A Crude Threat :The Limits of an Iranian Missile Campaign against Saudi Arabian Oil

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Joshua R. Itzkowitz Shifrinson and Miranda Priebe

Developments in Iran's ballistic missile program have made headlines over the last several years.[1] In the United States, Senator Carl Levin calls Iran's short- and medium-range missile arsenal "the number one threat in the Middle East," and Undersecretary of Defense for Policy Michèle Flournoy argues, "The threat from Iran's short- and medium-range ballistic missiles is developing more rapidly than previously projected."[2] Israeli officials similarly describe the Iranian missile program as "a matter of grave concern."[3] States around the Persian Gulf, meanwhile, worry that Iran's missiles are meant to intimidate and extract political concessions from them, with Saudi Arabia's King Abdullah noting that the Iranians "launch missiles in the hope of putting fear in the people and the world."[4]

These worries are not simply abstract concerns. At a time when the United States and its allies remain locked in a standoff with Iran over the latter's nuclear program, states around the Persian Gulf fear that Iran would retaliate for an attack on its nuclear program by striking regional oil installations and other strategic targets.[5] Iranian officials have threatened to use ballistic missiles in

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1. Ed Blanche, "Iran Stages Display of Missile Firepower," *Jane's Missiles and Rockets*, November 23, 2006; Alan Cowell and William J. Broad, "Iran Reports Missile Test, Drawing Rebuke," *New York Times*, July 10, 2008; and Dennis C. Blair, "Annual Threat Assessment of the U.S. Intelligence Community for the Senate Select Committee on Intelligence," 111th Cong., 2d sess., February 2, 2010.
2. Levin and Flournoy quoted in "The President's Decision on Missile Defense in Europe," hearing before the Senate Armed Services Committee, 111th Cong., 1st sess., September 24, 2009.
3. Angela Balakrishnan, "Barack Obama Calls for Tougher Iran Sanctions after Missile Tests," *Guardian*, July 9, 2008.
4. "Cables Show Arab Leaders Fear a Nuclear Iran," *Der Spiegel*, December 1, 2010, http://www.spiegel.de/international/world/0,1518,731877,00.html/.
5. Kenneth Katzman, *Iran: U.S. Concerns and Policy Responses*, CRS Report for Congress (Washington, D.C.: Congressional Research Service, Library of Congress, October 26, 2010), Order Code RL 32048, pp. 51–52; Patrick Clawson and Michael Eisenstadt, "The Last Resort: Consequences of Preventive Military Action against Iran," Policy Focus, No. 84 (Washington, D.C.: Washington Institute for Near East Policy, 2008), pp. 16–18; and Anthony H. Cordesman, "The United States, Israel, the Arab States, and a Nuclear Iran: Part Five: Iranian Capabilities to Respond to a Preventive Attack" (Washington, D.C.: Center for Strategic and International Studies, October 7, 2008), pp. 91–120.

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these attacks, with a senior military adviser to Ayatollah Ali Khamenei warning that Iran would fire its missiles against oil refineries and other critical infrastructure in the event of a U.S. or Israeli strike.[6] At the same time, Iran's efforts to develop and test its ballistic missile arsenal have led states in the region to improve their defenses around critical infrastructure, including oil facilities, with U.S. assistance.[7] In a telling comment, a representative of Saudi Arabian King Abdullah told a senior U.S. official that he "worries more about an Iranian missile launch against Saudi oil facilities than a terrorist attack . . . because he can take preventive measures against terrorism but not against Iranian missiles."[8]

A successful Iranian missile attack on Persian Gulf oil installations would have many of the same effects as a blockade of the Strait of Hormuz.[9] By disrupting oil production, a successful missile strike could reduce the supply of oil on the world market and cause a spike in oil prices.[10] Presumably, Iranian retaliation would be designed to impose substantial economic costs on an attacker.[11]

These concerns raise several questions. What are the capabilities of Iran's missiles? Likewise, what are the military vulnerabilities in oil networks? In light of the above scenario and the alarming reports about the Iranian missile arsenal, does Iran really have the missile capabilities to disrupt oil production? Is increased spending to harden oil infrastructure by Persian Gulf states worthwhile, or might such funds be better spent elsewhere? Overall, what damage could Iran inflict with a missile campaign against Gulf

6. Michael Smith, "Iran Threatens Gulf Blitz If U.S. Hits Nuclear Plants," *Sunday Times*, June 10, 2007.
7. Joby Warrick, "U.S. Steps Up Arms Sales to Persian Gulf Allies," *Washington Post*, January 31, 2010; and David S. Cloud, "U.S. Set to Offer Huge Arms Deal to Saudi Arabia," *New York Times*, July 28, 2007.
8. John M. Guilfoil, "The Embassy Cables: Saudis Fear Iranian Missile Strike More Than Terrorism," *Blast*, December 7, 2010, http://blastmagazine.com/2010/12/07/the-embassy-cables-saudis-fear-iranian-missile-strike-more-than-terrorism/.
9. Caitlin Talmadge, "Closing Time: Assessing the Iranian Threat to the Strait of Hormuz," *International Security*, Vol. 33, No. 1 (Summer 2008), pp. 82–117; Anthony H. Cordesman, "Iran, Oil, and the Strait of Hormuz," CSIS Brief (Washington, D.C.: Center for Strategic and International Studies, March 26, 2007), pp. 1–7; and Robert Strauss Center, "Strait of Hormuz: Assessing Threats to Energy Security in the Persian Gulf," University of Texas at Austin, August 2008, http://hormuz.robertstrausscenter.org/threat.
10. In 2008, global oil exports totaled 60.8 million barrels per day (mbd), including 40.1 mbd of crude oil and 20.7 mbd of refined products. Approximately 20.3 mbd came from the Middle East, which, given the location of oil fields, means the Persian Gulf region. See Organization of the Petroleum Exporting Countries (OPEC), *Annual Statistical Bulletin, 2008* (Vienna: OPEC, 2008), pp. 34, 36, 38.
11. Katzman, *Iran*, pp. 51–52; Clawson and Eisenstadt, *The Last Resort*, pp. 16–18; and Angus McDowall, "Iran Threatens to Cut Off Gulf Oil Exports If Nuclear Facilities Are Attacked," *Telegraph*, June 28, 2008.

oil installations—specifically, in the scenario below, Saudi Arabian facilities—and how would it go about launching such an attack?

Existing analyses of Iranian retaliatory options have not discussed the missile scenario. Instead, studies of Iranian options address Iran's capacity to close the Strait of Hormuz to oil tankers. Because the findings suggest that a blockade is unlikely to be wholly successful, prudent Iranian planners might consider additional ways, including missile launches, attacks by special forces and proxy groups, naval assaults, and conventional air campaigns, to disrupt the flow of Persian Gulf oil.[12] Of these options, a missile campaign is among the most plausible: aside from the concerns described above, U.S. intelligence officials have argued that Iran's missile arsenal is "an integral part of its strategy to deter and if necessary retaliate against forces in the region."[13] This study's analysis of the missile scenario builds upon past work on Iran's military capabilities and addresses the policy concerns identified above.

This article offers an initial answer to the questions highlighted above by examining whether Iran could use its ballistic missile arsenal to significantly reduce Saudi Arabia's oil production. Analyzing the threat to Saudi production provides a "worst-case" analysis from the perspective of the United States and its allies. Simply put, Saudi Arabia contains the largest confirmed oil reserves in the world, holds the greatest productive capacity of any state, and is the world's largest oil exporter.[14] If all Saudi oil production were to cease, 9.2 million barrels per day (mbd) of oil would be removed from world markets; only the combined loss of Emirate, Iraqi, Kuwaiti, Omani, and Qatari oil production would equal these figures.[15] Moreover, Saudi Arabia produces less oil than its maximum capacity. It has historically used its excess capacity to cushion oil markets by increasing production in crises to ensure a stable world oil supply. A successful Iranian missile strike could eliminate this cushion, making prices more volatile until production came back online.[16] All this means

12. Talmadge, "Closing Time," especially p. 115.
13. Blair, "Annual Threat Assessment of the U.S. Intelligence Community for the Senate Select Committee on Intelligence," p. 21.
14. BP, *Statistical Review of World Energy, 2010* (London: BP, June 2010), pp. 6–7; U.S. Energy Information Administration (EIA), "Country Analysis Brief: Saudi Arabia," Department of Energy, November 2009, pp. 2–3, 11; and U.S. Energy Information Administration, "Country Energy Profiles," Department of Energy, http://tonto.eia.doe.gov/country/index.cfm.
15. The combined production of Iraq, Kuwait, Oman, Qatar, and the United Arab Emirates was approximately 9.2 mbd in 2008. See OPEC, *Annual Statistical Bulletin, 2008*, p. 21; and U.S. Energy Information Administration, "Country Analysis Brief: Oman," Department of Energy, August 2009, p. 2, http://www.eia.doe.gov/cabs/Oman/Oil.html.
16. Permanent Subcommittee on Investigations, Senate Committee on Homeland Security and Governmental Affairs, "The Role of Market Speculation in Rising Oil and Gas Prices: A Need to Put the Cop Back on the Beat," S. Prt. 109-65, 109th Cong., 2d sess. (Washington, D.C.: U.S. Government Printing Office, June 2006), p. 13; and Alexander Kwiatkowski, "Oil Swings May Widen as Spare Capacity Shrinks: Energy Markets," *Bloomberg.com*, June 28, 2010.

that Saudi Arabia represents the most lucrative "target" if Iran (or, indeed, any state) is interested in reducing oil production to upset world energy markets.

Drawing from open sources, our analysis of Saudi Arabia's oil infrastructure and Iran's missile capabilities finds that Iran could not significantly reduce Saudi exports using its existing missile stockpile. Further, redundancies in Saudi infrastructure and limits on Iranian capabilities make some Saudi exports virtually impossible to disrupt. This does not mean that an Iranian missile campaign would be without cost: any missile campaign is almost certain to cause a large spike in oil prices.[17] Still, because we believe there would be no real damage to Saudi oil installations or disruption in oil production, governments could take steps, such as the release of strategic petroleum reserves, to calm energy markets.[18] In a military sense, the Iranian missile threat to Saudi Arabian—and, by extension, Persian Gulf—oil is overstated.

Our conclusion suggests that concerns surrounding Iran's capacity to retaliate for an attack on its nuclear program by launching missiles at Persian Gulf oil installations are militarily unfounded. Although Iran has other ways to penalize any nation that attacked its nuclear program, a missile campaign against oil infrastructure should not be a significant concern for policymakers. Further, funds currently devoted to hardening the region's oil infrastructure and improving its missile defenses are unnecessary. If, however, regional actors remain concerned about the ballistic missile challenge, the funds devoted to missile defense would be better spent adding backup, or "redundant," facilities to Gulf oil networks to mitigate the consequences of an attack, rather than trying to stop damage from occurring. This conclusion would change only if Iran begins to develop longer-range missiles that more effectively employed Global Positioning System (GPS) guidance.

The remainder of this article proceeds in eight sections. The following section specifies the working assumptions of our analysis. The next section provides a detailed description of Saudi Arabia's oil network and identifies likely Iranian targets. We then discuss Iran's missile capabilities and Saudi Arabia's defensive assets. Subsequently, we analyze the requirements and effects of an Iranian ballistic missile campaign. Next, the article considers potential Saudi countermeasures and what our findings suggest for other forms of Iranian re-

17. Oil and gas prices often move in response to perceived vulnerabilities in energy supplies. The economic effects of an attack may thus be out of proportion to actual supply disruptions. See Permanent Subcommittee on Investigations, "The Role of Market Speculation in Rising Oil and Gas Prices," pp. 1–4.
18. Olivier J. Blanchard and Jordi Gali, "The Macroeconomic Effects of Oil Shocks: Why Are the 2000s So Different from the 1970s?" NBER Working Paper, No. 13368 (Cambridge, Mass.: National Bureau of Economic Research, September 2007).

taliation. The article concludes by discussing the implications of our analysis for U.S. and allied policy in the Persian Gulf and understanding military vulnerabilities in oil networks writ large.

Setting and Assumptions

We do not consider an unprovoked Iranian attack on Saudi Arabian oil infrastructure likely. Because an attack would likely invite a violent international response, it is implausible that Iran would target these installations except over vital national security issues. Given current security concerns, Iran's use of ballistic missiles against oil installations would most likely follow a U.S. or an Israeli strike on Iran's nuclear facilities. Some analysts might question whether Iran would invite further punishment by retaliating against its neighbors and a key U.S. interest. Nevertheless, American and Persian Gulf leaders believe that Iran poses a real threat. Likewise, even if the scenario seems unlikely, this analysis presents a worst-case scenario that allows us to explore more general claims about Iran's missile capabilities and Saudi Arabian vulnerabilities. To do so, we make several simplifying assumptions.

First, we assume that Iran's goal would be to disrupt global oil supplies in an effort to retaliate for an attack while depriving Saudi Arabia—whose support for efforts to curb the Iranian nuclear program are well documented—of its principal source of revenue.[19] In other words, the aim of the missile campaign would be to prevent Saudi oil from reaching world markets. We therefore assume that the Iranian attack would employ all of Iran's missile assets.

Second, we consider the maximum damage Iran could cause given Saudi Arabia's independent capability to defend its oil network. We therefore assume that the United States does not become involved in the conflict. This assumption helps establish the absolute magnitude of the Iranian threat to Persian Gulf oil. If Saudi Arabia can defend its oil installations using its own forces, then analysts can challenge the notion of an Iranian threat to regional security. Conversely, if Iran can effectively shut down the Saudi oil network, then there is greater justification for efforts to improve Saudi Arabian defenses.

Third, we premise our analysis on a near-term clash between Iran and Saudi Arabia in which both sides fight with the military capabilities already in their arsenals.

Fourth, we assume that Iran enjoys access to perfect information regarding the location of Saudi oil facilities. Even if perfect information is unavailable,

19. Ian Black and Simon Tisdall, "Saudi Arabia Urges U.S. Attack on Iran to Stop Nuclear Programme," *Guardian*, November 28, 2010.

Iran could likely obtain very good information using open source services (e.g., Google Earth) and intelligence collected by Iranian agents.

Fifth, we assume that all of Iran's missiles fire and detonate as intended, without any "duds."[20] Although the fourth and fifth assumptions are unlikely in practice, they maximize Iran's chance of success in accordance with the worst-case-scenario nature of this exercise.

Finally, we consider only an Iranian ballistic missile attack. In practice, Iran could conduct special operations, air, and naval attacks alongside a missile strike.[21] It might also divert assets to attack shipping in the Persian Gulf or to blockade the Strait of Hormuz.[22] We focus exclusively on a ballistic missile campaign for analytic clarity, though we discuss the implications of this analysis for other forms of attack later in the article.

Saudi Arabia's Oil Infrastructure and Its Vulnerabilities

Saudi Arabia has the largest proven crude oil reserves in the world, with approximately 20 percent of the world total.[23] These reserves are distributed among eighty-five oil fields containing more than 1,000 producing wells, though most production comes from six to eight fields.[24] Saudi oil production is managed by Saudi Aramco, the state-owned oil company. Crude oil production averaged approximately 9.2 mbd in 2008 out of a potential capacity of approximately 11.8 mbd.[25] This represents nearly 13 percent of oil produced

20. During the Persian Gulf War, nearly 10 percent of Iraqi Scud missiles fired at Israel failed to explode. See George N. Lewis, Steve Fetter, and Lisbeth Gronlund, "Casualties and Damage from Scud Attacks in the 1991 Gulf War," DACS Working Paper (Cambridge, Mass.: Defense and Arms Control Studies Program, Center for International Studies, Massachusetts Institute of Technology, March 1993), pp. 29–30.

21. For example, the Iranian navy attacked Iraqi oil ports during the Iran-Iraq War. See Dilip Hiro, *The Longest War: Iran-Iraq Military Conflict* (New York: Routledge, 1991), p. 47.

22. Talmadge, "Closing Time."

23. The size of Saudi and world oil reserves is a subject of debate, but the fact remains that Saudi Arabia holds a significant share of proven oil reserves worldwide. See BP, *Statistical Review of World Energy, 2010,* pp. 6–7; and OPEC, *Annual Statistical Bulletin, 2008,* p. 18. For a critique of BP and OPEC data, see Matthew R. Simmons, *Twilight in the Desert: The Coming Saudi Oil Shock and the World Economy* (Hoboken, N.J.: Wiley and Sons, 2005).

24. Nawaf Obaid and Nathaniel Kern, "Saudi Arabia's Upstream and Downstream Expansion Plans for the Next Decade: A Saudi Perspective," Working Paper (Washington, D.C.: Center for Strategic and International Studies, October 2005), p. 5, http://csis.org/publication/saudi-arabias-upstream-and-downstream-expansion-plans-next-decade-saudi-perspective; Anthony H. Cordesman and Nawaf Obaid, *National Security in Saudi Arabia: Threats, Responses, and Challenges* (Westport, Conn.: Praeger, 2005), p. 310; and EIA, "Country Analysis Brief: Saudi Arabia," November 2009, pp. 2–3, 11. We thank one of the reviewers for pointing out that most production comes from a small number of fields.

25. For production figures, see OPEC, *Annual Statistical Bulletin, 2008,* p. 21. For total capacity, see Kate Dourian, "Saudi Arabia Starts Khursaniyah Oil Field Production," *Platts Oilgram Price Report*, September 4, 2008, p. 13. Slightly lower total production figures are reported in EIA, "Country

around the world daily.[26] Saudi Arabia is also the world's largest oil exporter with total exports of 8.4 mbd.[27] It is, however, a much more significant player in crude oil markets, with 18.2 percent of world crude exports (7.3 mbd), than in refined product markets (5.3 percent of world refined exports with 1.1 mbd product exports).[28]

Once pumped from fields, oil travels to processing facilities throughout Saudi Arabia via 15,000 kilometers (km) of pipelines and more than thirty pumping stations. These "downstream" facilities prepare the oil for domestic consumption or export.[29]

There are several basic steps in this process. Freshly pumped oil consists of an unstable mixture of oil, water, gas, and sand that can damage industrial equipment; non-oil elements must be removed before the oil can be further processed. Oil is therefore pumped directly from the fields to one of sixty gas-oil separation plants (GOSPs) where the elements are separated and the oil prepared for further processing.[30]

After leaving a GOSP, the majority of Saudi oil moves to stabilization plants for further treatment. Except for the approximately 2.6 mbd capacity found in the Central Arabian, Safaniya, Shaybah, and Zuluf fields, all Saudi oil is considered "sour": that is, it contains significant levels of hydrogen sulfide.[31]

Analysis Brief: Saudi Arabia," November 2009, p. 2; and Steven Mufson, "Saudi Arabia Works the Vast Desert to Pump Out More High-Quality Oil," *Washington Post,* November 17, 2007.

26. Total world production of 72.9 mbd is the average of 2008 production figures provided by OPEC and DOE/EIA. See OPEC, *Annual Statistical Bulletin, 2008,* p. 22; and U.S. Energy Information Administration, "World Crude Oil Production, 1960–2009," in *Annual Energy Review, 2009* (Washington, D.C.: EIA, Department of Energy, August 2010), p. 315, http://www.eia.doe.gov/aer/inter.htm.

27. This represents 14.8 percent of world exports. World export totals are the sum of crude and refined exports reported in OPEC, *Annual Statistical Bulletin, 2008,* pp. 34, 36.

28. Percentages are based on global crude exports of 40.1 mbd and refined exports of 20.7 mbd. See ibid., pp. 21–37.

29. EIA reports 9,000 miles of pipeline. See U.S. Energy Information Administration, "Country Analysis Brief: Saudi Arabia," Department of Energy, February 2007, p. 11. Saudi Arabia's major domestic pipeline is supported by eleven pump stations. Additionally, a 1998 U.S. military map of Saudi Arabian infrastructure shows more than twenty pump stations connecting fields and local facilities; John M. Collins, *Military Geography for Professionals and the Public* (Washington, D.C.: National Defense University Press, July 1998), p. 163.

30. Simmons, *Twilight in the Desert*, p. 104; Sunil L. Kokal and Abdullah Al-Ghamdi, "Performance Appraisals of Gas/Oil Separation Plants," *SPE Production & Operations,* Vol. 23, No. 2 (May 2008), pp. 287–298; and Ismail I. Nawwab, Peter C. Speers, and Paul F. Hoye, eds., *Aramco and Its World: Arabia and the Middle East,* 2d ed. (Dhahran, Saudi Arabia: Aramco, 1981), p. 215.

31. There is some confusion surrounding the term "sour" oil. We follow Aramco in using it to refer to oil that contains hydrogen sulfide. See Arthur P. Clark, Muhammad A. Tahlawi, William Facey, and Thomas A. Pledge, *A Land Transformed: The Arabian Peninsula, Saudi Arabia, and Saudi Aramco* (Dhahran, Saudi Arabia: Saudi Arabian Oil Co., 2006), p. 274; and Saudi Aramco, "Abqaiq Plants," http://www.saudiaramco.com/irj/portal/anonymous?favlnk=/SaudiAramcoPublic/docs/Our+Business/Oil+Operations/Production+Facilities/Abqaiq+Plants&ln=en. The capacities of Zuluf and Safaniya are based on 660,000 mpd capacity in Zuluf and 1.2 mbd capacity in

Hydrogen sulfide makes sour oil dangerous to transport via tanker because it is poisonous in its gaseous form and highly corrosive. The sour oil must therefore be "sweetened" by removing the hydrogen sulfide before it can be shipped to world markets.[32] This process—referred to as "stabilization"—occurs at one of five facilities in Saudi Arabia.[33] Abqaiq is by far the most important of these facilities, as it processes two-thirds of all Saudi oil (6.1 mbd) and has a potential capacity of 13 mbd.[34] Total capacity of the smaller plants is approximately 3.0 mbd.[35]

Safaniya. See Ivan Sandrea and Rafael Sandrea, "Growth Expected in Global Offshore Crude Oil Supply," *Oil and Gas Journal*, March 12, 2007, p. 34. Shaybah capacity (0.5 mbd) is from Amy Myers Jaffe and Jareer Elass, "Case Study on Saudi Aramco," presentation at the James A. Baker III Institute for Public Policy, March 1–2, 2007, p. 6, http://www.bakerinstitute.org/programs/energy-forum/publications/docs/NOCs/Presentations/Hou-Jaffe-SaudiAramco.pdf. The Central Arabian fields produce Arabian Super-Light oil, production of which averaged 0.250 mbd in 2004. See Anthony H. Cordesman and Nawaf Obaid, "Saudi Petroleum Security: Challenges and Responses," Working Paper (Washington, D.C.: Center for Strategic and International Studies, November 30, 2004), p. 9, http://csis.org/publication/saudi-petroleum-security; and Adurty V.C. Rao, O.M. Halawani, I.A. Mulhim, and B.M. Zayed, "Artificial Lift System Operation at Saudi Aramco Central Arabia Fields," presentation at the Seventeenth World Petroleum Congress, Rio de Janeiro, Brazil, September 1–5, 2002.

32. Nawwab, Speers, and Hoye, *Aramco and Its World*, p. 216.

33. The five stabilization facilities are located at Abqaiq, Juaymah, Jubail, Qatif, and Ras Tanura. Three facilities—Abqaiq, Ras Tanura, and Ras al-Juaymah—were reported in 2005. See Cordesman and Obaid, *National Security in Saudi Arabia*, p. 314. The 2007 EIA Country Analysis Brief included stabilization facilities for the planned Qatif Producing Plants program. See U.S. Energy Information Administration, "Country Analysis Brief: Saudi Arabia," Department of Energy, February 2007, p. 5. Aramco recently announced that the new Khursaniyah program includes facilities near Jubail to "process and stabilize" 500,000 bpd crude oil from the Abu Hadriya, Fadhili, and Khursaniyah fields. See Saudi Aramco, "Khursaniyah Program," http://www.saudiaramco.com/irj/portal/anonymous?favlnk=/SaudiAramcoPublic/docs/Our+Business/Projects/Khursaniyah&ln=en; and "Saudi Aramco Khursaniyah Oil and Gas and Hawiyah NGL Recovery Programmes, Saudi Arabia," http://www.hydrocarbons-technology.com/projects/saudi-aramco. Aramco previously noted the presence of stabilization facilities at Abqaiq, Juaymah, Ras Tanura, and Abu Hadriya. See Nawwab, Speers, and Hoye, *Aramco and Its World*, p. 216. No other source mentions an active stabilization plant at Abu Hadriya. EIA reports that the field was shut down in the 1980s. See EIA, "Country Analysis Brief: Saudi Arabia," February 2007, p. 7.

34. On the two-thirds figure, see Cordesman and Obaid, *National Security in Saudi Arabia*, p. 315. Daily throughput was calculated by multiplying all Saudi production by two-thirds. The two-thirds figure is supported by reports that Abqaiq is the main processing facility for Arabian Light and Extra Light oil blends, which together make up roughly 71 percent of Saudi productive capacity. See Aramco, "Abqaiq Plants"; and Khalid R. al-Rodhan and Nawaf Obaid, "Saudi Arabia's Sustainable Capacity and Security Issues," Working Paper (Washington, D.C.: Center for Strategic and Internationl Studies, May 2005), p. 10, http://csis.org/publication/saudi-arabias-sustainable-capacity-and-security-issues. Aramco reports that Abqaiq processes nearly 70 percent of all Saudi production. See Clark et al., *A Land Transformed*, p. 274. The *New York Times* is one of the few sources on Abqaiq's actual capacity (13 mbd); Saudi Aramco simply reports that Abqaiq's capacity is "more than 7 million barrels a day." See Hassan M. Fattah, "Suicide Bombers Fail to Enter Saudi Oil Plant," *New York Times*, February 25, 2006.

35. The Ras Tanura stabilization plant has a capacity of 0.96 mbd; Qatif and Jubail have 0.8 and 0.5 mbd capacity, respectively; and we estimate Juaymah at 0.75 mbd. For the Ras Tanura figure, see Saudi Aramco, "Ras Tanura Refinery," http://www.saudiaramco.com/irj/portal/anonymous?favlnk=/SaudiAramcoPublic/docs/Our+Business/Refining+%26+Distribution/Refining/Ras+Tanura+Refinery&ln=en; for the Jubail figure, see Saudi Aramco, "Khursaniyah Program." The

From a stabilization plant, crude oil is pumped either directly to a port for shipment abroad or to a refinery for processing into commercial products (e.g., gasoline). In the latter case, crude oil is moved to one of seven refineries.[36] After processing, the refined product intended for export is pumped to Saudi ports for loading onto oil tankers.

Saudi Arabia's ports can export more than 15.5 mbd of combined crude and refined product.[37] Its three major oil ports are located at Ras Tanura and Ras al-Juaymah on the Persian Gulf and Yanbu on the Red Sea.[38] Additional capacity is found at a series of smaller ports at Jeddah, Jizan, and Rabigh on the Red Sea, and Jubail, Ras al-Khafji, and Zuluf on the Persian Gulf.[39] As a rule of thumb, Ras Tanura and Juaymah handle approximately 75 percent (6.3 mbd) of all Saudi oil exports; most of the remaining 25 percent ships from Yanbu.[40]

Moving oil to the Red Sea ports depends more on pumping stations than

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Qatif stabilization plant became operational in 2004 and is intended to stabilize oil from the Qatif and Abu Safa fields. These fields produced 0.8 mbd in 2004, meaning the plant is at least that large. See EIA, "Country Analysis Brief: Saudi Arabia," February 2007, p. 5; and Cordesman and Obaid, *National Security in Saudi Arabia,* p. 313. We estimate Ras al-Juaymah stabilization capacity as the average capacity from Ras al-Juaymah, Qatif, and Jubail.

36. EIA, "Country Analysis Brief: Saudi Arabia," November 2009, p. 11.

37. This includes approximately 0.25 mbd exported via pipeline to Bahrain. See Geoff King, "Bahrain, Saudi Arabia in 350,000 b/d Pipeline Talks," *Platts Oilgram News,* October 30, 2009; and Saudi Economic Survey, "Bahrain to Import 25% More Crude from Saudi Arabia," October 2, 2002.

38. Ras Tanura has a capacity of at least 6 mbd. See EIA, "Country Analysis Brief: Saudi Arabia," November 2009, pp. 7, 10; and Amy Myers Jaffe and Jareer Elass, "Saudi Aramco: National Flagship with Global Responsibilities" (Houston, Tex.: James A. Baker III Institute for Public Policy, Rice University, March 2007), p. 86. Ras al-Juaymah has a reported capacity of 3–3.5 mbd. See EIA, "Country Analysis Brief: Saudi Arabia," November 2009, p. 7; Nawaf Obaid, "Saudi Arabia's Strategic Energy Initiative: Safeguarding against Supply Disruptions," presentation at the Center for Strategic and International Studies, Washington, D.C., November 9, 2006, http://www.csis.org/files/media/csis/events/061109_omsg_presentation1.pdf, p. 13; and EIA, email correspondence with authors, May 9, 2008.

39. Data on the capacity of the smaller ports are not available. For information on berths, see Anthony H. Cordesman, *Saudi Arabia: Guarding the Desert Kingdom* (Boulder, Colo.: Westview, 1997), p. 85; Jaffe and Elass, "Saudi Aramco," p. 86; and M. Webster Ewell, Dagobert Brito, and John Noer, "An Alternative Pipeline Strategy in the Persian Gulf," Working Paper (Houston, Tex.: James A. Baker III Institute for Public Policy, Rice University, March 2007), p. 7, http://www.rice.edu/energy/publications/docs/TrendsinMiddleEast_AlternativePipelineStrategy.pdf. Jubail and Jeddah are configured for refined product and petrochemicals and may be unable to export crude oil. EIA, email correspondence with authors; National Geospatial Intelligence Agency (NGIA), *Sailing Directions: Red Sea and Persian Gulf,* 15th ed. (Bethesda, Md.: U.S. Government, 2009), pp. 115–118, 349–351; and Saudi Aramco, "Jiddah Refinery Marine," http://www.saudiaramco .com/irj/portal/anonymous?favlnk=%2FSaudiAramcoPublic%2Fdocs%2FOur+Business%2FRefining+%26+Distribution%2FPorts+%26+Terminals%2FJiddah+Refinery+Marine&ln=en. We exclude further discussion of Jizan from our analysis because of its extremely small capacity. See Saudi Aramco, "Jizan Marine," http://www.saudiaramco.com/irj/portal/anonymous?favlnk=%2FSaudiAramcoPublic%2Fdocs%2FOur+Business%2FRefining+%26+Distribution%2FPorts+%26+Terminals%2FJizan+Marine&ln=en; and NGIA, *Sailing Directions*, pp. 134–135. Finally, although it is unclear whether the Zuluf oil terminal is in use, we follow Jaffe and Elaas in considering it operational. See Jaffe and Elass, "Saudi Aramco," p. 86; and NGIA, *Sailing Directions,* p. 355.

40. EIA, "Country Analysis Brief: Saudi Arabia," February 2007, pp. 19–20; and EIA, "Country Analysis Brief: Saudi Arabia," November 2009, p. 7.

Table 1. Overview of Saudi Arabian Production and Facilities

Category	Quantity (in millions of barrels per day)
Productive capacity	11.8
requiring stabilization	9.2
not requiring stabilization	2.6
Stabilization capacity	16.0
Abqaiq	13.0
Other facilities	3.0
Amount produced	9.2
stabilized at Abqaiq	6.1 (est.)
stabilized elsewhere	1.25 (est.)
not requiring stabilization	1.85 (2003 est.)
Amount exported	8.4
as crude oil	7.3
as refined product	1.1
Export capacity	> 15.5
Ras Tanura and Juaymah	9.0–9.5
Yanbu	6.5
Other	unknown

does transporting oil to the Gulf ports. Because Ras Tanura is less than 100 kilometers downhill from Abqaiq, oil can likely flow from Abqaiq to Ras Tanura largely by force of gravity. At least three pump stations line the route, but these may not be necessary for oil to reach the terminals.[41] When oil is moved uphill, however, pump stations are necessary to overcome the force of gravity.[42] Given that Yanbu and the other Red Sea facilities are more than 1,200 km to the east, mostly uphill, from Abqaiq, eleven pumping stations are used to move oil through the 1,400 km, 5 mbd "Petroline" connecting Abqaiq to the Red Sea oil ports.[43] Table 1 summarizes the preceding discussion of Saudi production and capacity.

We assume that an Iranian attack on Saudi Arabia's oil infrastructure would

41. Collins, *Military Geography for Professionals and the Public*, p. 163. A U.S. Army manual notes that pump stations are necessary only when gravity is insufficient to maintain oil flow or when one desires a higher flow rate than is achievable by gravity, or both. See U.S. Army Field Manual, "Chapter 4–Design," in *Military Petroleum Pipeline Systems*, FM No. 5-482 (Washington, D.C.: Department of the Army, August 1994), http://www.globalsecurity.org/military/library/policy/army/fm/5-482/index.html. For topographical information and distances, see Oxford, *Atlas of the World*, 10th ed. (New York: Oxford University Press, 2002), pp. 96–99.
42. For instance, Iranian attacks during the Iran-Iraq War on Iraqi pump stations reduced throughput on the Iraq-Turkey pipeline running uphill from the Kirkuk area. See "Iran and Iraq: A New Front in a Slow War?" *Economist*, January 3, 1981, p. 28; Roger Vielvoye, "Iran/Iraq War Takes Toll of Oil Facilities," *Oil and Gas Journal*, October 6, 1980, p. 48; and "Iraqi Crude Exports May Rise Further," *Oil and Gas Journal*, December 8, 1980, p. 54.
43. EIA, "Country Analysis Brief: Saudi Arabia," February 2007, p. 11.

try to cause the maximum amount of damage with the least possible expenditure of force. To select targets, we hypothesize that Iran would consider the quantity of oil flowing through each facility, redundancy of each facility (i.e., how readily a similar facility could replace its functions), size (i.e., concentration) of the target, and speed with which the targeted facility could be repaired.

Some facilities are unlikely targets because they are dispersed or redundant. For example, Iran is unlikely to attack Saudi oil fields. To stop production at an oil field, Iran would have to destroy the wells. This would require the destruction of many small targets spread over a large area; to halve production, for example, Iran would have to eliminate more than 500 wells spread across several thousand square miles.[44] GOSPs make poor targets for similar reasons: although not as numerous as wells, more than sixty such facilities are spread throughout the country.[45]

Nor is Iran likely to target pipelines, given their small size and ease of repair. Not only are there more than 15,000 km of pipeline in the country, but Aramco has taken steps to minimize the effects of pipeline damage. First, cameras and monitoring systems help to identify damage and expedite repairs. Second, pipelines have shutoff valves to limit oil losses from a rupture.[46] Third, Aramco pre-positions replacement parts throughout the country and can reportedly repair damage to pipelines within thirty-six hours.[47]

Finally, we do not believe that Iran would focus on Saudi Arabian oil refineries. As noted above, Saudi Arabia's refined products constitute a small percentage of Saudi exports and are comparatively less important as a percentage of global oil supplies compared with crude oil. Although we cannot totally discount an Iranian attack on Saudi refineries, the disparity in crude and refined production suggests that Iran's efforts would be best served elsewhere.

We conclude that Iran would target Saudi Arabian stabilization facilities. Five factors underlie this finding. First, destruction of the stabilization plants—with Abqaiq a particularly lucrative target—would prevent Saudi Arabia from transforming its sour crude into a product safe for export. Second, Saudi stabilization facilities have been targeted previously when a Saudi terrorist cell un-

44. The Ghawar Field alone covers 2,600 square miles. For the size of the oil field, see John C.K. Daly, "Saudi Oil Facilities: Al-Qaeda's Next Target?" *Terrorism Monitor,* Vol. 4, No. 4 (February 2006), p. 6.
45. GOSP capacity can vary, but even the newest facilities have a capacity of only 300,000 barrels per day. See Cordesman and Obaid, "Saudi Petroleum Security," pp. 10–11.
46. J.J. Dempsey, A.H. Al-Gouhi, and F.T. Connor, "A Computer Simulation of the Saudi Aramco East/West Crude Pipeline," Pipeline Simulation Interest Group, No. 9202 (1992), http://www.psig.org/papers/1990/9202.pdf, pp. 1–3; and Cordesman and Obaid, *National Security in Saudi Arabia,* p. 323.
47. Cordesman and Obaid, *National Security in Saudi Arabia,* p. 323.

successfully attacked Abqaiq with truck bombs.[48] Third, although the facilities are large (Abqaiq alone measures almost 3 km^2), the stabilization process occurs in towers concentrated in specific parts of each facility.[49] Fourth, each stabilization facility is within 300 km of Iran and thus within range of most Iranian missiles.[50] Finally, some of the stabilization towers were specifically designed for Saudi facilities, meaning they would take a significant amount of time to replace.[51]

As a next-best option, Iran might try to prevent oil from reaching the market by attacking the Saudi export system. Compared to the stabilization plants, the export system is a second-best option because of the small size of the targets and excess capacity. Nevertheless, we include the scenario because of the proximity of the Gulf ports to Iran. There is also a long history of warring states targeting oil export facilities. During World War II, for instance, the Allies targeted rail-lines and ports transporting Romanian oil to Germany.[52] Likewise, the Iran-Iraq War saw each country try to impede the other's oil exports by attacking export facilities. Iran, for instance, attacked Iraqi oil terminals off the Fao Peninsula, and the Iraqi air force launched a bombing campaign against Iran's Kharg Island terminal.[53]

The primary target of such an attack would be the Gulf ports through which most Saudi oil is shipped. Attacking the Gulf ports alone, however, would still enable Saudi Arabia to export at least 5 mbd (59 percent of current exports) through its Red Sea facilities.[54] Therefore, an attack on the export system might also target the Red Sea ports and pump stations along the Petroline.[55]

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48. Hassan M. Fattah, "Attack on Saudi Oil Facility Thwarted," *New York Times,* February 24, 2006; and Gal Luft, "An Energy Pearl Harbor? A Near Miss in Saudi Arabia Hints at Future Shocks," *Washington Post,* March 5, 2006.
49. Robert Baer, *Sleeping with the Devil: How Washington Sold Our Soul for Saudi Crude* (New York: Crown, 2003), pp. xxi–xxiii; and Khalid al-Rodhan, "The Impact of the Abqaiq Attack on Saudi Energy Security," Working Paper (Washington, D.C.: Center for Strategic and International Studies, February 2006), p. 3, http://csis.org/publication/impact-abqaiq-attack-saudi-energy-security.
50. National Geographic, *Atlas of the World,* 7th ed. (Washington, D.C.: National Geographic Society, 2000), pp. 95–96; and Google Earth, January 2010.
51. *Oil Fields as Military Objectives: A Feasibility Study,* CRS Report for Congress (Washington, D.C.: Congressional Research Service, Library of Congress, U.S. Government Printing Office, 1975), pp. 1–39.
52. Ronald C. Cooke and Roy Conyers Nesbit, *Target, Hitler's Oil: Allied Attacks on German Oil Supplies, 1939–1945* (London: William Kimber, 1985), pp. 70–77, 105–107.
53. Loren Jenkins, "Iraq and Iran Attack Each Other's Oil Installations," *Washington Post,* October 17, 1980; Hiro, *The Longest War,* p. 57; and Anthony H. Cordesman and Abraham Wagner, "Phase Four: Stalemate and War of Attrition on Land," in Cordesman and Wagner, eds., *The Lessons of Modern War,* Vol. 2: *The Iran-Iraq War* (Washington, D.C.: Center for International and Strategic Studies, 1990), chap. 7, pp. 5–7.
54. Exports of 5 mbd assume that Saudi Arabia has no prepositioned oil stocks on the Red Sea coast and depends solely on the Petroline. If it has prepositioned stocks, then it could export substantially more, given that Yanbu alone has an export capacity of 6.5 mbd.
55. A 1991 study by Aramco engineers suggests that shutdown of the last pump station along the Petroline would eliminate up to 56 percent of Petroline throughput. Robert Baer asserts that de-

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In the scenario we describe, Iran would attempt to destroy Saudi oil installations using its existing ballistic missile arsenal. Over the past two decades, Iran has worked to improve its short- and intermediate-range ballistic missile (SRBM and IRBM) capabilities. Since the end of the Iran-Iraq War, Iranian missile assets expanded from a handful of Scud-B missiles purchased from North Korea (known locally as Shahab-1s) to a large collection of imported and domestically produced missiles. Specific information on the Iranian stockpile is scarce, but most Iranian missiles appear to be road-mobile; some are becoming increasingly accurate.[56] Utilizing technology from China, North Korea, and Syria, Iran's most advanced SRBMs may be able to obtain a 100-meter circular error probable (CEP) with a system employing inertial guidance—possibly with GPS updates—and limited terminal maneuvering.[57] By way of contrast, the Scud-B employed by Iraq in the Persian Gulf War had a CEP of more than 1,000 meters.[58] There is no evidence, however, that Iran has taken the technological leap to successfully integrate GPS into a terminally guided missile able to achieve accuracies on par with Western and other advanced systems.[59] Table 2 presents a summary of the Iranian ballistic missile arsenal, excluding programs under development, unconfirmed, or believed terminated.[60]

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struction of the first pump station on the Petroline (Pump Station 1) would stop the flow of oil to the Red Sea. Given the ambiguity of Baer's report, we follow the Aramco study in assuming that destruction of any one pump station would reduce rather than stop the flow of oil. Baer, "The Fall of the House of Saud," *Atlantic Monthly,* May 2003, p. 54; and Dempsey, Al-Gouhi, and Connor, "A Computer Simulation of the Saudi Aramco East/West Crude Pipeline," p. 4.

56. Andrew Feickert, *Iran's Ballistic Missile Capabilities,* CRS Report for Congress (Washington, D.C.: Congressional Research Service, Library of Congress, August 23, 2004), Order Code RS21548, pp. 1–3; Steven A. Hildreth, *Iran's Ballistic Missile Programs: An Overview,* CRS Report for Congress (Washington, D.C.: Congressional Research Service, Library of Congress, November 8, 2007), Order Code RS22758; and Anthony H. Cordesman and Martin Kleiber, *Iran's Military Forces and Warfighting Capabilities: The Threat in the Northern Gulf* (Washington, D.C.: Center for Strategic and International Studies Press, 2007), pp. 137–148.

57. CEP is defined as the radius of the circle within which 50 percent of all missiles launched at a target will impact. Duncan Lennox, ed., *Jane's Strategic Weapons Systems* (hereafter *JSWS*), Vol. 50 (Alexandria, Va.: Jane's Information Group, 2009), pp. 71–72; Jane's Information Group, "Iran Tests Fateh 110A Ballistic Missile," *Jane's Missiles and Rockets,* September 23, 2002; Jane's Information Group, "Iran Tests Solid-Propellant Ballistic Missile," *Jane's Missiles and Rockets,* June 15, 2001; and "Fateh-110/NP-110/Mushak," *GlobalSecurity.org,* April 28, 2005, http://www.globalsecurity.org/wmd/world/iran/mushak.htm.

58. Bernard Rostker, "Iraq's Scud Ballistic Missiles," Department of Defense, July 25, 2000, http://www.globalsecurity.org/wmd/library/news/iraq/2000/scud_info/.

59. For comparison, the U.S. Army's ATACMS Block 1A has a CEP of 10–50 meters. Russian and Chinese designs that combine GPS with terminal guidance have CEPs of 10–30 meters. Lennox, *JSWS,* pp. 21–22, 123–125, 201–203; and Claremont Institute, "MGM-140B Block 1A," http://www.missilethreat.com/missilesoftheworld/id.74/missile_detail.asp.

60. Most notably, we exclude the Chinese M-9 and M-11 from the Iranian arsenal because neither has been displayed or tested in public. Although some reports note the rumored deployment of the systems, others suggest that China at most provided technical assistance on an indigenous Ira-

Furthermore, Iran has used missiles in past operations and often tests its weapons. In 1994 and 2001, for example, Iran fired Shahab-1s and -2s at Iraqi bases used by People's Mujahideen fighters to attack Iran.[61] More recently, Iran fired SRBMs and IRBMs during a series of missile tests and exercises.[62] It is unclear whether these tests were successful. Nevertheless, they suggest that the Iranian military is considering how its missile arsenal factors into its concept of operations.[63]

Whereas Iran's ballistic missile arsenal has become more sophisticated over time, Saudi Arabian ballistic missile defenses remain relatively limited. Saudi Arabia relies on the Patriot Advanced Capability-2 (PAC-2) system with approximately 800 interceptors for ballistic missile defense.[64] Standard operating procedure dictates firing two interceptors at each incoming missile, giving Saudi Arabia the ability to target the first 400 missiles before the stockpile is exhausted.[65] Initial reports from the 1991 Gulf War suggested that PAC-2 achieved a 70 percent success rate against Iraqi missiles. Subsequent investigations, however, indicated that the rate was closer to 10 percent.[66] Saudi Arabia

nian project without supplying the missiles. The weapons are also missing from the U.S. Air Force's list of Iranian missiles. See Lennox, *JSWS,* p. 73; Bates Gill, "Chinese Arms Exports to Iran," *Middle East Review of International Affairs,* Vol. 2, No. 2 (May 1998), pp. 60–61; "Iran Missile Program," *GlobalSecurity.org,* May 27, 2005, http://www.globalsecurity.org/wmd/world/iran/missile-overview.htm; "China's Missile Exports and Assistance to Iran," Nuclear Threat Initiative, September 27, 2005, http://www.nti.org/db/china/miranpos.htm; and National Air and Space Intelligence Center (NASIC), *Ballistic and Cruise Missile Threat* (Wright-Patterson AFB, Ohio: NASIC, U.S. Air Force, April 2009), Report No. NASIC-1031-0985-09, p. 11.

61. Charles P. Vick, "Shahab-2," *Globalsecurity.org,* February 1, 2007, http://www.globalsecurity.org/wmd/world/iran/shahab-2.htm; and "Iran Fires Missiles at Rebel Bases in Iraq," *New York Times,* November 7, 1994.

62. Frederic Wehrey, David E. Thaler, Nora Bensahel, Kim Cragin, Jerrold D. Green, Dalia Dassa Kaye, Nadia Oweidat, and Jennifer J. Li, *Dangerous but Not Omnipotent: Exploring the Reach and Limitations of Iranian Power in the Middle East* (Santa Monica, Calif.: RAND, 2009), pp. 64–66; Blanche, "Iran Stages Display of Missile Firepower"; Robin Hughes, "Iran Launches 'Great Prophet 2' Joint Military Exercise," *Jane's Defence Weekly,* November 8, 2006; Alan Cowell and William J. Broad, "Iran Reports Missile Test, Drawing Rebuke," *New York Times,* July 10, 2008; "Iran Tests Missiles Amid Nuclear Tension," *CNN.com,* September 27, 2009; and "Iran Test-Fires New Version of Fateh Missile," *CNN.com,* August 25, 2010.

63. Blair, "Annual Threat Assessment of the U.S. Intelligence Community for the Senate Select Committee on Intelligence," pp. 12–13.

64. Anthony H. Cordesman reports 372 PAC-2 and 432 PAC-2/Guidence Enhanced Munition (GEM) interceptors. See Cordesman, *Saudi Arabia: National Security in a Troubled Region* (Santa Barbara, Calif.: Praeger, 2009), pp. 228, 231.

65. Theodore A. Postol, "Lessons of the Gulf War Experience with Patriot," *International Security,* Vol. 16, No. 3 (Winter 1991/92), p. 145.

66. U.S. General Accounting Office (GAO), "Operation Desert Storm: Data Does Not Exist to Conclusively Say How Well Patriot Performed," GAO/NSIAD-92-340 (Washington, D.C.: GAO, September 1992), pp. 3–4; and Theodore A. Postol, "Lessons of the Gulf War Experience with Patriot," *International Security,* Vol. 16, No. 3 (Winter 1991/92), pp. 119–171. Although the PAC-2/GEM is designed to improve on the basic PAC-2, we assign it the same 10 percent attrition rate to maximize Iran's prospects.

Table 2. Iranian Ballistic Missiles, 2009

Ballistic Missile	Type	Range (kilometers)	Warhead (kilograms)	CEP (meters)[a]	Guidance	Number
CSS-8/Tondar 69[b]	SRBM	150	250	unknown	inertial	200
Fateh A-110[c]	SRBM	210	500	100	inertial-GPS	unknown; initial operating capability in 2004
Shahab-1[d]	SRBM	300	985	450–610	inertial	100–400
Shahab-2[e]	SRBM	500	750–770	700	inertial	100–450
Shahab-3[f]	IRBM	1,300	800	1,850–2,500	inertial	>30
Shahab-3A[g]	IRBM	1,500–1,800	500	1,000	inertial	unknown
Shahab-3B[h]	IRBM	2,000–2,500	500	unknown	inertial	unknown
Sejil/Ashoura[i]	IRBM	2,000	900	unknown	unknown	unknown
Musudan/BM-25[j]	IRBM	2,500–5,000	1,200	1,600	unknown	18

[a]CEP refers to the circular error probable of the missile, a measure of accuracy. An SRBM is a short-range ballistic missile and an IRBM is an intermediate-range ballistic missile. GPS refers to a missile that uses global positioning system in its guidance system.

[b]Duncan Lennox, ed., *Jane's Strategic Weapons Systems* (hereafter *JSWS*), Vol. 50 (Alexandria, Va.: Jane's Information Group, 2009), p. 79; and Andrew Feickert, *Iran's Ballistic Missile Capabilities*, CRS Report for Congress (Washington, D.C.: Congressional Research Service, Library of Congress, August 23, 2004), Order Code RS21548, pp. 1–2.

Table 2. *(Continued)*

[c]Lennox, *JSWS,* pp. 71–72; and "Fateh-110/NP-110/Mushak," *Globalsecurity.org.*

[d]Domestically produced Scud-B deployed with high-explosive warhead. All data except CEP and stockpile numbers are from Lennox, *JSWS,* p. 75. CEP and stockpile numbers are from Feickert, *Iran's Ballistic Missile Capabilities,* pp. 1–3. See also Anthony H. Cordesman and Martin Kleiber, *Iran's Military Forces and Warfighting Capabilities: The Threat in the Northern Gulf* (Washington, D.C.: Center for Strategic and International Studies Press, 2007), pp. 135–139; and Charles P. Vick, "Iranian Shahab-1/North Korean Scud-B," *GlobalSecurity.org*, February 27, 2007. There is disagreement on the number of Shahab-1 missiles in Iran's arsenal. Nevertheless, our analysis shows missile requirements far exceed even liberal estimates of Iranian missile stocks.

[e]Domestically produced Scud-C deployed with HE warhead; Lennox, *JSWS,* p. 75; Feickert, *Iran's Ballistic Missile Capabilities,* pp. 1, 3; and Cordesman and Kleiber, *Iran's Military Forces and Warfighting Capabilities,* p. 135. Note the same dispute described for the Shahab-1 applies to the Shahab-2.

[f]Alternately named Fajr-3, the Shahab-3 is a domestically produced, near replica of the North Korean No-Dong 1. Lennox, *JSWS,* pp. 76–78; Feickert, *Iran's Ballistic Missile Capabilities,* pp. 4–5 (for the Shahab-3); Gerald Frost and Irving Lachow, *GPS-Aided Guidance for Ballistic Missile Applications* (Santa Monica, Calif.: RAND, 1996), Report No. RP 474-1 (for the No-Dong 1); and National Air and Space Intelligence Center, *Ballistic and Cruise Missile Threat* (Wright-Patterson AFB, Ohio: NASIC, U.S. Air Force, April 2009), Report No. NASIC-1031-0985-09, p. 17. The Federation of American Scientists reports better accuracy based on reported developments in the No-Dong program. There is no evidence, however, that such advances have taken place in Iran. Federation of American Scientists, "Shahab-3/Zelzal-3," 2008, http://www.fas.org/programs/ssp/man/militarysumfolder/shahab-3.html; "Iran's Nuclear and Missile Potential: A Joint Threat Assessment by U.S. and Russian Technical Experts" (New York: EastWest Institute, May 2009), pp. 6-12, http://docs.ewi.info/JTA.pdf; and David Holloway and Theodore Postol, "Comments on 'Iran's Ballistic Missile Potential': A Paper by David Montague, Uzi Rubin, and Dean Wilkening" (New York: EastWest Institute, August 2009), p. 3.

[g]Lennox, *JSWS,* pp. 76–78.

[h]Ibid.

[i]Ibid., p. 71; Agence France-Press, "Iran Builds New Longer-Range Missile," November 26, 2007; Robert Wall, "Pentagon Sees Iranian 'Ashoura' Missile as Worrying Development," November 30, 2007, *aviationweek.com*; Michael Evans, "Military Experts Say 'New' Iranian Missile Is Just an Old One with a Different Name," *Times Online,* November 12, 2008; and Joshua Pollack, "Name That Missile," online post, November 1, 2009, http://www.armscontrolwonk.com/2519/name-that-missile.

[j]The missile was reportedly delivered from North Korea in 2005. Lennox, *JSWS,* p. 74.

has expressed interest in purchasing the more advanced Patriot PAC-3 system, but the system has not yet been procured.[67] Overall, the weakness of Saudi missile defenses relative to Iranian missile assets suggests the potential attractiveness of a missile campaign to Iranian planners.

Iran's missile stockpile consists of a mix of older and newer designs. Shahab-1s and -2s, domestically produced versions of the Scud-B and Scud-C, are the most accurate missiles with sufficient range to reach Abqaiq and the Petroline pump stations.[68] The analysis assumes that Iran would use the Shahab-1 against these facilities: although the Shahab-1 has a shorter range than the Shahab-2, its larger warhead and smaller CEP would maximize Iran's chance of success.[69] Estimates of the size of the Shahab-1 arsenal vary. Our analysis gives Iran the maximum 400 Shahab-1s in accordance with our worst-case assumption.[70] Although we do not address the Shahab-2 explicitly, the analysis illustrates the limited effect of 450 additional Shahab-type missiles.

We further assume that Iran would use the more accurate Fateh A-110 against Saudi Arabia's Persian Gulf oil terminals and stabilization facilities within the missile's 210 km range.[71] We do not know the size of the Fateh

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67. Jim Wolf, "Lockheed Sees Growing Interest in Patriot Missile," Reuters, August 23, 2007.

68. We believe that there is an important mistake in many reports on Shahab-2 capabilities. The Federation of American Scientists and Cordesman report that the Shahab-2 has a CEP of 50 meters. This is a low number given reports in *Jane's, GlobalSecurity.org,* and the media suggesting that the Scud-C (on which the Shahab-2 is based) has a CEP of several hundred meters. We believe that the lower figure results from confusion surrounding Iranian missile programs. In the 1990s, a joint Syrian-Iranian project produced a missile called the Scud-D modified for extended range. During the Cold War, however, the Soviet Union tested a different missile also labeled Scud-D that employed optical guidance for a 50-meter CEP; this missile never entered production. We hypothesize that researchers saw the Syrian-Iranian project, misattributed the Soviet Scud-D CEP to the new missile, and subsequently assumed that all Iranian Shahab-2s would enjoy similar accuracy. See Cordesman and Kleiber, *Iran's Military Forces and Warfighting Capabilities,* p. 139; "Shahab-2 (Scud-C)," Federation of American Scientists, February 29, 2008, http://www.fas.org/nuke/guide/iran/missile/shahab-2.htm; Jane's Information Group, "Scud Missile," *Jane's Strategic Weapons,* 2008; and "R-11/SS-1B Scud-A, R-300 9K72 Elbrus/SS-1C Scud B," *Globalsecurity.org,* November 24, 2007, http://www.globalsecurity.org/wmd/world/russia/r-11-specs.htm. We use the larger CEP because it accords better with reported Scud accuracy and would explain the Iranian decision to procure newer SRBMs.

69. Estimates of Shahab-1 CEP range from 450 to 610 meters. We use a middle-range estimate of 525 meters. If employing the Shahab-2, Iran would need to fire more missiles to compensate for its larger CEP and smaller warhead.

70. Although only Feickert reports 400 missiles, Cordesman and Kleiber report that Iran purchased upwards of 300 Shahab-1s beginning in the mid-1980s and has the ability to manufacture the Scud-B domestically. It is thus within the realm of possibility that Iran has upwards of 400 Shahab-1s. Feickert, *Iran's Ballistic Missile Capabilities,* pp. 1–3; and Cordesman and Kleiber, *Iran's Military Forces and Warfighting Capabilities,* pp. 135–139.

71. Iran tested a longer-range version of the Fateh in September 2010. Because it is unlikely that Iranian engineers achieved the nearly 50 percent improvement in missile range that would allow it to reach Abqaiq, this development should not affect our findings. See "Iran's Revolutionary Guard Gets New Missiles," *Boston Globe,* September 21, 2010; and "Iran Test Fires New Version of Fateh

stockpile, although a recent report suggests that the total may be as small as 10.[72] Given, however, the extensive testing of Iranian short-range missiles in recent years, and reports that Iran is producing a successor Fateh, our analysis assumes a worst case in which Iran has been producing the Fatehs in larger numbers. Based on Iranian production rates for the Shahab-2, Iran may have up to 150 Fateh missiles at its disposal. Iran had a maximum of 450 Shahab-2s at its disposal in 2007, 200 of which were reportedly purchased from North Korea in the early 1990s.[73] The remaining missiles were reportedly produced domestically after 1997.[74] Since the Fateh A-110 reportedly entered production in 2004 and is—like the Shahab-2—an SRBM, similar procurement rates would give Iran approximately 150 Fateh A-110s in 2010.

Describing the Attack: Iranian Requirements

This section analyzes the effects of a hypothetical Iranian attack against Saudi stabilization facilities. Next, it considers the results of an alternative, though militarily more demanding, attack against Saudi Arabian ports. Finally, it examines the sensitivity of our findings by illustrating how the results change with different assumptions regarding Iranian capabilities and Saudi vulnerabilities.

SCENARIO 1: ATTACKING THE STABILIZATION FACILITIES

As noted earlier, Abqaiq is the most important stabilization facility in Saudi Arabia. The heart of the facility consists of eighteen stabilization towers.[75] Ten of the towers are clustered in the northern part of Abqaiq, with the remainder in the southern half of the facility.[76] Cross-referencing Aramco photographs and descriptions of Abqaiq with Google Earth images of the facility, we believe

Missile," *CNN.com*, August 25, 2010. The distances involved require that Iran launch the Fateh from a small piece of land jutting into the Persian Gulf around 28°00′ N, 51°25′ E.

72. "Strategic Weapons Systems (Iran)," *Jane's Security Sentinel: The Gulf States*, May 13, 2009.

73. Cordesman and Kleiber, *Iran's Military Forces and Warfighting Capabilities*, pp. 135, 140.

74. Ibid., p. 140.

75. Saudi Aramco, "Abqaiq Plants." This figure contradicts the ten towers reported by Baer and al-Rodhan. Baer, *Sleeping with the Devil*, p. xxii; and al-Rodhan, "The Impact of the Abqaiq Attack on Saudi Energy Security," p. 3. The confusion might result from the reported presence of ten stabilization towers in the northern part of Abqaiq and additional towers in the southern part of the facility. See John L. Kennedy, "Giant Abqaiq Complex Handles 60% of Aramco's Crude Oil," *Oil and Gas Journal*, February 6, 1978. Based on the U.S. experience redeveloping oil infrastructure in northern Iraq, we believe that each tower operates independently. Like Saudi Arabia, oil from northern Iraq must be stabilized before export. In 2008, insurgents destroyed two towers at a stabilization plant near Kirkuk. After this attack, however, the undamaged towers continued to operate. U.S. Army officer, personal communication with authors, November 2009; and James Warden, "Kirkuk Refines Its Oil Industry," *Stars and Stripes*, July 15, 2008.

76. Kennedy, "Giant Abqaiq Complex Handles 60% of Aramco's Crude Oil."

that the northern towers fall in a 300 by 20–meter row while the eight southern towers are in a less linear configuration.[77] The towers themselves have a diameter of less than 6 meters. Less is known about the composition of Saudi Arabia's other stabilization facilities at Jubail, Ras al-Juaymah, Ras Tanura, and Qatif. Using Google Earth, we believe that the only structures within Ras Tanura matching the Abqaiq towers are within a 20 by 30–meter area.[78] We were unable to identify stabilization towers at Qatif, Jubail, and Ras al-Juaymah; given the similar capacities of the smaller facilities, we use the measurements of the Ras Tanura towers as a proxy. As discussed above, elimination of all the stabilization facilities would reduce Saudi exports to 2.6 mbd of naturally sweet oil.

We assume that a missile striking near the towers could produce sufficient overpressure to destroy the towers and their associated machinery. We estimate that it would take 15 pounds per square inch (psi) of peak overpressure to rupture the stabilization towers.[79] Using reference TNT blast curves and scaling to a 985-kilogram (kg) warhead, the Shahab-1 can produce 15 psi overpressure out to a distance of 30 meters.[80] Therefore, a missile falling within this lethal radius of a given tower would cause the tower's destruction.

To determine the requirements to destroy Abqaiq's northern towers, we treat each tower as an aimpoint and send the missiles in salvos of ten (one missile at each aimpoint).[81] Because the towers are close together and the weapons not perfectly accurate, a missile aimed at one tower could inadvertently de-

77. Saudi Aramco, "Abqaiq Plants"; and Kingdom of Saudi Arabia, Ministry of Petroleum and Natural Resources, "GAS-ABQ4" in "Photo Gallery: Page 2," 2006, http://www.mopm.gov.sa/mopm/detail.do?content=photo_gallery2; and Google Earth (accessed 2008–10). Towers are visible on Google Earth at 25°55′58.00″ N, 49°40′59.77″ E; 25°55′43.35″ N, 49°41′16.95″ E.
78. See Google Earth (accessed 2008–10) at 26°41′43.10″ N, 50°05′36.32″ E.
79. There is no publicly available information on overpressure requirements for stabilization towers. As a proxy, we used the 15 pounds per square inch (psi) of peak overpressure required to destroy petroleum fractionating towers. See Whitney Raas and Austin Long, "Osirak Redux? Assessing Israeli Capabilities to Destroy Iranian Nuclear Facilities," *International Security,* Vol. 31, No. 4 (Spring 2007), p. 20 n. 48.
80. The known relationship between overpressure and distance from impact can be scaled to larger warheads using $R_L = D \times W^{1/3}$, where R_L is the lethal radius of the warhead, W is the size of the warhead in kilograms, and D is the lethal radius for a 1 kg TNT warhead (for 15 psi, approximately 3 meters). Thus, $R_L = 3 \times 985^{(1/3)}$, or 29.8 meters. TNT blast curves taken from U.S. Navy, "Damage Prediction," in "Introduction to Naval Weapons Engineering," Federation of American Scientists, n.d., http://www.fas.org/man/dod-101/navy/docs/es310/dam_crit/dam_crit.htm. There is no available information on the actual explosive used in the Shahab warhead. We assume that it is TNT, recognizing that alternate warheads would produce 15 psi out to a greater distance; fewer missiles would then be required.
81. Following John Stillion and David T. Orletsky, *Airbase Vulnerability to Conventional Cruise-Missile and Ballistic-Missile Attacks: Technology, Scenarios, and U.S. Air Force Responses* (Santa Monica, Calif.: RAND, 1999), pp. 77–78. The results are not significantly different if aimpoints are placed on every other tower.

stroy a different one. We thus use a Monte Carlo simulation to produce a random landing point for each of the ten missiles according to a circular normal distribution.[82] We then determine whether the random landing point was within the lethal radius of any tower for each iteration of the simulation. If a missile lands within the lethal radius of a tower's center, we consider the tower destroyed.[83]

In calculating missile requirements, we assume that Iran wants to be at least 75 percent confident that its attack would destroy any given aimpoint.[84] The equations for these calculations appear in note 85.[85] The results of the simulation show that Iran would need to launch a minimum of 660 Shahab-1 missiles to target the ten northern towers even without Patriot attrition. Applied to the southern towers, the same approach shows that the remaining eight towers require at least 672 additional missiles. Iran would thus need more than 1,300 missiles to target Abqaiq's towers with 75 percent confidence of destroying any one tower. Including 10 percent Patriot attrition against the first 400 missiles raises the total for Abqaiq to 1,376 Shahab-1s. This does not mean there is a 75 percent chance all Abqaiq towers will be destroyed by 1,376 missiles. Rather, given that the probability of destroying each aimpoint is 75 percent, the likelihood that an attack would destroy all eighteen towers equals 0.75

82. CEP is used to determine the standard deviation of the circular normal distribution around the aimpoint: CEP/1.1774. We assume that the range and deflection errors are similar, so that

$$\text{CEP} = \frac{1.1774(\sigma_R + \sigma_D)}{2} = 1.1774\sigma_D.$$

See George M. Siouris, *Missile Guidance and Control Systems* (New York: Springer, 2004), pp. 311–313.

83. Because a missile could land within the lethal radius of two towers, both towers are considered "destroyed" by one missile.

84. Seventy-five percent is the standard success rate used to calculate munitions requirements by the U.S. Air Force. Requirements would be different if the Iranians chose a different probability of success. U.S. Air Force targeting officer, personal communication with authors, April 2008. For more information on U.S. targeting, see U.S. Air Force, "Intelligence Targeting Guide," Air Force Pamphlet No. 14-210, Federation of American Scientists, February 1, 1998, http://www.fas.org/irp/doddir/usaf/afpam14-210/index.html.

85. The overall probability of tower 1 being hit in the first salvo, P^1_{hit}, is given by

$$P^1_{hit} = 1 - P^1_{miss} = 1 - \prod_{n=1}^{10}(1 - P_n),$$

where P^1_{miss} is the probability that a missile misses tower 1, and P_n is the probability that tower 1 is hit by a missile intended for tower n in the 10,000 iterations of the simulation. The average likelihood that any given tower is destroyed in a given salvo, P_{hit}, is the average value of P^n_{miss} across all ten towers. The number of missiles required to target these towers, N, is thus given by the formula:

$$N = \frac{\log(1 - P_{success})}{\log(1 - P_{hit})},$$

where $P_{success}$ is the desired probability of success against one aimpoint assigned by the targeteers (in this case, 75 percent).

to the eighteenth, or less than 1 percent. If Iran wanted greater confidence that its attack would destroy all of the towers, it would need to launch more missiles.[86]

Applying the same approach to the other stabilization facilities and substituting Fateh A-110 specifications (500 kg warhead, 100 m CEP) shows that each facility requires 40 missiles with 10 percent Patriot attrition; destroying all 4 requires at least 160 missiles. Figure 1 summarizes the missile requirements.[87] These missile requirements are much lower than for Abqaiq because of the smaller size of the targets and the Fateh's greater accuracy.

SCENARIO 2: ATTACKING THE EXPORT SYSTEM

Iran might attack Saudi Arabia's export system as an alternative to targeting the stabilization facilities. We assume that to stop exports through the Persian Gulf ports, Iran would have to destroy the machinery and pipes associated with each tanker berth.[88] These berths come in various sizes and shapes. Table 3 summarizes each target's size and distance from Iran. Because the Gulf ports are close to Iranian territory, we assume that they could be targeted with the Fateh A-110.

Port facilities are significantly more dispersed than the stabilization facilities and surrounded by water. Given that a water impact would prevent warhead overpressure from destroying the loading platforms, we assume that Iran's missiles would have to directly impact an oil loading point to ensure destruction.[89] Our calculations treat a port target as destroyed if one missile hits the platform. Missile requirements, calculated using the equations listed in note 90, for port facilities number in the thousands and are shown in table 4.[90]

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86. For example, Iran would need to launch 3,130 missiles for 50 percent overall success against all 18 towers.

87. The equation is $N_{needed} = 0.9(N_{launched})$, where N_{needed} is the number of missiles required to destroy a target with 75 percent confidence and $N_{launched}$ is the number of missiles that must be launched to overcome Patriot attrition; 0.9 is the proportion of missiles that will reach a target with 10 percent attrition.

88. Because the pipelines feeding offshore terminals are underwater, Iran would have a limited ability to destroy them using ballistic missiles. We thus focus on the destruction of the berths.

89. U.S. Air Force targeting officer, personal communication with authors; and U.S. Navy, "Damage Prediction." This accords with the Iraqi experience at Kharg Island, where only direct hits successfully damaged the wharf. See Cordesman and Wagner, "Phase Four: Stalemate and War of Attrition on Land," pp. 5–9, 19–21.

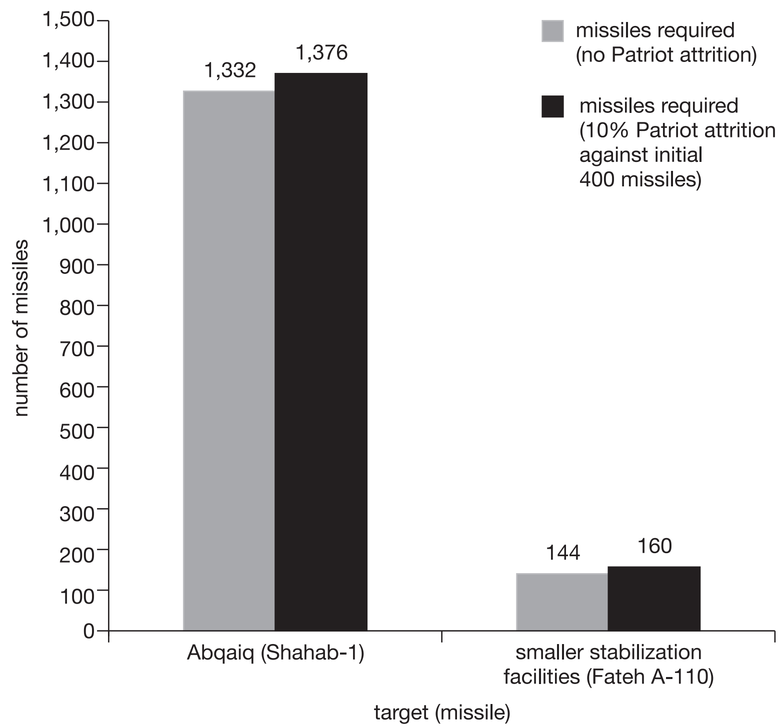
90. The probability of a direct hit on each rectangular platform with length *L* and width *W* is given by

$$P_{hit} = \sqrt{1-(0.5)\left(\frac{1}{\pi}\right)\left(\frac{L}{CEP}\right)^2} \times \sqrt{1-(0.5)\left(\frac{1}{\pi}\right)\left(\frac{W}{CEP}\right)^2}.$$

For circular targets with radius *r*, the probability of a hit is

$$P_{hit} = 1-0.5^{\left(\frac{r}{CEP}\right)^2}.$$

Figure 1. Missiles Required to Destroy Stabilization Facilities



Having targeted the Persian Gulf ports, Iran might next attack either the Red Sea ports or Petroline pump stations to prevent Saudi Arabia from diverting 5 mbd to the Red Sea terminals. In the former case, only Iran's longest-range missiles could reach the oil berths at the main Red Sea port of Yanbu.[91] We estimate the missile requirements using the warhead size and CEP of the Shahab-3A.[92] Calculations for the destruction of Yanbu's berths are included in table 4.

91. Yanbu has four crude oil berths and additional berths for refined products. Using Google Earth, we believe that each platform measures 35 by 20 meters. We focus solely on crude oil exports via Yanbu for this portion of our analysis. Saudi Aramco, "Yanbu' Crude Oil Terminal," http://www.saudiaramco.com/irj/portal/anonymous?favlnk=%2FSaudiAramcoPublic%2Fdocs%2FOur+Business%2FRefining+%26+Distribution%2FPorts+%26+Terminals%2FYanbu%27&ln=en; Saudi Ports Authority, "King Fahad Industrial Port Yanbu," http://www.ports.gov.sa/section/full_story.cfm?aid=1607&catid=20; NGIA, *Sailing Directions*, pp. 111–112; and Saudi Aramco, "Yanbu' Refinery Marine," http://www.saudiaramco.com/irj/portal/anonymous?favlnk=%2FSaudiAramcoPublic%2Fdocs%2FOur+Business%2FRefining+%26+Distribution%2FPorts+%26+Terminals%2FYanbu%27+Refinery+Marine&ln=en.
92. We exclude the smaller Red Sea ports from our analysis, owing to the difficulty of targeting Yanbu itself.

Table 3. Targets at Persian Gulf Ports

Port	Distance to Nearest Iranian Territory (kilometers)[a]	Targets	Size of Each Target (meters)[b]
Ras al-Juaymah[c]	200	6 mooring buoys[d]	15 (diameter)
Ras Tanura[e]		12 berths total	
Wharf	200	3 loading platforms	25 x 35
Sea Island 2	200	Sea Island loading platform	40 x 40
Sea Island 3	200	Sea Island loading platform	40 x 40
Sea Island 4	200	Sea Island loading platform	80 x 40
Jubail[f]	200	4 berths	25 x 35[g]
Zuluf[h]	175	1 mooring buoy	15 (diameter)[i]

[a]National Geographic, *Atlas of the World,* (New York: Oxford University Press,), pp. 95–96; and Google Earth, accessed January 2010.

[b]Sizes estimated using Google Earth (accessed 2008–09).

[c]Saudi Aramco, "Ju'aymah," 2010, http://www.saudiaramco.com/irj/portal/anonymous?favlnk=/SaudiAramcoPublic/docs/Our+Business/Refining+%26+Distribution/Ports+%26+Terminals&ln=en; and National Geospatial Intelligence Agency (NGIA), *Sailing Directions: Red Sea and Persian Gulf,* 15th ed. (Bethesda, Md.: U.S. Government Printing Office, 2009), p. 348.

[d]Each buoy has one berth.

[e]Each sea island holds two berths. Less is known of the wharf-based berths, but Google Earth images from 2004 to 2008 show tankers loading on both sides of the wharf from approximately three "loading platforms." Images of Ras Tanura from 2004 to 2008 show tankers loading on both sides of the wharf from approximately the same location on the wharf. From this, we infer that each wharf "loading platform" holds two berths. Saudi Aramco, "Ras Tanura," 2010, http://www.saudiaramco.com/irj/portal/anonymous?favlnk=%2FSaudiAramcoPublic%2Fdocs%2FOur+Business%2FRefining+%26+Distribution%2FPorts+%261Terminals%2FRas+Tanura&ln=en; and NGIA, *Sailing Directions,* pp. 345–347.

[f]NGIA, *Sailing Directions,* pp. 349–351, 354; Saudi Ports Authority, "King Fahd Industrial Port Jubail," 2003, http://www.ports.gov.sa/section/full_story.cfm?aid=1608&catid=19; Amy Myers Jaffe and Jareer Elass, "Saudi Aramco: National Flagship with Global Responsibilities" (Houston, Tex.: James A. Baker III Institute for Public Policy, Rice University, March 2007), p. 86; Anthony H. Cordesman, *Saudi Arabia: Guarding the Desert Kingdom* (Boulder, Colo.: Westview, 1997), p. 85; and M. Webster Ewell, Dagobert Brito, and John Noer, "An Alternative Pipeline Strategy in the Persian Gulf," Working Paper (Houston, Tex.: James A. Baker III Institute for Public Policy, Rice University, March 2007), p. 7, http://www.rice.edu/energy/publications/docs/TrendsinMiddleEast_AlternativePipelineStrategy.pdf.

[g]Because we are uncertain which facilities at Jubail are used for oil exports, we use the measurements for the wharf berths at Ras Tanura as a proxy.

[h]Jaffe and Jareer Elass, "Saudi Aramco: National Flagship with Global Responsibilities," p. 86; and Cordesman, *Saudi Arabia: Guarding the Desert Kingdom,* p. 85.

[i]Because we cannot locate the buoys at Zuluf, we use buoy measurements for Ras al-Juaymah as a proxy.

Table 4. Missiles Required to Destroy Port Facilities

Port	Missiles Required (No Patriot Attrition)	Missiles Required (10% Patriot Attrition against initial 400 missiles)
	Fateh A-110	Fateh A-110
Ras al-Juaymah	2,958	3,003
Ras Tanura		
Wharf	216	240
Sea Island 2	40	45
Sea Island 3	40	45
Sea Island 4	20	23
Jubail, Zuluf, Ras al-Khafji	2,753	2,875
	Shahab-3A	Shahab-3A
Yanbu	35,904	35,948

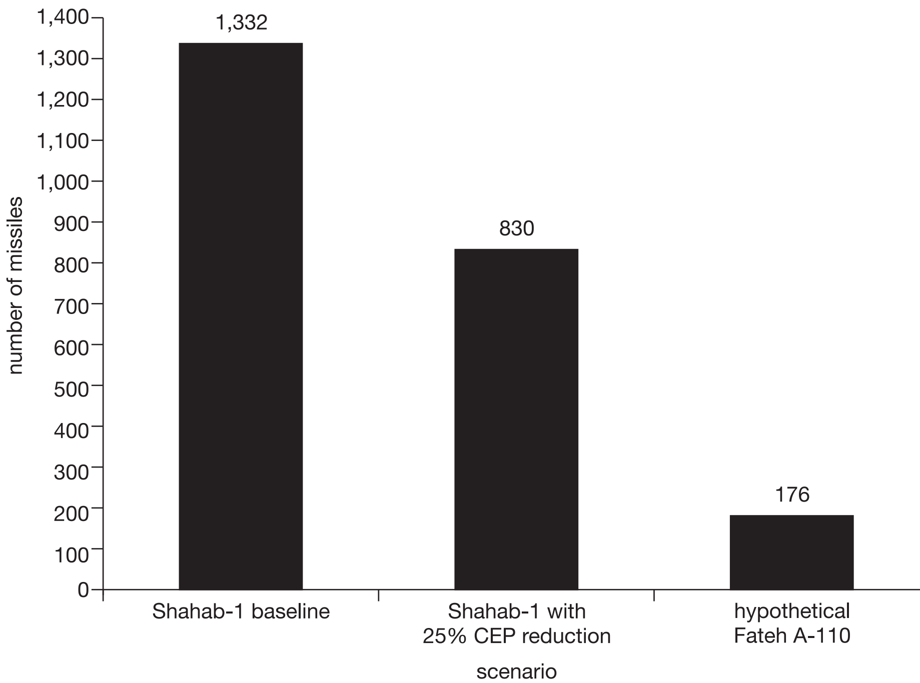
Iran could reduce exports via the Red Sea with a successful attack on Saudi Arabia's Petroline pump stations. An attack on Pump Station 1 is the most plausible scenario, because it falls within range of Shahab-1 and -2 missiles. Although the dimensions of Pump Station 1 are unknown, the locations of Pump Stations 3, 6, 9, and 10 are in the public record.[93] To identify the critical components of the pump stations, we looked for common features in images of the known stations. Doing so revealed a common set of five buildings covering an area of approximately 180 by 30 meters. Destroying these targets would require 660 Shahab-1s with Patriot attrition against the first 400 missiles. In context, this means that it would take 660 additional missiles to simply reduce the flow of oil to the Red Sea, in addition to the more than 6,000 Fateh missiles required to destroy the Persian Gulf ports.

SENSITIVITY ANALYSIS

This section considers how variations in our assessment of Iranian capabilities and Saudi facilities affect our calculations of Iranian missile requirements. We analyze the implications of these variations in the following section.

93. Although we cannot find its precise location, Pump Station 1 is reportedly close to Abqaiq. As the Petroline flows from Abqaiq to Yanbu, we hypothesize that it is located nearly adjacent to the Abqaiq facility. Baer, "The Fall of the House of Saud," p. 54. The locations to Pump Stations 3, 6, 9, and 10 are known because they have airfields, the coordinates of which have been reported to the International Civil Aviation Consortium and posted to *GlobalSecurity.org*. "Saudi Airfields," *GlobalSecurity.org*, April 27, 2005, http://www.globalsecurity.org/military/world/gulf/sa-airfields.htm. Assuming that Pump Station 1 is adjacent to Abqaiq, the distance from Pump Station 1 to Pump Station 3 is approximately 240 km. Distances via Google Earth (accessed 2008–10).

Figure 2. Changes in Missile Requirements for Abqaiq Resulting from CEP Reduction (no Patriot attrition)



First, the calculations are sensitive to changes in Iranian missile accuracy (see figure 2). Improving Shahab-1 CEP by 25 percent, which might be achieved with integrated GPS-inertial guidance in a Scud-type system, results in a nearly 40 percent decrease in missile requirements.[94] Along the same lines, a hypothetical Fateh with sufficient range to reach Abqaiq would reduce missile requirements for its destruction by 90 percent compared to the baseline Shahab-1 (figure 2). This holds despite the Fateh's smaller warhead. Thus, the situation facing Saudi Arabia could change dramatically if Iran embarks on a missile accuracy improvement program.

Relatedly, the calculations are sensitive to changes in the degree to which facilities are hardened against attack. For example, if stabilization towers cannot be destroyed by overpressure and instead require a direct hit, then the number of missiles required for the destruction of Abqaiq with Shahab-1s rises from 1,332 to more than 1 million with no Patriot attrition. Conversely, if the towers

94. Frost and Lachow, *GPS-Aided Guidance for Ballistic Missile Applications.*

can be destroyed with only 10 psi overpressure, then the lethal radius for the Shahab-1 warhead grows to 37.8 meters, and missile requirements for Abqaiq fall from 1,332 to 824.

Effects of an Iranian Attack

The effect of an Iranian attack on the Saudi oil network would depend on the number and characteristics of available missiles. With current assumptions, more than 1,300 Shahab-type missiles would be needed to target Abqaiq's towers. With the 400 missiles on hand, Iran would be unlikely to do significant damage. Increasing the desired probability of success raises missile requirements: for example, a 50 percent overall probability of destroying Abqaiq's towers would require more than 3,300 missiles. Moreover, even if Abqaiq was destroyed, Saudi Arabia would still be able to produce and stabilize 5.6 mbd of oil.[95] Therefore, even if Iran has many times the number of missiles we estimate, a significant portion of Saudi Arabian oil is secure.

That said, 150 Fateh missiles appear to be sufficient for Iran to destroy the smaller stabilization facilities.[96] Their destruction would remove an estimated 3.0 mbd stabilization capacity. Because, however, Abqaiq uses only 6.1 of its 13 mbd processing capacity, the destruction of these smaller facilities would not affect total output. This finding holds even if Abqaiq's capacity is significantly less than estimated. Although we believe that Abqaiq's actual capacity is much greater, Aramco only reports its capacity as "more than" 7 mbd.[97] Using 7 mbd as a lower bound, we calculate that Abqaiq's spare capacity could compensate for nearly all 1.25 mbd actually processed by the smaller stabilization facilities. The remainder could be replaced by additional production from Zuluf and Safaniyah. In short, 150 Fateh missiles would be insufficient to disrupt Saudi production even with conservative estimates of Saudi capacity.

Similarly, missile demands are such that an Iranian port attack would be unlikely to reduce Saudi Arabian exports. If Iran has 150 Fateh missiles, it could best employ them by targeting Ras Tanura's Sea Islands, as these facilities handle the port's largest tankers. Given, however, excess berthing capacity at the Red Sea and other Persian Gulf ports, a successful attack would have a mini-

95. This amount is based on the 2.6 mbd productive capacity of naturally "sweet" oil and the 3.0 mbd stabilization capacity outside of Abqaiq.
96. Assuming no Patriot interception, Iran requires 144 Fatehs. To eliminate Patriot cover, Iran could fire Shahab-type missiles or artillery rockets to "soak up" Saudi interceptors before launching Fatehs.
97. Saudi Aramco, "Abqaiq Plants."

mal effect on exports.[98] Overall, a Fateh attack on the Persian Gulf ports could reduce some of Saudi Arabia's excess export capacity without degrading actual exports.

Instead, hundreds of additional missiles would be needed for Iran to decrease actual exports. Even if the smaller Persian Gulf ports were rendered inoperable by other means, Iran would need to launch a minimum of 240 missiles at the Ras Tanura wharf in addition to those launched at the Sea Islands. Alongside a successful strike on the Sea Islands, destruction of the wharf would eliminate Ras Tanura's 6 mbd export capacity and leave Saudi Arabian exports dependent on Ras Juaymah (3 mbd) and the 5 mbd Petroline.[99] In this extreme case, Saudi Arabia could still maintain 8 mbd of exports, only 0.4 mbd below 2008 levels.

Of course, even if the Iranians were unable to fully destroy the Gulf ports, a missile attack could lead Saudi Arabia to divert a portion of its exports to the Red Sea ports. In either case, additional costs would accrue as oil was diverted to the Red Sea and countries normally serviced from the Gulf encountered longer transportation times.

What would happen, however, if Iran targeted all 400 Shahab-1s at a portion of Abqaiq? That is, what would be the maximum damage that the Shahab-1 stockpile could cause? Damage would be minimal, because 400 missiles are sufficient to destroy only one tower with a 60 percent chance of success. If the tower were destroyed, Abqaiq's total capacity would drop from 13 to 12.3 mbd.[100] Because, however, Abqaiq runs below half capacity, its destruction would have no long-term impact on Saudi Arabia's ability to stabilize oil. The facility could still handle its 6.1 mbd throughput with capacity to spare.

Although we do not believe that Iran has sufficient missiles to take Abqaiq offline, it is not impossible that Iran will eventually have the capability to do so. Abqaiq's destruction would have a significant effect on Saudi exports given that stabilization is a necessary step for the safe transport of most Saudi oil by tanker. Taking into account increased production from naturally sweet sources and assuming the other stabilization facilities could run at full capacity, ap-

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98. Destruction of the Sea Islands would eliminate four berths for very large crude carrier-class (VLCC) tankers and two berths for ultra large crude carrier-class (ULCC) tankers. Excluding Jeddah, the Red Sea ports have berthing for two ULCC and five VLCC tankers; on the Persian Gulf, Khafji alone has berthing for two VLCC and two Aframax-class tankers other than the six mooring buoys at Juaymah already used by ULCCs. Thus, Red Sea and Persian Gulf ports could compensate for losses at Tanura with two ULCC, seven VLCC, and two Aframax berths. See NGIA, *Sailing Directions*, pp. 345–355; and Joe Evangelista, ed., "Scaling the Tanker Market," *Surveyor,* Winter 2002, p. 6.
99. Because the capacity of the smaller Persian Gulf ports is unknown, we treat them as zero; actual requirements may be higher.
100. Assuming equal processing, each tower handles 0.7 mbd.

proximately 3.6 mbd could be taken offline by the destruction of Abqaiq. A maximum of 5.6 mbd, or 61 percent of current production, would then be available.[101]

If a successful Iranian attack against Saudi oil facilities occurred, how long would supply disruptions last? Estimating the time to repair damaged Saudi facilities depends on the extent of the damage, the ability of manufacturers to deliver replacement parts, and military-political conditions (e.g., repairs are likely to take longer if a war is raging). A Congressional Research Service (CRS) report from the 1970s estimated that significant damage to the Saudi oil network might take up to a year to repair, given the unique nature of the facilities.[102] Repairs to Kuwaiti oil infrastructure after the 1990–91 Persian Gulf War required two years, with exports resuming within nine months and reaching 83 percent of prewar levels by 1992.[103] Likewise, companies reported significant delays in repairing facilities and restarting production nearly two months after Hurricanes Rita and Katrina.[104] Given variation in previous repair times and the uniqueness of Saudi facilities, it is unclear how long it would take Saudi Arabia to repair the damage caused by a successful missile attack.

We can, however, estimate the time Saudi Arabia would have to repair the damage before the loss of Saudi oil affected world oil consumption. As noted, the loss of Abqaiq would curtail Saudi oil production by 3.6 mbd. In response, governments around the world could release oil from their strategic petroleum stockpiles to offset the loss while Saudi Arabia undertook repairs. The U.S. Strategic Petroleum Reserve alone holds more than 700 million barrels of oil; the International Energy Agency (IEA) reports total government-controlled oil reserves of 1.5 billion barrels among IEA members.[105] The U.S. stockpile alone

101. Total Saudi production is 9.2 mbd. Aside from Abqaiq, the four stabilization facilities have a combined capacity of 3 mbd. Naturally sweet production could reach 2.6 mbd. The maximum capacity taken offline is then equal to 3.6 mbd.
102. *Oil Fields as Military Objectives,* pp. 1–39. The report notes that Saudi facilities are the largest of their kind in the world and require specialized production of custom equipment. Similarly, Baer postulates that destruction of Abqaiq would take "months" to repair. Baer, "The Fall of the House of Saud," p. 54.
103. John Cranfield, "Fires Are Out, but Work Continues," *Petroleum Economist,* December 30, 1991, p. 17; and Bob Tippee, "Kuwait Pressing toward Preinvasion Oil Production Capacity," *Oil and Gas Journal,* March 15, 1993, p. 41; Kuwait produced 1.057 mbd in 1992 against 1.278 mbd in 1989. OPEC, *Annual Statistical Bulletin, 2008,* p. 21.
104. "Hurricanes Katrina and Rita," hearings before the Senate Committee on Energy and Natural Resources, 109th Cong., 1st sess., S. Hrg. 109-279 (Washington, D.C.: U.S. Government Printing Office, October 27, 2005), pp. 8–18.
105. International Energy Agency, "IEA Response System for Global Supply Emergencies" (Paris: International Energy Agency, 2007), p. 7; and United States Department of Energy, "Strategic Petroleum Reserve Inventory," November 30, 2010, http://www.spr.doe.gov/dir/dir.html. This figure does not take into account private and non-IEA government stockpiles.

would be sufficient to offset the losses from the destruction of Abqaiq for more than six months, given 2008 consumption rates. If all 1.4 billion barrels in government reserves were employed, the repair window would be nearly fifteen months.[106] A six-to-fifteen-month window is in the midrange of past repair experiences, suggesting that world oil consumption would not be impaired even after a successful Iranian attack.

Potential Responses to an Iranian Attack

This section briefly discusses a range of potential Saudi Arabian responses to an Iranian attack on its oil facilities. These options, however, are either costly or of limited likely effectiveness.

First, Saudi Arabia might consider procuring better missile defenses. Unfortunately, this is an expensive proposition. Even if Saudi Arabia procured the improved Patriot Advanced Capability 3 (PAC-3) system to replace the PAC-2, it is unclear whether the cost-benefit analysis would be in Saudi Arabia's favor. Standard operating procedure for the Patriot system specifies firing two interceptors at each incoming missile. As a result, each increment of growth in the Iranian arsenal requires a disproportionately large Saudi investment.

Second, Saudi Arabia might attempt to attack Iranian missile launchers to limit missile strikes. Even an unsuccessful anti-launcher campaign could reduce attacks as launchers are moved to avoid detection. The small area from which Iran can launch its most accurate missiles against Saudi Arabia would allow the Saudis to concentrate their efforts.[107] Iran, however, could simply respond by concentrating air defenses and other assets to protect launchers in the area. Furthermore, missile hunting has an inauspicious history: despite thousands of sorties, the U.S.-led coalition may not have destroyed a single Iraqi Scud launcher throughout Operation Desert Storm. These factors suggest a Saudi antimissile campaign would face severe limitations.[108]

Finally, and to the extent Iran employs GPS guidance in its missiles, Saudi Arabia might consider jamming GPS signals. GPS jamming, however, is of questionable utility. There are two types of GPS jamming.[109] With "smart" jamming, Saudi Arabia would erect emitters to create false GPS signals and divert

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106. This period is calculated by dividing the size of global reserves by lost Saudi production. These windows may be artificially narrow because Saudi production may gradually return rather than suddenly restart.
107. See note 71.
108. Mark E. Kipphut, "Crossbow and Gulf War Counter-Scud Efforts: Lessons from History," Counterproliferation Papers, Future Warfare Series, No. 15 (Maxwell Air Force Base, Ala.: USAF Counterproliferation Center, February 2003).
109. Scott Pace, Gerald Frost, Irving Lachow, David Frelinger, Donna Fossum, Donald K. Wassem,

Iranian missiles away from their targets.[110] This form of jamming, however, is most effective before GPS receivers lock on to the actual GPS signal. Saudi Arabia would therefore need to erect emitters on Iranian territory. This is not an impossible task, but Iran could move its missiles after it notices them repeatedly missing their targets.

The second option is "noise" jamming. With noise jamming, Saudi Arabia would block all GPS signals over a predetermined area. When a missile enters the jammed area, the loss of GPS forces it to rely solely on inertial navigation. Inertial guidance introduces navigation errors resulting from guidance drift, so the more time a missile spends in the jammed area, the less accurate it becomes. Because even a moderately powered noise jammer can block GPS signals out to more than 100 km, a Scud-type missile traveling at 1.5 km per second would then spend more than 1 minute in the jammed area, allowing time for significant errors to accrue.[111] Noise jamming, however, cannot discriminate friend from foe. Therefore, it would also disrupt Saudi GPS systems and hinder Saudi civilian and military operations. Noise jamming thus has significant drawbacks.

In sum, the limits of missile defense, missile hunting, and GPS jamming suggest that Saudi Arabia could not easily prevent an Iranian attack. Further investment in these areas would be costly and would not provide a large return.

Instead, given the problems associated with disrupting an Iranian attack, Saudi Arabia might consider efforts to mitigate potential damage. Although Iran is unlikely to cause significant damage with its current missile assets, damage mitigation would become important if Iran increases missile accuracy. Our analysis suggests, therefore, that Saudi Arabia should focus on improving and expanding its stabilization and port facilities.

If Saudi Arabia believes that a missile campaign is likely, then it should seek to reduce vulnerabilities in stabilization infrastructure. Stabilization is an essential step in safely exporting Saudi oil, yet the vast majority of Saudi Arabia's current capacity is concentrated in a small area. Saudi Arabia could reduce its vulnerability by building additional stabilization facilities around the kingdom and hardening existing infrastructure.[112]

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and Monica Pinto, *The Global Positioning System: Assessing National Policies* (Santa Monica, Calif.: RAND, 1995), p. 48.

110. Ibid., pp. 44–45; and Gerald Frost, *Operational Issues for GPS-Aided Precision Guided Weapons* (Santa Monica, Calif.: RAND, 1994), p. 27.

111. Pace et al., *The Global Positioning System*, pp. 52–53. For Scud velocity, see Charles P. Vick, "Iranian Shahab-1/North Korean Scud-B," *GlobalSecurity.org*, February 27, 2007, http://www.globalsecurity.org/wmd/world/iran/shahab-1-specs.htm; U.S. Air Force officer, personal communication with authors, January 2010; and Frost, *Operational Issues for GPS-Aided Precision Guided Weapons*, pp. 27–28.

112. Warrick, "U.S. Steps Up Arms Sales to Persian Gulf Allies."

Alternatively, if Saudi Arabia believes that a port attack is likely, it should stockpile floating mooring buoys to replace destroyed berths. This effort would replicate Saudi steps toward pipeline security, where replacement sections of pipeline are stockpiled beforehand. It would also mirror Iraq's efforts to compensate for damage sustained during the Iran-Iraq War.[113]

Implications for Other Scenarios

This section briefly reviews the implications of our findings for other Iranian retaliatory options—specifically, a conventional air campaign, naval assault, and attacks by special forces and proxy groups—and what they mean for future analyses. Although more work is needed to develop these scenarios, this study suggests that Saudi Arabia and the international community should not be overly concerned with other Iranian options for disrupting Saudi oil production.

CONVENTIONAL AIR CAMPAIGN

To disrupt Saudi Arabian oil production using a conventional air campaign, the Iranian air force (IRAF) would likely attack the stabilization and port facilities described above. Although IRAF can nominally field 118 fighter and 168 attack aircraft, large numbers of IRAF aircraft are obsolescent. Many are no longer operational, with IISS reporting 60 percent serviceability for Western aircraft and 80 percent for Soviet-Chinese types. In attacking Saudi Arabia, the IRAF could thus deploy approximately 66 fighters and 115 attack aircraft.[114] These would have to overcome as many as 126 modern Saudi fighters and long-range surface-to-air missiles.[115] Assuming this was successful, the IRAF's 115 attack aircraft would then have to overcome remaining Saudi Arabian fighters and air defenses to attack several dispersed targets.[116]

The preceding scenario seems an unlikely assignment for the IRAF because the numbers and qualitative edge are in Saudi Arabia's favor. Although we cannot discount the possibility that Iran would launch such an attack in extre-

113. "Persian Gulf Oil Exporters Brace for Next Step in Iran/Iraq War," *Oil and Gas Journal,* December 12, 1983, p. 41.
114. Authors' calculations, based on International Institute for Strategic Studies (IISS), *The Military Balance, 2008* (London: IISS, 2008), pp. 243–244; and Cordesman and Kleiber, *Iran's Military Forces and Warfighting Capabilities,* p. 95.
115. "Royal Saudi Air Force," *GlobalSecurity.org,* April 27, 2005, http://www.globalsecurity.org/military/world/gulf/rsaf.htm; IISS, *Military Balance, 2008,* p. 261; International Institute for Strategic Studies, *The Military Balance, 2009* (London: IISS, 2009), p. 265; and James C. O'Halloran, ed., *Jane's Land-Based Air Defence, 2008–2009* (Alexandria, Va.: Jane's Information Group, 2008), pp. 403–404, 410–411.
116. IISS, *The Military Balance, 2008,* p. 262; O'Hallorran, *Jane's Land-Based Air Defence, 2008–2009,* pp. 140, 417–418, 481–482; and Cordesman and Obaid, *National Security in Saudi Arabia,* p. 247.

mis, the relative balance of power suggests the questionable utility of a conventional air campaign. Still, if Saudi Arabia is worried about an Iranian air campaign, it could procure additional air defenses to deploy along avenues of potential attack and improve the readiness of the Royal Saudi Air Force.

NAVAL ASSAULT

Attacks by the Iranian navy would presumably target oil terminals along the Gulf coast. Iran conducted similar operations during the Iran-Iraq War when naval forces attacked the Iraqi Persian Gulf oil terminals.[117] The Iranian navy has several frigates and corvettes, and more than 100 smaller craft that could be used in an attack.[118]

To substantially reduce Saudi exports, however, Iran would need to destroy upwards of two dozen berths and buoys. Destroying such a large number of targets would be complicated by the small size and geographic dispersion of these targets. Likewise, unless an attack was well coordinated, initial assaults would alert the Saudi military and enable it to improve security at other ports. Even if these attacks were successful, Saudi Arabia could continue to export at least 5 mbd via the Red Sea ports. Meanwhile, unless a blockade was maintained around the Persian Gulf ports, Saudi Arabia could replace destroyed facilities with mooring buoys. In short, the large number of targets, excess network capacity, and Saudi repair options would limit the consequences of a naval attack.

Still, if Saudi Arabia is worried about an Iranian naval assault, the preceding analysis suggests that it could take two relatively easy steps to mitigate the consequences. First, it could stockpile oil on the Red Sea coast to take advantage of slack capacity at the Red Sea terminals. Second, it could stockpile mooring buoys and other parts to replace damaged facilities.

ATTACKS BY SPECIAL FORCES AND PROXY GROUPS

Iran might also consider using special forces or proxy groups to attack the Saudi oil network.[119] It is difficult to estimate the likelihood of success for these attacks. While Iran has reportedly built up its special forces and expressed interest in supporting local proxies, Saudi Arabia has recently taken steps to improve forces devoted to oil security; we cannot say which side would succeed in its mission.[120] Our analysis of Saudi infrastructure, however,

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117. Hiro, *The Longest War,* p. 47.
118. International Institute for Strategic Studies, *The Military Balance, 2010* (London: IISS, 2010), pp. 251–253.
119. Cordesman, "The United States, Israel, the Arab States, and a Nuclear Iran," pp. 100–120.
120. EIA, "Country Analysis Brief: Saudi Arabia," November 2009, p. 6; and Warrick, "U.S. Steps Up Arms Sales to Persian Gulf Allies."

suggests that attackers would likely face substantial difficulties because targets are widely dispersed and physically robust. For instance, to successfully incapacitate Abqaiq, an attacker would need to penetrate Saudi defenses and then destroy at least ten of the stabilization towers to lower Abqaiq's capacity below 2009 processing levels. Given the size and physical durability of the towers, this seems a difficult proposition for lightly armed assault forces. Moreover, Saudi security forces would be trying to defeat an attack throughout, adding another layer of complexity to an operation. Still, if Saudi Arabia worries about an asymmetric attack, it should continue improving its oil security forces and consider adding more redundancies to the oil network.

Conclusion

Overall, we judge the Saudi oil network to be secure against an Iranian missile attack given existing Iranian capabilities. Current Iranian missile holdings are insufficient in number and quality to destroy the stabilization facilities that would cause the greatest reduction in Saudi oil production. Although an Iranian missile attack could reduce some export capacity at the Persian Gulf oil ports, the lost capacity could be replaced by excess capacity at the Red Sea and smaller Gulf terminals. Dispersion and redundancies in the Saudi oil network make the rest of Saudi production difficult to incapacitate. In short, this analysis shows that a missile campaign is not a proximate military threat.

There is an important caveat to this assessment: although an Iranian missile campaign is unlikely to physically disrupt the flow of Saudi oil, any Iranian attack would likely have a significant impact on the world price of oil. A failed 2006 terrorist attack against Abqaiq, for instance, caused no damage to the facility, yet caused a temporary $2 increase in the per barrel price of oil.[121] We also cannot say whether shipping companies would continue tanker operations in a war zone; at a minimum, insurance rates for tankers transiting the region would increase. Thus, even a failed missile campaign could raise oil prices for consumers. Although we cannot predict the specific effect of an attack on market prices, it would likely be out of proportion to the physical damage inflicted. Still, because our analysis indicates the actual damage of an Iranian campaign would be minimal, these price shocks would be based on incomplete information, short-term uncertainty, and speculation. As the limited efficacy of Iranian attacks became clear, and if the international community worked to calm markets by, for instance, opening strategic petroleum reserves, prices should eventually fall.

121. Al-Rodhan, "The Impact of the Abqaiq Attack on Saudi Energy Security."

More generally, our analysis carries implications for understanding developments in the Iranian ballistic missile arsenal, energy security around the Persian Gulf, and regional security dynamics. First, our analysis adds nuance to the debate over Iranian missile capabilities. Whereas analysts in the United States often highlight the increasing range of Iranian missiles, the more worrisome development from the standpoint of regional security would be Iran's acquisition of increasingly accurate missiles.[122] Even moderate gains in accuracy—for example, improving Shahab-1 CEP by 25 percent—result in sizable reductions in the number of missiles required to destroy a facility. Therefore, sustained improvements in the accuracy of Iranian ballistic missiles would enable Iran to do significantly greater damage with an arsenal of a given size. Evidence that Iran has made the technological leap to designing missiles fully able to exploit the gains in accuracy from GPS-based guidance would be the most worrisome: at that point, Iran would be able to disrupt oil production even with a small arsenal.[123] In the future, technology transfer from more advanced nations, combined with greater sophistication within the Iranian program itself, could lead to more effective GPS employment. If Iran is found to be on an accuracy improvement curve, then it would be prudent for states around the Persian Gulf to harden facilities or add further redundancies to their oil networks; missile defenses, though costly, may also become an attractive option.

Second, this analysis can inform the international community's efforts to confront Iran over its nuclear program. Since the extent of the Iranian program first came to light, policymakers and analysts have considered using force to restrain Iran's nuclear ambitions. This debate weighs the prospective gains in slowing the Iranian program with the potential costs paid given Iranian retaliation. Our analysis demonstrates that Iranian retaliation is unlikely to cause real losses to oil supplies. There are still real reasons why the United States may not want to strike Iran—for instance, Iran could retaliate by arming proxies to fight U.S. forces in Afghanistan. Nevertheless, the missile threat to oil does not constitute a credible Iranian deterrent and, at least in a military sense,

122. See Hildreth, *Iran's Ballistic Missile Programs;* NASIC, *Ballistic and Cruise Missile Threat,* pp. 3, 14, 18; Blair, "Annual Threat Assessment of the U.S. Intelligence Community for the Senate Select Committee on Intelligence," p. 13; Associated Press, "Pentagon Studying Intel on Iranian Missile Test Launch as Congress Mulls Action," *FoxNews.com,* July 9, 2008; and Robert D. Walpole, "Iranian Ballistic Missile, WMD Threat to the U.S.," statement for the record to the International Security, Proliferation, and Federal Services Subcommittee of the Senate Government Affairs Committee, 109th Cong., 2d sess., September 21, 2000.
123. In addition to employing GPS guidance, such a missile must be able to mechanically respond to GPS guidance updates. Gerald Frost and Irving Lachow, *GPS-Aided Guidance for Ballistic Missile Applications* (Santa Monica, Calif.: RAND, 1996), Report No. RP 474-1.

concerns about Iranian retaliation against oil production should not factor significantly in the debate.

Third, this study holds general implications for U.S. policy in the Persian Gulf. Since President Jimmy Carter's administration, the United States has committed itself to maintaining the free flow of oil from the Persian Gulf. To achieve this aim, the United States has made a substantial military effort to defend the region, including fighting one major war in 1991 and devoting billions to military spending.[124] Our findings challenge part of the rationale for this effort. In showing that the Saudi oil network would be resilient in the face of a concerted attack by one of the most capable actors in the region, our research indicates that threats to regional oil production are overblown. By implication, the United States may be able to reduce its military commitment to the region.[125]

Finally, this article carries implications for understanding the vulnerability of oil infrastructure and oil networks. Simply put, oil is not an easy military target. Individual production facilities are large and physically robust, requiring a significant military effort to disable. Facilities are also geographically dispersed, necessitating systematic targeting. Given the presence of redundant facilities, some oil networks may have few, if any, targets that can incapacitate an entire system. Even if there are critical nodes, states can add facilities to limit the vulnerability of an oil network to disruption. If an attack is feared, meanwhile, states can stockpile replacement equipment to mitigate prospective damage. In sum, oil is a lucrative target, but it is not universally vulnerable.

124. Mark A. Deluchi and James J. Murphy estimate that the United States spends $30 to $60 billion per year to defend its interests in the Persian Gulf. Delucchi and Murphy, "U.S. Military Expenditures to Protect the Use of Persian Gulf Oil for Motor Vehicles" (Davis: Institute of Transportation Studies, University of California, Davis, March 2008), Report UCD-ITS-RR-93-3, p. 15.
125. For more on this point, see Eugene Gholz and Daryl Press, "Footprints in the Sand," *American Interest*, Vol. 5, No. 4 (March–April 2010), pp. 59–67.