SCIENCE & GLOBAL SECURITY
2021, VOL. 29, NO. 2, 67–89
https://doi.org/10.1080/08929882.2021.1951000

ARTICLE

Risks to Persian Gulf Cities from Spent Fuel Fires at the Barakah and Bushehr Nuclear Power Plants

Thomas G. A. S. Spence[a] and Ali Ahmad[b]

[a]Public Policy and International Affairs Program, American University of Beirut, Beirut, Lebanon; [b]Project on Managing the Atom, John F. Kennedy School of Government, Harvard University, Cambridge, MA, USA

ABSTRACT
Interest in nuclear power has grown in some Middle Eastern states despite poor economics, seismic activity, and attacks on nuclear facilities in the region. This article assesses risks from cesium-137 release and dispersal from spent nuclear fuel fires at Barakah in the United Arab Emirates and Bushehr in Iran to public health, the water supply, and the food security of major Persian Gulf cities. Doha, Dammam, Al-Hofuf, and Manama are most at risk of receiving 1.5 MBq/m^2 for a spent fuel fire at Barakah, while a spent fuel fire at Bushehr could affect Shiraz, Ahvaz, Basrah, and Kuwait City, albeit at lower probabilities. Absent a decision to end nuclear power in the region, options for reducing the potential risks of spent fuel fires on Persian Gulf populations include the timely transfer of spent fuel from pools into safer dry cask storage, multilateral disaster-response planning, and a commitment not to attack nuclear facilities.

ARTICLE HISTORY
Received 25 January 2021
Accepted 23 April 2021

Introduction

As of 2021, two Middle Eastern countries – Iran and the United Arab Emirates (UAE) – are operating nuclear power plants, and four countries (Egypt, Jordan, Saudi Arabia, and Turkey) plan to build them.[1] There has been much discussion about the policy drivers of these programs given a poor economic rationale, including the pursuit of energy security, diversification, technological progress, and latent proliferation capabilities.[2] Despite the Persian Gulf and broader Middle East having a history of earthquakes and deliberate attacks against nuclear sites by state and non-state actors, there has been comparatively little analysis of the potential regional impacts of a serious nuclear incident or accident at one of the operating or planned power reactors in Iran and the United Arab Emirates. This lack of attention is especially striking in the wake of the 2011 Fukushima disaster, wherein an earthquake and tsunami not only led to multiple reactor

CONTACT Thomas G. A. S. Spence tgs08@mail.aub.edu Department of Political Science and Public Administration, Public Policy and International Affairs Program, American University of Beirut, P.O. Box 11-0236, Riad El-Solh, Beirut 1107 2020, Lebanon

meltdowns but caused severe damage to spent fuel pools that nearly led to a much greater release of radioactivity and the resulting exposure of the population and widespread long-term land contamination.[3]

In other regions, increasing attention has been paid to the long-overlooked risks associated with spent nuclear fuel management and the potential consequences of fires in dense-packed spent nuclear fuel (SNF) pools, which typically have less containment than the reactor core and may contain much larger amounts of radioactivity. Frank von Hippel and his collaborators have highlighted these risks and the attendant human and economic costs.[4] This article focuses on spent fuel management and safety in the Persian Gulf, the potential release of radioactivity, focused on cesium-137, in the event of an accident or an attack triggering a spent fuel pool fire, and the impacts a release on major cities in the Gulf and on the Gulf waterway itself.

The following section offers an overview of spent nuclear fuel policies and plans in the Middle East states now pursuing nuclear energy. The third section examines accidents and armed attacks as possible spent nuclear fire triggers. The paper's methodology and modeling approach are presented in the fourth section. The fifth section models the release of cesium-137 due to a spent fuel fire in one of the pools at the UAE's Barakah site or one pool at Iran's Bushehr site. In the sixth section, the paper assesses the regional impact of such an event given the particular vulnerabilities of Gulf communities, some of which have a very large fraction of their population living just in one city, with a focus on public health, water, and food security.

Spent nuclear fuel policies in the Middle East

The discussion around spent nuclear fuel in the Middle East has generally been in the context of nuclear proliferation concerns, or as part of wider discussions on the feasibility of multilateral approaches to the entire fuel cycle, but SNF merits focus in its own right.[5] Spent nuclear fuel management policies in the six Middle East countries with nuclear power programs fall into three broad categories. The *ship-back* option is currently only available to the projects being carried out by Russia's Rosatom, in which the take-back of the SNF has been included as an incentive to advance Rosatom's commercial offer.[6] For Turkey and Egypt, where nuclear power faces notable public resistance, the SNF ship-back option is a means to minimize public disapproval.[7] For Iran, the 2015 Joint Comprehensive Plan of Action (JCPOA) commits it to export its spent fuel "for all future and present nuclear power and research reactors."[8] Details relating to the timing, export, volumes, and methods of SNF transport remain to be addressed in bilateral dealings between Iran and Russia.

The *no reprocessing* option is currently adopted only by the UAE, which committed not to enrich uranium or reprocess SNF in its "123 Agreement" with the United States which facilitates the transfer of U.S. nuclear technology. The agreement's terms can be renegotiated should the United States conclude a cooperation deal with another country in the region that the UAE deems more favorable than its own.[9] The UAE has no policy yet on managing SNF, including how the flow of SNF volumes would be handled and packed as Barakah ramps up production.[10]

The third category is *all options open*, which includes Saudi Arabia and Jordan. For Saudi Arabia, this policy may reflect an intention to create latent proliferation options given a perceived threat from Iran's nuclear program. Jordan's lack of an SNF policy may reflect a lack of progress on its nuclear program.[11]

As discussed in the next section, the volume of SNF present at any given time in the SNF pools and the packing method are critically important from a nuclear safety perspective. In some countries, including the United States, the lack of long-term geological storage plans has led to the re-racking of pools to hold more spent fuel. This, in turn, increases the risks associated with the wet storage of the SNF.[12] Given the lack of clear plans among the Middle Eastern countries pursuing nuclear power for removing spent fuel from wet storage, for either repatriation or dry cask storage, the mass of spent fuel stored in pools throughout the region is likely to keep increasing. This may eventually lead to dense packing and an increased risk of spent fuel fires in the event of an accident or attack.

SNF fire pathways

Spent fuel carries some degree of safety risk wherever and however it is stored due to its high level of radiotoxicity. This is particularly true in the period immediately after the spent fuel is removed from the reactor core.[13] Wet storage in spent fuel pools is among the highest-risk options. If the water in a spent fuel pool is drained, the decay heat of the spent fuel can cause significant temperature increases, potentially leading to a spent fuel fire, which could then disperse large amounts of radionuclides into the atmosphere, notably cesium-137 and iodine-131.[14] These two radioisotopes present the most danger in terms of public exposure because their volatilities are relatively high compared to other radioisotopes found in spent fuel.[15] Of these two, cesium-137 poses a more significant long-term danger. Its half-life of thirty years (as compared to eight days for iodine-131) is long enough for it to persist in the environment for extended periods without decontamination efforts. It is also a beta emitter with the potential to harm biological tissues with an activity of 3.215 TBq/g, and its high water solubility allows for biological uptake.[16] Cesium-137 levels have historically been used to assess the fallout from nuclear incidents because of their biological significance, ease of measurement, and relative persistence.[17]

Nuclear accidents

The Nuclear Regulatory Commission (NRC) in the United States has published reports on the risks of spent fuel fires in wet storage facilities since the 1980s, in which it assessed the risk to be low.[18] The NRC's assessments have been challenged by von Hippel and others.[19] The 2011 Fukushima disaster highlighted the high potential of spent fuel fires caused by external shocks – in this case, a seismic natural disaster.

Natural disasters of a scale that could severely damage a nuclear facility are also possible in the Persian Gulf region. The Bushehr plant is situated on Iran's northern shore, where the Zagros fold and thrust belt contains several fault zones, leaving the plant vulnerable to both strike-slip and reverse strike-slip earthquakes. More than 1,000 seismic events were recorded around Bushehr Province from 1900–2018, 100 of which had a magnitude greater than 5. An aftershock probabilistic seismic hazard analysis of these earthquakes has also shown that the area is susceptible to aftershocks, increasing the expected intensity of any given event.[20]

At Fukushima, the earthquake was compounded by a subsequent tsunami that inundated the power plant. The Persian Gulf has traditionally been viewed as relatively safe from tsunamis, as tectonic activity is not high enough to generate them *in situ*, and tsunamis entering the area through the Gulf of Oman are strongly attenuated.[21] However, in 2017 a 3 m tsunami struck an 8 km segment of coastline at Dayyer, south of Bushehr. The wave penetrated up to 1 km inland, causing five deaths and ~$10 M in damages. This event highlighted the possibility of meteorologically induced tsunamis, or meteotsunamis, impacting the Persian Gulf and potentially damaging coastal facilities, including nuclear power plants.[22]

While the spent fuel pools at Fukushima were not punctured and therefore did not leak, the contamination from the reactor meltdowns rendered the pools inaccessible for several days. At the same time, the pool's water levels gauges were rendered unreliable. The decay heat of the spent fuel led to evaporation from the pool, which would have caused the fuel in Unit 4's pool to become uncovered after ~2 weeks had it not been for a leak in the adjacent reactor well that replenished the pool's water levels. Further analysis suggests that if the fuel assemblies stored in the pool had become uncovered, they would have heated to over 1,000 °C, leading to a spent fuel fire.[23]

If a leak had occurred in the Fukushima spent fuel pools, this outcome would have been even more likely. The plant's design housed the pools on higher floors of the building, creating space below them into which water could drain. The two operating nuclear power plants in the Gulf at Barakah and Bushehr are also designed with elevated spent fuel pools – by 7.45 m at Bushehr and by 34.44 m at Barakah.[24] Similarly to Fukushima, this raises the risk that an incident might cause rapid water loss from the pools, uncovering of the spent fuel assemblies, and ultimately a spent fuel fire.

A second factor that increased the risk of a spent fuel fire at Fukushima was the weakness of the pools' containment structures. The roof of the building housing Unit 4's spent fuel pool was destroyed by a hydrogen explosion four days after the earthquake. A spent fuel fire would have enabled the release of volatile fission products directly to the atmosphere. Insufficiently strong containment structures in the Barakah and Bushehr plants are also of concern. At Barakah, the Nuclear Consulting Group has raised questions over the construction quality of the site's containment buildings following the discovery of cracking in their structures.[25] The containment structure at Bushehr is designed to withstand earthquakes of up to magnitude 8, but the advanced age of the structure and the history of damage caused by external attacks on the site have spurred concerns about the site's safety.[26]

Following the Fukushima nuclear disaster, Frank von Hippel and Michael Schoeppner conducted a comprehensive analysis that examined the potential impacts of the spent fuel fire that nearly took place in the plant's Unit 4 pool. Their analysis and subsequent projection of an equivalent incident occurring in the United States suggested that the NRC had greatly underestimated the impact of a spent fuel fire, potentially by a factor of 16.[27]

Attacks on nuclear facilities

Apart from the risk of a natural disaster or equipment failure, targeted attacks by hostile state or non-state actors have the potential to cause significant damage to SNF pools, a risk that was not seriously considered by the NRC until after the Fukushima disaster.[28] Although such a scenario remains unlikely, the historical prevalence of attacks on Middle Eastern nuclear facilities by both state and non-state actors makes a disruption to the reactor or SNF pool safety systems by an attack or act of sabotage a meaningful risk.

The history of attacks on nuclear installations in the Middle East is outlined in Tables 1 and 2. In recognition of the threat of such incidents, various international agreements have sought to lessen the risk of interstate conflict to operate nuclear facilities. The 1977 Additional Protocol 1 of the Geneva Conventions included nuclear power plants as an example of "installations containing dangerous forces" which "shall not be made the object of attack."[29] However, only a few years later the first attacks on a Middle Eastern nuclear facility were carried out; in 1981 Israel launched an air attack on the Osirak reactor in Iraq, drawing condemnation from the U.N. Security Council.[30]

Table 1. List of attacks against (or near) nuclear infrastructure in the Middle East.

Facility (country)	Function	Year	Brief description
Dimona (Israel)	Reactor (heavy water reactor used for plutonium production)	2021	**Syrian** missile exploded near the Dimona reactor facility.[34]
Al-Kibar (Syria)	Reactor (under construction at the time of the attacks)	2007	**Israel** attacked and destroyed Al-Kibar nuclear reactor.[35]
Dimona (Israel)	Reactor (operational at the time of the attack)	1991	**Iraq** launched Scud missiles at the Dimona plant, no damage was caused; **Hamas** targeted rockets at Dimona several times, e.g., 2014.[36]
Al-Tuwaitha (Iraq)	Research Reactor (operational at the time of the attack)	1991	**The United States** attacked two reactors in the Tuwaitha facility[37]
Al-Tuwaitha (Iraq)	Research Reactor (under construction at the time of the attacks)	1980 and 1981	**Iran** attacked Tammuz-1 (Osirak) reactor but inflicted little or no damage; one year later, **Israel** attacked and destroyed Tammuz-1 reactor in Tuwaitha facility.[38]
Bushehr (Iran)	Reactor (under construction at the time of the attacks)	Multiple attacks in 1980s	**Iraq** attacked two partially built power reactors in Bushehr site at least six times from March 1984 to November 1987.[39]

Table 2. List of cyber-attacks against nuclear infrastructure in the Middle East.

Facility (country attacked)	Function	Year of the attack	Brief description
Natanz (Iran)	Uranium enrichment facility	2011 and 2012	Two major cyber-attacks (known as Duqu and Flame) targeted Iranian nuclear facilities
Natanz (Iran)	Uranium enrichment facility	2010	Cyber worm named "Stuxnet" destroyed Iranian uranium enrichment centrifuges.[40]
Unknown facility (Syria)	Unknown	2006	Nuclear facilities are infected for espionage purposes.[41]

Following the Osirak attack, various IAEA resolutions sought to strengthen the protection of nuclear sites by extending the prohibition of attacks on all peaceful nuclear facilities and considering even the threat of an attack on such a site a violation of the U.N. Charter.[31] The repeated willingness demonstrated by Israel to strike nuclear targets is a significant regional concern given that by 2007 Israel had acquired "the capability to destroy even well-hardened targets in Iran with some degree of confidence."[32]

A further challenge to the safety of nuclear infrastructure, particularly in the Middle East, is the spread and willingness of non-state actors to launch attacks against nuclear targets in the region. In 2017, Houthi militants claimed to have launched a cruise missile at the UAE's Barakah site; the Nuclear Facilities Attack Database (NuFAD) also shows that Hamas launched a targeted rocket attack at Israel's Negev Nuclear Research Facility near Dimona in 2014 that was intercepted by missile defenses.[33]

In recent years, cyber-attacks have increasingly been deployed to target sensitive energy infrastructure, including nuclear facilities in the Middle East.[42] As demonstrated by the Stuxnet attack against Iran's Natanz uranium enrichment facility, cyber weapons can target computers and systems that control sensitive equipment. In this context, there is a real possibility of a cyber-attack that would either cause a widespread loss of power needed to run critical monitoring equipment or specifically target the cooling and water drainage systems of a spent nuclear fuel facility, which could lead to overheating of the fuel and eventually a spent fuel fire.

Reviewing the safety and security lessons learned following the Fukushima disaster, a U.S. National Academy of Science study noted that the "spent fuel pool study and expedited transfer regulatory analysis" needed to consider a broad range of potential threats including sabotage, insider, and cyber threats. MacLean et al. stated that the spent nuclear fuel pool is a likely target for cyber-attack because of its accessibility to external attackers.[43]

A discussion of the possible approaches to deter attacks on nuclear facilities is beyond the scope of this paper. However, it is worth mentioning that several strategies have been proposed, such as scaling up the role of the IAEA during wartime by accelerating inspections or establishing a permanent presence in conflict areas to improve confidence as to the peaceful purpose of safeguarded facilities and thereby deter strikes.[44] Alternatively, bilateral treaties could be signed in which potential combatants agree to more stringent restrictions on targeting nuclear sites. Such an agreement was signed between India and Pakistan in 1988, expanding protection to all nuclear facilities rather than limiting it to peaceful ones.[45]

Method and modeling approach

Source terms of Barakah and Bushehr's SNF pool

The core analysis of this paper simulates the release of cesium-137 from UAE's Barakah and Iran's Bushehr sites following a hypothetical spent fuel fire in one of the pools at either site. Cesium-137 was chosen as the isotope of interest because of its prevalence in the fallout from spent fuel fires and the longevity of its long half-life. The first 1.4 GWe reactor at Barakah Nuclear Power Plant, situated ~250 km west of Abu Dhabi, was connected to the power grid in August 2020. Three additional PWR-type reactors are planned for the site, bringing the total capacity up to 5.6 GWe. Assuming an average burnup in the reactor of 55 GWd/t (typical for an APR1400 reactor) and thermal efficiency of 33%, it was estimated that in its steady-state Barakah would produce ~100 metric tons (MT) of spent nuclear fuel per year. Given that the plant is designed to hold "up to 20 years of spent fuel in the wet pools," it was estimated that the spent fuel pools would contain a total of 2,000 MT of spent fuel when full.[46]

It is possible that the spent fuel pools at Barakah may reach a steady-state level of <20 years' worth of fuel; the UAE has expressed interest in both exporting spent fuel and transferring it to dry cask storage for long-term domestic management. However, given the uncertainty over which course of action the Emirati government will take, assessments indicating that the spent fuel could be left for the full 20 years to cool in wet storage, and challenges faced in the widespread adoption of dry cask storage in other countries, the assumption was made that Barakah would reach steady-state with the spent fuel pools at full capacity.[47]

Using data from the SFCOMPO database of spent fuel (which holds the recorded compositions of spent fuel samples from around the world), it was estimated that this mass of spent fuel, produced at an average burnup of 55 GWd/t, would contain ∼1.5 mg of cesium-137 per gram.[48] With an average storage time of 10 years, this equates to a total of 7,600 PBq of the cesium-137 split between the four pools. It was then assumed, as per Sandia National Laboratories' assessment of the Fukushima incident, that in the event of a spent fuel fire, ∼75% of the cesium stored in one of the four pools (or ∼1,440 PBq) would be released into the atmosphere over four days.[49]

The Iranian nuclear power plant at Bushehr currently operates with a single 1 GWe reactor. With Russian support, construction of a further 2.1 GWe of capacity is planned at the site, bringing the total planned capacity to 3.1 GWe. Based on a burnup of 42 MWd/t, it was estimated that the completed plant would produce ∼73 MT of spent fuel per year.[50] Given that the plant's spent fuel pools are designed to hold fuel for eight years after it is removed from the reactor, this implies total storage of 582 MT spent fuel by the time the plant reaches its maximum capacity.[51] In 2005, Iran agreed to export its spent fuel to Russia, which would likely take place after two to five years of cooling in wet storage.[52] This would reduce the total mass of spent fuel in Bushehr's pools, but exports have been limited amid ongoing concerns about the future of the JCPOA. For this analysis, therefore, it is assumed that delays or cancelations of these exports will result in the spent fuel pools operating at full capacity in the steady-state.

Based on the assumption that the plant's fuel would have an average burnup of 42 GWd/t, the SFCOMPO database was used to estimate the total quantity of cesium-137 in the steady-state spent fuel pools at 2,600 PBq (assuming an average storage time of four years). As in the Barakah case study, the fire simulations assumed a 75% release from one of the three pools (equivalent to 640 PBq) over four days.

Model setup

Given the variability of weather conditions, the spread of radioactive contamination can be best assessed in terms of probabilities based on daily simulations. The runs for each simulated spent fuel pool fire were conducted using the National Oceanic and Atmospheric Administration's (NOAA) HYSPLIT software.[53] To account for seasonality in meteorological effects, one run was conducted for each day from 2010 to 2019 (using meteorological data from the NOAA-NCEP/NCAR's global pressure level reanalysis archive, which contains data at six-hourly intervals with a spatial resolution of 2.5°), giving 3,652 total runs for each power plant. The simulations were initiated using the conditions listed in Table 3.

The emission height for each model was defined as 50 m above the spent fuel pool. This is a rough estimate, as the plume's characteristics would vary depending on wind speed and vertical temperature structure. However, it is consistent with plume height estimates of 25–75 m used in analyses of the Fukushima incident.[54] Each run had an emission duration of 96 h starting at the beginning of the simulation time, and a total simulation runtime of 120 h. The cesium-137 deposition was modeled using particles of 1 μm with a dry deposition velocity of 0.2 cm/s as used in previous studies on the fallout from spent fuel fires.[55] Wet deposition was also included in the model, although given the limited precipitation experienced in the Gulf region it was expected to have minimal impact. Results were obtained on an output grid with a spatial resolution of 0.05 degrees.

The output of each of these simulations was subject to additional impact analysis. The *con2stn* program within HYSPLIT was used to extract daily deposition values at areas of interest, which were then summed over the five days of each run to give a total deposition value for the simulation. The sites of interest were selected by choosing all cities in the region with populations $>$750,000. To this list were added the Qatari and Bahraini capitals of Doha and Manama, which, despite being smaller than 750,000 thresholds, are the largest and most significant urban centers in their respective countries.

To assess the geographic extent of contamination, the raw outputs for 2019 were also converted into ASCII files representing concentration contours using HYSPLIT's *concplot* program. Levels of 1.5 MBq/m^2 cesium-137 deposition were used for this analysis based on historical precedents. This level of contamination corresponds to the approximate threshold for population relocation

Table 3. Major simulation parameters for Barakah and Bushehr SNF facilities.

Power plant	Barakah	Bushehr
Emission coordinates (Lat, Lon)	23.96, 52.09	28.83, 50.89
Emission height	84.44 m	57.45 m
Emission rate	15 PBq/h	6.67 PBq/h
Emission duration	96 h	96 h
Total emissions	1,440 PBq	640 PBq
Steady-state production of SNF (*t*/year)	100	73
SNF volume at full capacity (*t*)	2,000	582
Number of planned reactor units	4	3
SNF burnup (GWd/t)	55	42

in both the Fukushima and Chernobyl accidents and has been used in other assessments of the risk posed by spent fuel fires.[56] Following the Fukushima disaster, it was estimated that without remediation, this level of deposition would lead to lifetime effective external doses of up to 118.5mSv per unit population density.[57] The ASCII contours representing 1.5MBq/m^2 deposition were then converted into ESRI shapefiles and subsequently binary rasters using the QGIS software. The rasters obtained for each run were then averaged to give an output raster representing the implied probability that an area would receive higher than 1.5 MBq/m^2 of cesium-137 in the event of a spent fuel fire. Although only the 2019 results are visualized, simulations were conducted for every day since 2010 to assess variability.

Results

Barakah

The methodology outlined above was utilized to assess the impact of potential SNF fires at the Barakah and Bushehr nuclear power plants. Figure 1 shows the spatial probability distribution of cesium-137 contamination exceeding the 1.5 MBq/m^2 threshold, which might require mass relocation, for a spent fuel pool fire at the Barakah site in 2019. The results indicate that the prevailing weather conditions would likely carry fallout southwards into the Rub' al-Khali desert. However, there remains a small but significant risk of contamination in highly populated areas to the north and west of the plant. Of particular concern are the cluster of population centers around Bahrain and Qatar (including Doha, Manama, Dammam, and Al-Hofuf, which together host around 3.4 million people, the population distribution of which is listed in Annex A). These cities showed contamination with cesium-137 higher than 1.5 MBq/m^2 in a significant percentage of the simulations, ranging from 4.7% for Manama to 11% for Doha. Other major cities, such as Kuwait City, Shiraz, Abu Dhabi, and Dubai showed notably lower contamination probabilities. It is interesting to note that Riyadh, the capital of Saudi Arabia, also has a relatively low, but non-zero probability.

The simulations also allow us to study the magnitude of cesium-137 contamination for each city. Some Gulf cities are susceptible to contamination levels well above the 1.5 MBq/m^2 threshold. For example, Manama and Al-Hofuf could receive cesium-137 deposition levels higher than 10 MBq/m^2, while Doha received contamination over 20 MBq/m^2 in some simulation runs. Higher levels of deposition increase the certainty of compulsory relocation and could make relocation efforts logistically more demanding since nearby areas will also be likely to receive higher deposition levels.

The time profile of cesium-137 contamination, available in the online supplemental material, yielded a few interesting observations. First, summer

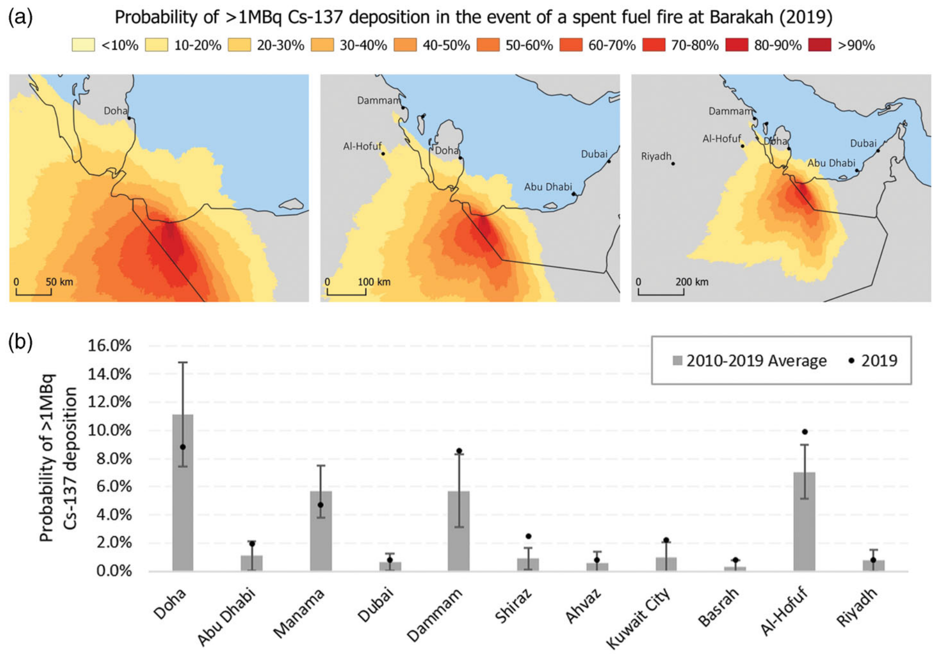

Figure 1. (a) Average probability contour distribution of cesium-137 contamination levels following a hypothetical SNF fire at the Barakah nuclear power plant in 2019; (b) Variation of the frequency of receiving cesium-137 contamination levels higher than 1.5 MBq/m^2 in major Gulf cities following an SNF pool fire at Barakah.

months (May to mid-September) seem to carry a considerably lower risk of cesium-137 contamination in major cities due to more favorable weather patterns. Of the studied cities, only Abu Dhabi received deposition levels higher than 1.5 MBq/m^2 during the releases modeled during the summer of 2019. The months in which the spread of radioactive contamination is most likely to impact population centers are January and February.

Bushehr

Similar to the modeling approach followed above for Barakah, the level of cesium-137 contamination was modeled for hypothetical releases from the Bushehr nuclear power plant on each day from 2010 to 2019. As shown in Figure 2, the results indicate that contamination over 1.5 MBq/m^2 is projected to be far less widespread than in the case of Barakah, with the most commonly impacted areas along the north coast of the Gulf. Consequently, the likelihood of large cities requiring relocation is considerably lower than in the modeled fires at Barakah. The city most likely to be impacted is Shiraz, which received contamination levels higher than 1.5 MBq/m^2 in around 2% of the simulation runs. Basrah, Ahvaz, and Kuwait City are also vulnerable, although with a low probability. Cities in Saudi Arabia, Qatar, and Bahrain tend to avoid contamination.

The daily impact of cesium-137 contamination resulting from a hypothetical spent fuel pool fire at Bushehr in 2019 (available in the online supplemental material) also confirms the lower impact of Bushehr compared to Barakah on the major Gulf cities. The same characteristic of lower contamination during the summer months is also observed in the case of Bushehr. However, the relatively high population density of Bushehr's immediate vicinity (Bushehr province had a population of over 1.1 million at Iran's last census in 2016, with a population density of 64/km^2) would still be a major concern in the event of a spent fuel fire, especially during summer months when wind intensity is low.[58] In contrast, the Western Region of Abu Dhabi, where Barakah is located, has a population of just over 200,000 with a density of only around 6/km^2.

Discussion

Vulnerability and risk factors of nuclear accidents in the Gulf

In the context of the analysis presented here, the identified threat is for a city in the Gulf to receive cesium-137 deposition higher than 1.5 MBq/m^2, the threshold above which a city-wide relocation would be needed to avoid

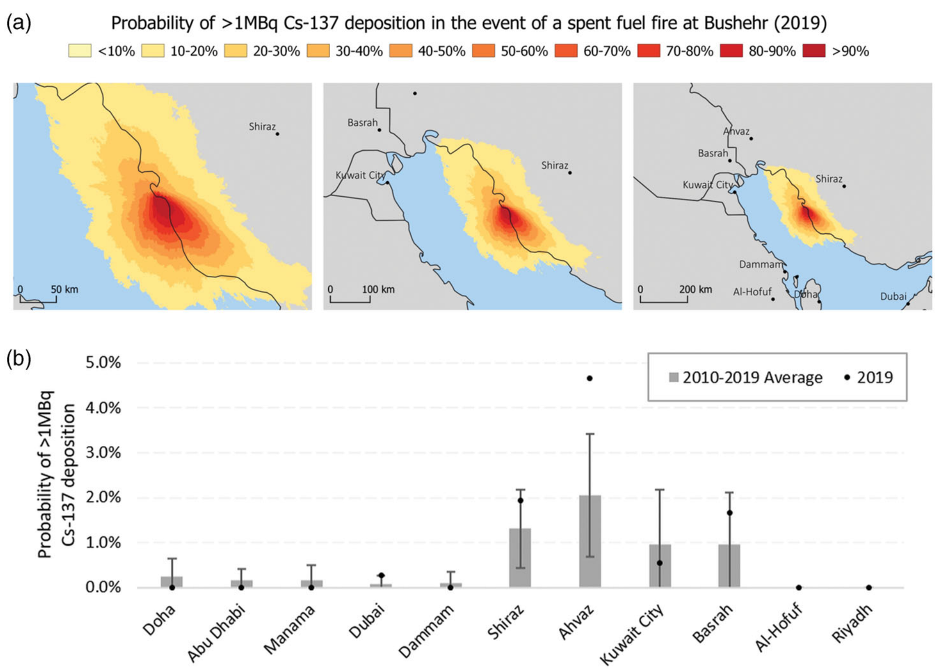

Figure 2. (a) Average probability contour distribution of cesium-137 contamination levels following a hypothetical SNF fire at the Bushehr nuclear power plant in 2019; (b) Variation of the frequency of receiving cesium-137 contamination levels higher than 1.5 MBq/m^2 in most impacted Gulf cities.

grave public health consequences. The likelihood that cities in the Gulf receive such a dose is extracted from the simulation results reported in the Results section above.

Since cesium distributes relatively homogenously throughout human visceral and muscle tissues, the use of an effective dose is an appropriate measure of its health impact.[59] The effective dose can be obtained by multiplying the activity within a specific spatial zone (or city) by the corresponding dose factor, which would depend on age and exposure time, among other factors. The effective dose of cesium-137 can be extracted from available dose coefficient data provided by the International Commission on Radiological Protection (ICRP).[60] The ICRP effective dose coefficient for cesium-137 over a period of one year ranges between 1×10^{-7} and 1.2×10^{-8} Sv/Bq.

One can estimate the one-year ingestion effective dose for an adult in the most impacted cities, Doha (via Barakah) and Ahvaz (via Bushehr), based on their modeled maximum activity values of 44 and 3 MBq/m^2, respectively. The estimated corresponding effective dose range would be 0.5–4.4 mSv for Doha; and 0.04–0.3 mSv for Ahvaz. At these low dose ranges, it would be hard to quantify public health risks. The effective dose values in the vicinity of both Barakah and Bushehr are expected to be much higher. It should be noted that the time distribution of the effective dose itself will also depend on other factors, such as protective interventions and decontamination efforts.

In terms of assessing "macro" vulnerabilities, three major proxy factors are used in this article: (1) population, which reflects the scale of public health challenges, relocation and resettlement, and economic activity; (2) water desalination dependency, which reflects the water security challenges that might arise due to water contamination and loss of desalination capacity; and (3) agricultural output, which sheds light on food security and economic challenges.

The number of impacted cities during each incident of radioactivity release and the corresponding probability of simultaneous relocation are shown in Figure 3. For most days (2,929 and 3,469 days for Barakah and Bushehr, respectively, out of a total of 3,650 days from 2010 to 2019), the simulated release of cesium-137 does not require relocation of any major Gulf city's population. In the remaining days, simulations show release levels that would result in the forced relocation of at least one major city. In the Barakah simulations, the probability of requiring a multi-city relocation decreases significantly as the number of exposed cities increases. In 511 runs, only one city is impacted (with a population range of 0.6–7.2 million). In a further 132 runs, two cities are simultaneously impacted (with a high variability of the population between 1.3 and 4.4 million). As for

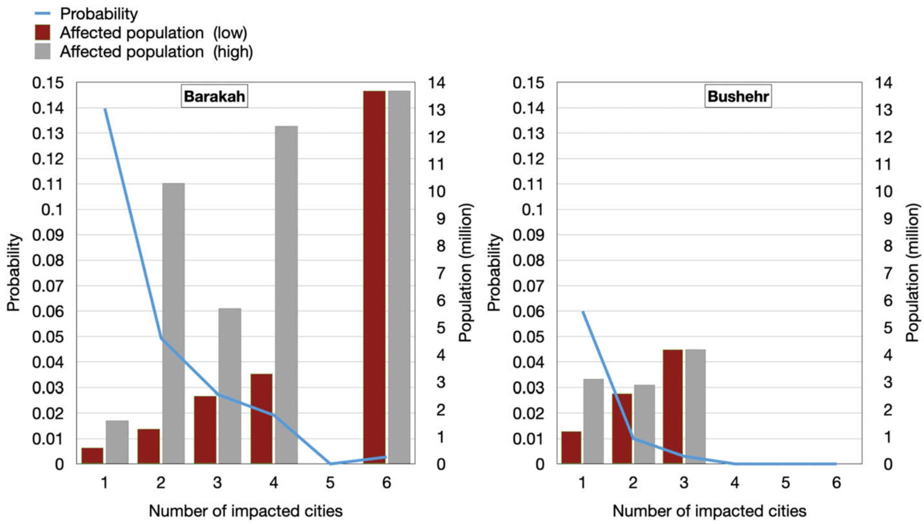

Figure 3. Probability and scale of impact of radiation exposure from SNF radiation release from Barakah and Bushehr based on 2010–2019 weather data.

Bushehr, in the 2010–2019 simulations, the number of impacted cities was much lower. In 176 runs, one city is impacted with a population range between 0.6 and 3.1 million. In only six runs, two cities are impacted with a total population between 1.3 and 4.5 million.

The public health risk for each city, shown in Figure 4, is the product of a city's probability of receiving cesium-137 contamination levels higher than 1.5 MBq/m^2 with its normalized population (see Annex A). As shown in Figure 4, Qatar's capital, Doha, and Saudi cities (particularly Dammam and Al-Hofuf) are particularly vulnerable to the public health effects of an SNF fire radiation release from Barakah. In the case of a Bushehr release, the most impacted city is Shiraz, but Kuwait City, Iraq's Basrah, and Iran's Ahvaz are also vulnerable.

The relative risk of water contamination can be assessed for major Gulf cities using the same approach (Figure 5). The water security risk is the product of a city's probability of receiving cesium-137 contamination levels higher than 1.5 MBq/m^2 with its normalized desalinated water capacity (see Annex A). By far, the most vulnerable Gulf city to water security issues resulting from contamination of Gulf waters by cesium-137 is Doha because of its near-complete dependency on water desalination and the high probability of exposure over 1.5 MBq/m^2. Some desalination plants are capable of removing cesium from seawater alongside sodium, either through coagulation and sedimentation or reverse osmosis, but in the event of direct fallout, plant operations would be interrupted as workers are evacuated.[61] Gulf cities that rely heavily on water desalination (Doha, Abu Dhabi, Dubai, Manama, Sharjah) only have a few days of storage capacity,

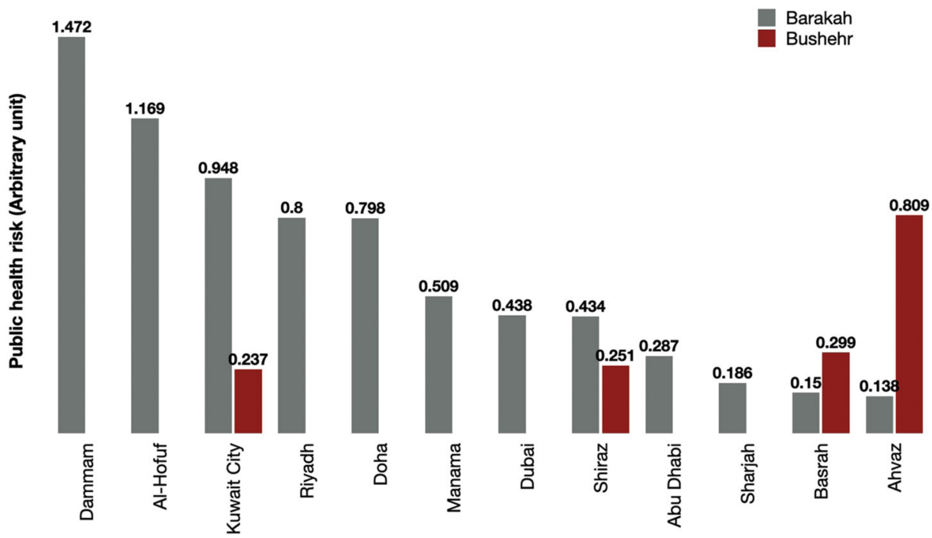

Figure 4. Population risk profile due to radiation exposure from SNF radiation release from Barakah and Bushehr in major Gulf cities based on 2010–2019 weather data.

so even a temporary shutdown in water production could have severe impacts.

It should be noted that, ultimately, all Gulf cities that rely on water desalination for their water supply will be impacted by cesium-137 contamination of water. Cesium-137 is soluble in seawater in its hydroxide form and can be spread across the Gulf's shores both by deposition, as modeled in our simulations, and by ocean transport. Because of this, even regional desalination plants which would continue to operate normally after a spent fuel fire have to contend with elevated cesium concentrations in their brine and sludge waste. In Japan, where cesium-137 levels in seawater declined quickly due to ocean currents, the Ozaku Purification Plant was unable to recycle and utilize its waste sludge for over a year after the Fukushima incident.[62] Contamination of surface freshwaters, such as rivers and lakes is also possible.[63] Surface water contamination would be particularly relevant to Iran's Ahvaz and Shiraz and Saudi Arabia's Al-Hofuf.

The third component of the relative risk assessment is the potential for food security shocks due to air, water, and soil contamination, which could impact agriculture. The ingestion pathway can be responsible for more widespread impacts from the disaster than fallout alone, as food grown in contaminated soil can be harvested and broadly distributed, similar to what happened at Fukushima. The vulnerability of Gulf cities to food security shocks as a result of a spent fuel fire is shown in Figure 6. The food security risk is the product of a city's probability of receiving cesium-137 contamination levels higher than 1.5 MBq/m^2 and its normalized agriculture share of GDP (see Annex A).

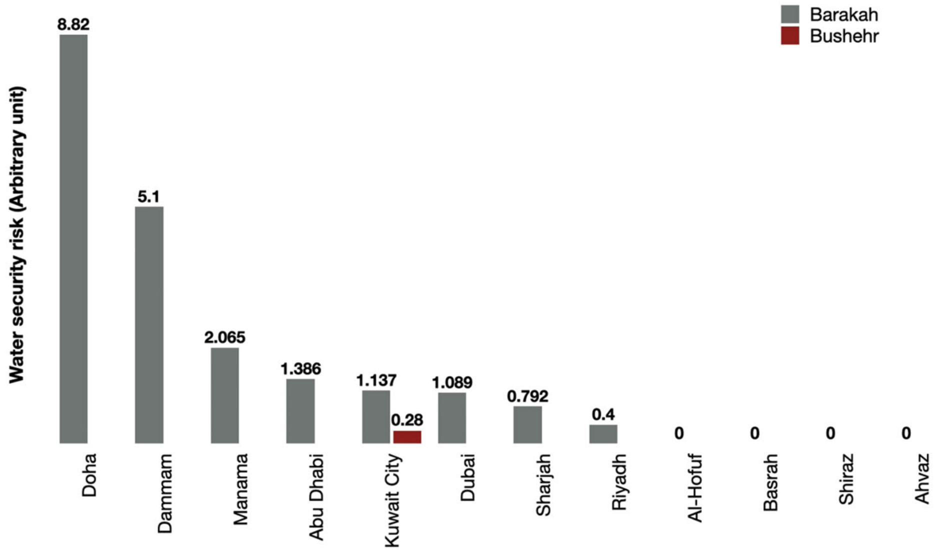

Figure 5. Water security risk profile due to radiation exposure from SNF radiation release from Barakah and Bushehr in major Gulf cities (dry deposition only) based on 2010–2019 weather data.

As shown in Figure 6, in the case of a Bushehr-based accident, the Gulf cities most vulnerable to food security shocks are Iran's Shiraz and Ahvaz because of their significant agricultural activity. Iraq's Basrah could also face a food supply shock because of its higher agricultural output in comparison to other Gulf cities. From Barakah, Dammam and Al-Hofuf are also vulnerable to various degrees of food security shocks. The fishery sector, across the Gulf, would likely also be disrupted. In the Fukushima case, although radiocesium activity was reduced rapidly due to ocean processes, it took four years for radiocesium levels to fall below regulatory limits.[64] In the Gulf, complete elimination of radiocesium in seawater might take even longer due to slower water diffusion processes.[65]

The three risk factors considered here may be interactive. If a city's population is relocated due to widespread contamination, the risk factors for both food and water become less significant as there is no longer a local population dependent on these resources. However, the loss of food and water production will impact other cities in the region (Abu Dhabi's water network is, for example, connected to Fujairah's) since those cities may need to provide for relocated populations. If a major city (or, for some of the smaller countries in the Gulf, the only city) is evacuated, economic activity would halt almost immediately. Because of the outsized economic harm that this could cause, and due to the enormous challenges associated with relocating potentially millions of people, a state may decide not to relocate the population but instead to accept the higher health risks

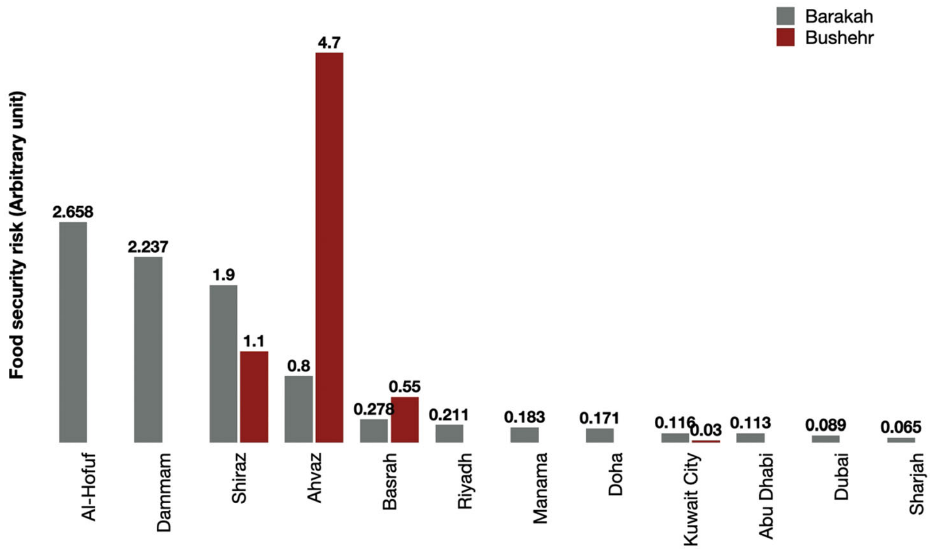

Figure 6. Food security risk profile due to radiation exposure from SNF radiation release from Barakah and Bushehr in major Gulf cities based on 2010–2019 weather data.

resulting from the fallout. Similarly, the loss of food or water production from an area could have such high costly impacts that governments might decide to raise radioisotope limits in food and water rather than abandon the resources. The margin for tolerance above the expected 1.5 MBq/m^2 threshold is likely to increase with the importance of the cities and resources affected and the cost of replacing them.

Conclusions

Several major cities in the Persian Gulf would be at risk in the event of a spent fuel fire. Due to its large wet storage facilities, the Barakah plant would present a considerably larger threat than Iran's Bushehr facility. In the case of a spent fuel fire at either of these sites, there is a small but significant risk that one or more major cities and smaller settlements in the region would receive levels of fallout that would contaminate food and water supplies and require relocating large numbers of people. Doha, Dammam, and Al-Hofuf are the most at-risk cities considering a combined public health, food security, and water supply impacts from a Barakah spent fuel pool fire. Relocation may also pose logistical challenges for these cities, as such operations would likely need to cross international borders – Qatar and Bahrain in particular have limited land to house evacuees. The most significant risks posed in the event of a spent fuel fire at the Bushehr plant are to the Iranian city of Shiraz, which would be particularly susceptible to public health and food security shocks. Iran's city of Ahvaz and Iraq's Basrah also would be susceptible to these impacts. In the event of a spent fuel pool fire at either Barakah or Bushehr, the common resources of the Gulf itself would suffer from significant radiological contamination, potentially spreading the impacts over a wider range of countries than the direct fallout.

The safest way to mitigate the risk of such disasters would be an agreement to end the deployment of nuclear energy in the Middle East and rely instead on the region's natural gas and renewable energy resources. Governments intent on pursuing nuclear power could reduce risks by timely transfer of spent fuel into dry cask storage, and ultimately into geological storage to avoid dense packing of spent fuel pools. Iran has agreed to transfer Bushehr's SNF to Russia and could seek to do so as soon as it has cooled sufficiently to do so safely. To further reduce accident risks, the construction quality and operational safety standards of existing and new plants in the region could be revisited, together with the IAEA and the participants in the JCPOA. States also should work to prevent future attacks on nuclear facilities; one model is a multilateral arrangement similar to the bilateral one reached between India and Pakistan. Finally, states could develop multilateral contingency plans for nuclear accidents and incidents involving potential radiation release in the region.

Data availability statement

Supporting data for this analysis are available in the article and the Supplementary materials.

Acknowledgment

The authors would like to thank the Middle East Initiative at Harvard University's Belfer Center for Science and International Affairs for supporting this research project.

Notes and References

1. Mycle Schneider et al., World Nuclear Industry Status Report 2020 (Paris: WNISR, 2020), 25–27. https://www.worldnuclearreport.org/-World-Nuclear-Industry-Status-Report-2020-.html.
2. Mohammad Al-Saidi and Mehran Haghirian, "A Quest for the Arabian Atom? Geopolitics, Security, and National Identity in the Nuclear Energy Programs in the Middle East," *Energy Research & Social Science* 69 (2020): 101582. https://doi.org/10.1016/j.erss.2020.101582; Ali Ahmad, *Energy Transitions in the Gulf: Key Questions on Nuclear Power*. Gulf Research Center, 2018, 25; Ephraim Asculai, "Nuclear Power in the Middle East," *The Nonproliferation Review* 19 (2012): 391–400. https://doi.org/10.1080/10736700.2012.734187; Carah Ong, "The Growing Danger of a Nuclear Middle East," *Middle East Report* 247 (June 2008). https://merip.org/2008/06/the-growing-danger-of-a-nuclear-middle-east/; Henry D. Sokolski, *Nuclear Power's Global Expansion: Weighing Its Costs and Risks*. Strategic Studies Institute, U.S. Army War College, 2010, 24.

3. Frank N. von Hippel and Michael Schoeppner, "Reducing the Danger from Fires in Spent Fuel Pools," *Science & Global Security* 24 (2016): 141–173. https://doi.org/10.1080/08929882.2016.1235382.
4. von Hippel and Schoeppner, Reducing the Danger, op. cit., 163–164; Frank von Hippel, Masafumi Takubo, and Jungmin Kang, "A Much Worse Accident That Almost Happened in Fukushima: A Fire in a Dense-Packed Spent-Fuel Pool," in *Plutonium: How Nuclear Power's Dream Fuel Became a Nightmare*, edited by Frank von Hippel, 81–97. Singapore: Springer, 2019. https://doi.org/10.1007/978-981-13-9901-5_5.
5. Makiko Tazaki and Yusuke Kuno, "Feasibility Analysis of Establishing Multilateral Nuclear Approaches (MNAs) in the Asian Region and the Middle East," *Sustainability* 6 (2014): 9398–9417. https://doi.org/10.3390/su6129398; Michael Schoeppner, "Detecting Clandestine Reprocessing Activities in the Middle East," *Science & Global Security* 26 (2018): 3–19. https://doi.org/10.1080/08929882.2018.1446540.
6. Névine Schepers, *Russia's Nuclear Energy Exports: Status, Prospects and Implications*. Stockholm, SIPRI, 2019, 3. https://www.sipri.org/publications/2019/eu-non-proliferation-and-disarmament-papers/russias-nuclear-energy-exports-status-prospects-and-implications.
7. Schneider et al., *World Nuclear Industry*, op. cit.
8. JCPOA, "Joint Comprehensive Plan of Action," 25, 2015. https://www.europarl.europa.eu/cmsdata/122460/full-text-of-the-iran-nuclear-deal.pdf.
9. "U.S.-UAE Agreement for Peaceful Nuclear Cooperation (123 Agreement)," U.S. Department of State, 15 January 2009. https://2001-2009.state.gov/r/pa/prs/ps/2009/01/114262.htm; Christopher M. Blanchard and Paul K. Kerr, *The United Arab Emirates Nuclear Program and Proposed US Nuclear Cooperation*. CRS Report, Library of Congress. 2010, 7. https://www.files.ethz.ch/isn/110029/154163.pdf
10. "Managing Used Nuclear Fuel," Emirates Nuclear Energy Corporation (ENEC), 2020. https://www.enec.gov.ae/discover/fueling-the-barakah-plant/managing-used-nuclear-fuel/.
11. Ali Ahmad, "The Saudi Proliferation Question," *Bulletin of the Atomic Scientists*, 17 December 2013. https://thebulletin.org/2013/12/the-saudi-proliferation-question/; Schneider et al., *World Nuclear Industry*, op. cit.
12. Frank N. von Hippel and Michael Schoeppner, "Economic Losses From a Fire in a Dense-Packed U.S. Spent Fuel Pool," *Science & Global Security* 25, 2 (May 2017): 80–92. https://doi.org/10.1080/08929882.2017.1318561.
13. Jessica Veliscek-Carolan, "Separation of Actinides from Spent Nuclear Fuel: A Review," *Journal of Hazardous Materials* 318 (November 2016): 266–281. https://doi.org/10.1016/j.jhazmat.2016.07.027.
14. National Research Council, *Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report*, 50 (Washington, DC: The National Academies Press, 2006). https://doi.org/10.17226/11263.
15. United Nations, *Sources, Effects and Risks of Ionizing Radiation* (New York: United Nations, 2013), 40. https://www.unscear.org/docs/publications/2013/UNSCEAR_2013_Annex-A-CORR.pdf.
16. E. Browne and J. K. Tuli, "Nuclear Data Sheets for A = 137," *Nuclear Data Sheets* 108, 10 (October 2007): 2173–2318. https://doi.org/10.1016/j.nds.2007.09.002; H. L. Finston and M. T. Kinsley, *The Radiochemistry of Cesium*, 13 (United States: U.S. Atomic Energy Commission 1961). https://doi.org/10.2172/4003916.

17. Organisation for Economic Co-operation and Development, *Chernobyl: Assessment of Radiological and Health Impacts*, 34 (Paris: OECD Publishing, 2003). https://doi.org/10.1787/9789264184879-en.
18. Edward D. Throm, "Beyond Design Basis Accidents in Spent-Fuel Pools — Generic Issue 82," *Nuclear Engineering and Design* 126, 3 (May 1991): 333–359. https://doi.org/10.1016/0029-5493(91)90024-C.
19. Robert Alvarez et al., "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," *Science & Global Security* 11, 1 (January 2003): 1–51. https://doi.org/10.1080/08929880309006; Jan Beyea, Ed Lyman, and Frank Hippel, "Damages from a Major Release of 137Cs into the Atmosphere of the United States," *Science & Global Security* 12, 1–2 (January 2004): 125–136. https://doi.org/10.1080/08929880490464775.
20. A. A. Lukk and Yu. L. Rebetsky, "Modern Geodynamics and Focal Mechanisms of Earthquakes near the Bushehr Nuclear Power Plant," *Izvestiya, Atmospheric and Oceanic Physics* 54, 10 (December 2018): 1477–1489. https://doi.org/10.1134/S0001433818100055; Nader Davoudi et al., "Aftershock Probabilistic Seismic Hazard Analysis for Bushehr Province in Iran Using ETAS Model," *Natural Hazards* 100, 3 (February 2020): 1159–1170. https://doi.org/10.1007/s11069-020-03854-8.
21. Mohammad Heidarzadeh et al., "Meteorological Tsunami of 19 March 2017 in the Persian Gulf: Observations and Analyses," *Pure and Applied Geophysics* 177, 3 (March 2020): 1231–1259. https://doi.org/10.1007/s00024-019-02263-8.
22. Amir Salaree, Reza Mansouri, and Emile A. Okal, "The Intriguing Tsunami of 19 March 2017 at Bandar Dayyer, Iran: Field Survey and Simulations," *Natural Hazards* 90, 3 (February 2018): 1277–1307. https://doi.org/10.1007/s11069-017-3119-5.
23. von Hippel, Takubo, and Kang, A Much Worse Accident, op. cit., 84; Frank von Hippel, Masafumi Takubo, and Jungmin Kang, *Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of U.S. Nuclear Plants: Phase 2* (Washington, D.C.: National Academies Press, 2016), 36. https://doi.org/10.17226/21874; United States Department of Energy, Sandia National Laboratories, Randall Gauntt, et al., *Fukushima Daiichi Accident Study: Status as of April 2012.* 195 (2012). https://doi.org/10.2172/1055601.
24. Kamal Hadad and Navid Ayobian, "Fuel Burnup and Fuel Pool Shielding Analysis for Bushehr Nuclear Reactor Vver-1000," *International Journal of Modern Physics E* 15, 04 (June 2006): 925–938. https://doi.org/10.1142/S0218301306004624; KEPCO, *APR-1400 Design Control Document Tier 2. Chapter 3: Design of Structures, Systems, Components and Equipment* (Korea Electric Power Corporation & Korea Hydro and Nuclear Power Co., 2018), 38–53. https://www.nrc.gov/docs/ML1822/ML18228A650.pdf.
25. Paul Dorfman, *Gulf Nuclear Ambition: New Reactors in United Arab Emirates*, 2 (The Nuclear Consulting Group, 2020).
26. Strategic Comments, "Iran Dismisses Post-Fukushima Nuclear Rethink," *Strategic Comments* 17, 3 (May 2011): 1–3. https://doi.org/10.1080/13567888.2011.581851.
27. von Hippel and Schoeppner, Economic Losses, op. cit., 89.
28. Alvarez et al., Reducing the Hazards, op. cit.; von Hippel, Takubo, and Kang, Lessons Learned, op. cit., 36; J. Sam Armijo and Allison M. Macfarlane, *Staff Evaluation and Recommendation for Japan Lessons-Learned Tier 3 Issue on Expedited Transfer of Spent Fuel* (December 18, 2013).
29. ICRC, Treaties, States Parties, and Commentaries – Additional Protocol (I) to the Geneva Conventions, 1977, 2021. https://ihl-databases.icrc.org/ihl/INTRO/470.
30. UNSCR, Security Council Resolution 487, 1981. http://unscr.com/en/resolutions/487.

31. IAEA, Protection of Nuclear Installations Devoted to Peaceful Purposes against Armed Attacks, 1983. https://www.iaea.org/sites/default/files/gc/gc27res-407_en.pdf.
32. Whitney Raas and Austin Long, "Osirak Redux? Assessing Israeli Capabilities to Destroy Iranian Nuclear Facilities," *International Security* 31, 4 (2007): 7–33. https://muse.jhu.edu/article/213649.
33. Reuters, "UAE denies Yemen's Houthis have fired missile toward UAE," *Reuters*, December 3, 2017. https://es.reuters.com/article/us-yemen-security-emirates-denial-idUSKBN1DX0DD; START, *Nuclear Facilities Attack Database (NuFAD)*, 2020. https://www.start.umd.edu/nuclear-facilities-attack-database-nufad.
34. Anna Ahronheim and Udi Shaham, "Syrian Missile Lands near Dimona Nuclear Reactor, Interception Fails," *The Jerusalem Post*, April 22, 2021. https://www.jpost.com/breaking-news/alarms-sound-in-south-of-israel-665953.
35. Oliver Holmes, "Israel Confirms It Carried out 2007 Airstrike on Syrian Nuclear Reactor," *The Guardian*, March 21, 2018. http://www.theguardian.com/world/2018/mar/21/israel-admits-it-carried-out-2007-airstrike-on-syrian-nuclear-reactor.
36. Reuters, "Gaza Militants Launch Rockets towards Israel's Dimona Nuclear Site," *Reuters*, July 9, 2014. https://www.reuters.com/article/us-palestinians-israel-dimona-idUSKBN0FE20I20140709.
37. Tracey Shelton, "The Legacy of Iraq's Bombed Nuclear Plant," *The World from PRX*, 2011. https://www.pri.org/stories/2011-06-12/legacy-iraqs-bombed-nuclear-plant.
38. David K. Shipler, "Israeli Jets Destroy Iraqi Atomic Reactor; Attack Condemned by U.S. and Arab Nations," *The New York Times*, June 9, 1981. https://www.nytimes.com/1981/06/09/world/israeli-jets-destroy-iraqi-atomic-reactor-attack-condemned-us-arab-nations.html.
39. Martin B. Malin, "Nuclear Energy in the Middle East? Regional Security Cooperation Needed," *Belfer Center*, 2017. https://www.belfercenter.org/publication/nuclear-energy-middle-east-regional-security-cooperation-needed.
40. James P. Farwell and Rafal Rohozinski, "Stuxnet and the Future of Cyber War," *Survival* 53, 1 (February 2011): 23–40. https://doi.org/10.1080/00396338.2011.555586.
41. Alexandra Van Dine, Michael Assante, and Page Stoutland, *Outpacing Cyber Threats: Priorities for Cybersecurity at Nuclear Facilities* (Washington, DC: NTI, 2016), 31. https://www.nti.org/analysis/reports/outpacing-cyber-threats-priorities-cybersecurity-nuclear-facilities/.
42. Van Dine, Assante, and Stoutland, *Outpacing Cyber Threats*, op. cit., 31.
43. von Hippel, Takubo, and Kang, Lessons Learned, op. cit., 186; Trevor MacLean, Robert Borrelli, and Michael Haney, "Cyber Security Modeling of Non-Critical Nuclear Power Plant Digital Instrumentation," In *Critical Infrastructure Protection XIII*, edited by Jason Staggs and Sujeet Shenoi, 87–100. Cham: Springer International Publishing, 2019. https://doi.org/10.1007/978-3-030-34647-8_5.
44. Burrus M. Carnahan, "Protecting Nuclear Facilities from Military Attack: Prospects after the Gulf War," *The American Journal of International Law* 86, 3 (1992): 524–541. https://www.jstor.org/stable/2203966.
45. FAS, "Agreement on the Prohibition of Attack Against Nuclear Installations and Facilities," 2021. https://fas.org/nuke/guide/india/doctrine/nucl.htm.
46. Sweng-Woong Woo et al., *Design Description and Comparison of Design Differences between APR1400 Plants* (United States: Nuclear Energy Agency, 2018). https://www.oecd-nea.org/mdep/documents/TR-APR1400-01%20Design%20Description%20and%20Comparison%20of%20Design%20Differences.pdf; IAEA, *Management of Spent Fuel from Nuclear Power Reactors Learning from the Past, Enabling the Future.* (Vienna: IAEA, 2020). http://public.eblib.com/choice/PublicFullRecord.aspx?p=6244680.

47. Sara Al Saadi and Yongsun Yi, "Dry Storage of Spent Nuclear Fuel in UAE – Economic Aspect," *Annals of Nuclear Energy* 75 (January 1, 2015): 527–535. https://doi.org/10.1016/j.anucene.2014.09.003; Robert Rosner and Rebecca Lordan, "Why America Should Move toward Dry Cask Consolidated Interim Storage of Used Nuclear Fuel," *Bulletin of the Atomic Scientists* 70, 6 (November 2014): 48–62. https://doi.org/10.1177/0096340214555107.
48. F. Michel-Sendis et al., "SFCOMPO-2.0: An OECD NEA Database of Spent Nuclear Fuel Isotopic Assays, Reactor Design Specifications, and Operating Data," *Annals of Nuclear Energy* 110 (December 2017): 779–788. https://doi.org/10.1016/j.anucene.2017.07.022.
49. Gauntt et al., Fukushima Daiichi Accident, op. cit.
50. Hadad and Ayobian, Fuel Burnup and Fuel Pool, op. cit.
51. Asghar Mohammadi, *Management of Spent Fuel from Bushehr Nuclear Power Plant* (Vienna: IAEA, 2016). https://nucleus.iaea.org/sites/connect/SFMpublic/TM%20Design%20Extension%20Conditions/10%20-%20IRAN%20-%20Mohammadi%20-%20spent%20fuel1.pdf.
52. Paul Kerr, "Iran, Russia Reach Nuclear Agreement," *Arms Control Association*, 2005. https://www.armscontrol.org/act/2005-04/iran-nuclear-briefs/iran-russia-reach-nuclear-agreement.
53. A. F. Stein et al., "NOAA's HYSPLIT Atmospheric Transport and Dispersion Modeling System," *Bulletin of the American Meteorological Society* 96, 12 (December 2015): 2059–2077. https://doi.org/10.1175/BAMS-D-14-00110.1.
54. von Hippel and Schoeppner, Reducing the Danger, op. cit, 166.
55. von Hippel and Schoeppner, Reducing the Danger, op. cit., 143.
56. von Hippel and Schoeppner, Reducing the Danger, op. cit., 154; Organisation for Economic Co-operation and Development, *Chernobyl*, op. cit., 39; von Hippel and Schoeppner, Economic Losses, op. cit., 82.
57. United Nations, *Sources, Effects and Risks*, op. cit., 193.
58. Statistical Center of Iran, Population and Housing Censuses, 2016. https://www.amar.org.ir/english/Population-and-Housing-Censuses.
59. World Health Organization, *Health Risk Assessment from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami, Based on a Preliminary Dose Estimation* (Geneva: WHO, 2013), 37. https://www.who.int/publications/i/item/9789241505130.
60. K. Eckerman, J. Harrison, H.-G. Menzel, C.H. Clement, "Compendium of Dose Coefficients based on ICRP Publication 60," *ICRP Publication* 119, Annual ICRP 41 Supplement (2012).
61. S. Kitada et al., "Removal of Radioactive Iodine and Cesium in Water Purification," *Desalination and Water Treatment* 54 (2015): 3494–501, https://doi.org/10.1080/19443994.2014.923205; Takao Sasaki et al., "Cesium (Cs) and Strontium (Sr) Removal as Model Materials in Radioactive Water by Advanced Reverse Osmosis Membrane," *Desalination and Water Treatment* 51, 7–9 (2013): 1672–1677. https://doi.org/10.1080/19443994.2012.704696.
62. Kitada et al., "Removal of Radioactive Iodine, op. cit., 3499.
63. Takahiro Nakanishi and Kazuyuki Sakuma, "Trend of 137Cs concentration in river water in the medium term and future following the Fukushima nuclear accident," *Chemosphere* 215 (2019): 272–279. https://doi.org/10.1016/j.chemosphere.2018.10.017.
64. Takami Morita et al., "Impacts of the Fukushima Nuclear Accident on Fishery Products and Fishing Industry," In *Low-Dose Radiation Effects on Animals and Ecosystems: Long-Term Study on the Fukushima Nuclear Accident*, edited by Manabu Fukumoto, 31–41. Singapore: Springer, 2020. https://doi.org/10.1007/978-981-13-8218-5_3.

65. R. Michael Reynolds, "Physical Oceanography of the Gulf, Strait of Hormuz, and the Gulf of Oman—Results from the Mt Mitchell Expedition," *Marine Pollution Bulletin* 27 (1993): 35–59. https://doi.org/10.1016/0025-326X(93)90007-7.

Annex A. Vulnerability factors

Table A.1. Population distribution in major Gulf cities (Source: World Population Review, https://worldpopulationreview.com/).

City	Population	Normalized population
Doha	641,380	0.09
Manama	634,508	0.09
Dammam	1,252,523	0.17
Al-Hofuf	836,727	0.12
Abu Dhabi	1,482,816	0.21
Riyadh	7,231,447	1.00
Dubai	2,878,344	0.40
Sharjah	1,684,649	0.23
Kuwait City	3,114,553	0.43
Basrah	1,352,210	0.19
Shiraz	1,651,362	0.23
Ahvaz	1,244,250	0.17

Table A-2. Dependency on desalinated water supply in major Gulf cities.

City	Water desalination dependency (% of water supply)	Normalized desalinated water capacity
Doha	98%	0.98
Manama	35.60%	0.356
Dammam	60%	0.6
Al-Hofuf	0	0
Abu Dhabi	99%	0.99
Riyadh	50%	0.5
Dubai	99%	0.99
Sharjah	99%	0.99
Kuwait City	52%	0.517
Basrah	0%	0
Shiraz	0%	0
Ahvaz	0%	0

Table A.3. Agricultural output in major Gulf cities.

City	Agriculture share of GDP (%)	Normalized agriculture output
Doha	0.18%	0.019
Manama	0.30%	0.032
Dammam	2.50%	0.263
Al-Hofuf	2.50%	0.263
Abu Dhabi	0.77%	0.081
Riyadh	2.50%	0.263
Dubai	0.77%	0.081
Sharjah	0.77%	0.081
Kuwait City	0.50%	0.053
Basrah	3.30%	0.347
Shiraz	9.50%	1.000
Ahvaz	9.50%	1.000