairpower.net/APA-Grumble-Gargoyle.html, Kopp, C. (2014, January 27). NKMZ 40V6M/40V6MD/40V6MT Universal Mobile Mast. Retrieved December 06, 2017, from

Finally, the B-2 "Spirit," the Air Force's stealth bomber, would likely be the most important component of an American strike on Iran. Although the B-2 has a slightly lower range, payload capacity, top speed, and number in active service than the B-52 or B-2, its stealth capabilities give the aircraft "the unique ability to penetrate an enemy's most sophisticated defenses and threaten its most valued, and heavily defended, targets."[274] Although the B-2's stealth capabilities are classified, according to *GlobalSecurity.org*, its RCS is "widely reported to be about -40dBm^2" (.0001 m^2) though some sources quoted by *GlobalSecurity.org* claim a much larger RCS.[275] It seems as though the commonly referenced number is at least close to accurate, former Air Force Chief of Staff Larry Welch claimed that "the B-2 has a radar cross section in the 'insect category'"[276] which according to *GlobalSecurity.org* would give it an RCS of around .001 m^2, off by one order of magnitude.[277] As such it is ideal for use in a strike on Iran's well-defended and fortified nuclear facilities and has been described as such by experts and government officials.[278] Although the B-2 is commonly cited to have a payload capacity of 40,000 pounds,[279] it was upgraded to be able to carry two 30,000 pound GBU-57 "MOP" bunker-buster bombs, seemingly giving it a combined payload capacity of 60,000 pounds.[280] The B-2 has numerous potential armament combinations that include nuclear and guided- and unguided-conventional weapons. The entire active force of 20 B-2s is based at Whiteman AFB in Missouri[281] although there are several potential bases around the world. In 2002, the United Kingdom allowed the United States to build the specialized facilities required to house the B-2 on the island of Diego Garcia in the Indian Ocean,[282] and that location would likely be used as a launching point for a strike on Iran using B-2s.[283]

Bombs

The United States has several bombs (without self-propulsion) that would potentially be used in a strike on Iran's nuclear program: the penetrating munitions (GBU-28 and GBU-57 "Massive Ordinance Penetrator" (MOP)) and the conventional (500-pound Mark 82 (GBU-30) and 2000-pound Mark 84 (GBU-32)), all of which can be configured to act as Precision-Guided

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http://www.ausairpower.net/APA-40V6M-Mast-System.html, and Richardson, G., & Wittenberg, P. (n.d.). Horizon calculator - radar / visual. Retrieved December 06, 2017, from http://members.home.nl/7seas/radcalc.htm

274 United States Air Force. (n.d.). Air Force Fact Sheets.

275 Pike, J. (2011, July 11). Radar Cross Section (RCS). Retrieved December 06, 2017, from https://www.globalsecurity.org/military/world/stealth-aircraft-rcs.htm

276 Mizokami, K. (2017, September 28). See also Sean O'Connor's forum post on B-2 RCS at https://forum.keypublishing.com/showthread.php?2278-what-are-the-RCS-of-missiles

277 Pike, J. (2011, July 11). Radar Cross Section (RCS). Note that some sources actually give the insect an RCS that is an order of magnitude smaller than the commonly cited RCS for the B-2, see https://books.google.com/books?id=YK4-DwAAQBAJ&pg=PA198&lpg=PA198&dq=tlams+rcs&source=bl&ots=K_cEAS-dwJ&sig=KJBNQScJh3PdSnFNKcUeTpYRKZQ&hl=en&sa=X&ved=0ahUKEwi4oZPr29DXAhVH6oMKHVDhBsEQ6AEITjAH#v=onepage&q=tlams%20rcs&f=false

278 See https://www.theatlantic.com/magazine/archive/2007/09/the-plane-that-would-bomb-iran/306133/ https://www.politico.eu/article/iran-military-fighters-defense-kerry-nuclear/

279 For instance, see United States Air Force. (n.d.). Air Force Fact Sheets.

280 Cordesman, A. H., & Toukan, A. (2010), 152.

281 United States Air Force. (n.d.). Air Force Fact Sheets.

282 Childs, N. (2002, September 17). UK island to house stealth bombers. Retrieved December 06, 2017, from http://news.bbc.co.uk/1/hi/uk/2265159.stm

283 See Cordesman, A. H., & Toukan, A. (2010).

Munitions (PGMs).[284] All are carried on the B-2, which is the only platform that would use them in a strike on Iran as it is the only platform which would overfly the target sets. The MOP "is specifically designed to go after very dense targets—solid granite, 20,000 [pounds per square inch] concrete, and those hard and deeply buried complexes,"[285] which describes many of Iran's nuclear sites. The varying effectiveness of these weapons, the tradeoffs in choosing to arm the B-2 with each, and other considerations are discussed in Sections VII and VIII below in the context of Iran's facilities.

Air-Launched Cruise Missiles

Cruise missiles are high-accuracy self-propelled bombs that are designed to travel great distances following launch before destroying targets. According to Carlo Kopp of *Air Power Australia*,

> The purpose of all modern cruise missiles is to provide an autonomous precision weapon which provides enough range performance for the launch vehicle to remain outside the footprint of opposing air defences, and to deliver the warhead to the target with reasonable odds of weapon survival.[286]

Cruise missiles are difficult to shoot down, in part due to their size and potential stealth characteristics, and in part due to their low-altitude flights, which allow them to use terrain masking to remain undetected, and attack routes "chosen to minimise weapon exposure time to the target's terminal SAM/AAA defences."[287] According to Kopp,

> Cruise missiles are at greatest risk during the terminal dive at the target, as they will usually be directly exposed to terminal defences. SAM systems like the S-300PMU(SA-10) … were specifically designed to kill cruise missiles, and the Russians have actively marketed the 9M331 Tor (SA-15) for this purpose.[288]

Iran possesses both systems referenced by Kopp as well as the Pantsir-S1 (SA-22), which serves the same function as the Tor, and their capabilities are discussed in Section VI.

U.S. cruise missiles can defeat defensive systems in three main ways: route planning, stealth, and inflight retargeting. Route planning was mentioned above and remains important to any cruise missile attack in order to limit the amount of warning and engagement opportunities a defender has for each cruise missiles. Cruise missiles with stealth capabilities make it more difficult to engage by making the detection range for the cruise missile longer, thus giving the defender less time to react and potentially penetrating within the defense systems' minimum engagement range before the defender can react. *GlobalSecurity.org* notes that,

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284 Federation of American Scientists. (n.d.). Joint Direct Attack Munition (JDAM) GBU-29, GBU-30, GBU-31, GBU-32. Retrieved December 06, 2017, from https://fas.org/man/dod-101/sys/smart/jdam.htm

285 Sirak, M. C. (2011, November 16). Bunker-Busting Behemoth. Retrieved December 06, 2017, from http://www.airforcemag.com/Features/newtech/Pages/box111611mop.aspx

286 Kopp, C. (2004). Cruise Missile Options for Australia. *Australian Aviation*. Retrieved December 6, 2017, from https://www.ausairpower.net/PDF-A/TE-ALCM-Dec-04-PA.pdf, 38.

287 Kopp, C. (2004). Cruise Missile Options for Australia, 39.

288 Ibid, 38.

> Low-observable [cruise missiles] can be difficult to engage and destroy, even if detected. Cruise missiles with an RCS of 0.1 m^2 or smaller are difficult for surface-to-air missile (SAM) fire-control radars to track. Consequently, even if a SAM battery detects the missile, it may not acquire a sufficient lock on the target to complete the intercept.[289]

According to Kopp, the air-launched cruise missile likely to be used by the United States in a strike on Iran, the AGM-158 JASSM, was "built for high stealth for exactly this reason."[290]

Finally, the "inflight retargeting"[291] capabilities of some modern cruise missiles help to negate the disadvantage of Cruise missile defense (CMD) somewhat as an attacker can reallocate resources following SAM destruction of some of its missiles to ensure that all aim points are destroyed, so long as it has allocated enough weaponry to the attack that the remaining missiles are sufficient to destroy the targets.

Together, the advantages of route planning, stealth, and inflight retargeting are likely enough to overwhelm any CMD so long as the attacker has tasked enough missiles. CMD is difficult for reasons discussed in Section VI, and a defender can only shoot down so many cruise missiles before its defenses are overwhelmed. Route planning and stealth ensure that this CMD task is challenging for the defender, maximizing the proportion of missiles that are able to get past the CMD systems. Inflight retargeting ensures that if enough missiles breach the minimum CMD range envelope, that they can be targeted to destroy all desired aim points.

The U.S. air-launched cruise missiles that would likely be used for a strike on Iran are JASSM-ER (Joint Air-to-Surface Standoff Missile – Extended Range), though other U.S. cruise missiles could potentially be used as well. The JASSM-ER is a variant of the earlier AGM-158 JASSM that uses the same airframe and is superficially identical but with much longer-range (1,000 km instead of 370 km) due to upgrades to its engine and fuel storage capabilities and a different, two-stage penetration warhead, which is beneficial for striking hardened targets, as are somewhat common in the Iranian nuclear target set.[292] A *GlobalSecurity.org* description of the JASSM-ER design goals highlights how it is ideal for the mission conceived here, particularly the role assigned to B-1Bs: "The additional range provided by the JASSM-ER missile benefits the B-1B with responsive, precision-engagement capability while remaining clear of highly defended airspace and beyond the range of long-range, surface-to-air missiles."[293]

Other U.S. cruise missiles either lack the range or the stealth capabilities to make them suited to coastal below-radar-horizon-launch attack. The AGM-86 ALCM (air-launched cruise missile) has the range for such an attack but it is an older, non-stealthy model which Iran's modern SAM systems such as the Tor were designed to defend against,[294] and the United States has limited numbers in its inventory due to the de facto replacement of the ALCM by more advanced systems.[295] The JSOW (Joint Stand-Off Weapon) has the stealth capabilities that the ALCM lacks but currently lacks sufficient range to attack deep within Iran where the important nuclear facilities

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[289] Pike, J. (2011, July 11). Radar Cross Section (RCS).
[290] Kopp, C. (2004). Cruise Missile Options for Australia.
[291] See Ibid, 39.
[292] Pike, J. (2011, July 7). JASSM-Extended Range (JASSM-ER). Retrieved December 06, 2017, from https://www.globalsecurity.org/military/systems/munitions/jassm-er.htm
[293] Ibid.
[294] www.pvo.su. (2009, May 8). ЗЕНИТНЫЙ РАКЕТНЫЙ КОМПЛЕКС 9К330 "ТОР" (SA-15 Gaunlet). Retrieved December 06, 2017, from http://pvo.guns.ru/tor/tor.htm
[295] Center for Strategic and International Studies. (n.d.). Missile Threat: CSIS Missile Defense Project. Retrieved December 06, 2017, from https://missilethreat.csis.org/

are located.[296] In 2017, there was movement towards purchasing a longer-range JSOW-ER, although the weapon's range (250 nmi, roughly 460 km) is likely still too short.[297] The final cruise missile worth acknowledging is the AGM-88 HARM (High-speed Anti-Radiation Missile), which is designed to strike radar-emitting air defense systems and would be used in a SEAD operation if U.S. planners chose to conduct one.[298]

Naval Aviation

A strike by long-range bombers would likely be supported by carrier-based naval aviation and ship- and submarine-launched cruise missiles. The need to achieve surprise in order to avoid defensive measures such as the removal of key equipment from target facilities and the placing of air defenses on high alert places limits on the number of carrier strike groups (CSGs) and thus on the associated carrier-based planes and naval cruise missiles available for a strike. CSGs are tracked assiduously,[299] and moving multiple CSGs into a particular area can make headlines.[300] Such a move would likely be seen as threatening and a potential precursor to a strike on Iran, especially given that an attack on Iran's nuclear facilities would almost certainly be preceded by an increase in tensions between the United States and Iran.

It seems likely that two CSGs could be moved into the vicinity of Iran without raising alarms in the Iranian politico-military establishment. This estimate is based on the nearly continuous presence of a carrier in the Middle East region since attacking the Islamic State (IS) in 2014[301] and the rarity of the US using more than two carriers in formation at any point in time.[302] To avoid spooking Iran, at least one of the CSGs would likely have to approach Iran from beyond its naval radar range, likely from the southeast in the Indian Ocean as other approach routes (the Mediterranean and Black Seas) would require supporting aircraft to fly over third-party airspace to support an attack on Iran.

Each CSG is composed of one carrier (Nimitz-Class), one guided-missile cruiser (Ticonderoga-Class), two guided-missile destroyers (Arleigh Burke-Class), one attack sub (Los Angeles- or Virginia-Class), and a supply ship.[303] The Nimitz-Class aircraft carriers would supply naval airpower in a strike on Iran. First deployed in 1975, the nuclear-powered carriers are

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[296] Federation of American Scientists. (n.d.). AGM-154A Joint Standoff Weapon [JSOW]. Retrieved December 06, 2017, from https://fas.org/man/dod-101/sys/smart/agm-154.htm

[297] Drew, J. (2017, June 12). U.S. Navy To Flight Test Quadruple-Range JSOW-ER. Retrieved December 06, 2017, from http://aviationweek.com/awindefense/us-navy-flight-test-quadruple-range-jsow-er, Scott, R. (2017, June 9). Raytheon contracted for extended-range JSOW test. Retrieved December 06, 2017, from http://www.janes.com/article/71278/raytheon-contracted-for-extended-range-jsow-test, and Raytheon [Raytheon]. (2014, February 6). *JSOW, MALD and HARM vs. The Advanced Threat* [Video file]. Retrieved from https://youtu.be/5Pu_PKpEhqU

[298] Federation of American Scientists. (n.d.). AGM-88 HARM. Retrieved December 06, 2017, from https://fas.org/man/dod-101/sys/smart/agm-88.htm

[299] See Pike, J. (n.d.). Where are the Carriers? Retrieved December 06, 2017, from https://www.globalsecurity.org/military/ops/where.htm

[300] Mizokami, K. (2017, May 17). Two U.S. Aircraft Carriers Are Now Prowling the Pacific. Retrieved December 06, 2017, from http://www.popularmechanics.com/military/navy-ships/a26550/us-aircraft-carriers-pacific/

[301] Pike, J. (n.d.). Where are the Carriers?

[302] LaGrone, S. (2017, November 09). UPDATED: 3 U.S. Carrier Strike Groups to Exercise for 4 Days in the Sea of Japan. Retrieved December 06, 2017, from https://news.usni.org/2017/11/08/3-u-s-carrier-strike-groups-exercise-4-days-sea-japan

[303] United States Navy. (n.d.). The Carrier Strike Group. Retrieved December 06, 2017, from http://www.navy.mil/navydata/ships/carriers/powerhouse/cvbg.asp

equipped with four squadrons of strike aircraft (the Navy calls these VFA squadrons), which can contain either F/A-18C "Hornets" or F/A-18E/F "Super Hornets."[304] Both Hornets and Super Hornets are 4.5th generation fighters without true stealth capability and have a top speed of Mach 1.7.[305] The "clean" combat radius for the F/A-18C is 1,089 nmi[306] and for the F/A-18E/F, it is 1,275 nmi.[307] Depending on the type of attack envisioned by the United States, the F/A-18s could be used in a variety of roles including suppression of enemy air defense (SEAD), maintaining air defenses for the CSG, and other fighter missions.[308] However, some type of SEAD operation would likely have to occur in order to fly the F/A-18s over Iran safely due to their lack of stealth, and the cruise missiles the F/A-18 is equipped with have too short of a range to attack centrally located Iranian facilities. Without such an operation, carrier-based aviation would likely be limited to the same long-range, cruise-missile-platform role of the B-1B and B-52 that is discussed above, without the same advantage of carrying the JASSM-ER for strikes deep within Iran.

Naval-Launched Cruise Missiles (TLAMs)

CSGs bring more than just naval airpower to the table. Naval-launched cruise missiles such as "Tomahawk" Land Attack Missiles (TLAMs) could strike non-hardened nuclear targets. Recent use of 59 TLAMs to strike an air base in Syria suggests that TLAMs could be ideally suited to hit some of the aboveground aim points that the United States would strike in an attempt to interdict Iran's nuclear program.[309]

Although TLAMs "have less explosive yield than larger bombs carried by manned U.S. aircraft," they can be effective against non-hardened targets like the Syrian planes and have some advantages over other weapons in terms of both political concerns and resource allocation.[310] TLAMs can be launched from all combat ships in a CSG other than the aircraft carrier.

The Tomahawk missiles were originally designed in the 1970s and have been through several iterations (called "Blocks"). The current active blocks are the Block-III TLAM-C[311] and the Block-IV TLAM-E, which both have ranges of 900 nautical miles (nmi).[312] The Block–IV TLAM-E is the most advanced Tomahawk missile and has the capability of in-flight retargeting, a missile-based camera with live imaging, and faster launch times than previous versions.[313] According to CSIS's Missile Threat project, the Block-IV is the only version still manufactured, and all pre-Block-IV Tomahawks "will be converted to the Block IV capability."[314] Both the Block-III TLAM-C and the Block-IV are capable of carrying a "1,000-pound-class unitary

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[304] United States Navy. (n.d.). United States Navy Fact File. Retrieved December 06, 2017, from http://www.navy.mil/navydata/fact.asp and United States Navy. (n.d.). Carrier Air Wing. Retrieved December 6, 2017, from http://www.navy.mil/media/ggallery/other/140908_Carrier-Air-Wing.pdf
[305] Ibid.
[306] Ibid.
[307] Ibid.
[308] Cordesman, A. H., & Toukan, A. (2010).
[309] Lamothe, D. (2017, April 06). Why the Navy's Tomahawk missiles were the weapon of choice in strikes in Syria. Retrieved December 06, 2017, from https://www.washingtonpost.com/news/checkpoint/wp/2017/04/06/why-the-navys-tomahawk-missiles-are-the-most-likely-option-for-a-strike-in-syria-against-assad/
[310] Ibid.
[311] Conventional munitions version. There was also a Block-III TLAM-D which carried submunitions. United States Navy. (n.d.). United States Navy Fact File.
[312] Ibid.
[313] Center for Strategic and International Studies. (n.d.). Missile Threat: CSIS Missile Defense Project.
[314] Ibid.

warhead" (1,000-pound conventional explosive).[315] Historical TLAM use (pre-Block-IV upgrades) suggests that "success rates for [Block-III] strikes were above 90% [and] in all, Tomahawks' firing power shows a greater than 85% success rate."[316]

TLAMs are an older system and thus are only semi-stealthy due to advances in technology since they were developed. Tomahawk missiles have an RCS of 0.5 m^2 which is about half that of an F/A-18 or typical non-stealthy cruise missile.[317] TLAMs also have the advantage of flying close to the ground, which makes them more difficult to detect and engage for systems that rely on horizon-limited radar.[318]

The United States currently has an estimated 3,000 to 4,000 TLAMs in inventory, and fired 100-200 in strikes on Libya in 2011 and 900 on the first day of the First Gulf War, giving perspective to the various magnitudes that an attack could have.[319] To gain a conservative estimate of Tomahawk missiles available for a strike on Iranian facilities, we can scale up the number of Tomahawks used in the recent U.S. strike on a Syrian airbase (mentioned above) to extrapolate out a lower boundary for the number of TLAMs that a CSG would fire. In the Syrian strike, two U.S. destroyers, the *USS Ross* and *USS Porter* fired a collective 59 missiles in the course of the attack representing roughly 30 TLAMs fired per destroyer.[320] Scaling that up to a CSG, if we assume that all four TLAM-equipped ships in the CSG launch an equal number to the destroyers in the Syrian attack, the United States could launch around 120 TLAMs per CSG available for the strike. According to a 1999 CRS report on "Cruise Missile Inventories and NATO Attacks on Yugoslavia," "the cruisers, destroyers, and attack submarines in a forward-deployed Navy aircraft carrier battle group might carry a total of 300 or more Tomahawks in their missile launchers."[321] It seems unlikely that a CSG would employ all of its missiles in a single strike, and accounting for conservation of a significant portion of TLAMs in inventory, 120 to 150 TLAMs used per CSG, with possibly two CSG's available, seems like a reasonable estimate. It is also possible that the United States could attempt to increase the quantity of TLAMs available for a mission against Iran by attempting to sneak more submarines into the waters around Iran, unattached to CSGs. Submarines could use their lower detectability to significantly extend the range that could be hit by TLAMs by allowing for launch from within the Persian Gulf without having to transit a CSG through the Strait of Hormuz, though operating them to launch a substantial Tomahawk attack without the defense of surface ships could be risky.

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[315] United States Navy. (n.d.). United States Navy Fact File.

[316] Federation of American Scientists. (n.d.). BGM-109 Tomahawk. Retrieved December 06, 2017, from https://fas.org/man/dod-101/sys/smart/bgm-109.htm

[317] Pike, J. (2011, July 11). Radar Cross Section (RCS). Note that while *GlobalSecurity.org* writes within the body of the page that TLAMs have an RCS of 0.05 m^2, this appears to be a typo as the 0.5 m^2 number in their list matches up well with other sources.

[318] Deagel.com. (n.d.). Tactical Tomahawk. Retrieved December 06, 2017, from http://www.deagel.com/Offensive-Weapons/Tactical-Tomahawk_a001146005.aspx

[319] Daniels, J. (2017, April 08). Obama once looked to downsize Tomahawk missile system used in Syria strike. Retrieved December 06, 2017, from https://www.cnbc.com/2017/04/07/obama-once-looked-to-downsize-tomahawk-missile-system-used-in-syria-strike.html

[320] Lamothe, D. (2017, April 06). Why the Navy's Tomahawk missiles were the weapon of choice in strikes in Syria.

[321] O'Rourke, R. (1999). *Cruise Missile Inventories and NATO Attacks on Yugoslavia*. Washington, D.C.: Congressional Research Service.

Why not local forces?

Much of the motivation for using non-locally-based forces such as long-range bombers, naval aviation, and cruise missiles is the political difficulty of launching strikes from the bases of third-party nations and the common requirement of consent (known as "Contingency Access") from the host country prior to launching a strike from a foreign base or through its territory or airspace.[322] The United States has historically been unable to rely on Contingency Access from its allies for military operations, particularly for strikes as described in the 2016 RAND report: "Access Granted: Political Challenges to the U.S. Overseas Military Presence, 1945-2014." Strike missions were the least likely of all operation types analyzed by RAND to be granted Contingency Access with 11 out of 33 (33%) instances rejected outright and four other instances (total 45%) found to have access granted but restricted.[323] The RAND report lists several historical example that illustrate the problems of relying on Contingency Access including the refusal of France and Spain to allow the U.S. to overfly their airspace during the 1986 strike on Libya, "Operation El Dorado Canyon," and the 2003 invasion of Iraq where Turkey denied the United States use of its territory.[324][325][326] Such a refusal could be even more likely in the case of the U.S.'s Middle East allies, which may be unwilling to suffer the domestic political consequences and risk retaliation from Iran for allowing a direct attack on a neighbor from their air bases. As the *Washington Post* notes in its article on the 2017 TLAM strike on the Syrian air base mentioned above,

> The decision [to use TLAMs] may have been driven in part by political concerns. The closest airfield the United States uses in the region is Incirlik Air Base in Turkey, but an operation against the Syrian government would likely require Turkish consent. The United States also has strike aircraft in other countries in the Middle East, but their use also could raise diplomatic issues. If the Trump administration decided to use manned aircraft, the most likely option was naval aircraft.[327]

These political concerns, plus the reduced possibility of maintaining surprise as local governments are informed of the U.S. strike plan, give non-locally-based forces a clear advantage in an interdiction strike on Iranian nuclear facilities.

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[322] Pettyjohn, S. L., & Kavanaugh, J. (2016). *Access Granted: Political Challenges to the U.S. Overseas Military Presence, 1945–2014*. Santa Monica, CA: RAND Corporation.
[323] Pettyjohn, S. L., & Kavanaugh, J. (2016), 76.
[324] Pettyjohn, S. L., & Kavanaugh, J. (2016).
[325] The Economist. (2009, May 02). All at sea. Retrieved December 06, 2017, from http://www.economist.com/node/13570088
[326] See also Yeo, A. (2017). The Politics of Overseas Military Bases. *Perspectives on Politics, 15*(1), 129-136. doi:10.1017/S1537592716004199 and Cooley, A. (2017, November 20). US Military Bases Abroad. Retrieved December 06, 2017, from http://www.oxfordbibliographies.com/view/document/obo-9780199756223/obo-9780199756223-0034.xml
[327] Lamothe, D. (2017, April 06). Why the Navy's Tomahawk missiles were the weapon of choice in strikes in Syria.

Table 1: US Bomber Capabilities[328]

	B-52	B-1B	B-2
Range (mi) - Unrefueled - With weapons	8,800[329]	7,455[330] 3,444	Approximately 6,900
Speed (mph)	650	900	"High subsonic"[331]
Payload Capacity ('000s lbs)	Approximately 70	75	40 or 60[332]
RCS (m^2)	100[333]	10[334]	.0001 - .001[335][336]
Number Active	58	62	20

[328] Data in this table are from United States Air Force. (n.d.). Air Force Fact Sheets unless otherwise cited.
[329] Pike, J. (n.d.). B-52 Stratofortress. Retrieved December 06, 2017, from https://www.globalsecurity.org/wmd/systems/b-52-specs.htm
[330] Pike, J. (n.d.). B-1B. Retrieved December 06, 2017, from https://www.globalsecurity.org/wmd/systems/b-1b-specs.htm
[331] Ibid. and Mizokami, K. (2017, September 28). Why the B-2 Stealth Bomber Might Be America's Most Dangerous Weapon. Retrieved December 06, 2017, from http://nationalinterest.org/blog/the-buzz/why-the-b-2-stealth-bomber-might-be-americas-most-dangerous-22528
[332] Cordesman, A. H., & Toukan, A. (2010), 152. and Mizokami, K. (2017, September 28).
[333] Pike, J. (2011, July 11). Radar Cross Section (RCS).
[334] Ibid.
[335] Ibid.
[336] Mizokami, K. (2017, September 28).

Table 2: US Cruise Missiles[337]

	Yield (lbs)	Range (km)	Inventory	Platforms
AGM-86C	3,000	950	Likely low	B-52[338]
AGM-86D	1,200[339]	1,320	Likely low	B-52[340]
Block-IV TLAM-E	1,000	1,600	3,000-4,000[341]	CSGs, SSNs
JASSM	950	370	2,000	B-1B, B-2, B-52, F/A-18
JASSM-ER	950	1,000	2,500[342]	B-1B, B-52[343]
JSOW-C	1,000[344]	>100[345]	14,000[346]	B-1B, B-2, B-52, F/A-18[347]

[337] Data in this table are from Center for Strategic and International Studies. (n.d.). Missile Threat: CSIS Missile Defense Project unless otherwise cited.
[338] Kristensen, H. M. (2013, April 22). B-2 Stealth Bomber To Carry New Nuclear Cruise Missile. Retrieved December 06, 2017, from https://web.archive.org/web/20140422075113/http://blogs.fas.org/security/2013/04/b-2bomber/
[339] Center for Strategic and International Studies. (n.d.). Missile Threat: CSIS Missile Defense Project. and Federation of American Scientists. (n.d.). AGM-86C/D Conventional Air Launched Cruise Missile. Retrieved December 06, 2017, from https://fas.org/nuke/guide/usa/bomber/calcm.htm
[340] Kristensen, H. M. (2013, April 22). B-2 Stealth Bomber To Carry New Nuclear Cruise Missile.
[341] Daniels, J. (2017, April 08). Obama once looked to downsize Tomahawk missile system used in Syria strike.
[342] Pike, J. (2011, July 7). JASSM-Extended Range (JASSM-ER).
[343] By 2018 according to Gady, F. (2016, August 16). US B-52 Bomber Drops First Stealthy Cruise Missile From Bomb Bay. Retrieved December 06, 2017, from https://thediplomat.com/2016/08/us-b-52-bomber-drops-first-stealthy-cruise-missile-from-bomb-bay/
[344] Pike, J. (n.d.). AGM-154 Joint Standoff Weapon [JSOW]. Retrieved December 06, 2017, from https://www.globalsecurity.org/military/systems/munitions/agm-154.htm
[345] Raytheon. (2017, November 09). AGM-154 Joint Standoff Weapon (JSOW). Retrieved December 06, 2017, from https://www.raytheon.com/capabilities/products/jsow/
[346] Planned purchases through 2007. Does not account for attrition inventory or possibility of purchase cancelation. As of October 2002, USAF had acquired 1,000 JSOWs. Pike, J. (n.d.). AGM-154 Joint Standoff Weapon [JSOW].
[347] Federation of American Scientists. (n.d.). AGM-154A Joint Standoff Weapon [JSOW].

VI. Iranian Air Defenses

Early Warning and Radar

Iran has a network of early-warning radar systems to notify it of any enemy aircraft entering or operating in or around its airspace. Information on this system and its capabilities available in the open literature is limited. To date, the most comprehensive analysis of Iran's early-warning radar system was offered by Andrew Krepinevich, the President of the Center for Strategic and Budgetary Assessments in his testimony before the Senate Armed Services committee from February 2015, where he noted that:

> Iran's early warning system appears incapable of providing reliable detection of low-observable aircraft; however, it is assessed to be effective against fourth generation fighters. Most notably, three long-range early warning radars have been constructed in the past few years—two Ghadir radars with 1,000 km ranges and one Sepehr radar with a 3,000 km range. They provide 360-degree coverage of the entire country and significant coverage of the region. Tehran claims these radars can detect and identify aircraft, cruise missiles, ballistic missiles, and low-altitude satellites. There is an additional network of twenty-four shorter-range early warning radars located throughout the country. Assuming these capabilities function "as advertised," Iran could have warning of a ballistic missile strike or non-stealthy cruise missile strike.[348]

Of the two domestically produced long-range systems mentioned by Krepinevich, more is known about the Ghadir. The two publically announced Ghadir sites are located near the city of Ahvaz in the southwest Iranian province of Khuzestan and near Garmsar, which is located in north-central Iran in the Semnan province.[349] There is another radar instillation that *IHS Jane's* identifies as "what appears to be a prototype Ghadir located at an air defence base in Tehran province."[350] It is, however, unlikely to extend the detection range significantly, particularly in the case of a U.S. attack, due to its status as an older model, proximity to the Ghadir at Garmsar, and location further to the northwest away from the likely direction of a U.S. attack. The Ghadir is designed to be relatively robust against attack by anti-radar missiles and electronic warfare attacks,[351] though the blog *WarIsBoring* notes that it "is unlikely to survive very long in an intensive war with the United

[348] Krepinevich, A. F. (2015, February 25). *Statement Before the Senate Armed Services Subcommittee on Strategic Forces on the Implications for U.S. Security of Growing Nuclear Capabilities in the Middle East*, Senate, 114th Cong., 7.
[349] Binnie, J. (2015). Iran reveals existence of second Ghadir long-range radar. *IHS Jane's Defence Weekly, 52*(34).
[350] Ibid.
[351] Binnie, J. (2014). Iran officially unveils new long-range radar. *IHS Jane's Defence Weekly, 51*(28).

States, but in the case of a limited engagement such as an American attack on Iran's nuclear facilities, the [Ghadir] could help Iran organize its defenses."[352]

Very little is known about the Sepehr, besides its publicized range of 3,000 km. *IHS Jane's* analysis of Iranian radar site construction found "a slightly different [from the Ghadir] long-range surveillance radar in Kordestan province" in western Iran, which it said could be the Sepehr system.[353] The range quoted by Krepinevich for the Ghadir appears to be the range at which it can detect ballistic missiles, with its ability to detect aircraft extending only 600 km according to *Reuters*.[354] Assuming the same ballistic missile range in the case of the Sepehr and scaling down its range by the same amount (both systems seem designed to detect ballistic missiles due to their altitude detection ranges), its adjusted range is around 1,640 km.[355] According to an *RT* article quoting Iranian air defense commanders, the Sepehr was over 40% deployed as of February 2015 with the goal of full deployment by March 2015.[356]

Jane's Defense Weekly analysis of these new over-the-horizon (OTH) radar systems sees them as meant to provide evidence of continued Iranian efforts to develop "a network of long-range surveillance radars that probably use low-band frequencies with the aim of detecting low-observable objects such as the B-2 Spirit bombers that would spearhead a U.S. attack the [Iran's] nuclear facilities."[357] As discussed in Krepinevich's testimony, however, "as advertised" function of the Ghadir and Sepehr would likely exclude early warning against true stealth aircraft, and according to *Reuters*, "top U.S. commander General Martin Dempsey in April [2015] said the 'military option' against Iran remains intact."[358] While the Ghadir can detect targets as small as "even the tiniest of birds,"[359] according to former Air Force Chief of Staff Larry Welch, "the B-2 has a radar cross section in the 'insect category.'"[360] Iran's OTH capabilities could, however, limit non-B-2 operations by carrier-based F/A-18s if they are able to provide effective detection of fourth-generation fighters.

Long-Range SAMs

Beyond large, indigenously developed OTH radar systems and other early warning radars, much of Iran's air-defense radar coverage is provided by Surface-to-Air Missile (SAM) radar systems. In terms of detection coverage, the most important SAM systems are long- and very-

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[352] Al Salami, J. (2014, June 4). Iran Can Now Detect U.S. Stealth Jets at Long Range. Retrieved December 06, 2017, from https://warisboring.com/iran-can-now-detect-u-s-stealth-jets-at-long-range/
[353] Binnie, J. (2015). Iran reveals existence of second Ghadir long-range radar.
[354] Ibid. and Reuters Staff. (2015, July 05). Iran deploys new home-built long-range radar. Retrieved December 06, 2017, from https://www.reuters.com/article/us-iran-security-radar/iran-deploys-new-home-built-long-range-radar-idUSKCN0PF08Z20150705
[355] The article actually lists the Ghadir ballistic missile detection range as 1,100 km. 3,000 * 600 / 1,100 = 1636.
[356] RT. (2015, February 15). Sealing off skies: Iran finalizes 360 degree early warning air defense radar. Retrieved December 06, 2017, from https://www.rt.com/news/232515-iran-sepehr-radar-installed/
[357] Binnie, J. (2015). Iran reveals existence of second Ghadir long-range radar.
[358] Reuters Staff. (2015, July 05). Iran deploys new home-built long-range radar.
[359] Binnie, J. (2014). Iran officially unveils new long-range radar.
[360] Mizokami, K. (2017, September 28).

long-range systems such as the S-300PMU-2, the Bavar-373, and the S-200 Angara because they are necessarily paired with high-powered, long-range radar systems. These systems also provide most of the engagement coverage within Iran's air defense system through their long-range missiles.

The S-300PMU-2 "Favorit" was developed by Russia between 1995 and 1997 as an upgraded version of previous S-300 long-range SAM systems with the primary goal of improving ballistic missile defense capabilities.[361] The S-300 is comparable in performance to the Western MIM-104 Patriot according to *CSIS Missile Threat*[362] and Carlo Kopp of *Air Power Australia*.[363] Although more recent Russian systems such as the S-400 "Triumf" and S-500 "Prometheus" are more capable, in 2006 Kopp stated that "The S-300 SAM systems [are] one of the most lethal, if not the most lethal, all altitude area defence SAM systems in service."[364] However, Kopp placed the B-2 as an example of an aircraft (along with the F-22A Raptor) that the S-300PMU-2 did not threaten.[365] The 48N6E2 missile, the second-generation version of the missile used by the S-300PMU family, is likely slightly more capable than the 486E2, which had "an ability to engage targets with an RCS as low as 0.02 square metres at an unspecified range, and an autonomous search capability."[366][367] The range of the missile was increased from 150 km to 200 km with the introduction of the second edition 48N6E2 missile, which also reduced the minimum altitude at which the missile could engage targets to 20-30 feet above ground.[368][369][370] According to Russian sources quoted by *Air Power Australia*, the S-300PMU-2 missile has a probability of kill of 80-93% for "aerial targets" and 40-80% for cruise missiles.[371] The S-300PMU-2 is thought to be effective against "aircraft with no stealth, reduced RCS capabilities, or limited aspect stealth, such as the F-15E, F-16C, F/A-18E/F" with its primary weakness to manned fighter aircraft being "high-speed, low-altitude terrain masking using Terrain Following Radar, supplemented by offboard near-realtime [Intelligence, Surveillance, and Reconnaissance] data, support jamming and standoff missiles."[372]

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[361] Kopp, C. (2009, May 29). Almaz-Antey S-300PMU2 Favorit / SA-20 Gargoyle. Retrieved December 06, 2017, from http://www.ausairpower.net/APA-S-300PMU2-Favorit.html
[362] Center for Strategic and International Studies. (n.d.). Missile Threat: CSIS Missile Defense Project.
[363] Kopp, C. (2006, February 25). Almaz S-300 - China's "Offensive" Air Defense. Retrieved December 06, 2017, from https://web.archive.org/web/20110928142727/http://www.strategycenter.net/research/pubID.93/pub_detail.asp
[364] Ibid.
[365] Ibid.
[366] Kopp, C. (2014, January 27). Almaz S-300P/PT/PS/PMU/PMU1/PMU2 / Almaz-Antey S-400 Triumf / SA-10/20/21 Grumble / Gargoyle.
[367] Kopp, C. (2009, May 29). Almaz-Antey S-300PMU2 Favorit / SA-20 Gargoyle.
[368] Ibid.
[369] O'Connor, S. (2017, July 13). Iran deploys S-300 to Bushehr. Retrieved December 06, 2017, from http://www.janes.com/article/72263/iran-deploys-s-300-to-bushehr
[370] Kopp, C. (2014, January 27). Almaz S-300P/PT/PS/PMU/PMU1/PMU2 / Almaz-Antey S-400 Triumf / SA-10/20/21 Grumble / Gargoyle.
[371] Ibid.
[372] Ibid.

The Bavar-373 is essentially an Iranian attempt to copy the Russian-made S-300 and construct the entire system domestically.[373] Although the Bavar-373 was not active as of September 2017, the commander of Iran's air defense forces stated that the system had been completed and tested and would be active by March 2018,[374] though the system has seen delivery delays in the past.[375] The Bavar-373 was built as a replacement for the S-300 following a refusal to ship the system to Iran by then-Russian President Dmitry Medvedev in 2010.[376]

The S-300 is effective, not only against aircraft but also cruise missiles, making it difficult to destroy with a cruise missile SEAD operation without missiles with "a sufficiently low radar signature to penetrate inside the minimum engagement range of the SAM before being detected - anything less will see the inbound missile killed by a self-defensive SAM shot."[377] In order to counter low-observable cruise missile attacks within this minimum engagement range, the S-300 is often paired with "Tor-M2E (SA-15D Gauntlet) and Pantsir-S1/S2 (SA-22) self-propelled point defence SAM systems as a rapid reaction close in defensive Counter-PGM system" (both systems will be discussed below).[378] Iran currently has deployed all four S-300PMU-2 batteries that it purchased from Russia.[379] As of July 2017 their locations, according to *IHS Jane's Defence Weekly*, were near Bushehr, near Fordow, near the Tehran-Mehrabad Airport, and at Khavar Shahr southeast of Tehran.[380]

According to Cordesman and Toukan, Iran's "medium to long-range systems [were] low capability or obsolescent" as of 2010,[381] prior to the delivery of the S-300PMU-2 and Bavar-373 systems. Around that time, the "highest performing SAM operated by Iran" was the S-200 Angara, which was "the largest and longest ranging Surface to Air Missile developed and operationally deployed by the Warsaw Pact nations during the Cold War."[382] It is unclear exactly the range and specifications of Iran's S-200 inventory. According to *The Military Balance 2017,* Iran operates the S-200 Angara (SA-5 Gammon),[383] which is the oldest variant of the S-200 and has a maximum range of 150-180 km according to *CSIS Missile Threat*.[384] The view that Iranian S-200 systems are this older type is supported by *CSIS Missile Threat's* listing of Iran as having purchased the missile

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[373] Pike, J. (n.d.). Bavar-373. Retrieved December 06, 2017, from https://www.globalsecurity.org/military/world/iran/bavar-373.htm
[374] PressTV. (2017, September 3). Iran's air defense system operational by March 2018: Cmdr. Retrieved December 06, 2017, from http://www.presstv.com/Detail/2017/09/03/533862/Iran-Farzad-Esmaili
[375] Pike, J. (n.d.). Bavar-373.
[376] UPI. (2010, September 22). Russia pulls plug on Iran arms deal. Retrieved December 06, 2017, from https://www.upi.com/Top_News/World-News/2010/09/22/Russia-pulls-plug-on-Iran-arms-deal/UPI-49941285186093/
[377] Kopp, C. (2014, January 27). Almaz S-300P/PT/PS/PMU/PMU1/PMU2 / Almaz-Antey S-400 Triumf / SA-10/20/21 Grumble / Gargoyle.
[378] Ibid.
[379] International Institute for Strategic Studies (IISS). (2017). *The Military Balance, 2017*. London: Routledge, 378-379.
[380] O'Connor, S. (2017, July 13). Iran deploys S-300 to Bushehr.
[381] Cordesman, A. H., & Toukan, A. (2010).
[382] Kopp, C. (2009, June 28). Almaz 5V21/28 / S-200VE Vega. Retrieved December 06, 2017, from http://www.ausairpower.net/APA-S-200VE-Vega.html
[383] International Institute for Strategic Studies (IISS). (2017). *The Military Balance, 2017*, 378-379.
[384] Center for Strategic and International Studies. (n.d.). Missile Threat: CSIS Missile Defense Project.

variant that is used by the original S-200 Angara.[385] However, "Iran is known to have updated and upgraded its stock of S-200 systems from 2007, with test firings taking place in November 2010" according to *IHS Jane's*.[386] Such an upgrade could include extension of missile range up to later generation maximum of 300 km and improvements to C3I and tracking capabilities.[387] Depending on what variant of the S-200 Iran's upgrades are meant to replicate, probability of kill for an S-200 missile launch ranges from 45-98% for the oldest S-200 Angara variant, to 72-99% for the S-200D Dubna.[388] According to *The Gulf Military Balance: Volume II,* "while the upgraded system may be more effective than the old SA-5/S-200, it is unlikely to pose a significant threat to American or Israeli aircraft as a long-range air-denial weapon."[389] In terms of detection range, the 5N62 "Square Pair" radar units that are used with the S-200 have a range of 270 km according to Sean O'Connor of *IHS Jane's* although data on the capabilities of this radar system are somewhat scarce.[390] Like the S-300, the S-200 has minimal short-range and low altitude defense capabilities with a minimum engagement range of 7 km and a minimum engagement altitude of 300 m (around 1000 feet),p[391] but the system was "not intended to counter close-in targets [and] this should not be considered a design flaw of the system."[392]

According to CSIS's Missile Threat, Iran had seven S-200 SAM sites (Bandar Abbas, Hamadan, Tehran S, Tehran E, Bushehr, Esfahan, Semnan) with six active in 2007.[393] Unlike the S-300, the S-200 is notably "static" in that it takes great effort to move the system due in part to the enormity of the missiles used by the system and the instability of the missile fuel.[394][395] It seems unlikely that the S-200 incorporates a mast into its static configuration in order to mitigate the problem of the radar horizon as it is not among the battery components listed by *Air Power Australia*[396] and Sean O'Connor discussed in 2010 the horizon limitations of Iran's S-200 placement at Esfahan.[397]

Cruise Missile Defense and Modern Short-Range SAMs

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[385] Ibid.
[386] Foss, C. F., & O'Halloran, J. C. (2012). *IHS Jane's Land Warfare Platforms 2012-2013: Artillery & Air Defence*. Jane's Information Group, 718.
[387] Ibid, 717.
[388] Kopp, C. (2009, June 28). Almaz 5V21/28 / S-200VE Vega.
[389] Cordesman, A. H., & Gold, B. (2014). *The Missile and Nuclear Dimensions* (Vol. II, The Gulf Military Balance). Washington, D.C.: Center for Strategic and International Studies, 68.
[390] O'Connor, S. (2007, July 22). The S-200 SAM System: A Site Analysis. Retrieved December 06, 2017, from https://geimint.blogspot.co.uk/2007/07/s-200-sam-system-site-analysis.html
[391] Foss, C. F., & O'Halloran, J. C. (2012), 718.
[392] O'Connor, S. (2007, July 22). The S-200 SAM System: A Site Analysis.
[393] Center for Strategic and International Studies. (n.d.). Missile Threat: CSIS Missile Defense Project.
[394] Kopp, C. (2009, June 28). Almaz 5V21/28 / S-200VE Vega.
[395] Center for Strategic and International Studies. (n.d.). Missile Threat: CSIS Missile Defense Project.
[396] Kopp, C. (2009, June 28). Almaz 5V21/28 / S-200VE Vega.
[397] O'Connor, S. (2010, January 07). Strategic SAM Deployment in Iran. Retrieved December 06, 2017, from http://www.ausairpower.net/APA-Iran-SAM-Deployment.html

Since the invention of the cruise missile, cruise missile defense (CMD), involving the interception of launch platforms or the destruction of cruise missiles before they reach their targets, "has remained a persistent headache."[398] Despite significant investment, CMD remains difficult even for the most advanced militaries in the world.[399] The first (and easier) method of defense, intercepting launch platforms, is unlikely. Iran is unlikely to use its relatively weak conventional navy or anti-submarine warfare capabilities to challenge a CSG or other TLAM platforms,[400] and the mission as seen in this paper is specifically designed to avoid the engagement of air-launched cruise missile platforms by Iranian air defense systems. This is compounded by the political difficulty of Iran justifying striking U.S. cruise missile platforms prior to launch, as such platforms will not have established themselves as hostile until after launching their cruise missiles.[401]

Part of the difficulty of intercepting and destroying cruise missiles post launch stems from the nature of cruise missile flight. Because cruise missiles fly at very low altitudes, their flight is often masked by terrain features, which can make them difficult to detect with "line-of-sight," horizon-limited radar systems.[402] Iran's mountainous geography could give a U.S. cruise missile strike advantages, and historical evaluation indicates placement of Iranian SAM system as potentially exacerbating or at least doing little to mitigate these terrain weaknesses.[403] According to *Air Power Australia*, even without these mistakes:

> Reliance on land based SAM systems for terminal defence of target areas[404] is a popular but relatively ineffective strategy, as high performance SAMs with expensive high power-aperture radars are required, and even with mast mounted antennas to improve coverage the footprint is bounded by ranges of miles to at most tens of miles.[405]

While it is possible that the advanced SAM systems that Iran has imported in recent years (S-300PMU-2, Tor-M1E, and Pantsir-S1E) could perform this CMD role as advertised, the relative ineffectiveness of shooting the "arrow instead of the archer" should not be understated.[406]

The most important systems for point defense against cruise missiles, PGMs, and other ranged attacks on Iranian nuclear facilities are the Tor-M1E (SA-15 Gauntlet) and Pantsir-1 (SA-

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[398] Kopp, C. (2007, April 15). Defeating Cruise Missiles. Retrieved December 06, 2017, from http://www.ausairpower.net/Analysis-Cruise-Missiles.html
[399] Lockie, A. (2016, August 09). The US has no good defense against cruise missiles - and it's a huge problem. Retrieved December 06, 2017, from http://uk.businessinsider.com/us-military-lacks-cruise-missiles-defense-2016-8
[400] Cordesman, A. H., Wilner, A., Gibbs, M., & Modell, S. (2013). *The Conventional and Asymmetric Dimensions* (Vol. I, The Gulf Military Balance). Washington, D.C.: Center for Strategic and International Studies, 81.
[401] Kopp, C. (2007, April 15). Defeating Cruise Missiles.
[402] Lockie, A. (2016, August 09). The US has no good defense against cruise missiles - and it's a huge problem.
[403] See O'Connor, S. (2010, January 07). Strategic SAM Deployment in Iran.
[404] As it appears Iran is doing.
[405] Kopp, C. (2007, April 15). Defeating Cruise Missiles.
[406] Ibid.

22 Greyhound).[407][408] According to an unclassified 2010 U.S. Department of Defense report on Iranian military capabilities, "Iran acquired modern TOR-M1 short range surface-to-air missiles in 2007" as part of a larger trend towards "a significant upgrade to existing Iranian air defense capabilities and improve[d] ability to protect senior leadership and key nuclear and industrial facilities."[409] According to Cordesman and Toukan, the 29[410] Tor-M1Es Iran acquired[411] were Iran's "only modern short-range point defense system" as of their 2010 analysis.[412] The Tor system is a "low- to medium-altitude, short-range" SAM system designed to defend against not only aircraft but also cruise and missiles and PGMs.[413] Of particular note is the centrality of the Tor system's anti-cruise missile and anti-PGM missions in its design process and the production capabilities of the system.[414][415] The Tor has a detection range of 24 km and an engagement range of 12 km and can engage two targets simultaneously.[416] According to *Air Power Australia*, the Tor-M1 has a kill probability of 45-80% for a single shot against a "fighter-type object," which is likely higher than the same measure for a cruise missile or PGM.[417] It is unclear how the Tor-M1 would perform against modern cruise missiles (compared with the previous generation missiles for which it was designed), and given its engagement limitations how it would perform against a coordinated "time-on-target" attack by the United States where missiles would presumably arrive simultaneously, but the Tor-M1E's high technical capabilities as compared to many of the other Iranian air defense systems make it worth considering.

Much like the Tor, the Pantsir also focused quite heavily on countering PGM and cruise missile threats. According to *Air Power Australia*, this specifically includes "high survivability in [an environment of] massive employment of HARM-type antiradar missiles" and "a capability of destroying high precision weapons, such as Tomahawk cruise missile."[418] The Pantsir is capable of engaging four targets simultaneously using missiles, at ranges between 1.2 and 20 km.[419] It also has a 30 mm gun for engaging closer range targets if necessary.[420] Both the Tor and Pantsir systems

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[407] International Institute for Strategic Studies (IISS). (2017). *The Military Balance, 2017*, 378-379.
[408] Center for Strategic and International Studies. (n.d.). Missile Threat: CSIS Missile Defense Project.
[409] Department of Defense. (2010, April). Unclassified Report on Military Power of Iran. Retrieved December 6, 2017, from https://fas.org/man/eprint/dod_iran_2010.pdf, 6.
[410] Cordesman, A. H., & Kleiber, M. (2007). *Iran's Military Forces and Warfighting Capabilities: The Threat in the Northern Gulf*. Washington, D.C.: Center for Strategic & International Studies, 63.
[411] Iran acquired 750 missiles with its Tor-M1E systems. Cordesman, A. H., & Peacock, M. (2015), 77.
[412] Cordesman, A. H., & Toukan, A. (2010).
[413] Cordesman, A. H., & Toukan, A. (2010).
[414] Ibid.
[415] Kopp, C. (2009, July 14). 9K330/9K331/9K332 Tor M/M1/M2 Self Propelled Air Defence System / SA-15 Gauntlet. Retrieved December 06, 2017, from http://www.ausairpower.net/APA-9K331-Tor.html
[416] Cordesman, A. H., & Toukan, A. (2010).
[417] Kopp, C. (2009, July 14). 9K330/9K331/9K332 Tor M/M1/M2 Self Propelled Air Defence System / SA-15 Gauntlet.
[418] Kopp, C. (2009, July 15). KBP 2K22/2K22M/M1 Tunguska SA-19 Grison / 96K6 Pantsir S1 / SA-22 Greyhound. Retrieved December 06, 2017, from http://www.ausairpower.net/APA-96K6-Pantsir-2K22-Tunguska.html
[419] Note that Air Power Australia says 2 for Pantsir-S1. Ibid. and Center for Strategic and International Studies. (n.d.). Missile Threat: CSIS Missile Defense Project.
[420] Ibid.

are self-contained and can operate independently although according to *CSIS Missile Threat's* description of Pantsir organization, "they typically operate in batteries of between two and ten launcher vehicles and are occasionally accompanied by a separate command and control vehicle."[421][422] According to *IHS Jane's*, Iran planned on acquiring "at least 10 Pantsyr-S1E… air-defence systems" from Syria in 2007-2008.[423]

Worth considering again is the 2017 Tomahawk strike on a Syrian airbase discussed above in Section V's discussion of TLAMs. Russian SAM forces in Syria are equipped with some of the most advanced systems that the country has built (S-300s, S-400s, and Pantsirs), and as *Popular Mechanics* notes, could have attempted to defend the Syrian airbase from the strike if they had chosen to, especially given their advance warning of the attack.[424] The article notes that the Russians chose not to do so, and one potential reason could be doubts or an unwillingness to show their hand about the true capabilities of their systems for CMD.

> There is no greater open question in the defense world than just how effective Russian anti-aircraft weapons really are against American technology. Russia generates money and international leverage by selling systems that it claims can thwart American weapons. But the United States' jamming, cyberwarfare, smart missiles, and advanced decoys are designed to defeat these digitally-linked Russian systems. There would be no greater marketing disappointment than shooting at U.S. cruise missiles and missing, which would demonstrate the deterrent Russia is selling may not work as advertised.[425]

The effectiveness of CMD systems is an "open question," and the ability of such systems to live up to their claims could drastically affect the outcome of a U.S. strike on Iran. The overall difficulty of defending against cruise missiles and weaknesses in Iran's own placement of its CMD SAM systems all point in favor of CMD having a limited impact on a U.S. strike, although the United States would likely take significant precautions such as launching a significant surplus of TLAMs and stealthy JASSM-ERs to destroy each aim point, with inflight retargeting in order to ensure that enough will make it through Iranian defense systems.

Older or Obsolete SAMs

Iran has several older short- to medium-range SAM systems as well, which largely are not advanced enough to shift the military balance of Iranian air defenses significantly, particularly in

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[421] Kopp, C. (2009, July 14). 9K330/9K331/9K332 Tor M/M1/M2 Self Propelled Air Defence System / SA-15 Gauntlet.
[422] Center for Strategic and International Studies. (n.d.). Missile Threat: CSIS Missile Defense Project.
[423] https://web.archive.org/web/20071018002847/http://janes.com/defence/news/jdw/jdw070522_1_n.shtml
[424] Pappalardo, J. (2017, November 14). Putin Could Have Tried to Shoot Down Trump's Missiles. Why Didn't He? Retrieved December 06, 2017, from http://www.popularmechanics.com/military/weapons/news/a25985/putin-didnt-shoot-down-cruise-missiles-trump/
[425] Ibid.

an attack where the main penetration of Iran's air defense network is made using highly advanced B-2 stealth bombers. Iran has two SAM systems that are based on the 1970s French Crotale SAM system, the Chinese HQ-7 (also known as the FM-80 (CSA-4) or FM-90 (CSA-5)) and the indigenously built Shahab Thaqeb (mentioned below). There is relatively little data available on the HQ-7 but its capabilities can be extrapolated from those of the Crotale. As a shorter-range system, the Crotale shares many characteristics and capabilities with the Pantsir and Tor systems.[426] The Crotale was designed to counter low-flying, supersonic fighters and its capabilities could potentially make it applicable for the "counter-PGM role" as well, although *Air Power Australia* notes that some of its specifications make it suboptimal for such a role.[427]

Iran reportedly has 45 S-75 Volhov (SA-2 Guideline) systems, which are a very old Russian system that Cordesman calls "outdated"[428] and Sean O'Connor describes as "widely exploited."[429] The S-75 is the SAM system which shot down U2 pilot Francis Gary Powers over the USSR in the 1960 U2 incident, illustrating its age.[430] The USSR stopped manufacturing the S-75 in the 1980s and replaced the system with the S-300.[431]

All the systems listed in this section likely fall at least to some degree under the "low capability or obsolescent" umbrella suggested by Cordesman due to their age. Iran may also possess some number of Chinese HQ-2 "Gin Sling" (CSA-1) systems which are upgraded versions of the S-75.[432] While the HQ-2 has undergone multiple upgrades, through at least the 1980s, it was being phased out of Chinese air defense arsenals as of 2010.[433] According to O'Connor,

> The HQ-2, however, should be regarded as potentially more reliable [than the HAWK (discussed below)], as it is… a Chinese-produced weapon with which the West should have a lesser degree of technical familiarity insofar as electronic counter-countermeasures performance, if not kinematic performance, is concerned.[434]

The MIM-23 HAWK (Homing All the Way Killer) was developed in the 1950s and became operational in 1962, making it another older, pre-revolution SAM system that Iran still features in

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[426] Kopp, C., & Andrew, M. (2010, September 08). CPMIEC HQ-7/FM-80/FM-90 / CSA-4/CSA-5 Sino-Crotale Self Propelled Air Defence System. Retrieved December 06, 2017, from http://www.ausairpower.net/APA-HQ-7-Crotale.html
[427] Ibid.
[428] Cordesman, A. H., & Peacock, M. (2015), 234.
[429] O'Connor, S. (2010, January 07). Strategic SAM Deployment in Iran.
[430] Although Cordesman elsewhere states that Iran possesses an earlier variant, the S-75 Dvina, it seems likely that this is simply an accidental grouping of Iran's S-75s under the earliest variant's name. Cordesman, A. H., & Peacock, M. (2015), 234.
[431] Kopp, C. (2009, July 03). Almaz S-75 Dvina/Desna/Volkhov. Retrieved December 06, 2017, from http://www.ausairpower.net/APA-S-75-Volkhov.html
[432] Pike, J. (n.d.). HQ-2 "Gin Sling". Retrieved December 06, 2017, from https://www.globalsecurity.org/military/world/china/hq-2.htm
[433] Kopp, C. (2009, March 31). PLA Area Defence Missile Systems. Retrieved December 06, 2017, from http://www.ausairpower.net/APA-PLA-IADS-SAMs.html
[434] O'Connor, S. (2010, January 07). Strategic SAM Deployment in Iran.

its current air defense organization. Iran's 16 HAWK battalions in 2015[435] (down from 22 in 2010)[436] make it one of the more widespread SAM systems in the Iranian network. As O'Connor noted in 2010,

> The HAWK has been a mainstay of Iranian strategic air defense since its acquisition before the Islamic Revolution. While numbers have dwindled, with roughly half of the Iranian HAWK sites currently active, the system is still widely deployed at numerous locations. The Iranian HAWK deployments are interesting as they represent a tactical SAM system deployed in a strategic capacity.[437]

According to Cordesman, there are "at least 19 unoccupied sites [that could be used] for the HQ-2 and/or Hawk."[438] This may be part of a larger Iranian strategic plan of holding back air defense resources to allow for redeployment to sites of reserves in the case of a decapitating strike or to use the empty sites "as dispersal sites for existing air defense assets, complicating enemy targeting."[439] Such a strategy is also suggested by the configuration of Iran's S-200 sites.[440] O'Connor, however, suggested a different explanation:

> Another reason for the lack of deployed SAM systems could be that the shorter-ranged HQ-2 and HAWK systems are no longer viewed as being effective enough to warrant widespread use. HQ-2 sites are currently 33% occupied, with HAWK sites being approximately 50% occupied, perhaps signifying more faith in the HAWK system but still demonstrating a potential overall trend of perceived un-reliability. Iran does have reason to suspect the reliability of the HAWK SAM system against a Western opponent, as the missile was an American product and has been in widespread use throughout the West for decades.[441]

These concerns are echoed by Cordesman and Abdullah Toukan who noted in their 2010 presentation on "Options in Dealing with Iran's Nuclear Program" that "HAWKS and IHAWKs do not have capable [Electronic Countermeasure]."[442] Such limitations are common among Iran's significant inventory of older SAM systems, which makes its overall strategic air defense picture perhaps weaker than numbers and inventories at first convey. Beyond the technical capabilities of Iranian radar and SAM defenses, historically doubts were raised about Iranian anti-air unit skill and the ability of some of their older systems (such as the S-200, HAWK, and others listed above)

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[435] Cordesman, A. H., & Peacock, M. (2015), 233.
[436] O'Connor, S. (2010, January 07). Strategic SAM Deployment in Iran.
[437] Ibid.
[438] Cordesman, A. H., & Peacock, M. (2015), 233.
[439] O'Connor, S. (2010, January 07). Strategic SAM Deployment in Iran.
[440] O'Connor, S. (2007, July 22). The S-200 SAM System: A Site Analysis.
[441] O'Connor, S. (2010, January 07). Strategic SAM Deployment in Iran.
[442] Cordesman, A. H., & Toukan, A. (2010), 84.

to stand up to an attack from a modern military such as that of the United States due to "radar sensor and battle management/C4I systems [that] have major limitations."[443]

The 2K12 Kub (SA-6 Gainful) is another older system that the USSR exported to the Middle East in the early 1970s.[444] A mobile, medium-range SAM system, the Kub was found to be more effective than either the SA-2 Guideline or the SA-3 Goa during the 1973 Yom Kippur War.[445] The Rapier SAM system is a short-range air defense system built by the United Kingdom which was first deployed in 1971.[446] These systems were delivered prior to the Iranian Revolution and are likely outdated, although Cordesman notes that there is evidence that Iran has upgraded them domestically, which may indicate a more significant plan to build indigenously produced replicas.[447] According to the British Army, the modern Rapier system has a radar detection range of 16 km and a maximum missile range of 8.2 km, although this is a different and likely much more capable variant than the original version possessed by Iran.[448] Iran also has the even older British Tigercat SAM system (the land-based version of the Seacat), which preceded the Rapier system and was replaced by it in the late 1970s.[449]

Domestic SAMs

Iran has advertised in recent years its efforts to build domestically sourced defense systems, most of which are copies or similar to systems which it already has in inventory. SAM systems that fall under this umbrella include the Mersad (MIM-23 HAWK),[450] Raad (Buk),[451] Ya Zahra and Shahab Thaqeb (Crotale),[452] Sayyad missiles (RIM-66 SM-1 and HQ-2),[453] and the Bavar-373 (S-300) (discussed above). Iran also has numerous other domestically produced radar systems that it claims have low-RCS detection abilities and that may or may not be combat related. Such systems include the Bina, Nazir, Keyhan, Fat'h-14, and Arash-2.[454] While Iran claims a great many things of its domestically produced defense systems, it seems likely that some of these capabilities are exaggerated as much of the language used by Iranian leaders in discussing these systems borders

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443 Ibid.
444 Kopp, C. (2009, July 06). 2K12 Kub/Kvadrat Self Propelled Air Defence System / SA-6 Gainful. Retrieved December 06, 2017, from http://www.ausairpower.net/APA-2K12-Kvadrat.html
445 Ibid.
446 Cordesman, A. H., & Peacock, M. (2015), 234.
447 Ibid.
448 The British Army. (2017, January 16). Rapier. Retrieved December 06, 2017, from http://www.army.mod.uk/equipment/23277.aspx
449 Ibid.
450 Kopp, C. (2010, July 17). Reassessing Iran's Air Defences. Retrieved December 06, 2017, from http://www.ausairpower.net/APA-NOTAM-170710-1.html
451 Farley, R. (2014, December 1). Forget Future Nukes: What About Iran's Missiles? Retrieved December 06, 2017, from http://nationalinterest.org/feature/forget-future-iranian-nukes-what-about-irans-missiles-11753
452 Cordesman, A. H. (2014). *Iran's Rocket and Missile Forces and Strategic Options*. Center for Strategic and International Studies, 30.
453 Binnie, J. (2017, January 4). Iran tests Talash air defence system. Retrieved December 06, 2017, from http://www.janes.com/article/66654/iran-tests-talash-air-defence-system
454 Mehr News Agency. (2015, September 01). Iran unveils advanced Nazir, Bina radar systems. Retrieved December 06, 2017, from https://en.mehrnews.com/news/109717/Iran-unveils-advanced-Nazir-Bina-radar-systems

on propaganda at times. According to Cordesman and Bryan Gold's 2014 book, *The Gulf Military Balance: Volume II,*

> Iran has made many claims for systems it later did not deploy, or deployed only in token numbers, or deployed in forms that lacked anything like the capability claimed—such as a radarless version of a supposed SA-6 clone. It is far from clear that Iran has the production base required to build a robust air defense network. Moreover, anecdotal unclassified reporting indicates that Iran lacks effective test and evaluation methods and has politicized its technology to the point it sometimes believes its own rhetoric. Exaggerated claims are a sin common to all weapons developers and military powers but there are signs that Iran sins more than most.[455]

This view of Iranian exaggeration is shared by Western defense planners and media, with *The Observer* noting that "the Western world has shown little interest," even in advanced Iranian systems such as the Bavar-373.[456] Overall, Iran's domestically produced systems seem to be *at most* as supplements to the known aerial defense systems that Iran already possesses and do not shift the military balance significantly, especially in an attack by stealth B-2s where the limiting factor is the ability of the B-2s and cruise missiles to defeat Iran's most advanced import systems, the S-300PMU-2 and the Tor and Pantsir short-range SAMs.

Man-Portable SAMs

According to *The Military Balance 2017,* Iran also possesses several man-portable air defense systems, including the Strela-2 (SA-7 Grail), Strela-3 (SA-14 Gremlin), Igla-S (SA-24 Grinch), and Chinese QW-1, QW-18, and HN-5A,[457] that could pose a risk to low-flying aircraft that are attempting to use terrain masking to avoid larger SAM systems. Such systems could threaten aircraft flying over central Iran, but difficulties with reaction time due to the lack of paired radar systems to inform users of a strike, redundancy with traditional SAM systems, and the ability of B-2s to fly at altitudes above the range[458] of these man-portable systems combine to make them likely of limited use against a one-off, surprise interdiction strike by the U.S. like the one envisioned here.

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[455] Cordesman, A. H., & Gold, B. (2014). *The Missile and Nuclear Dimensions* (Vol. II, The Gulf Military Balance), 69.
[456] Halpern, M. (2017, September 06). With World Distracted by North Korea, Iran Amasses New Weaponry. Retrieved December 06, 2017, from http://observer.com/2017/09/iran-missile-defense-system-bavar-373/
[457] International Institute for Strategic Studies (IISS). (2017). *The Military Balance, 2017*, 377.
[458] Pike, J. (n.d.). SA-18 Grouse (Igla 9K38). Retrieved December 06, 2017, from https://www.globalsecurity.org/military/world/russia/sa-18.htm

Anti-Aircraft Artillery

Iranian anti-air defenses around Fordow also include "anti-aircraft artillery (AAA), which is generally considered to be obsolete" when compared to SAM systems but would be more difficult to disable using Electronic Warfare (EW) methods.[459] Iran has other AAA in its inventory according to Cordesman and Toukan[460] and *The Military Balance 2017,*[461] and potential use of this unusual approach to modern air defense could be relevant in a more comprehensive air mission over Iran. In the case of a limited strike using primarily very-low-observable B-2 bombers, AAA guns are likely even less effective than the Iranian SAM defense network due to the stealth capabilities of B-2s.

Air Force Interceptors

Although Iran's roughly 40[462] F-14A Tomcat interceptors could potentially play a role in repelling a U.S. interdiction strike on Iran's nuclear program, Cordesman and Toukan list several weaknesses of the Iranian air defense system that would limit the success of a defensive effort by Iranian fighters. Iran's "long C4I Early Warning delay time, long response [and] scramble time by combat aircraft, low operational readiness rate of combat aircraft, low combat aircraft sortie rates," and a "high loss exchange ratio in a closing, [beyond visual range] environment and visual engagement environment" combine to make the Iranian fighter force an ineffective response to a concerted U.S. air attack.[463] Although O'Connor saw Iran's interceptor force of F-14A Tomcats as important to its air defense strategy in 2010 (largely due to weaknesses in Iran's SAM network at the time), Iran is unlikely to be able to scramble its F-14s in time to challenge a B-2 and cruise missile strike.

Air Defense Balance Conclusion

As of Sean O'Connor's 2010 analysis of "Iranian SAM Deployment" for *Air Power Australia*, Iran's air defense system was insufficient to counter an attack that incorporated cruise missiles, electronic warfare, and stealth.[464] While the landscape of Iranian air defenses has shifted significantly since then (with the largest developments being Iran's purchase of the S-300PMU-2, Tor-M1E, and Pantsir-S1 systems), overall changes to the strategic picture for a U.S. interdiction strike are likely relatively modest. As Iran's new systems represent a more serious challenge to an

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[459] Zone of immunity: Iran bolsters Fordow defences Jane's Defense Weekly Vol 49 Issue 51
[460] Cordesman, A. H., & Toukan, A. (2010).
[461] International Institute for Strategic Studies (IISS). (2017). *The Military Balance, 2017*, 377.
[462] Axe, D. (2016, June 28). Fact: Iran's Air Force Flies American-Made F-14 Tomcats. Retrieved December 06, 2017, from http://nationalinterest.org/blog/the-buzz/revealed-irans-air-force-flies-american-made-f-14-tomcats-16758, 5.
[463] Cordesman, A. H., & Toukan, A. (2010).
[464] O'Connor, S. (2010, January 07). Strategic SAM Deployment in Iran.

attacking air force than the previous generation, though analysis of radar range curves and statements by SAM developers suggests these advances are likely not enough to counter the significant strike capabilities offered by the B-2 bomber and a coordinated barrage of cruise missiles that would likely be employed by the United States. Although it does seem relatively likely that the United States could still achieve a relatively overwhelming victory over Iran's air defenses in 2017, this picture has certainly shifted in the last ten years in favor of the defender introducing more uncertainty in the outcome. Iran has [also?] made a significant and public push towards self-sufficiency in the production of defense systems with a laundry list of new systems including the Sepehr and Ghadir very-long-range OTH radar systems, the S-300-based Bavar-373, and many other short- and medium-range SAM and radar systems. Continued improvement of Iranian air defenses, either through continued import of increasingly modern systems or progress in producing advanced systems domestically, could make a U.S. attack more challenging over time. Russia has offered Iran the opportunity (which Iran has rejected) to purchase the more advanced S-400 Triumf system, which could extend the engagement range of Iran's SAM systems from 300 km (if Iran possessed a fully upgraded S-200) to 400 km, thus reducing the coverage of Iranian territory that the United States could strike using air-launched cruise missiles. As most of the crucial Iranian nuclear facilities (Esfahan, Natanz, and Fordow) are already near the limit of U.S. cruise missile range, increased range of Iran's SAM systems could have significant implications for a future attack.

The air war that occurred between the Ukrainian Air Force and Russian-supplied separatists in eastern Ukraine in 2014 provides an analog for the use of some of Iran's Russian-made short-range and man-portable SAM systems. The separatists were armed with many of the same SAM systems that the Iranians have, including variants in the Strela, Igla, Pantsir, and Tor families and were able to shoot down "Ukrainian helicopters, fighter jets and transport aircraft at a devastating pace" according to *Newsweek*.[465] Although there are substantial differences between the two situations, the important lesson to draw from the Ukrainian conflict is the technical capability of the separatists' systems, with which the Iranians are equipped, to shoot down 4th generation fighters such as the MiG-29 and likely U.S. equivalents such as the F-15, F-16, and F/A-18. This reinforces the assumption that U.S. planners would be unlikely to risk sending F/A-18s or non-stealth bombers over Iranian air defenses without a SEAD operation.

Although Iran's air defense systems have not been combat tested, their extent represents Iran's increasing commitment to defending its own airspace and suggests that Iran will likely continue to improve its air defense network for the near future. Iran's increasingly sophisticated SAMs combine essentially to preclude conventional use of non-stealthy planes over Iranian airspace without a major SEAD operation, and to limit penetrating strikes against targets on the interior of Iran and hardened targets that require bunker-buster bombs to B-2s.

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[465] Peterson, N. (2016, October 13). In Opinion: Putin has achieved a no-fly zone over Ukraine. Retrieved December 06, 2017, from http://www.newsweek.com/putin-has-achieved-no-fly-zone-over-ukraine-506433

Table 4: Iranian Air Defense Systems

	Eng. Range (km)	Det. Range (km)	Number
Very-long-range OTH Radar			
- Sepehr	n/a	Estimated 1,640	1
- Ghadir	n/a	600	2
Early Warning Radar	n/a	Unknown	24
Other Radar			
- 1L119 Nebo	n/a	330[466]	2[469]
- Kasta-2E2	n/a	95[467]	2[470]
- 1L222 Avtobaza	n/a	150[468]	2[471]
Long-range SAM			
- S-300PMU-2 (SA-20B Gargoyle)	200	300	4 btn[474]
- S-200 Angara (SA-5 Gammon)	180-300[472]	270[473]	10[475] (7 sites)
- Bavar-373	Likely ~200	Likely ~300	Not yet depl.
Medium-range SAM			
- MIM-23B IHAWK/Shahin	40[476]	100[479]	16 btn[480]
- S-75 (SA-2 Guideline)	50[477]	65	45[481]
- HQ-2 "Gin Sling" (CSA-1)	50[478]	65	7 sites[482]
Short-range SAM			
- Tor-M1E (SA-15 Gauntlet)	12[483]		
- Pantsir-S1E (SA-22 Greyhound)	20		
- HQ-7/FM-80 (CSA-4)			

466 Kopp, C. (2008, April 29). NNIIRT 1L119 Nebo SVU / RLM-M Nebo M. Retrieved December 06, 2017, from http://www.ausairpower.net/APA-Nebo-SVU-Analysis.html
467 For targets with 2 m^2 RCS. Almaz – Antey Air and Space Defence Corporation. (n.d.). "Kasta-2E2" (39N6E) Radar System. Retrieved December 06, 2017, from http://www.almaz-antey.ru/en/catalogue/millitary_catalogue/1219/1241/1335
468 Electronic warfare system. Possibly thought to be the system that brought down RQ-170 Sentinel stealth drone over Iran in 2011. Deagel.com. (n.d.). 1L222 Avtobaza. Retrieved December 06, 2017, from http://www.deagel.com/Tactical-Vehicles/1L222-Avtobaza_a002725001.aspx
469 Cordesman, A. H., & Peacock, M. (2015), 77.
470 Ibid.
471 Ibid.
472 Kopp, C. (2009, June 28). Almaz 5V21/28 / S-200VE Vega.
473 O'Connor, S. (2007, July 22). The S-200 SAM System: A Site Analysis.
474 International Institute for Strategic Studies (IISS). (2017). *The Military Balance, 2017*, 378-379.
475 Cordesman, A. H., & Peacock, M. (2015), 233.
476 Deagel.com. (n.d.). MIM-23 Hawk. Retrieved December 06, 2017, from http://www.deagel.com/Defensive-Weapons/MIM-23-Hawk_a000846001.aspx
477 Federation of American Scientists. (n.d.). V-75 SA-2 GUIDELINE. Retrieved December 06, 2017, from https://fas.org/nuke/guide/russia/airdef/v-75.htm
478 Federation of American Scientists. (n.d.). V-75 SA-2 GUIDELINE.
479 Approximation. See *IHS Jane's Land Warfare Platforms: Artillery and Air Defence* 741
480 Cordesman, A. H., & Peacock, M. (2015), 233.
481 Ibid.
482 As of 2010. O'Connor, S. (2010, January 07). Strategic SAM Deployment in Iran.
483 Kopp, C. (2009, July 14). 9K330/9K331/9K332 Tor M/M1/M2 Self Propelled Air Defence System / SA-15 Gauntlet.

- 2K12 Kub (SA-6 Gainful) - Rapier	10[484] 25[485] 6.5[486]	25[487] 36[488] 20[489] 60-90[490] 12[491]	29[492] 10+[493] 6[494] 5 sqn[495]
Man-portable SAM - Strela-2 (SA-7 Grail) - Strela-3 (SA-14 Gremlin) - Igla-S (SA-24 Grinch) - QW-1 Vanguard/Misagh-1 - QW-18/Misagh-2 - HN-5A	 4.2[496] 4.5[497] 6[498] 5[499] 5[500] 4.4[501]	 n/a n/a n/a n/a n/a n/a	 "Large numbers"[502]

[484] Kopp, C., & Andrew, M. (2010, September 08). CPMIEC HQ-7/FM-80/FM-90 / CSA-4/CSA-5 Sino-Crotale Self Propelled Air Defence System.
[485] Kopp, C. (2009, July 06). 2K12 Kub/Kvadrat Self Propelled Air Defence System / SA-6 Gainful.
[486] Cordesman, A. H., & Peacock, M. (2015).
[487] Pike, J. (n.d.). SA-15 GAUNTLET / 9K331 Tor. Retrieved December 06, 2017, from https://www.globalsecurity.org/military/world/russia/sa-15.htm
[488] Kopp, C. (2009, July 15). KBP 2K22/2K22M/M1 Tunguska SA-19 Grison / 96K6 Pantsir S1 / SA-22 Greyhound.
[489] Kopp, C., & Andrew, M. (2010, September 08). CPMIEC HQ-7/FM-80/FM-90 / CSA-4/CSA-5 Sino-Crotale Self Propelled Air Defence System.
[490] Pike, J. (n.d.). Straight Flush. Retrieved December 06, 2017, from https://www.globalsecurity.org/military/world/russia/straight-flush.htm
[491] The British Army. (2017, January 16). Rapier.
[492] Cordesman, A. H., & Kleiber, M. (2007), 63.
[493] Hughes, R. (2007, May 22). Iran set to obtain Pantsyr via Syria. Retrieved December 06, 2017, from https://web.archive.org/web/20071018002847/http://janes.com/defence/news/jdw/jdw070522_1_n.shtml
[494] Cordesman, A. H., & Peacock, M. (2015), 76.
[495] Ibid, 233.
[496] Pike, J. (n.d.). SA-7 GRAIL (9K32M Strela-2). Retrieved December 06, 2017, from https://www.globalsecurity.org/military/world/russia/sa-7.htm
[497] Pike, J. (n.d.). SA-14 GREMLIN 9K34 Strela-3. Retrieved December 06, 2017, from https://www.globalsecurity.org/military/world/russia/sa-14.htm
[498] Pike, J. (n.d.). SA-18 Grouse (Igla 9K38).
[499] Pike, J. (n.d.). QW-1. Retrieved December 06, 2017, from https://www.globalsecurity.org/military/world/china/qw-1.htm
[500] Ibid.
[501] Wikipedia. (2017, December 06). HN-5. Retrieved December 06, 2017, from https://en.wikipedia.org/wiki/HN-5
[502] Cordesman, A. H., & Peacock, M. (2015), 233.

VII. Prioritizing Targets

This section groups Iran's nuclear sites, and thus potential targets for an interdiction strike, into target sets by geographic location. A single target set, such as the one at Natanz, may have facilities at various points along the weapons production chain, and grouping them potentially allows a single strike aircraft to attack multiple facilities. Geographic grouping has the added benefit of potentially grouping related activities since they are often done in close proximity to each other. For instance, the many buildings associated with the UCF at Esfahan are all components of Iran's nuclear conversion effort. Because a strike on the entire conversion effort is much more valuable than the sum of its component parts (in that it temporarily halts conversion entirely), grouping the many targets at the site to create one, larger target set makes sense for target prioritization. Below is a list of target sets with commentary on how well they match each of the three criteria set out in the "Target Criteria" section: strategic value, target difficulty, and political considerations. The target sets are listed in order of desirability, from most important to least important.

Esfahan (Conversion)

In terms of strategic value, the Uranium Conversion Facility (UCF) at Esfahan is near the top of the list, exceeded possibly only by enrichment facilities. I have given Esfahan priority over enrichment facilities due to the ease of destroying the Esfahan target, the UCF's dominance over an entire horizontal segment of the weapons production chain, and the accessibility of Esfahan to U.S. cruise missile strikes. Its destruction would effectively cut off Iranian access to new UF_6, making its enrichment program reliant on current stocks or imports until the facility could be rebuilt or replaced. While this doesn't preclude enrichment of UF_6 that Iran already possesses, it limits Iran's ability to acquire more (which it would almost certainly need to build a stockpile of multiple weapons). Esfahan's destruction could also limit Iranian ability to reconvert the "weapons-grade" uranium hexafluoride into metal for fabrication and assembly (thus trapping it in limbo) if the UCF is where that process is planned to take place. The time to replace the UCF is unclear, although inferences can be drawn from the timeline of the construction of the UCF itself. Iran spent six years, 1999 to 2005, from the initiation of construction on the UCF at Esfahan to the beginning of production.[503] Although Iran could likely instigate a crash program in the case of destruction of the conversion facility and draw on expertise from operating the UCF to construct a replacement in less than six years, a substantial period of time to replace its uranium conversion throughput would still be necessary. A fastest-case scenario for an Iranian rebuild to bring its conversion back online could then be one or one and a half years instead of six, while a conservative estimate might be that Iran could halve the time off its initial six-year construction for a rebuild time of three years. If Iran were forced to spread its resources to rebuild several aspects of its nuclear program simultaneously, this second timeframe seems more plausible. This

[503] Nuclear Threat Initiative. (n.d.). Facilities.

would limit Iran to enriching only the UF_6 in its stockpile for up to three years after a strike, and Iran could potentially be unable to reconvert this highly-enriched UF_6 to metal.

In terms of target difficulty, the UCF is not hardened or buried like Iran's enrichment facilities[504] and thus is relatively easy to destroy. The UCF is relatively condensed (50 buildings spread over approximately one-quarter square mile in total) making it relatively easy to retarget missiles midcourse if SAM defenses destroy all of the cruise missiles initially assigned to an aim point. Esfahan is also the closest of the three primary sites (Esfahan, Natanz, and Fordow) to Iran's southeast coast and thus is the easiest for the United States to attack with cruise missiles. Though Iran might claim that the UCF is part the civilian Nuclear Research Center at Esfahan, it is clearly a viable military target and thus the political concerns of striking Esfahan are likely minor, especially relative to the potential gains.

Though the UCF is colocated with the Zirconium Production Plant (ZPP), the Fuel Manufacturing Plant, the Fuel Plate Fabrication Plant, and the Enriched UO_2 Powder Plant,[505] it is unlikely that these plants have much strategic value as targets with the disabling of the IR-40 reactor at Arak.[506]

Natanz and Fordow (Enrichment)

The preliminary concern for both Natanz and Fordow is target difficulty. Conventional wisdom on the issue of an interdiction strike targeting Iran is clear: Iran's enrichment facilities are one of the most important, if not the most important, target set.[507] Although I have given Esfahan priority as a target, this is not meant to diminish the importance of Natanz and Fordow. Indeed, any interdiction strike that hopes to delay Iran for a significant period of time should target both conversion and enrichment. As the strategic value of enrichment targets is not in question, the primary remaining concern is that of target difficulty, which much of the remainder of this section is devoted to. There are some political considerations which are relevant to both sites and they are touched on below as well.

Natanz is buried around 20 meters (65 feet) underground, about one third the depth of Fordow, and is by far the easier of the two facilities to destroy.[508] The area where the Natanz underground production halls are located was excavated, and the halls were built and then covered. This gives planners good information on the depth of the facility, the size of the production halls, and the precise locations at which to aim in order to achieve maximum damage.[509] An American attack on Natanz would likely take one of two routes: either an attempt to place multiple GBU-28s on the same aim point in succession in order to burrow to the production halls or overkilling of the target using a GBU-57 MOP. If the U.S. chose to use a GBU-28, which can penetrate 100 feet of

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504 Cordesman, A. H., & Toukan, A. (2010), 124.
505 Henderson, S., & Heinonen, O. (2015), 11.
506 Nuclear Threat Initiative. (n.d.). Facilities.
507 See Cordesman, A. H., & Toukan, A. (2010) and Long, A., & Rass, W. (2007).
508 Reuters Staff. (2012, January 12).
509 Levi, M. (2006, April 18). Iran's Sitting Duck. Retrieved December 06, 2017, from https://query.nytimes.com/gst/fullpage.html?res=9C03EEDA173FF93BA25757C0A9609C8B63

soil or 20 feet of concrete before exploding,[510] the U.S. could conceivably penetrate Natanz with one weapon if the concrete ceiling of the facility is less than nine feet thick.[511] The thickness of the ceiling of Natanz's production halls is unclear, and although the commonly used measurement of "over two meters"[512] is roughly at the limit of the GBU-28's capabilities, it is possible that other defenses such as ceiling layering could put the Natanz production halls just barely out of reach for a single GBU-28.[513] Mark Fitzpatrick stated that despite the fortifications of the FEP, it is "nevertheless possible to damage it with precision bombing with one sortie to create a crater and second sortie to burst through the bottom of the crater to the facility below."[514] The same method was suggested by Whitney Raas and Austin Long in "Osirak Redux?"[515]

Another significant challenge of the Natanz facility is the enormous size of its two production halls. If the United States were able to breach the facility with a centrally placed GBU-28, it would have a 5-psi overpressure area that covered approximately 14.4% of the facility.[516] Such a destruction rate could significantly dent Iran's enrichment efforts, but would not ensure the incapacitation of the entire facility, or destruction of all the centrifuges therein which is a prerequisite for mission success. If the United States chose to use the larger and more penetrative MOP, it could hit the production halls easily[517] and the 2,700-kg explosive yield of the weapon[518] would almost certainly destroy all of the centrifuges in the facility. Using the UN's Kingery-Bulmash Blast Parameter Calculator, the entirety of each Natanz production hall would have an overpressure of at least 3.75 psi, and a detonation in the center of the hall would achieve a 5-psi overpressure for 61.5% of the production hall.[519] An explosion of this size would be sufficient to

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[510] Pike, J. (n.d.). Guided Bomb Unit-28 (GBU-28) - BLU-113 Penetrator. Retrieved December 06, 2017, from https://www.globalsecurity.org/military/systems/munitions/gbu-28-specs.htm

[511] To do this we solve a simple system of equations using the assumptions for feet of soil (f_s) and feet of concrete (f_c) in the sentence above. The depth of Natanz gives us: $f_s + f_c = 65$. The limitations of the GBU-28 give us: $f_c/20 + f_s/100 < 1$. Solving for this system of equations, we get that $f_s > 56$ and $f_c < 9$. All this assumes that the concrete is reinforced to the same level in the Natanz and GBU-28 test situations.

[512] Albright, D., & Hinderstein, C. (2003, March 14).

[513] Cordesman, A. H., & Al-Rodhan, K. R. (2007). *Gulf Military Forces in an Era of Asymmetric Wars*. Westport, Conn.: Praeger Security International, 415.

[514] Reuters Staff. (2012, January 12).

[515] See Long, A., & Rass, W. (2007).

[516] Area of 5 psi overpressure according to Cordesman: $pi * 92^2 = 26{,}590\ ft^2$ ($2{,}470\ m^2$) which is 7.6% of the size of a Natanz production hall. This radius is significantly smaller than the value of 126.3 feet (38.5 m) found by calculating the radius for GBU-28's 286 kg tritonal warhead using the Kingery-Bulmash Blast Parameter Calculator. Such a calculation would give an area of $4{,}657\ m^2$. The area of one production hall according to ISIS analysis is 170 m by 190 m or 32,300 m. See Cordesman, A. H., & Toukan, A. (2010), 200., Stilwell, B. (2017, February 20). This Is Why Bunker Buster Bombs Are Made From Spent Howitzer Barrels. Retrieved December 06, 2017, from https://www.realcleardefense.com/articles/2017/02/21/this_is_why_bunker_buster_bombs_are_made_from_spent_howitzer_barrels_110846.html, and United Nations. (n.d.). UN - SaferGuard - Kingery Bulmash Blast Parameter Calculator. Retrieved December 07, 2017, from https://www.un.org/disarmament/un-saferguard/kingery-bulmash/

[517] See Cordesman, A. H., & Toukan, A. (2010), 153.

[518] Ibid.

[519] Assuming a 2,700 kg (6,000 lb) TNT warhead. Although the HE material of the warhead is unknown, TNT seems to be a reasonable assumption as other listed weights for the warhead (5,300 lbs) would have the equivalent yield to the TNT warhead above if the HE explosive material were tritonal (which is used in the GBU-28). The radius for 5 psi overpressure is roughly 79.5 m (260 feet).

destroy the centrifuges at Natanz, and dropping one MOP on each production hall could be an effective way of destroying the facility's centrifuge production.[520] There exists a third underground building at the Natanz site, which a 2003 ISIS analysis suggests is likely a support or storage facility.[521] This building is smaller but is also buried and would likely be a supplemental target for a U.S. strike as its destruction furthers the aim of dismantling Iran's centrifuge program through the potential destruction of support systems or centrifuge storage.

Though Iran likes to claim that Natanz is a "commercial facility"[522] and would likely attempt to use this designation to inflict political pain on the United States, its claim does not hold up to scrutiny.[523] This potential political speedbump for the United States is also substantially outweighed by the benefits of destroying all of Iran's centrifuges and enrichment capacity.

The destruction of Fordow is a far greater challenge than that of Natanz. According IISS expert Mark Fitzpatrick, "the chamber at Fordow might be 'impenetrable,' due to its presumed depth."[524] Robert Hewson, the Editor of *Jane's Air-Launched Weapons* was also skeptical of the United States' ability to destroy the enrichment hall itself with a conventional airstrike. According to Hewson,

> Given that it (Fordow) is a relatively recent development, it has probably been designed with a lot of attention to protecting it against conventional strikes. You don't necessarily have to obliterate it, mind. You could block the exits, block access to power, isolate it from life outside, and then you have effectively switched it off.[525]

Taking the opposing view, the American Air Force claims it has both the weaponry and training needed to execute a destructive strike on the enrichment hall. The 30,000-pound GBU-57 "Massive Ordnance Penetrator" (MOP), mentioned above, is the world's largest non-nuclear weapon and is designed precisely to hit targets like the FFEP. Former Defense Secretary Ashton Carter was direct when asked whether the MOP could destroy Fordow: "Yes. That's what it was designed to do."[526] After being dropped from the B-2 or the B-52, the only two planes equipped to carry it, the MOP

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[520] Note that 5 psi is a high standard for the destruction of relatively delicate centrifuges and was imposed due to the seriousness of the mission and the desire to destroy all centrifuges. Effects at 3 psi are enough to level unfortified houses and should be more than sufficient for destroying centrifuges. See FEMA. (2003). *Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings* (Risk Management), Chapter 4.
[521] Albright, D., & Hinderstein, C. (2003, March 14).
[522] Kerr (2017). *Iran's Nuclear Program: Status,* 21.
[523] Natanz has enough centrifuges to enrich uranium for a weapons program but not enough to supply a nuclear power reactor and is generally accepted as the center of a potential military enrichment program. See Albright, D., Brannan, P., Strickler, A., & Walrond, C. (2011). *Natanz Enrichment Site: Boondoggle or Part of an Atomic Bomb Production Complex?* Institute for Science in International Studies.
[524] Reuters Staff. (2012, January 12).
[525] Ibid.
[526] Crowley, M. (2015, June 24). Plan B for Iran.

hits the ground at "supersonic speed" and "can burrow through 200 feet of earth and 60 feet of concrete [after impact] before detonating."[527]

Assessment is complicated by the lack of firm information about Fordow's underground facilities, at least in unclassified material. According to retired Air Force Colonel Sam Gardiner: "Fordow [unlike Natanz] is an unknown. Where is the enrichment chamber? How deep? Which direction does the tunnel go?"[528] For the U.S. military to have confidence in its plan to destroy Fordow, it needs this information. If the United States does know where to aim (something that this paper assumes to be the case), then "the question is, how many turns do you get at the apple?" according to "a former senior intelligence official" quoted by *The Washington Post*.[529] An analyst quoted by *Reuters* argued that "Fordow was at the very limit of the bomb's capacities, which he said could reach down to a maximum of 60 meters" (196 feet).[530] According to a *Wall Street Journal* article on the MOP, "the Pentagon envisages guiding two or more of the bunker busters to the same impact point, in sequence, extending the weapon's burrowing power" in the hope of solving this problem and "senior officials say the results show the bomb—when dropped one on top of the other—is now more capable of penetrating fortified nuclear facilities in Iran."[531]

If the MOP cannot destroy the cascade halls, then the United States is left with the option suggested by Hewson of trying to disable the facility through strikes on access points and systems that are required for full operation. A *Jane's Defense Weeky* article on Fordow's defenses suggests an "a 100 x 40 m heating, ventilation and cooling (HVAC) building that is sunk into the mountain and has presumably been massively structurally reinforced" and "the facility's five northern entrances" as potential target points at the site beyond the cascade hall.[532] Although Anthony Cordesman of the Center for Strategic and International Studies believes that "strikes targeted against its entrances could disable the facility for a substantial time,"[533] such a strike would not be as much of a setback for the Iranian enrichment program as the destruction of the enrichment hall. As he notes:

> That's a temporary solution. Entrances can be cleared and rebuilt. Replacing centrifuges and their nuclear material takes longer. Any president who risks an attack on Iran may insist on inflicting more damage than a few bulldozers can undo.[534]

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527 Bender, J. (2015, June 25). The 30,000-pound bomb that could be used against Iran's nuclear facilities 'boggles the mind'. Retrieved December 06, 2017, from http://uk.businessinsider.com/the-30000-pound-bomb-that-could-be-used-against-irans-nuclear-facilities-boggles-the-mind-2015-6

528 Reuters Staff. (2012, January 12).

529 Warrick, J. (2012, February 29). Iran's underground nuclear sites not immune to U.S. bunker-busters, experts say. Retrieved December 06, 2017, from https://www.washingtonpost.com/world/national-security/experts-irans-underground-nuclear-sites-not-immune-to-us-bunker-busters/2012/02/24/gIQAzWaghR_story.html

530 Reuters Staff. (2012, January 12).

531 Barnes, J. E., & Entous, A. (2015, April 03). Pentagon Upgraded Biggest 'Bunker Buster' Bomb as Iran Talks Unfolded. Retrieved December 06, 2017, from https://www.wsj.com/articles/pentagon-worked-to-improve-biggest-bunker-buster-bomb-as-iran-talks-unfolded-1428078456

532 Zone of immunity: Iran bolsters Fordow defences Jane's Defense Weekly Vol 49 Issue 51

533 Crowley, M. (2015, June 24). Plan B for Iran, 2.

534 Ibid.

If the U.S. military were uncertain whether a strike using MOPs could destroy FFEP, it would likely opt for some combination of the two strategies in order to hedge its bets. While the United States may have intelligence and testing data that allows it to determine effectiveness of an FFEP strike, the controversy in the open literature means that this paper will assume that the United States will attempt to incapacitate FFEP using MOPs and potentially attempt to close off tunnel entrances if surplus resources are available.

Fordow has some political implications as an airstrike target, though they are outweighed by the strategic value of destroying all of Iran's enrichment facilities. FFEP is located near the city of Qom, "a city considered one of the holiest in Shia Islam," and an attack on the facility could "risk a furious religious uprising throughout the region" even if Qom were not hit according to an article in *Haaretz*.[535]

The destruction of the whole of a horizontal segment of the nuclear production chain is greater than the sum of its parts. Consequently, while Esfahan is separable as a target from Natanz and Fordow, the enrichment sites are paired, both in terms of prioritization and means. Knocking all of Iran's enrichment capabilities out places an indefinite halt on its enrichment program until more centrifuges can be built while the destruction of only one enrichment facility simply slows the rate of enrichment. If both facilities are destroyed, Iran will be heavily dependent on how fast it can build new centrifuges, a capability that the United States could look to strike as discussed below. Natanz and Fordow are also paired in that their destruction requires the assignment of B-2s carrying enormous bunker-buster bombs, which has implications for force allocation and employment as discussed in Section VIII.

Lashkar Abad (Laser Enrichment)

The facility at Lashkar Abad requires a weighing of strategic and political concerns. The facility is not hardened and well within cruise missile range, but it is unclear whether significant uranium enrichment activity occurs at this facility today and thus whether it would be worth striking. As we shall see in the following section, a surplus of cruise missiles available for an attack on Iran means that the decision to include Lashkar Abad in a target list is an *and* not an *or* decision, as there are more than sufficient forces to hit all other targets on the list. However, it is unclear whether the United States would wish to attack Lashkar Abad if enrichment were not taking place as the United States could suffer political consequences of attacking "innocent bystanders."

Centrifuge Manufacturing

All targets beyond this point begin to raise important political considerations about increasing the scale of an attack on Iran, thus increasing potential retribution, anti-American sentiments, and cost, that likely overbalance potentially diminishing returns from attacking less

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535 Information from this link which was down when I went back to cite: https://www.haaretz.com/cries-of-hold-me-back-may-lead-israel-to-strike-iran-1.6986

important or non-critical facilities. Although the United States is not extremely limited in resources to commit to the Iran mission, its resources (particularly the number of B-2s committed to destroy internal or hardened targets) are not endless, raising another consideration for a large-scale operation. Ultimately, such concerns must be weighed against the strategic value that the targets are assigned by U.S. military planners.

The centrifuge enrichment plants near Esfahan, 7th of Tir Industries and Farayand Technique could easily be included in a cruise missile strike if desired as they are within range of both TLAMs and JASSM-ERs. Of the other sites identified as potential centrifuge production workshops, Kaveh Cutting Tools in the northeast of Iran could be attacked using TLAMs although it is not in range of JASSM-ERs. Its distance from the majority of Iran's SAM defenses might mean that the more advanced JASSM missiles would be unnecessary for a strike. Those sites around Teheran are out of range of all U.S. cruise missiles unless the U.S. chose to try to secretly launch from a submarine in the Persian Gulf. Attacking these facilities with TLAMs would likely be difficult as well as Tehran is one of the areas of most concentrated air defenses in all of Iran. The destruction of such facilities would likely require the tasking of a B-2 carrying 500-pound PGMs to destroy all centrifuge manufacturing sites in the area.

There are potentially important political concerns for attacks on centrifuge manufacturers as many are located in urban areas in or around Teheran and Esfahan, increasing the likelihood of civilian collateral damage. Such concerns may set a higher bar for target inclusion, or encourage the U.S. to attack selectively only manufacturers specializing in a certain subset of centrifuge components (those that produce rotating components for example), in order to limit the number of strikes required near urban areas while still maximizing delay to Iran's enrichment efforts.

Mining and Milling

Of Iran's mining and milling operations, milling seems like the more attractive target given that it has historically taken Iran longer to finish constructing its uranium mills than the mines it has paired them with,[536] unless the U.S. could collapse the shafts of the Saghand mine (the larger of the two). It is unclear whether the destruction of Iran's mining and milling operations would have much effect due to the significant stockpiles of yellowcake Iran currently has which are sufficient to construct numerous nuclear weapons. All of Iran's mining and milling facilities are well within cruise missile range for both JASSM-ERs and TLAMs.

Bushehr-1

While Bushehr-1 certainly provides Iran with technical skill and knowledge that would be valuable in constructing a nuclear weapon, and theoretically Bushehr-1 could be used to produce significant quantities of plutonium if operated without safeguards, the poor reactor configuration for producing high-grade plutonium, use of IAEA safeguards, and political risk of nuclear fallout from attacking such a reactor likely make it an unattractive target for U.S. military planners.

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[536] See International Atomic Energy Agency & OECD Nuclear Energy Agency. (2016), Section on "Iran (Islamic Republic of)" starting on 273.

Arak

Arak as a site does not offer much that would be attractive to a military planner if Iran has indeed rendered the core of the IR-40 inoperable such that it cannot be salvaged and restarted without constructing a new core. Other potential targets at the site include facilities that could be used for reprocessing and the HWPP. These would take less time to rebuild than it would take to construct a new core, and thus their destruction would serve only to divert resources from more critical missions while worsening the political implications of an interdiction strike for the U.S. by expanding its scale. As Iran's own estimates for constructing a new reactor (by 2021) and the amount of time it took Iran to build the IR-40 the first time (around 10 years) indicate, building an operable new reactor for the site would likely take more time than acquiring a bomb through the uranium pathway. Although Iran would likely continue work on the plutonium pathway after a U.S. strike if only to diversify its nuclear program, it does not appear that following the JCPOA, the plutonium pathway or Arak are the most immediate proliferation concern for Iran. If Iran were able to procure a functioning core for the IR-40 reactor that would produce the same rate of high-grade plutonium as the original planned core in a relatively short period of time, the prioritization calculus would likely be different. Due to the IR-40's crucial place on the plutonium pathway as the only reactor that produces weapons-grade plutonium in quantities large enough to build multiple nuclear weapons, the IR-40 would become one of the top two sites for the U.S. to attack along with Esfahan.

Research

The United States could also choose to attack research facilities such as nuclear-focused universities in Teheran, the Teheran Nuclear Research Center, or the Esfahan Nuclear Technology Center with the goal of killing Iranian nuclear scientists [and destroying research facilities] to delay Iran's nuclear program but such a tactic seems bloodthirsty and out of character for a U.S. strike, particularly given the breadth of targets the United States could destroy to delay Iran's program without creating an international uproar. It is also impossible to evaluate the strategic value of doing so as almost no information has been published in recent years on the remaining research that would be required for Iran to build a nuclear weapon.

Parchin is an exception to this as it is a clearly military site that has been thought to be a part of Iran's pre-nuclear testing program in the past, and likely could be included as a nuclear target without the same political implications.

VIII. Potential Strikes

With 120 to 150 TLAM-E missiles available per carrier strike group[537] and a small number of additional missiles potentially available to be launched by submarines that could be positioned in the Persian Gulf, the United States could launch upwards of 300 TLAMs in an attack on Iran.

[537] Around 300 available but keeping a substantial portion in reserve.

Cruise missiles are ideal for use on the aboveground UCF at Esfahan. Esfahan is the closest of the three main facilities to the southeast coast, roughly 290 km inside the range of TLAMs if launched 300 km off Iran's southeast coast, giving ample range for pathways designed to evade SAM system detection, and around 150 km inside the range of below-radar-horizon-launched JASSM-ER missiles launched 100 km off Iran's coast. As each B-1B is capable of carrying 24 JASSM-ERs,[538] the United States would need to employ only around four B-1Bs to place two JASSM-ERs on each building at Esfahan (total of 100). The United States could certainly use more than this, even accounting for a desire to hold forces in reserve (it has 62 B-1Bs and 2,500 JASSM-ERs), but the key takeaway is that the United States has more than enough cruise missiles to destroy the UCF complex and any other aim points of interest at Esfahan. The United States could also potentially attempt to use cruise missiles to attack Natanz, which is further than Esfahan but within the nominal range of both the JASSM-ERs and TLAMs, although such missiles would likely be relatively inefficient due to the lack of surplus range to optimize paths to evade Iranian air defenses and less effective at completing the most important strategic objective of an attack on Natanz, which is the destruction of the two hardened production halls. Still, cruise missiles could potentially be used to strike aboveground buildings at the Natanz site although the United States would likely prefer to attack them with a B-2 due to the aforementioned range challenges. Cruise missiles could also be used to strike several of Iran's centrifuge manufacturing facilities as well as the country's mining and milling operations if the U.S. chose to do so.

It is unclear how many of the fleet of 20 B-2 bombers, the United States would be willing to use for a strike on Iran. In the base scenario for resource allocation conceived by this paper, the United States is willing to use a quarter (5/20), and due to their vital status for the mission, the role of each B-2 and its armament is discussed below. This analysis assumes safe overflight by B-2 bombers, which seems likely given both the assumptions and statements made by Russian SAM developers about their systems and the known capabilities of the B-2. In order to destroy the production halls at Natanz and Fordow, the United States would likely need to use at least three B-2s carrying bunker buster weapons, potentially leaving two B-2s available for other missions and targets or for redundancies.

Whether to arm B-2 tasked with destroying Natanz production halls with GBU-28s or MOPs raises questions of resource allocation. To equal the destructive footprint of a MOP attack, the United States would likely need to penetrate each Natanz production hall with four to five

538 Beckhusen, R. (2017, November 26). B-1 Bombers Are Flying a Record Numbers of Missions. Retrieved December 06, 2017, from http://nationalinterest.org/blog/the-buzz/b-1-bombers-are-flying-record-numbers-missions-23368

GBU-28s.[539] As each B-2 is likely capable of carrying 8 GBU-28 bombs,[540] there is essentially equal destructive power delivered by equipping the B-2 tasked with destroying Natanz with GBU-28s or MOPs. This is, however, contingent on a single weapon being able to breach the production halls, no sure thing for the GBU-28s as discussed above. The deciding factors in favor of equipping the Natanz B-2 with MOPs are the greater penetration capabilities of the MOP, which are more than sufficient to breach the Natanz production halls with a single weapon, and the flexibility that the use of MOPs provides in attacking Fordow. The United States would almost certainly desire redundancies in armaments (multiple B-2s tasked with the same mission) for an attack on Iran, particularly given the sensitivity and difficulty of the mission. By employing a B-2 carrying MOPs to destroy Natanz, the same configuration that would be used to attack Fordow, the United States would be able to pool its redundancies across the two facilities by flying an extra MOP-armed B-2 with the first B-2 attacking Natanz, and then allowing the spare to continue onwards to Fordow if both weapons work successfully. All three MOP-armed B-2s, those tasked with Natanz, Fordow, and the reserve, are interchangeable in terms of their armament, providing flexibility to planners in case of weapons failure that would not exist if using GBU-28s on Natanz.

This minimum configuration of three B-2s attacking Iran's hardened enrichment facilities leaves two additional B-2s under the base scenario. Depending on U.S. confidence in the ability of cruise missile strikes to reach Natanz, one B-2 could be employed to destroy aboveground structures such as PFEP at the Natanz site. This B-2 could also potentially attack tunnel entrances and support buildings at Fordow, depending on U.S. confidence in the ability to breach the cascade hall using a MOP attack. Such a B-2 could be equipped with 80 500-pound bombs or 16 2000-pound bombs,[541] though due to the non-hardened nature of the aboveground targets and the flexibility that more weapons would provide, the 500-pound bomb configuration seems more likely. Such bombs would have a 5-psi overpressure radius of 25.9 m (85 feet) and a 3-psi overpressure radius of 35.9 m (118 feet).[542] The PFEP, the primary aboveground target for a strike on Iran's enrichment program, consists of five aboveground buildings, three of which are a little over 30,000 square feet in size and two of which are slightly smaller. Assuming a 30,000-square-foot size for all buildings, the United States would need to hit each with two[543] 500-pound bombs to achieve 5-psi overpressure for the entire facility, or one to achieve 3-psi. Such calculations do not account for the potential destruction of PGMs by point-defense SAM systems prior to

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[539] 61.5% / 14.4% = 4.27. May need slightly more or less depending on the falloff in psi for different size weapons. The potential inflationary effects of enclosed detonation underground could also lower the relative requirements for GBU-28s as the MOP is an indivisible weapon (at least one must be dropped to destroy each production hall). See United Nations. (2015). *Quantity and separation distances* (2nd ed., Vol. 20, International Ammunition Technical Guideline). New York, NY: United Nations Office for Disarmament Affairs. for discussion increased destructive potential of underground explosions.

[540] See Pike, J. (n.d.). B-2 Spirit. Retrieved December 06, 2017, from https://www.globalsecurity.org/wmd/systems/b-2.htm

[541] The 500-pound Mk82 bomb contains 192 lbs (87 kg) of tritonal HE, while the 2000-pound Mk84 contained 946 lbs (429 kg) of HE (likely also tritonal). Both can be configured to operate as precision weapons. Cordesman, A. H., & Toukan, A. (2010), 152. and Moïse, E. E. (2005). *The A to Z of the Vietnam War*, 56.

[542] Assuming a TNT explosive.

[543] Actually 1.32 if calculated using area ratios. One detonation covers nearly the entire facility (75.7%).

detonation. To account for this, let us assume that the United States decides to drop four 500-pound bombs on each PFEP building for the sake of redundancy. This would use up 20 Mk82s, or one-quarter of the B-2's 500-pound bomb load, leaving 60 remaining to attack other targets at Natanz or elsewhere. If the United States wished to destroy all aboveground buildings at Natanz (roughly 30 excluding the PFEP), this would allow it to deploy two 500-pound bombs per aim point. This use presumes that no cruise missiles are tasked with striking Natanz, which is unlikely but possible given it is inside but near the outer limits of the range of both TLAMs and JASSM-ERs.

In the base attack scenario, the United States still has one or two remaining B-2s available to deploy, depending on whether one is tasked with attacking Natanz. Likely deployment strategies fall under one of two umbrellas: either the addition of another MOP-armed attacker to give the United States "another bite at the apple" of breaching Fordow and destroying the third underground chamber at Natanz or another 500-pound-armed bomber tasked with destroying other non-hardened targets such as research and centrifuge production facilities elsewhere in Iran. Depending on U.S. knowledge of where Iran's centrifuges are stored, these options may have different levels of appeal. If the United States is uncertain whether it will destroy all centrifuges at Natanz by attacking the two production halls and PFEP, then equipping the remaining bomber with MOPs to destroy the third underground building and give the United States one more MOP to drop on Fordow is an easy choice. If the United States is certain that all of Natanz's centrifuges are in PFEP or the production halls, then the choice becomes more complex as the United States must weigh the relative value of attacking Fordow (including potential diminishing returns and wasted resources if the facility has already been breached) with striking other targets that may have been included in this target set for various reasons, such as research sites or secret facilities. If the United States chose to include strikes on centrifuge manufacturing in its attack plan, this would include more cruise missile strikes on sites around Esfahan and Kaveh Cutting Tools in the northeast and likely the tasking of another B-2 using 20-40 500-pound bombs to hit four centrifuge manufacturing sites around Teheran. Such a B-2 could also be used to attack the Parchin explosives testing complex to the southeast of Teheran.

While the United States could employ more B-2s in a mission, the value of doing so depends almost entirely on whether the United States has identified more targets (beyond Esfahan, Natanz, and Fordow) that it believes are worth striking or if it sees significant returns from more sorties attempting to breach Fordow. This is a similar choice to that which faced the United States in the above paragraph when determining the employment mission of its fourth and fifth B-2s. The general lack of concrete information regarding the fortifications of Fordow and the United States ability to breach them makes it difficult to make a definitive determination here but the question faces planners of an interdiction strike on Iran.

To summarize, the United States requires a cruise missile barrage of 100 to 250 JASSM-ERs and TLAMs attacking Esfahan and Natanz[544] as well as at least three B-2s equipped with six total MOPs for an effective attack on Iran's nuclear program. These B-2s will be used to attack at

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[544] 100 to strike Esfahan UCF alone and 100 to 150 to hit aboveground buildings at Natanz including PFEP if chosen to attack with cruise missiles.

least two aim points at Natanz (Production Halls A and B), and one aim point at Fordow using the technique of dropping bombs on the same location to extend the depth range of the weapons. If the United States feels that it is unable to reliably reach and destroy aboveground buildings at Natanz using cruise missiles, one B-2 could be employed using 500-pound GBU-30 bombs and could destroy them. The employment of other B-2s depends on a variety of factors, including the desire for more MOP sorties attacking Fordow, interest in destroying the third underground building at Natanz, or the identification of other targets outside of Iran's conversion and enrichment facilities that the United States wants to target. The UCF facility of Esfahan will likely be the focal point of a cruise missile attack by the United States, although cruise missiles may also be employed to target aboveground facilities at Natanz such as PFEP and centrifuge assembly buildings. If the United States wanted to target Lashkar Abad, it could be easily included in a cruise missile attack due to the surplus of cruise missiles available, the lack of point CMD defenses around the facility, and the small size of the target facility. Should the United States wish to attack other centrifuge production or research facilities around Teheran, another B-2 would likely be required. Overall, these resource requirements seem very achievable, particularly in a political scenario where the United States sees Iranian proliferation as a serious enough threat that it decides to launch a surprise attack using military force.

IX. Timelines

An important determinant in whether the United States should choose to launch an interdiction strike on Iran is the amount of extension Iran's breakout time. Prior to the JCPOA, Iran's breakout time was between a few weeks and seven months depending on how many centrifuges Iran was operating and the enrichment level feeding into its cascades, according to Olli Heinonen of the Washington Institute.[545] According to Heinonen, one of the key goals of the JCPOA for the P5+1 was to extend Iran's breakout time to a year, which was achieved for the first 10 years of the deal.[546]

Changes under the JCPOA benefit a military attacker in several ways: they increase information on nuclear sites due to JCPOA's transparency and disclosure measures, close off the plutonium path by disabling the IR-40, and concentrate enrichment targets by limiting the number of centrifuges at each site and requiring centrifuges that are not operational to be stored in specific areas. All of these give the interdictor a smaller and better defined target set, increasing the likelihood of striking all important targets and the delay that would be caused by doing so.

A successful U.S. strike as proposed above would extend Iran's breakout time in several ways, although the exact effects are difficult to determine due to information uncertainties. There are caveats at each point of potential delay, such as the potential that Iran could purchase supplies

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[545] Heinonen, O. (2015, March 28). Iran's Nuclear Breakout Time: A Fact Sheet. Retrieved December 06, 2017, from http://www.washingtoninstitute.org/policy-analysis/view/irans-nuclear-breakout-time-a-fact-sheet

[546] Nephew, R. (2016, July 28). Based on breakout timelines, the world is better off with the Iran nuclear deal than without it. Retrieved December 07, 2017, from https://www.brookings.edu/blog/markaz/2015/07/17/based-on-breakout-timelines-the-world-is-better-off-with-the-iran-nuclear-deal-than-without-it/

of UF_6 on the black market or take other steps to avoid parts of the production chain, but without those avoidance measures, the likely effects of a U.S. interdiction strike that successfully destroys all targets are as follows:

- *Destruction of yellowcake, UF_6, and other uranium stockpiles*. It is unclear how easily these would be destroyed because they are stocks of materials and not delicate equipment like most of the other targets but due to IAEA restrictions on nuclear material, much of these materials would be stored at sites that are targeted by U.S. attacks. Destruction of inventory would require Iran to start from scratch in feeding the nuclear production chain.
- *Destruction of conversion capabilities*. Iran would be unable replenish UF_6 stocks and begin enrichment likely for up to three years, but estimated for at least one and a half based on original UCF construction time.
- *Destruction of centrifuges*. Iran would be unable to enrich natural or LEU UF_6 in its inventory to weapons grade until new centrifuges were produced. According to Heinonen, Iran would need approximately 5,000 Separative Work Units (SWUs) worth of centrifuge enrichment, roughly equivalent to a year's worth of operation of 5,000 of Iran's basic IR-1 centrifuges or 1,000 of one of Iran's more advanced IR-2m centrifuges, to produce a "significant quantity" of weapons-grade uranium, enough to build a weapon.[547]
- *Destruction of centrifuge manufacturing*. This significantly impedes the replacement rate of Iran's destroyed centrifuges, substantially lengthening the delay caused by destruction of centrifuges.
- *Destruction of mining and milling*. This disrupts feed to Iran's conversion facilities.

Other potential impacts such as the effects of disruption of Iranian research are largely dependent on unknown factors.[548]

Although exactly how far the destruction described here would set back Iran is unclear, preliminary estimates and observations can be made. The first is that feed for Iran's enrichment program be delayed by up to three years through destruction of the UCF, disruption of uranium mining, and destruction of stockpiles of uranium materials. By the end of the third year, Iran would likely be able to rebuild the UCF (assuming double original construction speed) and with partial operation of the mining and milling operations be able to supply enough material to build several weapons each year.

The time it takes Iran to reach the magical 5,000 SWU number required to produce enough weapons-grade uranium is highly sensitive to the assumptions built into the model related to production rates, types of centrifuges, failure rates, active percentage, and SWU/year output for centrifuges, which is uncertain to some degree for all Iranian models except the IR-1. Based upon the sensitivity analysis I have performed (presented in simplified form in a table in Appendix),

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[547] Ibid.

[548] Such as Iran's progress on its weaponization development.

both destruction of centrifuges and major disruption of centrifuge manufacturing capabilities is necessary for an impact on Iranian centrifuge enrichment that is proportionate to the maximum three-year time period that could be caused by disruption to conversion and uranium stockpiles.

It is likely that Iran would look to resolve both of these three-year issues simultaneously, as conversion and centrifuge enrichment are independent activities and thus attacks on both do not compound the breakout time but instead increase it by the greater of the two increases from the individual strikes. In sum, three years breakout time seems like the upper limit of delay to Iran's nuclear program, assuming an orderly and concerted attempt to recover from an interdiction strike and produce a nuclear weapon and no further interdiction strikes to disrupt recovery.

The second major takeaway is that there is value in attacking multiple targets in the same vertical production chain. Though some targets may not extend Iran's breakout time directly, they may make it more difficult for Iran to patch problems that a U.S. attack has created for its nuclear program. In the case of stockpiles, conversion, mining, and milling, this value comes from redundancy: the destruction of any one would limit the Iranian nuclear program, but by attacking all, the United States would force Iran to fix many problems simultaneously at little extra cost to the United States. In the case of centrifuge stocks and manufacturing, the effect is compounding in that the destruction of Iranian centrifuges eliminates SWU output from Iranian enrichment facilities, while the disruption of centrifuge manufacturing slows the rate at which this lost SWU output can be replaced. In both cases, the value to the interdictor is in creating many holes for the proliferant to plug so it cannot dedicate resources to one problem that might be worked around or resolved quickly.

X. Conclusion

Several important conclusions can be drawn from this analysis. First, the United States currently maintains superiority along the conventional military dimensions necessary to execute an interdiction strike against Iran's nuclear program. Such a strike remains an effective military tool in the U.S. counter-proliferation arsenal, both as a threat to force Iran to the negotiating table and as a backstop against Iranian breakout efforts should negotiations fail. Although Iran has worked in recent years to shift the military power balance in its favor, more work must be done in improving its anti-stealth and CMD capabilities for Iran effectively to counter a potential U.S. interdiction attack. Second, the United States can expect at most a three-year delay to Iran's nuclear breakout time in the case of a completely successful attack assuming a concerted attempt by Iran to produce a nuclear weapon following the attack. It is possible that a delay this significant could force Iran to abandon its nuclear ambitions and settle on more favorable treaty terms, or a strike could convince Iran to redouble its efforts and construct an even more robust nuclear program that could be more difficult for future attacks to disrupt. Third, the United States is able to leverage its considerable resources to conduct a successful attack on multiple targets with synergistic effects. Some of the most important weapons for an interdiction attack on Iran are unique to the U.S.

arsenal, including the B-2 and GBU-57 MOP, which could make it difficult for other countries to replicate the likely success of a U.S. attack.

Some of this paper's analysis has broader implications for U.S. military power and the nuclear interdiction literature more broadly. As noted, the key weapons required to execute a successful interdiction strike are very-long-range, stealth cruise missiles such as the JASSM-ER and very-low-observable air platforms such as the B-2 that are capable of penetrating relatively sophisticated and well-defended air defense systems. If the United States foresees needing to execute additional conventional strikes on well-defended infrastructure within enemy nations, it should continue to invest in these capabilities, which could be bolstered by the addition of an advanced stealth naval-launched cruise missile to replace the TLAM. For the interdiction literature, this paper offers a systematic method for prioritizing targets, breaking down the nuclear weapons production chain and describing the considerations an interdictor should take into account when planning an attack. It suggests targeting entire horizontal segments of the nuclear cycle first, and then expanding to multiple segments that are vertically similar in order to build in redundancies and prevent quick workarounds by proliferants. Together, these two conclusions point to the United States, which has both the technological advantages and the resources necessary to strike many well defended targets simultaneously, as a key military interdictor for the foreseeable future.

Appendix A: Satellite Imagery

Natanz

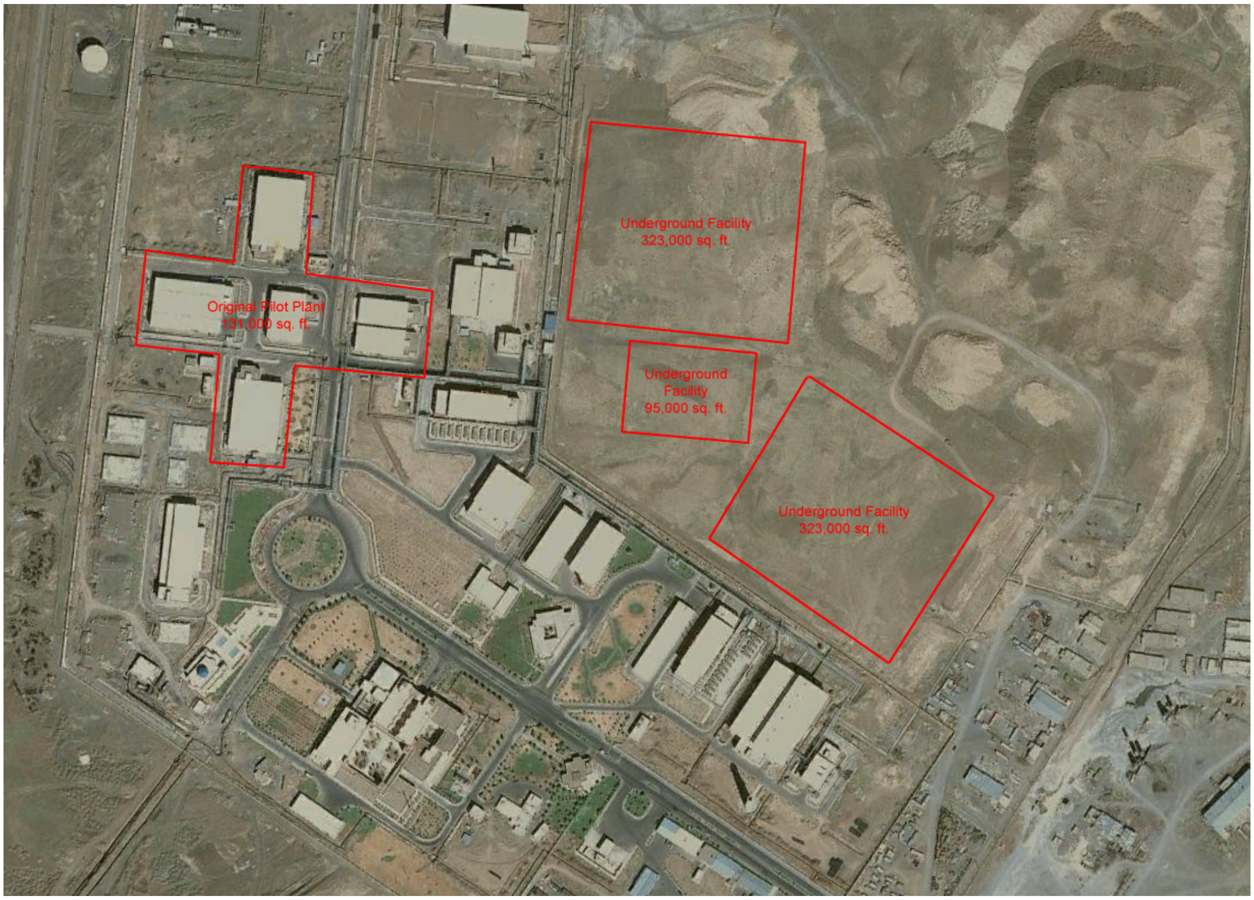

Figure 2: Natanz facility with enrichment halls labeled. The "Original Pilot Plant" in the image is the PFEP and the "Underground Facilities" are the three underground buildings that make up the PFEP. The administrative building is in the bottom left of the image.[549]

[549] https://publicintelligence.net/iran-nuclear-site-natanz-uranium-enrichment-site/ which appears based on https://www.globalsecurity.org/wmd/world/iran/images/natanz_gl_dg_060102.swf

Esfahan

Figure 3: The Esfahan Nuclear Technology Center from above. On the left is an older section of the cite and near the top of the image in the mountains some tunnel entrances have been identified. See next map for discussion of right side of the map. Source: ISIS.

Esfahan UCF Close-Up

Figure 4: Close up of two portions of the Esfahan Nuclear Technology Center. The upper red area is the Zirconium Production Plant (ZPP) which produces material used in reactor fuel production. The lower red area is the Uranium Conversion Facility (UCF). Source: ISIS.

Fordow

Figure 5: Fordow facility. The larger red ring traces the security perimeter of the facility while the smaller red polygons mark the locations of tunnel entrances. The precise location of the enrichment hall is unknown in the open literature.

Arak

Figure 6: Arak facilities. HWPP is outlined on the center right and the IR-40 reactor complex is outlined in red in the upper middle of the image. Entire facility is ringed by the black line which seems to be some sort of fence or security perimeter. Source: ISIS.

Appendix B: Mapping

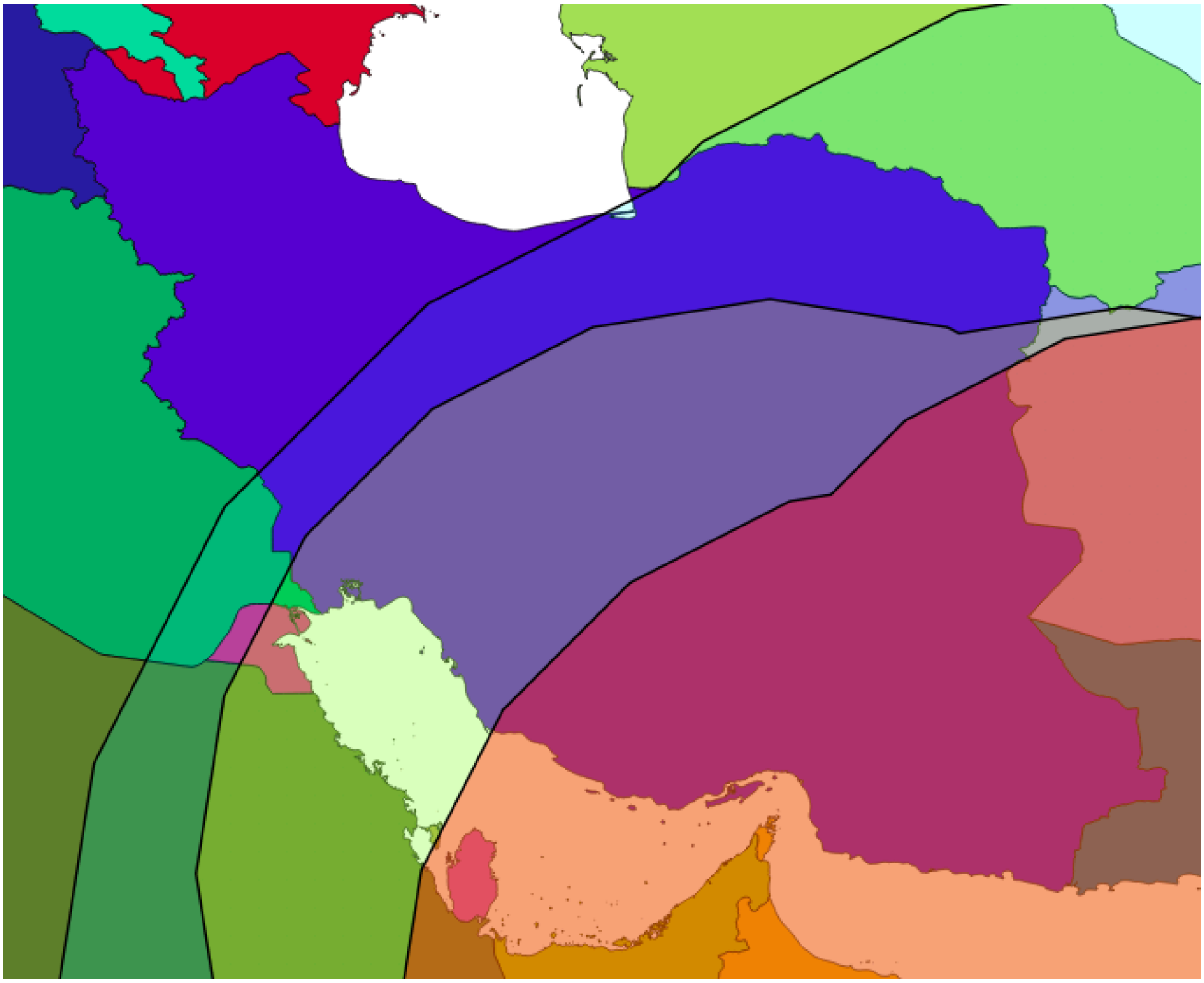

Figure 7: Range rings for strike. From greatest to least coverage area: TLAMs, below-radar-horizon JASSM-ERs, high-altitude JASSM-ERs. B-2s have the range to strike anywhere in Iran.

Figure 8: Locations of key nuclear sites within Iran. See following maps for Teheran and Esfahan insets. Source: ISIS.

Figure 9: Locations of key nuclear sites in and around Teheran. Source: ISIS.

Figure 10: Locations of key nuclear sites around Esfahan. Source: ISIS.

Appendix C: Timeline Sensitivity Analysis

Parameters								
Centrifuges destroyed?	N	Y	N	Y	Y	Y	Y	Y
Production disrupted?	N	N	Destroyed	33%	50%	67%	75%	75%
Centrifuges undamaged								
IR-1	6,104	-	6,104	-	-	-	-	-
Production per year								
IR-1	3,000	3,000	-	2,000	1,500	1,000	750	750
IR-2m	1,000	1,000	-	667	500	333	250	250
Time to install	-	-	-	-	-	-	-	3 months
Time to 5,000 SWU (years)	0.596	1.154	0.827	1.423	1.635	2.000	2.308	2.641

Figure 11: Sensitivity analysis results for time to reach 5,000 SWU assuming all centrifuges operational, 1 SWU/year for IR-1, 4.5 SWU/year for IR-2m, and no other centrifuge operation.

The above table shows the results of a simple sensitivity analysis using the two centrifuge models that Iran is known to have produced in substantial quantities and for which data are available on their SWU/year output. The table represents numerous possible scenarios including attacks on centrifuge inventory and manufacturing, with assumptions that are more favorable towards the United States placed further to the right. The assumptions of each scenario are shown in the top two rows, which indicate the extent of damage to Iran's centrifuge manufacturing and centrifuge inventories. The time to reach 5,000 SWUs, the amount seen by Heinonen as enough to produce material for a uranium weapon[550] is calculated using a week-by-week model of centrifuge production, installation, and enrichment (SWU output). As can be seen on the bottom row of the table, attacks on centrifuge inventory or production alone do not significantly set back Iran's centrifuge manufacturing but a synergistic interaction between the two leads to significant increases in breakout time towards the right of the table.

[550] Heinonen, O. (2015, March 28). Iran's Nuclear Breakout Time: A Fact Sheet.