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"Osirak Redux? Assessing Israeli Capabilities to Destroy Iranian Nuclear Facilities"

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Osirak Redux?
Assessing Israeli Capabilities to Destroy Iranian Nuclear Facilities

Caption: Possible Israeli attack routes
Map source: National Geospatial Intelligence Agency

Introduction

As of this writing Iran's nuclear ambitions have been the subject of serious debate within the international community for over two years. Iran contends its nuclear program is entirely peaceful and insists the Nuclear Non-Proliferation Treaty (NPT) guarantees the right to nuclear technology for peaceful purposes; the United States asserts that Iran intends to use its civilian nuclear facilities as a cover for nuclear weapons development[1]. Spanning the middle ground are France, Germany, and the UK, currently engaged in ongoing but periodically stalled negotiations over the status of Iran's uranium conversion and enrichment activities, and the International Atomic Energy Agency (IAEA), which acknowledges "concerns" regarding Iranian nuclear intentions but maintains there is no convincing evidence that Iran's true objective lies in militarizing its nuclear program.

With very few exceptions, Israel has repeatedly stated its unequivocal opposition to a nuclear-armed Iran, and much speculation exists in the media today about Israel's military intentions towards Iran[2]. Even though Israeli leaders have publicly maintained that no military action is under consideration, they have not ruled it out and multiple reports have indicated that Israel is indeed contemplating a preventive military strike to remove the threat of an Iranian nuclear capability[3]. This is not without precedent: On June 7, 1981, Israel launched one of the most ambitious preventive attacks in modern history. Eight Israeli Air Force (IAF) F-16s supported by eight IAF F-15s destroyed the Iraqi reactor at Osirak in one of the earliest displays of what has become known as "precision strike." None of the IAF planes were lost, and, despite the political repercussions, the raid was considered a great success.[4]

More than twenty years later, some in Israel are again mulling the possibility of preventive action against an unfriendly state's attempts to gain nuclear weapons, this time Iran. In a report given to Prime Minister Sharon in 2003, a group of Israeli and American scholars and analysts present a grand strategy that calls for Israel to develop and maintain a "Long Arm" capability for long-range precision strike. This report, known as Project Daniel, further argues that this "Long Arm" be used for preventive action against attempts by unfriendly states to gain weapons of mass destruction (WMD).[5] The project's chair, Louis Rene Beres, reiterated this view in a recent op-ed, calling on Israel to maintain strong preventive capability against adversaries' attempts to develop WMD even as it develops anti-ballistic missile systems.[6]

As Iran's nuclear program moves forward, the argument of the Project Daniel group may seem increasingly compelling to the government of Israel (as well as outside observers in the U.S. and elsewhere). Yet no unclassified net assessment of Israel's current capability to destroy Iranian nuclear facilities exists.[7] The capabilities of the IAF have grown dramatically in the past two decades, yet the Iranian facilities are a significantly more challenging target than Osirak.

This paper will attempt to fill this gap in the existing literature by providing a rough net assessment of an Israeli strike on known Iranian nuclear facilities. It will do so by taking the strike on Osirak as a generic template for the strike and then attempting to update the scenario to account for both the improved IAF capabilities and the much tougher Iranian defenses. The paper will first present a short overview of the Osirak raid, followed by a description of the nature and location of the Iranian nuclear facilities in the context of targeting for the IAF. The next section will attempt a rough estimate of the "weaponeering" necessary to destroy the target set. The third section will discuss the forces the IAF and Iran possess relevant to this planned strike, while the fourth will attempt to evaluate potential attack routes and the interaction of the forces. The paper will conclude with a brief discussion of the likely outcome of an Israeli attack and some policy considerations based on this outcome.

In addition to specific assessment of the Iran-Israel scenario, this paper will also provide insight to the more general phenomenon of the use of precision-guided weapons as a counterproliferation tool. As concern over WMD proliferation grows, the use of precision-guided weapons for strikes on individual targets may become even more appealing. The Bush Administration has already made military counterproliferation part of its national strategy[8]. The case of Iran provides a template for the prospective use of precision weapons and problems associated with the use against various targets of interest, especially nuclear-related, hardened, and well-defended targets.

The Osirak Strike

The Israeli raid on the Osirak reactor was a high-risk gamble born out of desperation. The government of Prime Minister Menachem Begin was divided on the wisdom of the raid in discussions that began almost immediately after Begin's election in 1977. The Iraqi program had been underway for several years at that point, but had made only moderate progress. New intelligence available in May 1977 indicated that the nuclear complex at al-Tuwaitha was growing rapidly and that the reactor facility might soon be ready. The debate was intense enough and the risk high enough that Begin stated he would not act without the support of the full cabinet. Several in the cabinet, including the Deputy Prime Minister and the head of the Mossad intelligence service were strongly opposed. Others, including most notably the Agricultural Minister Ariel Sharon, were in favor.[9]

Begin decided to wait as long as possible before acting. In the meantime, the Mossad would take steps to buy additional time. These steps included allegedly sabotaging the reactor cores for Osirak before the French could deliver them, as well as assassinating Iraqi nuclear officials. At the same time, the IAF began contingency planning for a strike on Osirak.

The plan to buy time worked to some degree, but could not stop the Iraqi nuclear program. In October 1980, the Mossad reported to Begin that the Osirak reactor would be fueled and operational by June 1981. Begin called another cabinet meeting, where the intense debate about both the possibility and utility of attacking Osirak was renewed. Agriculture Minister Sharon again weighed in on the side of attacking. When some argued that the attack would alienate both the United States and Europe, Sharon allegedly quipped "If I have a choice of being popular and dead or unpopular and alive, I choose being alive and unpopular."[10] Prime Minister Begin ultimately agreed and the rest of the cabinet fell in behind him. Osirak would be struck before it became operational.[11]

A sixteen-plane strike package launched from Etzion airbase in the Sinai. The flight profile was low altitude, across the Gulf of Aqaba, southern Jordan and then across northern Saudi Arabia. Two F-15s remained circling over Saudi Arabia as a communications link back to Israel.

The remaining six F-15s and the F-16s continued on to al-Tuwaitha, the site of the Osirak reactor. The F-16s carried two Mk 84 2,000 lb bombs with delayed fuses. These bombs were "dumb," meaning that they had no guidance other than that provided by the aircraft dropping them. The F-16 did have onboard targeting systems that would make the dumb bombs fairly accurate, but it would require the plane to get close to the target.

The strike package arrived near Osirak undetected and at low altitude. The F-16s formed up on predetermined points to begin their bombing runs, while the F-15s set up barrier combat air patrols to intercept Iraqi fighters. At four miles from the target, the F-16s climbed to five thousand feet in order to dive at Osirak and release their bombs. Despite some navigation problems and Iraq air defenses, at least eight of the sixteen bombs released struck the containment dome of the reactor.

The strike package then turned and climbed to high altitude, returning much the way it had come. All sixteen of the planes successfully returned to Israel after recrossing Jordan. The results of the raid were spectacular. The reactor was totally destroyed, leaving much of the surrounding area undamaged. President Ronald Reagan, upon being shown satellite imagery of Osirak after the strike, is alleged to have called it "a terrific piece of bombing."[12]

The Iranian Nuclear Industry

Nuclear power is seen as a symbol of power, modernity, and energy independence in Iran (and many other countries). Iranian officials have claimed that by 2020, the growing population of the country and the expected global demand for oil will require the extensive use of nuclear power to meet the nation's growing energy needs while still enabling significant petroleum exports[13]. The Nuclear Non-Proliferation Treaty (NPT) allows states access to all peaceful nuclear technologies within certain guidelines. In essence, signatories to the NPT can adhere to the treaty (or appear to adhere to the treaty) with intent to later, after acquiring the necessary technology and infrastructure, withdraw from the treaty and rapidly develop a nuclear weapon[14].

It is apparent that the Iranians have learned important lessons from the Osirak raid: the Iranian nuclear complex is large, carefully concealed, and spread extensively throughout the country. Iran has developed a widespread civilian nuclear power program in its country over the last few decades, including full front-end and back-end nuclear fuel cycle technology[15]. Acknowledged industrial-scale facilities include a light-water reactor at Bushehr, uranium mining in Yazd, uranium conversion, uranium enrichment, fuel fabrication, a heavy water production facility, and the continuing construction of a heavy-water research reactor[16]. Smaller, lab-scale projects include clandestine plutonium reprocessing and laser enrichment, as well as experiments involving uranium metal[17]. Questions remain regarding the legitimacy of these facilities and Iranian intentions for their use in nuclear weapons development.

There are two primary routes to a nuclear weapons program that a latent proliferator could pursue: taking advantage of the front end of the nuclear fuel cycle to enrich uranium or utilizing the back end to produce plutonium[18]. Iran appears to be pursuing parallel paths towards a viable nuclear weapon by developing indigenous uranium enrichment capabilities to produce weapons-grade uranium (generally accepted as greater than 90% ^{235}U) and by investing in a heavy-water plutonium production reactor (PPR) and associated facilities for reprocessing spent fuel for plutonium separation.[19] At present, it appears Iran's progress towards enriching uranium is significantly more advanced than its plutonium production ability. While there are legitimate uses of the outcomes of both these processes, these routes must be examined for their potential military applications[20]. While some of Iran's nuclear activities are suspect, it is important to distinguish between those which are predominantly civilian and those that pose the most serious threat to nuclear weapons development and proliferation, as an attack on purely civilian sites would waste valuable resources that could be better employed against critical targets.

Front End (Uranium Production)

Iran's uranium program consists of uranium mines, an industrial-scale uranium conversion facility (UCF), uranium enrichment via both gas centrifuge technology and laser isotope separation, and the construction of nuclear power plants at Bushehr and Arak as the recipients of indigenously-produced nuclear fuel. Front-end fuel cycle technology is spread around the country, from mining at the Saghand mine in Yazd and the Gchine mine near Bandar Abbas, industrial-scale uranium conversion at the Esfahan Nuclear Technology Center (ENTC), and laboratory-scale conversion at the Tehran Nuclear Research Center (TNRC), uranium enrichment via gas centrifuge technology primarily located at Natanz, and laser-based uranium enrichment at the TNRC and Lashkar Ab'ad, to fuel fabrication also located at the ENTC. These activities and their application to the militarization of a nuclear weapon are discussed below in detail.

Mining and Milling

Iran has proven uranium reserves of 3,000 tons and an estimated 20,000-30,000 tons of uranium reserves that could be mined[21]. Currently, Iran has two large operational uranium mines, the larger at Yazd and the smaller at Gchine. The IAEA is well aware of the activity at these sites and is actively pursuing any concerns that arise over the mines and their product. Milling of the mined uranium ore (separation into U_3O_8, or yellowcake) occurs on an industrial scale at the ENTC in Esfahan. Mining and milling activities provide a domestic source of U_3O_8 for subsequent processing at the Uranium Conversion Facility (UCF) at the ENTC.

Uranium Conversion

Much of the current controversy surrounding Iran's nuclear program has centered on the UCF at the ENTC. The UCF is designed to process U_3O_8 into the gaseous form uranium hexafluoride (UF_6), which is subsequently transported to uranium enrichment centers. Once enriched (nominally to 5% ^{235}U by weight), the UF_6 is returned to the UCF for further processing into low-enriched uranium oxide (UO_2) for light-water nuclear reactor fuel. The UCF design, as reported by Iran to the IAEA, contain plans for conversion lines for the production of depleted, natural, and 19.7% enriched uranium metal as well as natural UO_2 for use as fuel in heavy-water nuclear reactors[22]. The UCF is designed to support the annual production of 200 tons of UF_6. Under negotiations with France, Germany, and the UK, Iran had agreed to freeze conversion activities while discussions continued regarding Iran's nuclear program, but as of this freeze, Iran had produced 40-45 tons of UF_6 and had processed 37 tons of yellowcake into UF_4 and other products, although it did not continue to convert the UF_4 into UF_6 until Tehran resumed activity at the UCF in August of 2005.

Uranium Enrichment

Iran has secretly pursued the ability to indigenously enrich uranium through both gas centrifuges at the Natanz enrichment facility and by laser isotope separation at the TNRC and Lashkar Ab'ad. The Natanz enrichment facility has two components – one section above ground is designed to house 1200 centrifuges as a pilot enrichment plant and maintenance building, and a large, underground commercial facility intended to contain over 50,000 centrifuges[23]. Gas centrifuges can be used to enrich uranium intended for reactor fuel, which this facility is certainly capable of, or they can be used to enrich uranium to higher concentrations of uranium-235. Iran has installed over 100 assembled centrifuges into its pilot facility and an unknown number into the underground commercial buildings, although officials claim that uranium has not been introduced on a large scale and has been limited to only a few centrifuges and not enriched to levels higher than 2%[24]. With respect to the development of weapons manufacturing, this site is the most troublesome evidence that Iran has progressed significantly in its pursuit of nuclear weapons.

Natanz uranium enrichment facility. Source: Globalsecurity.org

Laser isotope separation, on the other hand, has never been used on an industrial scale for uranium enrichment. A small, laboratory sized laser research center was established in Tehran during the 1990's but was dismantled before 2003, all without IAEA knowledge. Iran built a larger, secret pilot laser isotope separation center in Lashkar Ab'ad and has used this facility to enrich uranium to no more than 13% ^{235}U, according to environmental testing by the IAEA and declarations from third countries. These facilities have since been dismantled and the equipment is now held under IAEA safeguards at Karaj.

Bushehr Nuclear Reactor Complex

The Bushehr light-water nuclear reactor complex has been under construction since 1974. Originally intended to be of German design, the construction for two reactors began in the 1970s but was destroyed by Iraqi raids during the Iran-Iraq war in the mid-1980s. Undeterred, the Iranians continued negotiations with international energy suppliers and since early 1995 have been under contract with the Russians for a 1000 MW_e light water reactor, a type of reactor suitable only for electrical power production.

The agreement with the Russians includes an arrangement for the provision of fuel rods from Russia, as well as their repatriation to Russia once burned in the reactor. The reactor itself is under IAEA safeguards, and is scheduled to first become critical in late 2006.

Back End (Plutonium Production)

The second means of producing material for nuclear weapons is to utilize the back end of the fuel cycle. As uranium fuel is burned in a reactor, plutonium isotopes are created. Plutonium-based nuclear weapons rely on plutonium-239 as fuel, preferably uncontaminated with other plutonium isotopes (specifically plutonium-240)[25]. Weapons-grade plutonium is usually made from heavy-water reactors, those that use natural uranium fuel and are cooled and moderated with heavy water (made of hydrogen isotopes containing an extra neutron) instead of normal "light" water. Once the fuel has been burned in the reactor, the spent fuel rods can be removed and reprocessed. Reprocessing, or separating the plutonium from the remaining uranium and fission products, can significantly reduce the amount of long-term waste and can be used as fuel for certain reactor types but can also be diverted to military use. Notably missing from Iran's nuclear complex is a large-scale reprocessing center, although some lab-scale work has been performed.

Heavy-Water Production Plant

In 2002, the Tehran admitted the existence of a heavy-water production plant located near Arak. While heavy water is not a "nuclear activity" in its own right, heavy water can be used as the moderator in nuclear reactors to produce plutonium. Because of this potential usage, heavy water production plants are generally placed under IAEA safeguards. The Arak plant is designed to produce 8 tons of D_2O per year initially, far more than Iran's zero-power heavy-water research reactor requires. According to IAEA documents, a second heavy-water production line, also for 8 tons D_2O/year, was started in 2003.

Heavy-Water Reactor Program

In addition to the heavy water production plant, the designs for two 40MW heavy water nuclear reactors – also to be located at Arak – were disclosed to the IAEA. These two reactors, ostensibly for medical and research isotope production, have the ability to produce a significant amount of plutonium that could be used for nuclear weapons. An accompanying reprocessing facility has not been declared, but plans for unspecified "hot cells" to be located near the Arak reactors – possibly for plutonium separation – have been submitted to the IAEA. These two reactors, currently under construction, are scheduled to go into operation in 2014.

Narrowing the Target Set

Assuming that a military strike is issued, Israel cannot hope to destroy Iran's entire nuclear infrastructure: facilities are distributed across the country and there are too many sites to plan to attack them all. To have a reasonable chance of success, both in the mission and in the ultimate goal of rendering Iran's nuclear program impotent, the target set must be narrowed to concentrate on the critical nodes in Iran's nuclear infrastructure. Most experts agree that the most difficult part of nuclear weapons development is obtaining the nuclear material itself; thus, if the means of fissile material production can be destroyed, the setback for Iran will be maximized. Iran's nuclear complex has three critical nodes: Esfahan, with its conversion facility, the Natanz enrichment facility, and the heavy water plant and future plutonium production reactors at Arak.

In the past, concern over Iran's nuclear weapons program centered on Tehran's agreement with Russia to build a light water civilian reactor complex at Bushehr[26]. For the purposes of this paper, however, the Bushehr reactor is not considered a crucial element to a successful Iranian nuclear weapon and will not be included in the target set. Bushehr, as discussed below, is simply not essential to an Iranian nuclear weapons program.

Three reasons for concern about the Bushehr reactor are typically given. First, the United States has expressed concern that the availability of nuclear technology from Russia could enable the Iranians to strengthen their nuclear weapons program by concealing delivery of controlled equipment under the cover of legitimate civilian purposes. Second, concerns have been voiced that the knowledge and expertise of Russian nuclear engineers will be shared with the Iranians. Finally, the issue of spent fuel and the Iranian ability to separate plutonium from the spent fuel raises a third set of concerns.

The concerns voiced by many over the Bushehr reactor are easily refuted. First, the transfer of technology to Bushehr is close to completion, while simultaneously monitored by the IAEA to ensure no illicit transfers of material. Secondly, Russian scientists and engineers who are employed at the Bushehr reactor likely know nothing more about nuclear weapons development than the Iranians – nuclear power engineering is quite different than weapons development – and the Bushehr reactor deals with Russia are heavily scrutinized. Lastly, on February 27, 2005 Iran and Russia signed an agreement in which Russia would provide the nuclear fuel for the Bushehr reactor, however, at the point of discharge the spent fuel would be returned to Russia. This repatriation of spent fuel is simple to follow and confirm (either independently or through the IAEA) and denies Iran the opportunity to harvest plutonium from Bushehr spent fuel.

Additionally, the design of the particular reactor at Bushehr produces extremely undesirable plutonium. If Iran were to use this reactor as a means to produce plutonium as a fuel for nuclear weapons, the reactor would either require refueling far more often (on the order of weeks to a few months, not 18 months as designed), which would undoubtedly be noticed, or would result in a plutonium-based nuclear weapon that would be highly unreliable[27]. Based on Iran's willingness to safeguard the Bushehr reactor and agree, however reluctantly, to return the spent fuel to Russia, it is likely that Tehran considers Bushehr to be of limited utility for weapons production.

In addition to Bushehr, the three facilities whose civilian purposes are questioned most often are the Arak heavy water facility (also the site of a planned plutonium production reactor), Iran's Uranium Conversion Facility (UCF) located at the Esfahan Nuclear Technology Center, and the uranium enrichment facility nearing completion at Natanz. These three sites present a serious dual-use challenge – it is certainly within Iran's rights to develop a complete fuel cycle; however, these facilities are required for nuclear weapons production and the secrecy which Iran has displayed regarding the construction and ultimate use of these complexes makes their development suspicious.

Iran's UCF is the starting point for Iran's uranium enrichment program, providing the means for production of UF_6. The loss of a domestic supply of UF_6 for enrichment activities as well as the loss of lines for the conversion of UF_6 back to uranium metal would have a great effect on Iran's ability to produce enough enriched uranium for a nuclear weapon in the future. Because the agreement with Russia for fueling the Bushehr reactor requires Russia to provide fuel for the reactor, loss of the UCF would not have an immediate effect on Iran's ability to supply electric power. Destruction of the UCF would, however, severely limit Iran's indigenous capabilities in terms of enrichment and fuel fabrication, as the primary means of production of UF_6 and UO_2 would be destroyed[28].

Similarly, the loss of the UCF will slow Iran's plutonium production reactor operations schedule, as the UCF is the main facility that converts uranium ore to natural uranium fuel. This fuel will be used in the plutonium producing heavy water reactors scheduled to be built at Arak. Even though the PPR at Arak is years away from completion, denying Iran the capability to manufacture fuel for these reactors will decrease the likelihood that Iran is able to construct a plutonium-based nuclear weapon, as it is likely that an agreement with any country for the provision of fuel for Arak would also require Iran to return spent fuel to prevent reprocessing from taking place.

Destruction of the UCF is complicated, however, by the activities that have already taken place. Many tons of uranium exist at the UCF in various chemical forms. Destruction of the facility will certainly result in the release of tons of UF_6, UF_4, and other fluorine and uranium products into the atmosphere. In addition to the environmental contamination due to the release of uranium, the presence of fluorine in the atmosphere will almost certainly result in significant production of hydrofluoric acid, an intensely corrosive substance that has the potential to cause extensive damage. Complicating the situation is the proximity of the city of Esfahan, a metropolis of close to four and a half million people. Assuming that the Israelis are willing to assume the risks inherent in attacking a chemical facility close to a major city, the destruction of the UCF at the ENTC would interrupt the production of UF_6 feed gas for uranium enrichment, as well as the preparation of UO_2 fuel for heavy-water reactors.

The Natanz enrichment facility is probably the most troublesome of Iran's nuclear facilities, as considerable progress has been made without international knowledge. Rumors in the open press have linked the serial proliferator A.Q. Khan with the development of centrifuges for the Natanz site, fueling suspicion that Iran's true intentions lie in the production of weapons-grade uranium[29]. The plant is composed of a pilot fuel enrichment plant and a much larger commercial facility. The pilot plant is housed in six buildings above ground, designed to house about 1200 centrifuges. The commercial facility has been built underground, with three huge underground structures intended to hold more than 50,000 centrifuges. The site itself is located approximately 200 miles south of Tehran, about 40 miles from the nearest city.

To ensure that this facility is no longer able to enrich uranium, Israel must be certain that the vast majority of the centrifuges at Natanz are completely destroyed. It would be possible for Iran to enrich uranium using less than 1000 centrifuges (although it would take significantly longer than using 50,000) meaning that over 98% of the centrifuges must be destroyed beyond repair. A window of time thus appears during which a military strike would be most beneficial: after the centrifuges have been installed but before large quantities of UF_6 have been introduced to increase the likelihood of the destruction of enrichment capability without running the risk of Iran enriching some quantity of uranium and removing it from the facility.

The final fissile material production facility that could be targeted is the heavy water plant and associated plutonium production reactors under development at Arak. The heavy water plant is an extremely large facility located in central Iran approximately 150 miles southwest of Tehran. The site itself is about 20 miles from the nearest town.

Iran currently has only a small research reactor that uses heavy water as coolant, but the Arak HW facility is believed to be able to produce over 16 tons of heavy water per year – much more than required by this reactor and more than almost all civilian applications. It is possible, though not likely, that Iran has built a larger plutonium production reactor (PPR) that has not been discovered, but Iranian officials have stated their intentions to build heavy-water reactors in the near future which will utilize some of the heavy water produced at Arak. Plans have been discussed with Russian officials to begin building a full-scale, power-producing PPR at Arak beginning in mid-2004 and scheduled for completion in 2008.

Construction of a plutonium production reactor by Iran should be viewed with deep suspicion by the international community: plutonium-producing heavy-water reactors of the kind Iran intends to build are the most dangerous plutonium proliferation risk. Iranian officials have told the IAEA (only after direct questioning) that they also intend to build reprocessing facilities at Arak in order to separate “long-lived isotopes” from spent fuel burned in future PPRs at the site[30]. It is highly likely that the Arak facility’s ultimate purpose is for the production of weapons-grade plutonium – the same hot cells can be used to recover plutonium from spent fuel, and with all the facilities required on site, the plutonium manufacturing process can be streamlined. Even though construction on the reactor is in only the initial stages, the Arak facility is a serious concern, and eliminating the heavy water plant will significantly slow Iran’s plutonium production process.

Weaponeering

Available Munitions

The IAF has developed substantially better munitions for attacking hardened point targets, such as reactor containment facilities or buried centrifuge plants than it had in 1981. These improvements come in two forms: enhanced accuracy and enhanced penetration. The combination of these characteristics in munitions makes them both easier to deliver and more likely to destroy the target.

The introduction of precision-guided munitions (PGMs) to the IAF in the 1980s and 1990s changed the dynamics of bombing. Accurate delivery no longer required approaching at low altitude and then "popping up" to dive directly at the target as at Osirak. Instead, using both Global Positioning System (GPS) and laser guided bombs (LGBs), Israeli aircraft can approach at low altitude and perform a short climb near the target to "loft" the guided (but unpowered) bomb. They can then quickly dive back down below the radar horizon.[31]

Alternately, they could deliver munitions from high altitude. This has the disadvantage of exposing the aircraft to enemy radar and surface to air missiles (SAMs). However, it places the aircraft more or less beyond the range of less accurate but more voluminous ground fire (including everything from small arms up to automatic cannons) as well as giving longer standoff range from the target.[32]

Both GPS and LGB munitions also offer greatly enhanced accuracy. The F-16s used against Osirak had a computerized aiming system, which, if the aircraft could make a reasonably steady approach, would give the unguided bombs a Circular Error Probable (CEP) of roughly 8 to 12 meters.[33] In contrast, GPS munitions have a roughly comparable (if not better) accuracy dropped from high altitude and long standoff range. LGBs have substantially better accuracy, with modern LGBs having a CEP of less than 3 meters. Both GPS and LGB munitions have less restrictive "envelopes" for accurate launch than computer aided bombing, as they can maneuver themselves on target after launch.[34] The IAF, well equipped with PGMs, thus has considerably greater ability to hit fixed targets safely than in 1981.

Israeli Air Force F-151 Ra'am in flight
Official Israeli Air Force Photo

Similarly, munitions for attacking hardened and/or buried targets have been extensively developed since the Osirak raid. These weapons, known as penetrating warheads or "bunker busters," have seen extensive use by the U.S. Air Force and the

IAF has closely [35]monitored these operations. Early versions of these weapons are essentially delay-fused bombs that have been modified to have a more “pointed” shape and extensively structurally reinforced. Impacting at high speed and steep angles, the kinetic energy of these munitions allows them to penetrate tens of feet of earth, and even several feet of reinforced concrete. Later versions include warheads designed to detonate in stages to increase penetration.[36] Note that for optimal penetration these weapons must be dropped from fairly high altitude, which implies that the IAF will be flying a high-altitude attack profile, at least in the terminal approach phase.

The IAF currently has access to a domestic penetrating weapon, a 1000-lb class bomb known as the PB 500A1.[37] The government of Israel has also expressed interest in acquiring two heavier penetrating warheads from the United States. In September 2004, Israel announced that it would acquire approximately 5000 PGMs from the U.S., including about 500 GBU-27s equipped with the 2000-lb class BLU-109 penetrating warheads.[38] More recently, Israel has received approval to purchase one hundred GBU-28s equipped with the 5000-lb class BLU-113 warheads.[39] Note that for clarity, the remainder of the paper will refer to the BLU-113 and BLU-109 (the penetrating warhead) rather than GBU-27 and GBU-28 (the entire bomb).

As a final note on weaponeering capabilities, Israel maintains two elite special forces units dedicated to assisting with air strikes, one dedicated to laser target designation (Sayeret Shaldag/Unit 5101) and one to real time bomb damage assessment (Unit 5707).[40] These units are extremely well-trained and could potentially be infiltrated to the target zone prior to attack. While it would be both difficult and risky to deploy these units inside Iran, they would be very useful in aiding the strike package, particularly in bad weather.

Destroying the Target Set

Natanz

Natanz is by far both the most difficult and most important target to destroy. The main enrichment facility apparently has two large (25,000-32,000 m^2) halls located 8 to 23 m underground and protected by multiple layers of concrete.[41] The combination of large size and target hardening mean that only a very robust strike could hope to destroy or at least render unusable the centrifuges.

In order to ensure penetration of a target with high levels of hardening, one technique is to use LGBs targeted on the same aimpoint but separated slightly in release time to “burrow” into the target. Essentially one bomb hits the crater made by the previous weapon, a technique contemplated by the U.S. Air Force in the first Gulf War.[42] This takes advantage of the extremely high accuracy of LGBs in combination with a penetrating warhead. The IAF appears to have purchased penetrating LGBs with this technique in mind. Gen. Eitan Ben-Elyahu, former commander of the IAF and a participant in the Osirak strike, commented on this method of attacking hardened facilities in *Jane’s Defense Weekly*: “Even if one bomb would not suffice to penetrate, we could guide other bombs directly to the hole created by the previous ones and eventually destroy any target.”[43]

For such a heavily hardened target, the BLU-113 5000-lb penetrators would be the most likely weapon to use. An individual weapon capable of penetrating up to 6 m of concrete or 30 m of earth, as noted earlier, might be sufficient to penetrate the protective earth and concrete over the Natanz facility, but two properly sequenced almost certainly would. The probability of two LGBs aimed at the same point hitting essentially one on top of the other is roughly 0.5, assuming a 0.6 probability of a direct hit for each weapon, a 3 meter radius crater, a 3 meter CEP for "near misses" and 0.9 reliability for each bomb.[44]

The question then is how many BLU-113s penetrating fully into the centrifuge halls would be needed to ensure destruction? Each BLU-113 contains 306 kg of Tritonal explosive, which would yield peak overpressures of 10 pounds per square inch (psi) at a distance of over 20 m in a free air burst.[45] This level of overpressure is sufficient to destroy most structures and would presumably be more than sufficient to ruin centrifuges. Each BLU-113 would therefore cover about 2000 m^2 with this level of overpressure. In order to have a high probability of achieving this level of overpressure over almost the entire area of the centrifuge halls, approximately 40 pairs of BLU-113s would need to be launched. With a 0.5 probability of successful penetration per pair, this means approximately 20 BLU-113s would detonate within the halls, covering almost 40,000 m^2 with 10 psi overpressure.

This is an extreme case and would probably result in massive overkill. The confined nature of the Natanz facility would magnify blast effects of the warheads that penetrated. There would also be additional damage from shrapnel and incendiary effects. Further, in addition to the 20 weapons that penetrated into the actual facility, there would be an additional 52 weapons detonating over the facility (with 0.9 reliability, eight weapons would be presumed to miss the facility completely or fail to detonate).

It is more likely that 3 BLU-113s detonating in each hall would be sufficient. Even in a free air burst (as opposed to the confined space of the Natanz facility), this would cover 20-25% of the area in 10 psi overpressure. Further, gas centrifuges, though often utilizing extremely durable materials such as maraging steel, are also sensitive electronic devices that must be precisely balanced to function. Each BLU-113 would generate 3 psi (sufficient to moderately damage normal buildings) at a distance of over 40m. Three detonations would cover about 50-60% of the facility with this level of peak overpressure. Combined with collapsing ceiling, fragmentation (lethal fragments being potentially thrown more than 100m) and incendiary effect, this would likely be sufficient to ruin most if not all of the centrifuges present. According to some analysts' estimates, even this might be overkill, as centrifuges in operation are inherently vulnerable to even disruptions in the power supply.[46]

Achieving 3 detonations in each hall would require the delivery of 6 pairs of BLU-113s apiece, for a total of 12 pairs or 24 weapons. In addition to the 6 weapons that actually penetrated the centrifuge halls, 15-16 of the BLU-113s would be expected to detonate overhead, possibly collapsing the entire structure. This gives further confidence in the successful destruction of the facility. If additional confidence were desired, the BLU-113 entry points could be targeted by additional weapons of either BLU-109 or BLU-113 class (see alternate weaponeering packages in the force application section below).

In addition to the underground centrifuge facility, the above ground pilot plant should be destroyed as well. It does not appear to be hardened, so two 2000-lb bombs would likely be sufficient to destroy it. These need not be penetrating warheads.

Uranium Conversion Facility

The Esfahan UCF is not buried, though some evidence of tunneling is visible near the Esfahan complex.[47] The exact dimensions of the Esfahan UCF are not readily available. Based on photographs and commercial satellite imagery, the facility appears to be rectangular with dimension of roughly 180 m length and a varying width of 40 m up to 80 m.[48] This facility does not appear to be heavily hardened, but the IAF may wish to use penetrating weapons nonetheless to pierce the walls and ensure detonation near critical components.

Esfahan uranium conversion facility
Source: Globalsecurity.org

In this case, the smaller BLU-109 would be a good weapon to use. Unlike Natanz, the weapons could penetrate singly, so extremely high accuracy is less important. In a free air burst, the BLU-109s 240 kg of Tritonal explosive would produce 10 psi of over pressure at a distance of about 19 m. The facility appears to be roughly 10,000 m^2, so 9 BLU-109s would be sufficient to expose almost the entire facility to sufficient overpressure to rupture chemical storage tanks (which occurs at 10-12 psi).[49] The accuracy of LGBs is such that there is a much greater than 0.9 probability of the weapon falling with 10 m of the aimpoint, which is close enough for area damage. Combined with a reliability of 0.9 for the weapons themselves, targeting the facility with 12 BLU-109s should be more than sufficient to guarantee its destruction.[50]

Arak

Arak heavy water facility and suspected plutonium production reactor
Source: Globalsecurity.org

The Arak facility has two target sets. The first is the heavy water production plant and the second is the heavy water reactor construction site. Neither target is hardened, so they are relatively simple to destroy.

The central element of the production plant is a set of towers wherein the Girdler-Sulfide enrichment method is used to manufacture heavy water. There are three main and nine smaller towers in the complex. These towers are roughly 3 m in diameter and are located in two clusters of approximately 80 m length and 30 m width. Assuming these towers are roughly as durable as petroleum fractionating towers, 15 psi would be sufficient to collapse them.[51]

A non-penetrating 2000-lb LGB such as the GBU-10 with a warhead of 428 kg of Tritonal would generate 15 psi peak overpressure at a distance of about 19 m. Two of these weapons would be sufficient to cover each of the clusters with sufficient force to destroy the towers. Three weapons targeted on each cluster should be more than sufficient to ensure destruction of the target complex.

The heavy water reactor construction site consists of an unfinished containment dome and cooling facility. Though some progress has been made at this site, it is unclear if it would be worthwhile to target. Presuming it is worth targeting, but that it is still incomplete, four 2000-lb weapons should be more than sufficient to destroy this target complex.

The total number of weapons needed to have reasonable confidence in destroying all three target sets is thus 24 5000-lb weapons and 24 2000-lb weapons. The next question to be answered is can these weapons reach their targets with any confidence? This is dealt with in the following section.

Force Application

Israeli Deep Strike Capabilities

In the more than two decades since the Osirak strike, the IAF's deep strike capability has improved dramatically. This has increased the range and lethality of Israel's "Long Arm." An early display of this growing capability was the 1985 IAF strike on the Palestinian Liberation Organizations headquarters in Tunis, a more than 4000 km round trip.[52]

In terms of aircraft, Israeli deep strike capability remains centered on F-15s and F-16s. However, Israel now fields 25 of the F-15I Ra'am and approximately 25-50 of the F-16I Soufa, both of which are specially configured for the deep strike mission.[53] The F-15I is the Israeli version of the F-15E Strike Eagle, an extremely capable variant of the F-15 which has been modified to optimize its air-to-ground capability. The F-15I is equipped with conformal fuel tanks (CFTs), which combined with external drop tanks could likely give it an unrefueled combat radius of roughly 1700 kilometers while carrying four 2000-lb bombs.[54] These bombs, discussed in more detail below, can be targeted using either the LANTIRN or LITENING targeting pod. In addition, the F-15I has a built in electronic warfare and countermeasures system and can carry AIM-120 AMRAAM , AIM-9 Sidewinder, and Python 4 missiles for air-to-air combat.

The F-16I is an F-16 Block 52/60 variant produced specifically for Israeli deep strike requirements. Like the F-15I, the F-16I has CFTs to extend its radius of action. The F-16Is exact combat radius is unknown, but is believed to be in the 1500-2100 km range with CFTs and external fuel tanks.[55] Given the Israeli decision to forgo additional F-15I procurement in favor of increased F-16I procurement, its range is presumably not significantly less than the F-15I. It is equipped with the same targeting systems as the F-15I and could deliver two 2000-lb bombs while carrying external fuel tanks.

In addition to these dedicated deep strike aircraft, Israel also has a large fleet of F-16s which could potentially be retrofitted with the F-16I's CFTs. In particular, Israel has approximately 50 F-16D aircraft which have a "dorsal spine" modification. This dorsal spine is a fairing extending from the rear of the cockpit to the vertical stabilizer. It apparently houses a significant anti-radar Wild Weasel system, self-protection jamming, as well as other specialized electronics. These aircraft, if retrofitted with CFTs, could accompany the deep strike aircraft and provide significant suppression of enemy air defense (SEAD) capability.

The IAF also has over 40 F-15A and F-15C aircraft which could be used as fighter escorts for the strike and SEAD aircraft. The F-15A/C is a highly capable fighter and can potentially be fitted with the same CFTs as the F-15I. Each F-15 could carry a mix of AMRAAM, Python 4, and Sidewinder missiles.

Improved aircraft, in conjunction with the various communications, intelligence and support assets of the IAF/IDF, have greatly enhanced Israeli deep strike capability. However, it's most likely target is both farther away and better protected than either Osirak or the PLO headquarters in Tunis. The next section details some of Iran's air defenses.

An Israeli Air Force F-161 Soufa launches from a desert airstrip
Source: Official Israeli Air Force Photo

Iranian Air Defense

The Iranian military is an odd amalgamation of high and low tech. Prior to the fall of the Shah in 1979, Iran was the United States' premiere client state, and as such was well armed with the best that the U.S. could provide. Yet following the revolution, much of the technical competence was removed from the military as technicians and skilled officers were killed or fled from the zealots. In their place, the Iranian Revolutionary Guard Corps (IRGC), also known as Pasdaran, created a mass army of poorly trained and equipped infantry that battered the more technically minded Iraqi army into a bloody stalemate. Subsequently, Iran has sought to upgrade its military technology with purchases from Russia and elsewhere.[56]

At present, the Iranian air defense appears non-trivial but certainly not incredibly potent. It is comprised of three elements: aircraft, SAMs, and anti-aircraft artillery (AAA). The sections below detail current Iranian capabilities in each.

Iranian Air Defense Aircraft

Both the inventory and capability of the Islamic Republic of Iran Air Force (IRIAF) remains qualitatively poor. Maintenance and training are both insufficient to produce an air force capable of competing with a first class air force such as the IAF. However, the IRIAF would have substantial advantages confronting IAF strike packages over Iran.[57]

The IRIAF inventory of air defense aircraft includes a variety of platforms. These holdings are summarized in the table below.

Aircraft Designation	Approximate Number in Service	Country of Origin
F-14A	25	U.S. (pre-revolution)
F-4D/E	60	U.S. (pre-revolution)
MiG-29A	40	U.S.S.R. (includes impounded Iraqi aircraft)
F-5E/F	50	U.S. (pre-revolution)
Mirage F1EQ	12	France (impounded Iraqi aircraft)
F-7M	30	P.R.C.
F-6	16	P.R.C.

Several observations about the inventory can be made. First, all of the U.S. aircraft are of 1970s vintage, with little opportunity to acquire spare parts, much less upgrades. Second, the P.R.C. aircraft are Chinese versions of older MiG aircraft (the F-6 being a copy of the MiG-19 and the F-7M being an upgraded copy of the MiG-21). Third, the Mirage aircraft are also of 1970s vintage, and, having "inherited" from the Iraqi Air Force rather than purchasing them, the IRIAF probably does not have the best training and maintenance program for them. Finally, the MiG-29 is undoubtedly the most modern of the IRIAF's air defense aircraft, developed by the U.S.S.R. at approximately the same time as the F-15 and F-16.[58]

The advantages Iran accrues from fighting in its own airspace are twofold. First, their aircraft will be operating near their bases and therefore would be less concerned with refueling. Second, the Iranian aircraft could rely heavily on Ground Control Intercept (GCI) radar to guide them to IAF aircraft. This advantage is significant, particularly if the use of GCI could allow the IRIAF aircraft to begin an engagement from a favorable position (e.g. attacking from behind the IAF aircraft).[59]

Details of IRIAF aircraft armament are even less clear than details of the aircraft themselves. An array of missiles has been reported as ordered by Iran, yet it is uncertain which have actually been delivered and integrated into the IRIAF fleet. The possible arsenal is listed in the table below:

Missile Designation	Missile Type	Country of Origin
AIM-9P	SR; IR	U.S. (pre-revolution)
AIM-7F	BVR; R(SA)	U.S. (pre-revolution)
AIM-54	BVR; R(A)	U.S. (pre-revolution)
MIM-23B	BVR; R(SA)	U.S. (pre-revolution)
AA-8	SR; IR	U.S.S.R.
AA-9	BVR; R(A)	U.S.S.R.
AA-10	BVR; R(A)	U.S.S.R.
AA-11	SR; IR	U.S.S.R.
R-550	SR; IR	France
PL-2	SR; IR	P.R.C.
PL-5	SR; IR	P.R.C.
PL-7	SR; IR	P.R.C.
PL-9	SR; IR	P.R.C.

Types: SR=Short-range (<10 km); BVR=Beyond Visual Range (>10 km); IR=Infrared/heat-seeking; R(SA)=Radar, semi-active; R(A)=Radar, active

The above list is subject to many of the same limitations as the IRIAF aircraft fleet. The U.S. missiles are all from the 1970s, with all the problems of reliability that implies. The AIM-54 Phoenix missiles reportedly have been inoperative since the mid-1980s; the IRIAF has reported that in its place they have modified the MIM-23B SAM to replace the AIM-54 on its F-14A aircraft. The effectiveness of this modification is questionable, but it does indicate both the ingenuity of the IRIAF and its desperation to arm its aircraft. The Soviet missiles, on the other hand, would be quite effective, particularly the AA-10 Alamo and AA-11 Archer. However, it is uncertain whether they have actually been acquired and successfully integrated into the fleet. The same is true of the Matra R-550 Magic. Finally, the IRIAF, given Iran's good relations with the P.R.C., probably has integrated the PL-2, PL-5, and PL-7 and quite possibly PL-9, which is a reasonably advanced and effective weapon.[60]

Iranian Surface to Air Missiles

The Iranian SAM inventory is a similar mixed bag to its aircraft inventory, with the further complication that it is divided between the IRIAF, IRGC and the Army. The table below summarizes Iran's likely SAM holdings:

System Designation	Approximate Number in Service	System Type	Country of Origin
MIM-23B	150	LR; R(SA)	U.S. (pre-revolution)
Rapier	30	SR; R/O	U.K (pre-revolution)
SA-2/HQ-2	45	LR; R(Co)	U.S.S.R./P.R.C.
SA-5	15	VLR; R(Co/SA)	U.S.S.R.
SA-6	25?	LR; R(Co/SA)	U.S.S.R.
Shahab Theqeb	?	SR; R(Co)	Iran
FM-80	10	SR; R(Co)	P.R.C.
Tigercat	10	SR; O	U.K (pre-revolution)
RBS 70	50?	SR; R/L	Sweden

Types: SR=Short Range (<10km); LR=Long Range (>10km); VLR=Very Long Range (>100 km); R(SA)=Radar, Semiactive guidance; R/O=Radar acquisition; Optical guidance; R(Co)= Radar, Command guidance; R/L= Radar acquisition, Laser guidance

This inventory has numerous limitations. The centerpiece of Iranian SAM systems is the MIM-23B Improved HAWK, which is of late 1960s vintage. The combination of age and lack of spare parts probably reduces the utility of the Iranian I-HAWKs (though they reportedly shot down a fair number of Iraqi aircraft during the Iran-Iraq War). Further, Israel also uses the HAWK system and is thus likely to have developed significant ECM capability against it. The SA-2 and SA-5 are both outdated; with the most recent improvements to them being in the 1970s. All of the short-range systems are older as well. The SA-6, which might or might not be in service, is somewhat more effective. However, its use against the U.S. by both Iraq and Serbia has shown it to be of limited utility against first class air forces. The Shahab Theqeb is an Iranian version of the older Crotale system and is thus fairly unsophisticated.[61] Despite Iranian attempts to purchase the advanced Soviet/Russian SA-10 "Grumble" SAM, there are no confirmed reports of delivery.[62]

Recent reports indicate Iran is attempting to purchase 29 Soviet/Russian SA-15 "Gauntlet" SAM systems.[63] This would add a modern low/medium altitude mobile SAM with a phased array tracking radar to Iran's arsenal. However, the maximum engagement range for the system is believed to be 12,000 m, with a maximum target altitude of 6,000 m. Given that the IAF strike package would likely be flying at above 5,000 m and could drop PGMs from thousands of meters away, it is unlikely that these weapons would present a major risk to the strike aircraft. In contrast, the older I-HAWK is reported to able to engage targets at an altitude of over 17,000 m at a range of 40 km.[64]

In addition to the systems listed above, Iran fields a number of man portable air defense systems (MANPADS). These systems are shoulder-fired, and while unlikely to shoot down a prepared jet fighter, are still numerous enough to mention. The Iranian inventory includes the SA-7, SA-14, SA-16, HN-5A, and possibly Stinger.

Iranian AAA

Iran is generously supplied with AAA. In general, AAA counts more on volume of fire than accuracy to down aircraft, and at higher altitudes is ineffective. However, sufficient volume of fire can be even more effective than SAMs, as it cannot be jammed with ECM. Iranian AAA inventory is summarized in the table below:

System Designation	System Type	Approximate Number in Service	Country of Origin
ZSU-57-2	SP; 2x57mm; U	80	U.S.S.R.
ZSU-23-4	SP; 4x23mm; R	75	U.S.S.R.
ZU-23-2	T; 2x23mm; U	280	U.S.S.R.
M1939	T; 1x85mm; R?	250	U.S.S.R.
S-60	T; 1x57mm; R	190	U.S.S.R.
L/70	T; 1x40mm; U	50	Sweden
Skyguard	T; 2x35mm; R	24	Switzerland

Types: SP=Self-Propelled; T=Towed; U=Unaided optical fire control; R=Radar assisted fire control

In combination with the SAM inventory, the Iranian AAA inventory can provide substantial defense to key points. However, a major weakness remains tying all of these systems together in an Integrated Air Defense System (IADS). Without an effective IADS, the Iranian systems will be forced to make engagements with little or no support from other systems, limiting the overall effectiveness of the various systems. Further, this could limit the ability of the Iranian air defense to use interceptors and SAMs in the same area due to potential fratricide concerns.

Possible Attack Routes: North, Central and South Options

Now that the capabilities of both Israel and Iran have been noted and the most appropriate targets for the Israeli attack determined, the next question is one of route planning. The Israelis have three basic options. The first is to fly north over the Mediterranean, refuel from airborne tankers and then fly east over Turkey to Iran. The second is to fly southeast, skirt Jordan and Saudi Arabia, and then fly northeast across Iraq (essentially the Osirak route), possibly refueling in the air along the way. Alternately, the Israelis could fly northeast across Jordan and Iraq. Finally, the Israelis could fly southeast and then east along the Saudi/Iraqi border to the Persian Gulf and then north, again possibly refueling along the way. This section will evaluate the pros and cons of each route to determine which, if any, is plausible.

The Northern Route

The northern route has three main legs. The first is from Israeli airbases to the Turkish border. The likely bases that aircraft would be launched from are Hatzerim (near Beersheba), Hatzor, (near Ashdod), and Ramat David (near Haifa).[65] To simplify, calculations will be done from the base the longest distance from the target set, in this case Hatzerim. Note that this distance could be shortened by moving planes between bases before the strike launched, though this could potentially provide warning to other countries' intelligence services. From Hatzerim to the Mediterranean is approximately 80 km, and then north to Turkey is approximately 500 km.

The second leg crosses Turkey from west to east a short distance north of the Syrian border. The basic route begins east of Adana, passes south of Diyarbakir, and ends at the Iranian border west of Orumiyeh. This is a total distance of about 840 km.

The final leg is southeast across Iran to the endpoint of Arak, Natanz, and Esfahan. As in calculating the start point, the end point will be the furthest target, in this case Esfahan. From the border crossing near Orumiyeh to Esfahan is approximately 800 km. The total route length is thus roughly 2220 km.

This route is longer than the estimated unrefueled combat radius of the Israeli strike aircraft, but carries the advantage of aerial refueling over the Mediterranean. Tankers are quite vulnerable, and being able to refuel over the international waters of the Mediterranean would be a big advantage. Israeli tanker assets are not well documented, but appear to consist of 5-7 KC-707s and 4-5 KC-130Hs.[66] The KC-130s, due to their drogue refueling design, would be unable to refuel F-16s and F-15s. However, the KC-707s probably have the capability to deliver roughly 120,000 lbs of jet fuel each at a range of 1000 nautical miles.[67] For a strike package of 50 aircraft, this would be about 12,000 to 16,000 lbs of fuel per aircraft. As the actual distance to the refueling point, as noted, is less than 400 nautical miles, there should be more than this much fuel available.

By refueling in the Mediterranean, the strike package could feel confident of its ability to maneuver against Iranian air defenses. Further, by flying out by this route, refueling would be possible (and necessary) on the return flight. However, the refueling on the inbound leg of the flight would take place very early, so only a limited amount could be offloaded to each aircraft before they would be full again. Refueling would have to take place near the Turkish coast, as the total distance from Adana to Esfahan is about 1640 km, very close to the combat radius predicted for the F-15I. The IAF tankers could wait near the Turkish border to refuel the strike package on the way out, potentially protected by other IAF aircraft.

Also on the downside, this route passes quite close to several Turkish air force bases, including two large ones: Incirlik (near Adana) and Diyarbakir. Incirlik is a major NATO base, and Diyarbakir is the headquarters of Turkey's Second Tactical Air Force. Turkish interception of the flight is thus quite possible, as the Turkish Air Force fields modern F-16s, although Turkish SAMs are quite out of date (Nike series dating to the 1950s along with a few of the more modern Improved Hawk and the British Rapier).[68] Similarly, U.S. forces at Incirlik might be called upon to engage the Israelis as part of the NATO commitment.

Turkish reaction to an Israeli incursion is uncertain. While they would undoubtedly be furious, the central question is would they fire on Israeli aircraft? Turkey and Israel have enjoyed good military and economic relationships over the past decade, even if political rhetoric is sometimes harsh. On the other hand, the current Turkish government has moved somewhat away from Israel.

Once over the border with Iran, this route passes near a number of Iranian Air Bases: Tabriz, Sharohki (near Hamadan), Kermanshah, Khatami (near Esfahan), and

Vahdati (near Dezful).[69] The major bases near Tehran are slightly farther. This would put the strike package in range of a number of possible intercept squadrons during both ingress and egress.

The Northern Route Syrian Variant

If the IAF were reluctant to accept the political problems of flying over Turkey, it could instead cross Syria for most of the east-west leg of this route. It would then only have to cross Turkish airspace very briefly near the Iranian border. However, Syria would almost undoubtedly fire on Israeli aircraft. This route would thus accept significantly higher operational risk for somewhat lower political costs.

The Central Route

The central route is the most direct route, but carries major political difficulties. It has one or two main legs, depending on how it is flown. The first option, with two legs, goes southeast over the Gulf of Aqaba and then northeast near the Jordanian-Saudi border and across Iraq. The second option, a direct flight, goes northeast across Jordan and Iraq.

The first leg of option one would be from Ramat David (the furthest from the target) to the Gulf of Aqaba. This is basically the entire length of Israel, so planes might be relocated further south before the strike, but, as noted above, it is assumed for simplicity and operational security that all planes launch from home base. The length of this leg would be roughly 360 km.

The second leg of option one is from the northern end of the Gulf of Aqaba to the target zone. This leg is extremely long, with the furthest target, Natanz, roughly 1800 km away. The total distance traveled, 2160 km, would be scarcely less than the northern route. Tanking would be required at some point.

The second option, directly across Jordan and Iraq, is shorter. From Hatzerim to Natanz would be roughly 1750 km. This is just beyond the estimated combat radius of the strike aircraft.

Both of these options would require cooperation (or at least acquiescence) from the Jordanians and especially the Americans in Iraq. The flight path of option two is directly over Jordan and would pass near both the capital of Amman and a major air base at Azraq ash Shishan. Either would traverse all of Iraq, and any refueling that was done would likely need to be done over Iraq. It would be all but impossible to accomplish without the Americans and probably the Jordanians noticing.

While any strike against Iran by Israel will be interpreted by having U.S. backing, this option would provide unambiguous evidence of it. The repercussions of unambiguous support might lead to increased Shia resentment and violence against the U.S. in Iraq, as well as making the U.S. a major target of Iranian-backed Shia terrorists such as Hezbollah. Ultimately, as with Turkey, it is unlikely that the U.S. or Jordan would fire on Israeli aircraft, but this route appears even riskier than the northern route for political and military reasons. Israeli tankers would be extremely vulnerable, and U.S. or Jordanian forces could potentially disrupt refueling without firing a shot merely by being in the area. This could make the entire operation impossible.

This route would cross less of Iran en route to the target area. It would avoid the base at Tabriz, though the other bases noted above would still be in range. Iranian air defense on the Iraqi border might potentially be on higher alert than along the Turkish border.

The Southern Route

The southern route covers perhaps the least well-defended airspace, at least in its initial legs. However, it is also quite long and poses refueling challenges. It runs west to east across northern Saudi Arabia to the Persian Gulf, then north/northeast into Iran.

The first leg would be the Ramat David to the Gulf of Aqaba route noted above, a distance of 360 km. As with that route, aircraft could be shifted to bases further south to avoid much of this distance. From Aqaba it would cross Saudi Arabia south of the Iraqi border, from the coast near the town of Haql to the Persian Gulf coast near Ra's al Khafji. This is a distance of roughly 1350 km.

The second leg would cross the Persian Gulf into Iran, and then north to the target zone. The furthest target would be Natanz, a distance of about 700 km. This makes the total route length on the order of 2410 km, easily the longest route of the three.

The route passes near several Saudi air bases. These include King Faisal (near Tabuk), Al Jawf, Ha'il, and King Khalid. It is also only slightly farther from King Abdul-Azziz.[70] There are significant Saudi assets stationed at several of these bases, including F-15s and E-3 AWACS radar aircraft. Further, Saudi Arabia has invested significantly in its Peace Shield IADS, purchased from and maintained by Raytheon. The Saudis also have a separate ground based air defense command equipped with many Improved Hawk and a few Patriot SAMs.

On paper this appears to be a highly formidable air defense system. However, Saudi readiness levels are alleged to be very low.[71] Pilots are woefully unprepared for air-to-air combat, and the IADS is reputed to have limited ability to distinguish friend from foe. In addition, much of Saudi Arabia's northern air defense was intended to protect against Iraq, and presumably readiness levels are much lower now that the threat from Saddam Hussein has been removed. In addition, the question would still remain whether the Saudis would attack an Israeli incursion or simply launch a massive diplomatic protest.

A more serious issue would be that of refueling. The route would be significantly longer than the estimated combat radius of the strike aircraft. The IAF would thus have two options, both dangerous. It could attempt to refuel the strike package over Saudi territory, which would be subject to disruption by Saudi forces, or worse the downing of a tanker, which even the Saudi IADS should be able to do if the Saudis chose to. Alternately, it could refuel over the Persian Gulf, which might be less subject to disruption. It would still require flying the tankers across Saudi Arabia, and would also put the tankers in a position to possibly be engaged by IRIAF interceptors. Also, the route would also pass near several IRIAF bases: Bushehr, Vahdati, Esfahan, and Abadan (a non-military but potentially usable airfield). Shiraz is only slightly further.[72]

All of the routes pose significant operational and political risk. The rest of this analysis will remain neutral on the issue of route selection and instead concentrate on likely Iranian opposition near the target areas, regardless of route. The reader should be mindful that the other operational risks noted above might be entailed in any IAF attack.

The Likely Correlation of Forces

The following analysis is based on the presumption that the IAF will attack using 25 F-15Is and 25 F-16Is. As noted earlier, the IAF could potentially field a larger package, but this would require in some cases fairly extensive modification as well as probably taxing IAF refueling and command and control. This "package" would probably consist of three smaller packages, one for each of the likely targets.

The interaction of this strike package with Iranian air defense is highly contingent. In the Osirak strike, the IAF escaped all but the most desultory engagement with AAA around the reactor site. It is unlikely that the IAF would be so lucky against Iran, but the lack of an IADS means that the level of engagement could potentially be quite low.

As noted earlier, the quality and readiness of Iranian equipment is unknown. While it is certainly nowhere near the level of the IAF, if equipped with SAM-6s and moderate reliability and effectiveness in its interceptor fleet, Iran could create a credible response to the IAF incursion. In contrast, if reliability and effectiveness are low, and the SAM fleet is limited to the outmoded HAWKs, then the IAF could brush aside the Iranian forces with relative ease.

Rather than attempt to map the various contingent outcomes, we will simply look at the number of aircraft that would have to arrive on target to deliver the ordnance noted in the previous section on weaponeering. From that, we can see the attrition levels the Iranian air defense would have to generate in order to prevent the strike from being successful. We can then make some rough guesses about the likelihood of this occurring.

In the case of Natanz, twelve F-15Is would have to arrive at the target complex if each carried two BLU-113s (one on each set of CFT hardpoints) in addition to external fuel tanks and air-to-air missiles. However, it is unclear if this would be an effective loadout.[73] If each carried only one BLU-113 (along the centerline) in addition to external fuel tanks and air-to-air missiles, then twenty-four would have to arrive at the target complex. Note that if the F-15Is carried only one BLU-113, they could potentially carry up to four additional BLU-109s on the CFT hardpoints.[74]

Esfahan and Arak require less aircraft to deliver the requisite ordnance. In the case of Esfahan, six F-16Is would have to arrive at the target complex if each carried two BLU-109s in addition to external fuel tanks and air-to-air missiles. For Arak, only five F-16Is would have to reach the target.

Assuming a strike package of 25 each of F-15Is and F-16Is, then the Iranian air defense would have to impose significant attrition to cause the mission to fail. The IAF could assign two additional F-16Is loaded with 2000-lb bombs to both Arak and Esfahan and then have ten left for SEAD and air-to-air missions. The Iranian air defense would have to down 3 out of 7 assigned to Arak and 3 out of 8 assigned to Esfahan, roughly 40% attrition. This would be almost unimaginable given Iranian assets, as even the disastrous U.S. raid on Ploesti in World War II only sustained 32% attrition (admittedly out of a much larger total number). Even smaller U.S. strikes flown into North Vietnam never experienced anything near this level of attrition, at least after the introduction of electronic countermeasures to SAMs, and in both World War II and Vietnam the enemy was forewarned.[75]

The major vulnerability would be attrition in the F-15I force, assuming each carried only one BLU-113. Then the Iranian air defense would only have to impose an attrition rate of 8% (downing 2 out of 25) to cause the mission to fail to deliver the designated ordnance. This is certainly within the realm of possibility. For example, IAF ground attack aircraft sustained massive attrition in the first days of the 1973 Yom Kippur war, including 8% of total fighter strength on the first day. However, it should be noted that the average daily attrition of IAF aircraft in that conflict was only about 3%.[76]

A more relevant example would be the U.S. raid on Libya in 1986. This strike, code-named EL DORADO CANYON, was similar in nature to the proposed IAF strike. It used roughly the same number of aircraft (in this case 24 F-111s) flying very long routes (from England and around France to the Mediterranean). The build-up to EL DORADO CANYON in the media was such that the Libyans had at least as much warning as the Iranians could expect. In that case only one U.S. aircraft was lost, for an attrition rate of just over 4%.

However, another 31 aircraft actually took part in the raid and none were downed, for an overall attrition rate of just under 2%. Further, it is not clear why the single F-111 was lost and it may in fact have been shot down by a U.S. Navy F-14. Finally, the U.S. F-111s were using an earlier generations of LGB, and some, due to other constraints, made their attack run at very low altitude (150 m in some cases).[77]

Of course, reliability is an issue with aircraft as well as munitions. If even one F-15I failed to complete the mission due to reliability problems, then the Iranians would only have to down one aircraft. If two failed to function, then the mission would fail to deliver ordnance without the Iranians even firing a shot.

Also, it should be clear that the IRIAF does not have to actually down any IAF aircraft. They could effectively cause the mission to fail if it could succeed in engaging the IAF aircraft and causing them to dump their ordnance in order to maneuver. In Vietnam, this happened with some frequency to U.S. strike aircraft. With the advantage of good GCI and/or SAMs, this might be very possible for the IRIAF to accomplish as well. This further argues that the IAF might want to allocate some of the F-16Is for air-to-air or SEAD mission. Alternately, as discussed below, they might want to build some redundancy into the difficult Natanz strike.

Alternate Weaponeering Based On Force Application Requirements

The IAF could supplement the F-15I attack on Natanz by assigning F-16Is armed with BLU-109s to attack the BLU-113 aimpoints. While less certain of penetrating than the massive BLU-113s, the BLU-109 is a very capable weapon in itself. Assuming that six F-16Is were assigned to supplement the F-15Is, each could deliver two BLU-109s on each of six BLU-113 aimpoints. This would result in a greater than 0.75 probability of at least one weapon, BLU-109 or BLU-113, penetrating the Natanz facility.[78] The actual amount of explosive contained in the BLU-109 and BLU-113 is quite similar, so a high confidence of destruction could be obtained in this manner.

Also, as noted earlier, the BLU-113 armed F-15Is could carry two or four BLU-109s, adding more firepower. This would mean that if each carried one BLU-113 and two BLU-109s, the strike package of 25 F-15Is would have 25 BLU-113s and 50 BLU-109s. Two of these weapons would be presumed to be targeted on the pilot plant, but the rest could be used for the underground facility. Even if the Iranian air defense imposed 40% attrition (10 aircraft downed), 15 BLU-113s and 30 BLU-109s would arrive on target, even without supplemental F-16Is.

Conclusion

The foregoing assessment is far from definitive in its evaluation of Israeli military potential. However it does seem to indicate that the IAF, after years of modernization, now possesses the capability to destroy even well-hardened targets in Iran with some degree of confidence. The operation appears to be no more risky than the earlier attack on Osirak and provides at least as much benefit in terms of delaying Iranian development of nuclear weapons. This benefit might not be worth the operational risk and political cost. Nonetheless, this analysis demonstrates that Israeli leaders have access to the technical capability to carry out the attack. The question then becomes one of will and individual calculation. Other priorities, such as the election of Hamas to the leadership of the Palestinian Authority, the turmoil surrounding the Israeli leadership, and the Iranian leader's recent statements about Israeli existence, may take precedence.

More generally, this assessment illustrates the utility of precision-guided weapons for counterproliferation. Assuming that the intelligence is available to identify targets of interest, precision-guided weapons can fill an important role of destroying the target with increased confidence, leading to smaller strike packages and lower risk to personnel and equipment. While limitations still exist, especially in the case of hardened targets, precision-guided weapons have become extremely capable, particularly when strike aircraft are confronted by relatively low-quality air defense. The use of precision strike for counterproliferation should therefore not be discounted lightly.

Appendix A: Variation in Parameters of the BLU-113 Sequenced Penetration

N_{hit}	0.6	0.3	0.5	0.7	0.5	0.15	0.7
N_{nm}	0.4	0.7	0.5	0.3	0.5	0.85	0.3
CEP	3	3	3	2	3	2	3
LR	3	2	2.5	3	3	3	2
Rel	0.9	0.85	0.9	0.95	0.9	0.9	0.9
Prob	0.497	0.19	0.39	0.7	0.42	0.12	0.53

N_{hit}= Percentage of munitions that directly hit aimpoint (i.e. non-Gaussian distribution)
N_{nm}= Percentage that exhibit Gaussian distribution of a given CEP
CEP= Circular Error Probable; radius in m around aimpoint in which half of Gaussian distributed munitions will fall
LR= Lethal Radius; in this case the radius in m around the impact point of the first BLU-113 that the second must hit within to penetrate the Natanz facility
Rel= Reliability; the probability the BLU-113 will function properly
Prob= the cumulative probability of the two BLU-113s functioning and impacting sufficiently close for the second to penetrate the Natanz facility

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[1] The NPT guarantees the application of nuclear technology for peaceful purposes to all parties, including the technology inherent to the nuclear fuel cycle. The "nuclear fuel cycle" refers to the facilities required for nuclear power development. These include the "front end" of the cycle, uranium mining, milling, conversion, enrichment, and fuel fabrication, as well as the "back end" of the cycle involving spent fuel reprocessing and waste management. Unfortunately, the facilities that enable the nuclear fuel cycle are the same as those used for weapons production.

[2] See, for example, Uzi Mahnaimi and Sarah Baxter, "Israel readies forces for strike on nuclear Iran," *The Sunday Times* (online), December 11, 2005; http://www.timesonline.co.uk/article/0,,2089-1920074,00.html; Ian Bruce, "Israelis plan pre-emptive strike on Iran," *The Herald* (online), January 10, 2006. http://www.theherald.co.uk/news/53948.html; and Josef Federman, "Israeli Hints at Preparation to Stop Iran," *Washington Post*, January 22, 2006.

[3] The terminology of preventive versus preemptive attack is often muddled in the current public discourse. For purposes of this paper, "preventive" refers to an attempt to forestall a shift in the relative balance of power between states. "Preemptive", in contrast, is taken to mean an attempt to "spoil" an imminent attack. In terms of Israeli history, the 1967 Six Day War is clearly preemptive, while the 1981 raid on Osirak is preventive. See Dan Reiter, "Exploding the Powder Keg Myth: Preemptive Wars Almost Never Happen," *International Security*, v.20, n.2 (Autumn 1995) pg. 5-8 for a short but lucid discussion of the differences between the two.

[4] For details on the 1981 raid, see Rodger W. Claire, *Raid on the Sun*, (New York: Broadway Books, 2004) and Shelomoh Nakdimon, *First Strike: The Exclusive Story of How Israel Foiled Iraq's Attempt to Get the Bomb*, (New York: Summit Books, 1987).

[5] *Israel's Strategic Future: The Final Report of Project Daniel*, full text available online at: http://www.acpr.org.il/ENGLISH-NATIV/03-ISSUE/daniel-3.htm.

[6] Louis Rene Beres, "Israel's Security Strategy," *Washington Times*, August 19, 2004.

[7] Some recent works have addressed the possibility of preventive attack and the potential consequences, but have not presented any actual net assessment of Israeli capabilities against Iranian defenses. Instead, they have simply stated that attacking Iranian facilities would be more difficult than Osirak. See Sammy Salama and Karen Ruster, "A Preemptive Attack on Iranian Nuclear Facilities: Some Possible Consequences," Center for Nonproliferation Studies Research Story, August 12, 2004, http://cns.miis.edu/pubs/week/040812.htm and Yiftah Shapir, "Iranian Missiles: The Nature of the Threat," Tel Aviv Note n.83, Jaffee Center for Strategic Studies, http://www.tau.ac.il/jcss/tanotes/TAUnotes83.doc.

[8] See *The National Security Strategy of the United States of America*, Section V, September 2002, http://www.whitehouse.gov/nsc/nss.html. The 2006 version does not differ on this point, http://www.whitehouse.gov/nsc/nss/2006.
[9] This summary is drawn primarily from Claire, *Raid on the Sun*.
[10] Quoted in Claire, pg. 98.
[11] The code name for the operation is given as both Operation Opera and Operation Babylon.
[12] Quoted in Claire, pg. 221. The reaction of Reagan, one of George W. Bush's heroes, upon first being informed of the bombing is also worth noting. He is supposed to have shrugged and said, "Well, boys will be boys." See Claire, pg. 218.
[13] Reza Aghazadeh, "Iran's Nuclear Policy: Peaceful, Transparent, Independent" Presentation by the Vice-President of Iran, IAEA Headquarters, May 6, 2003
[14] Chaim Braun. and Christopher Chyba, "Proliferation Rings: New Challenges to the Nuclear Nonproliferation Rings," *International Security*, v.29, n.2 (Fall 2004). For more detail on the nuclear fuel cycle, see Ronald Knief, *Nuclear Engineering: Theory and Technology of Commercial Nuclear Power*, 2nd ed., (New York: Hemisphere Publishing, 1992).
[15] The "front end" of the nuclear fuel cycle refers to all activities engaged in prior to placing fuel in a reactor, while the "back end" refers to post-irradiation activities. Front end technology includes uranium mining, milling, conversion, enrichment, and fuel fabrication, while back end technology focuses mainly on reprocessing and waste management procedures.
[16] Unless otherwise noted, the following summary of Iran's nuclear activities has been taken from the following sources: Director General, IAEA, "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," GOV/2004/11 (Vienna, February 24, 2004), Director General, IAEA, "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," GOV/2003/63 (Vienna, August 26, 2003), Director General, IAEA, "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," GOV/2003/75 (Vienna, November 10, 2003)
[17] Andrew Koch and Jeanette Wolf, "Iran's Nuclear Facilities: A Profile", Center for International Studies, Monterey, CA, 1998. Available at http://www.nti.org/e_research/profiles/Iran.
[18] The term "latent proliferators" refers to those actors who build civilian nuclear facilities which can then be militarized and used for nuclear weapons production. See Braun and Chyba, "Proliferation Rings".
[19] "Latest Developments in the Nuclear Program in Iran, In Particular on the Plutonium Way", French presentation, NSG 2003 Plenary Meeting, May 2003.
[20] The consequences that stem from the NPT's explicit legality of peaceful national nuclear programs are that many states, Iran included, could use their peaceful technology for nefarious purposes. In particular, Iran's arguments that indigenous conversion and enrichment technology is required for the manufacture of fuel for the country's reactors is accurate, as well as the stated purpose of investigation of fuel reprocessing activities for the separation of medical isotopes and spent fuel waste management.
[21] *Islamic Republic of Iran*, IAEA Report, 2002. Available at http://www-pub.iaea.org.
[22] Director General, IAEA, "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," GOV/2004/83 (Vienna, 15 November, 2004).
[23] David Albright and Corey Hinderstein, "The Centrifuge Connection", *Bulletin of the Atomic Scientists*, v.60, n.2 (March/April 2004), pp. 61-66
[24] Director General, IAEA, "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," GOV/2004/11 (Vienna, February 24, 2004).
[25] The generally accepted value for weapons-grade plutonium is greater than 93% ^{239}Pu.
[26] CIA, Unclassified Report to Congress on the Acquisition of Technology Relating to Weapons of Mass Destruction and Advanced Conventional Munitions, January 1 through June 30, 2002. Available at http://www.cia.gov/cia/reports.
[27] Studies have shown that plutonium can be harvested from light water reactors that will result in a weapon with a high probability of failure. However, even a "failure" would result in massive destruction. For study of the use of light-water reactors for plutonium production and weaponization, see "Plutonium from Light Water Reactors as Nuclear Weapon Material", Harmon W. Hubbard, April 2003, available at www.npec-web.org. Again, we have discounted Bushehr as a viable target because of the transparency with which Iran has agreed to return fuel to Russia and assume that any illicit activity regarding spent fuel and large-scale plutonium reprocessing would be noticed.

[28] This assessment, of course, is based on the lack of knowledge of any other industrial-scale conversion facilities in the country. It is possible that another large conversion facility exists clandestinely, and it is also quite possible that small-scale conversion capabilities exist at the Tehran Nuclear Research Center or at other locations throughout the country.
[29] "Inquiry Suggests Pakistani Sold Nuclear Secrets", William J. Broad, David Rohde and David E. Sanger, *The New York Times*, December 22, 2003, and "Pakistani's Nuclear Black Market Seen as Offering Deepest Secrets of Building Bomb", William J. Broad and David E. Sanger, *The New York Times*, March 21, 2005.
[30] Director General, IAEA, "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," GOV/2003/63 (Vienna, August 26, 2003).
[31] Many modern LGBs, such as the U.S. Paveway III, are designed for low-altitude release in the face of strong enemy air defense, with Paveway III able to travel over 10 miles when lofted towards a target at low altitude. GPS munitions, such as the U.S. Joint Direct Attack Munition (JDAM), are somewhat less suited for low-level release, as the GPS system takes a short amount of time to acquire the satellite constellation. However, the integral inertial navigation system (INS) in most GPS-guided munitions ameliorates this problem. JDAM, for example, is cleared for launch from a variety of altitude and velocity combinations. See *Jane's Air Launched Weapons* entries for JDAM and Paveway, as well as C.R. Anderegg, *Sierra Hotel: Flying Air Force Fighters in the Decade After Vietnam*, (Washington, D.C.: Air Force History and Museums Program, 2001), chapter 12; and Richard Van Atta and Ivars Gutmanis, "The Development and Deployment of Precision-Guided Munitions for Standoff Attack," in Richard Van Atta, *et.al, Transformation and Transition: DARPA's Role in Fostering and Emerging Revolution in Military Affairs, volume 2-Detailed Assessments*, (Washington, D.C.: Institute for Defense Analyses, 2003).
[32] See Barry Posen, "Command of the Commons: The Military Foundation of U.S. Hegemony," *International Security*, v.28, n.1 (Summer 2003) for discussion of the costs and benefits of operating in the airspace above and below approximately 15,000 feet. Though specifically discussing the U.S. military, the general line of argument applies to any advanced air force, such as the IAF.
[33] CEP is the standard measure of accuracy for munitions and is the radius of a circle around the aimpoint that 50% of weapons fired at a target will land within. Computer aided bombing accuracy is dependent on a number of factors that can generate error. Further, since the bomb is unguided, error propagates with range. The 8 to 12 m CEP given can be considered near optimal at short range (2km), and is roughly comparable to both anecdotal evidence and general calculations of error for this type of bombing. For the theory behind error calculation in computer aided bombing, see Morris Drells, *Weaponeering: Conventional Weapons System Effectiveness*, (Reston, VA: American Institute for Aeronautics and Astronautics, 2004), pg. 70-93. Qualification for pilots in computer aided bombing is on the order of 6 to 12 milliradians (mils) CEP, where 1 mil=1 m at 1 kilometer.
[34] See *Jane's Air Launched Weapons* entries for JDAM and Paveway. LGB error is a special case, as they exhibit non-Gaussian distribution of error, with a significant percentage of hits being direct hits. This translates to essentially no error in many cases unless a gross error occurs due to system failure. Many modern LGBs (such as the Enhanced Paveway III) include INS and GPS to ensure accurate guidance even if the weapon loses laser lock for some reason. See Drells, pg. 96-104. Even the earliest LGBs, when properly used, had a probability of directly impacting the target of about 0.5, so this paper takes that as the baseline for non-Gaussian distribution. See Anderegg, pg. 124-125.
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[36] For an overview of penetrating munitions, see Clifford Beal, "Striking Deep Hardened-Target Attack Options Grow," *Jane's International Defense Review*, v.27, n.7 (July 1994) and Secretary of Defense/Secretary of Energy *Report to Congress on the Defeat of Hard and Deeply Buried Targets*, July 2001.
[37] See *Jane's Air Launched Weapons* entry for PB 500A1.
[38] "American Sale of New Bombs to Israel Sends Message to Iran," *The Times (London)*, September 22, 2004. For details, see *Jane's Air Launched Weapons* entry for BLU-109. The penetration capability is given as 1.8 to 2.4 m of concrete depending on angle of impact.
[39] "Pentagon Notifies Congress of Potential 'Bunker Buster' Sale to Israel," *Defense Daily*, April 29, 2005. For details, see *Jane's Air Launched Weapons* entry for Paveway III Penetration Bombs. The penetration capability is credited as at least 6 m of concrete (presumably reinforced concrete) and 30 m of earth.
[40] See *Jane's Sentinel Eastern Mediterranean* entry for IAF, August, 2005.

[41] See http://www.globalsecurity.org/wmd/world/iran/natanz.htm and http://www.isis-online.org/publications/iran/natanz03_02.html.

[42] See *Gulf War Air Power Survey*, v.2, part 1, pg. 240-241. The U.S. considered using up to four weapons targeted on each aimpoint to dig into buried targets.

[43] Quoted in Alon Ben-David, "Paveway III sale to bolster Israeli strike capability," *Jane's Defense Weekly*, May 4, 2005. Note that unlike earlier LGBs, most modern LGBs incorporate inertial navigation and/or GPS systems so that if the laser designation is lost due to dust or smoke from the first bomb, the second is still going to continue towards the designated target with high precision.

[44] This is derived from the formula $P_k=1-0.5^{(LR/CEP)}$, where P_k is the probability of successful landing within the lethal radius of the target. Here the "lethal radius" is crater size, so the probability of a near miss still landing in the crater is $1-0.5^{(3/3)}=0.5$. In the case of two "near misses," the lethal radius is reduced to 1.5 meters; in other words if the first bomb lands within 1.5 m of the aim point, then the second bomb will definitely hit the 3 m crater if it lands within 1.5 m of the aimpoint as well. With these assumptions, there are four probability branches: direct hit-direct hit; direct hit-near miss; near miss-direct hit; near-miss near-miss. These branches have a probability of (0.6*0.6=0.36); (0.6*(0.4*0.5)) =0.12; ((0.4*0.5)*0.6=0.12); and $(0.4*0.3)^2=0.014$). This yields a cumulative probability of 0.64, which is then multiplied by the cumulative reliability (0.9*0.9=0.81) to yield a probability of 0.5. The assumption of crater width is based on the 0.37 m diameter of a GBU-28 combined with the effect of the explosion occurring in the ground, which will rupture the ground surrounding the explosion as well as being vented to some degree out of the entryway of the warhead. This is presumed to create sufficient structural damage to allow the second BLU-113 to penetrate easily if it impacts within about 1.8-3.6 m radius (10-20 times the diameter of the bomb) of the entry point of the first bomb. For a brief discussion of the mechanics of buried explosions, see Geoffrey Forden, "Nuclear Bunker Busters," *Breakthroughs*, v.11, n.1 (Spring 2002). Though Forden is discussing buried nuclear explosions, the principles are similar for conventional explosives, albeit on a much smaller scale. This calculation is very sensitive to changes in the parameters, so some variations are presented as an appendix table.

[45] Derived from known TNT blast curves and the formula for scaled distance $Z=D/W^{1/3}$. Despite otherwise using the metric system for calculations, most vulnerability data are in psi, so the authors have used psi rather than kilopascals to represent overpressure. *See Jane's Air Launched Weapons* entry for Paveway III for warhead data. Vulnerability data taken from the U.S. Defense Intelligence Agency, *Physical Vulnerability Handbook-Nuclear Weapons*.

[46] Terence Henry, "The Covert Option," *The Atlantic Monthly*, December 2005, pg. 56 quotes non-proliferation analyst Jon Wolfstahl: "If the [electrical] current powering the magnet fluctuates…you can send the centrifuge flying out of its case, careening across the room like a bowling pin, and knocking out the rest of the centrifuge cascades." This may be an overly optimistic assessment, but it does point out the vulnerable nature of centrifuge cascades.

[47] See http://www.globalsecurity.org/wmd/world/iran/esfahan-imagery-tunnel2.htm.

[48] This is based on the imagery at http://www.globalsecurity.org/wmd/world/iran/esfahan_comp-zonea.htm as well as photographs in *Jane's Sentinel Eastern Mediterranean*, Israel entry, October 2005 and FBIS photographs from the Fars News Agency.

[49] Data from *Physical Vulnerability Handbook*.

[50] As with the centrifuges of Natanz, some analysts believe that the damage threshold for the Esfahan UCF is actually much lower. Henry, "The Covert Option," notes that former CIA officer Reuel Marc Gerecht claims a backpack full of explosives would be sufficient to severely damage Esfahan.

[51] Data from *Physical Vulnerability Handbook*.

[52] The strike, code named Operation Wooden Leg, was in response to the hijacking of the *Achille Lauro* cruise ship. See "Israel Calls Bombing a Warning to Terrorists," *New York Times*, October 2, 1985.

[53] This estimate is based on Israeli acquisitions from Boeing and Lockheed Martin. The first two F-16Is were delivered in February 2004 and the rate of delivery has been roughly two per month since. Estimates for the total number of delivered F-16Is delivered at the end of 2004 are roughly 18-20. *Jane's Security Sentinel-Eastern Mediterranean* lists the IAF as having initiated a 50 aircraft buy in November 2003, which should be completed by the end of 2005. See Global Security: http://www.globalsecurity.org/military/world/israel/f-16i.htm; *Jane's Security Sentinel-Eastern Mediterranean*, August 8, 2005; and Stockholm International Peace Research Institute: http://www.sipri.org/contents/armstrad/REG_IMP_ISR_94-04.pdf.

[54] Actual combat radii are classified, so this estimate is based on a variety of sources. The official ferry range (the range the aircraft can fly one way without refueling) for the F-15E using CFTs and three external fuel tanks is given by the U.S. Air Force as 3840 km. Other sources suggest that the actual ferry range is in excess of 5600 km. *Jane's All the World's Aircraft* lists it as 4445 km. In terms of combat radius, the number most often cited for the F-15E is 1270 km, which appears to be with CFTs and a full weapons load. By replacing two weapons with external fuel tanks, the combat radius could be extended. A simple estimate can be derived from comparing the fuel load with CFTs only (approximately 23,000 pounds) with the fuel load of CFTs plus two 610 gallon external tanks (approximately 31,000 pounds). This ratio is about 1.35, which when multiplied by 1270 km yields a combat radius of roughly 1700 km. This estimate also appears to roughly conform with the official ferry range, as with three drop tanks and CFTs the F-15E can carry about 35,300 pounds of fuel, or a ratio of about 1.53. This yields a combat radius of about 1900 km, or a ferry range of 3800 km. Ferry range assumes no combat maneuvering, but the official estimate, as noted is probably highly conservative. Some sources list the combat radius of the F-15E as in excess of 1800 km, so the 1700 km estimate is probably conservative as well. Breguet calculations based on a specific fuel consumption of .9, a constant velocity of 700 mph, constant coefficient of lift, lift to drag ratio of 6.193 and a take-off weight of 80,000 lbs with 30,000 lbs of fuel also produce results in this range (approximately 1800 km radius), not accounting for weapons release. See John Anderson, *Introduction to Flight*, 5th edition, (Boston: McGraw-Hill, 2005); *Jane's All The World's Aircraft* entry for F-15; Air Force Fact Sheet F-15, http://www.af.mil/factsheets/factsheet.asp?fsID=102; Global Security, http://www.globalsecurity.org/military/systems/aircraft/f-15-specs.htm; Jaffee Center Middle East Military Balance, http://www.tau.ac.il/jcss/balance/airf.pdf; Air Force Technology, http://www.airforce-technology.com/projects/f15/; and F-15E Strike Eagle, http://www.f-15estrikeeagle.com/weapons/loadouts/oif/oif.htm.

[55] The F-16D, which the F-16I is based on, has internal fuel storage of almost 5900 pounds and an estimated combat radius of approximately 540 km. With the addition of CFTs, one 300 gallon centerline and two 600-gallon external fuel tanks, the F-16I could carry about 19,000 pounds of fuel. Using the simple estimation method above, this is a ratio of 3.22, which would give the F-16I a combat radius of about 1730 km. As the CFTs have much lower drag than the external fuel tanks, the actual combat radius will probably be higher. At least one source, the Jaffee Center, reports a combat radius of 2100 km, so this estimate is probably conservative. It appears to be roughly in line with other estimates. Jane's *All the World's Aircraft* lists 1361 km as the combat radius in a hi-lo-lo-hi profile for the F-16C Block 50 with CFTs, a centerline 300 gallon external fuel tank, and two 370 gallon underwing fuel tanks (roughly 17,100 lbs of fuel), while carrying two 2000-lb bombs and two Sidewinder missiles. This estimate is also in line with the official U.S. Air Force ferry range of in excess of 3200 km. This ferry range is with two 600 gallon and two 370 gallon fuel tanks for a total of 18,700 pounds of fuel, a ratio of 3.28. This yields a radius of about 1770 km and a ferry range of 3540 km. *See Jane's All The World's Aircraft* entry for F-16; Air Force Fact Sheet F-16, http://www.af.mil/factsheets/factsheet.asp?fsID=103; Jaffee Center Middle East Military Balance, http://www.tau.ac.il/jcss/balance/airf.pdf; Global Security, http://www.globalsecurity.org/military/systems/aircraft/f-16-specs.htm and Air Force Technology, http://www.airforce-technology.com/projects/f16/.

[56] See Anthony Cordesman, "Iran's Developing Military Capabilities," Center for Strategic and International Studies draft paper, December 2004, for an overview of current Iranian military organization. On the history of the IRGC and regular military relations, see Sharam Chubin and Charles Tripp, *Iran and Iraq at War*, (Westview Press; Boulder, CO; 1988), chapter 2.

[57] This assessment and the inventory lists for all systems are derived primarily from Cordesman, pg. 25-28; *Jane's World Air Forces* entry for IRIAF; *Jane's World Armies* entry for Iran; and Global Security, http://www.globalsecurity.org/military/world/iran/airforce.htm.

[58] See *Jane's All the World's Aircraft* entries for each of the individual aircraft.

[59] For an idea of the advantage GCI confers, see Anderegg, and Marshall Michel, *Clashes: Air Combat Over North Vietnam 1965-1972*, (Naval Institute Press; Annapolis, MD; 1997).

[60] See *Jane's Air Launched Weapons* entries for each missile.

[61] See *Jane's Land-based Air Defense* entries for individual systems.

[62] See *Jane's Sentinel Gulf States*, October 21, 2005 entry for Iran.

[63] "Iran Plans to buy 29 Tor-M1 Systems," *Jane's Missiles and Rockets*, January 2006.

[64] See *Jane's Land-based Air Defence* entries for SA-15 and HAWK.

[65] See Global Security: http://www.globalsecurity.org/military/world/israel/airfield.htm.
[66] See Global Security: http://www.globalsecurity.org/military/world/israel/iaf-equipment.htm and *Jane's World Air Forces* entry for Israel.
[67] See http://www.fas.org/nuke/guide/usa/bomber/kc-135.htm.
[68] See International Institute for Strategic Studies *Military Balance 2005* entry for Turkey.
[69] See Global Security: http://www.globalsecurity.org/military/world/iran/airfield.htm.
[70] See Global Security: http://www.globalsecurity.org/military/world/gulf/sa-airfields.htm.
[71] See Anthony Cordesman, *The Military Balance in the Gulf: The Dynamics of Force Development*, CSIS Working Draft, April 2005, pg. 131-134.
[72] See Global Security: http://www.globalsecurity.org/military/world/iran/airfield.htm.
[73] While the F-15I has the gross weight capacity to carry 2 BLU-113s along with external fuel, it is unclear if the CFT hardpoints can effectively carry 5000-lb bombs.
[74] With a maximum take-off weight of 81,000 lbs, the F-15I (empty weight of 32,000 lbs) could carry one BLU-113s (approximately 4500 lbs), four BLU-109s (approximately 8000 lbs total), 31,000 lbs of fuel, two AMRAAMs (or equivalent, weight approximately 1000 lbs total), and two Sidewinders (or equivalent, weight approximately 500 lbs total) for a total weight of 77,000 lbs, which still leaves weight available for targeting pods and 20mm cannon ammunition (and of course pilots). Given the range requirements of the mission, the IAF might choose to only load two BLU-109s rather than four.
[75] On Ploesti, see, *inter alia*, Stephen Sears, *Air War Against Hitler's Germany*, (New York: Harper Row, 1964), pg. 74. Out of 165 aircraft sent on the raid, 53 failed to return. This includes aircraft lost due to mechanical failure and so probably overstates the effectiveness of German air defense. On Vietnam, see Marshall Michel, *The Eleven Days of Christmas: America's Last Vietnam Battle*, (San Francisco, CA: Encounter Books, 2002), chapter 8. On the third and worst night of the Linebacker II raids against the heavily defended Hanoi region, 6 B-52s out of 45 (13% attrition) were lost. Admittedly, these were strategic bombers, not fighter-bombers. On tactical fighter losses in Vietnam, see Marshall Michel, *Clashes: Air Combat Over North Vietnam 1965-1972*, (Annapolis, MD: Naval Institute Press, 1997).
[76] In a conflict of 18 days duration, the IAF lost about 115 out of 358 fighter-bombers. This works out to a daily loss rate of about 2.5-3%. See Eliot Cohen and John Gooch, *Military Misfortunes: The Anatomy of Failure in War*, (New York: The Free Press, 1990), pg. 104 and 110.
[77] See Joseph Stanik, *El Dorado Canyon: Reagan's Undeclared War with Qadaffi*, (Annapolis, MD: Naval Institute Press, 2002).
[78] The probability of at least two direct hits on the aimpoint out of four weapons (two BLU-113 and two BLU-109) is 0.74, assuming the base case of 0.9 reliability and 0.6 probability of a direct hit. This does not account for any near misses but does disregard the possibility of the BLU-113s both missing and the two hits being BLU-109s.